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ECSC STEEL PROGRAMME

RESEARCH

DEVELOPMENT

81 • 90

Edited by J. FERRON

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Commission of the European Communities

ECSC STEEL

TEN YEARS OF RESEARCH AND DEVELOPMENT 1981-90

Edited by J. Ferron

«Nous ne coalisons pas des États,
nous unissons des hommes.»
(Jean Monnet, «Mémoires»)

The same is true of the activities of the European coal and steel community.

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Over the last decade, the European steel industry has been subject to profound changes, with, on the one hand, the modernization of production plants allowing high levels of productivity with large savings in energy and raw materials requirements to be achieved, and, on the other hand, the development of grades of steel for which the quality, dimensional tolerances and characteristics of use have, for many of them, little in common with previous products.

The R&D efforts undertaken by the European steel industry, despite the crisis which has prevailed for the greater part of this decade, have played a vital role in the success of these changes.

This report, which is illustrated and includes an extensive bibliography, will provide steelmakers as well as planners with greater details of the effort made over these years and will also help in locating the many references included in this document, both for the manufacture of steel as well as its use.

A special chapter is devoted to research work being carried out in parallel under several other ECSC programmes in the field of environmental protection and social research work: health and safety at work, ergonomics, industrial medicine, use of by-products.

It should be noted that the collaborative work that has been set up between Community researchers has also meant that redundancy of effort has been reduced, that much larger and longer-term projects which exceed individual financial capabilities have been able to be undertaken, and that it has also created suitable conditions for the development of a true European spirit, as demonstrated by many Community synergies.

Contents

The 'steel' research programme is a model of cooperation in industrial research. Its experience, stretching back over more than 35 years, makes it the doyen of all the Community research programmes.

The financial contribution of the Community towards steel research has increased during this period from USD 240 000 (original reference currency) to over ECU 45 million per year (1990), resulting from the levy as defined in the ECSC Treaty. This fund allows a certain number of new projects to be financed every year, which demonstrates the interest and efficiency of cooperation within the Community.

Through the scientific and technical progress achieved during this programme, the ECSC aims at:

(i) improving the international competitiveness of our industry, and in particular in the context of the creation of the single European market;

(ii) satisfying the requirements of society by improving the quality of life;

(iii) enhancing the technological choice within the Community by creating a large research base.

In order to achieve these objectives, the following actions have been undertaken:

(a) development of understanding of the characteristics of steel and its components;

(b) reduction of production and manufacturing costs;

(c) improvement in the quality and reliability of products;

(d) development of processes and products which are technically and economically ahead of those of the competition;

(e) strengthening standardization and increasing harmonization of standards and codes.

These actions are carried out within the current circumstances, not only economic but also social, of the Community, in so far as they are aimed at reducing energy and raw materials costs and are concerned with environmental protection and the quality of life in general.

In fact, the steel industry must adapt to new regulations, and thus conform with the resolution of the Council of Ministers, adopted on 7 February 1983, concerning the adoption and implementation of a policy and a programme of action involving environmental protection (1982-86). This resolution states that 'environmental policy is a structural policy which must be implemented independently of uncertainties in the economic climate', which increases preventive aspects and the need to integrate environmental protection into all other Community policies.

Nevertheless, if we consider that the fight against pollution has serious financial repercussions on production costs for steel industry products, then it is vital that the steel industry be helped to solve the problems with which it is confronted through a means of judicious allocation of Community funds. This will ensure that steel becomes a material with a greater added value within the connotation of overall quality. To ignore this state of affairs could, in the medium or long term, have not-inconsiderable consequences on the ability of European manufacturers to maintain their international competitiveness. This is why the objectives being aimed at in this field include:

(i) efficiency, safety and reliability of pollution control installations, with optimal cost;

(ii) savings in raw materials and energy costs;

(iii) elimination of the transfer of pollution from one phase to another (air/ground/water);

(iv) innovation in the field of 'clean technologies';

(v) utilization of advances made in the fields of new technologies (biotechnology, robotics, expert systems, etc.).

There remains much to do in Europe. A combined effort by the European steel industry is more than ever a vital factor in maintaining and improving this industrial base.

The 35 years' experience of the ECSC constitutes a model for the future, whose improvement must result in complete success.

The task is huge, but the will to succeed is just as great.

May this publication provide everyone with an indication of the progress made and of the challenges to be met in the years to come.

A. García Arroyo
Director of Technological Research

During the decade corresponding to the 1980s, the European steel industry has undergone marked changes. These are characterized by the modernization of the production tool allowing high performance to be achieved in both productivity and in energy and metal efficiency, and also by the production of steels in which for many the quality, the dimensional tolerances and the uses have little in common with the products originating during previous decades.

The endeavours in research and development which have been actively pursued by the European steel industry, despite the crisis which has deeply affected the first part of this period, have played an essential role in the success of these deep changes.

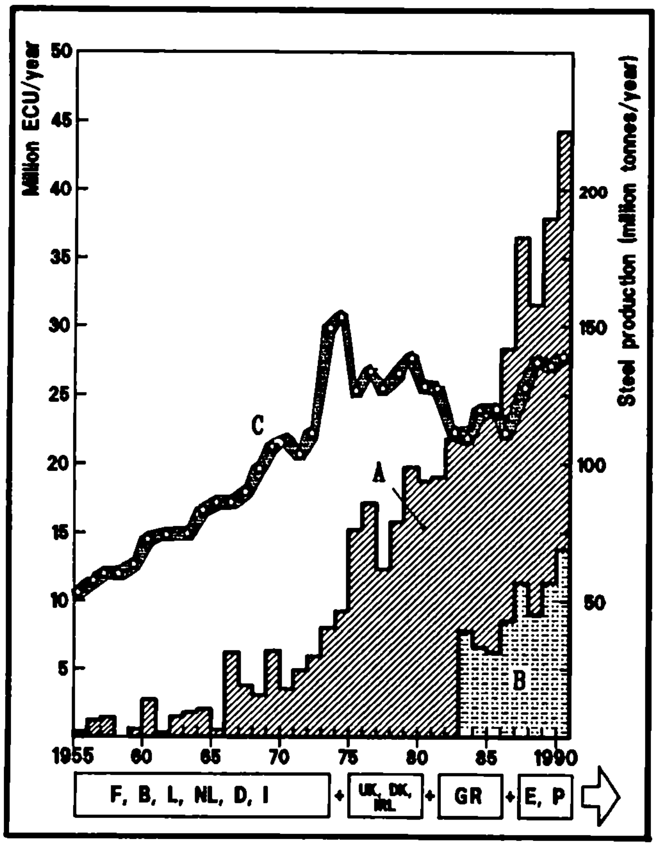
The ECSC has contributed to this success through the 'steel' research programme in addition to creating a specific pilot and demonstration programme intended to assist industry in bridging the critical stage between successful research and large-scale application.

It is also interesting to note that since its origin in 1951, the signatories of the Treaty of Paris which set up the ECSC had already foreseen the importance which research and development was to represent for the industries covered by the Treaty, since Article 55 of the Treaty required the High Authority to 'encourage technical and economic research concerning the production and development of the consumption of steel and coal, as well as the safety of workers employed in these industries'.

Nevertheless, the initial steps remained modest and the first steel programme to be adopted four years later, in 1955, comprised a total aid of USD 240 000. In practice, it was only from the middle of the 1960s that the system can be considered to be well established and contributing noticeably to the research effort launched by the European steel industry.

Following this period, support continued to grow with the years as the accompanying graph (Figure 0-1) shows in actual units of currency, although correction for depreciation does not alter the trend.

Figure 0-1
ECSC contribution to steel research funding



A – Total budget: Research + pilot and demonstration.
B – Pilot and demonstration budget.
C – ECSC steel production in million tonnes/year.

One of the undoubted successes of the ECSC during the major crisis of the steel industry during 1975 and the following years was the understanding that reduction of the research budget was not a logical move, contrary to the beliefs of many people.

This graph also shows the significant level of additional support provided by the pilot and demonstration programme from 1983 onwards.

Thus in 1990, support for research including the pilot and demonstration programme, reached ECU 45 million.

Involving industry in the ECSC financing system has, from the very start, meant it is represented on all the bodies represented in the assembly of organizations participating in the selection of research projects for support as well as in following up their implementation.

A permanent concertation has thus been set up between the steel industry and the Commission (initially the High Authority) for the management and evolution of these research programmes; and this structure is probably not entirely divorced from the remarkable capacities of adaptation of these programmes in response to the rapid technical changes occurring in our industry.

Projects presented to the Commission are examined by committees composed of experts of a very high level, each representing a country of the Community (CRT for the research programme, CDT for the pilot and demonstration programme).

Those projects which are accepted are then passed, before any official and definitive decision at Commission level, before the Consultative Committee of the ECSC, a body on which industry, the union bodies and the Commission are represented on an equal footing.

We should also mention the executive committees which are charged with following the progress of research, and if need be to reorient it; as well as the restricted groups for following the pilot and demonstration projects which have a greater requirement to protect their confidential nature.

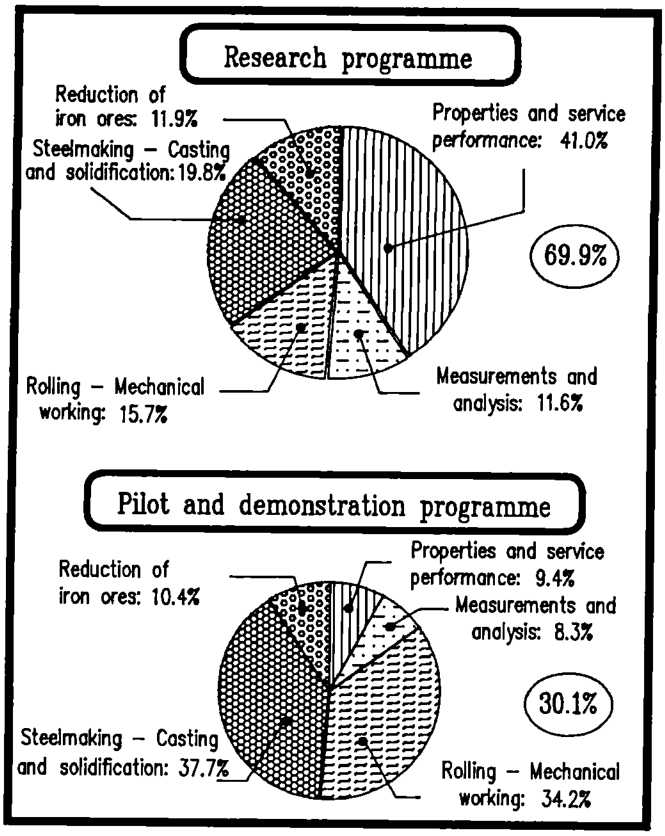
This is one of the aspects of the ECSC programmes which has contributed largely to its success.

In fact, the 15 executive committees and the six groups of experts each cover a specific technical field. They comprise specialists from various countries together with ECSC staff charged with following current research and they meet twice a year to examine the development of research work.

Besides the advantage of the soundness of decisions made, these committees have created contacts between the experts, who thus get to meet on a regular basis, which greatly exceed the restricted nature of the research projects involved. All the studies which have been carried out into the evaluation of the ECSC programmes have cited the existence of these contacts as one of the major spin-offs of these programmes.

The annual budgets committed to the research programme, and from 1983 onwards to the pilot and demonstration programme, have increased from ECU 19 to 45 million over the last decade. This represents, according to the year concerned, between 6 and 9% of the whole R&D budget of the European steel industry.

Figure 0-2
Distribution of ECSC funding by sector of activities (1988-90)



In total, the contribution made by the Commission to the research and pilot and demonstration programmes has reached ECU 292 million, compared with ECU 130 million for the previous decade.

The allocation to each of the technical sectors is shown in Figure 0-2.

Depending on the project, the ECSC contribution represents between 40 and 60% of the total budget. There are thus some 15% of the European steel industry programmes which are concerned with ECSC support for steel research.

In reality, the ECSC participation is much higher. In fact, this contribution is mainly applicable to the prospective field of the research programme, aimed at medium-term applications.

Using this definition, and removing from the global industrial programmes everything concerning the solution of local and specific problems, it is estimated that the ECSC support reaches, in one way or another, nearly half of the programmes in the industry which are of a general and prospective character.

At this level it is easy to understand that the ECSC support has been an important factor in the success of research and development in the Community steel industry over the last decades.

A short history of the evolution of the steel research programme of the ECSC shows that emphasis was initially laid on aspects of raw materials, iron ore and coke, and on the possibilities of increasing production of those tools producing cast iron and steel.

The decade of the 1960s saw this emphasis transferred to the pure oxygen-refining processes which were becoming common in the Community steel works, as well as continuous casting which was taking off. The developments in automation of production processes, from the blast furnace to the rolling mill, showed the need for reliable measurements which led to the setting-up of the metrology programmes. Community research into the properties of steel also started during this period.

The energy crisis which ensued in the middle of the 1970s deeply marked the decade. Efforts were naturally transferred to energy savings at each stage of production, and in general to cost reductions. At the same time stress was laid on improving both the quality and performance of products in order to increase the range of applications in the face of competitive materials (setting-up of coordinated transnational programmes such as offshore applications).

The period of the 1980s, which is the subject of this report, has confirmed the previous orientations.

Confronted by the vast increase in projects being submitted, the ECSC has increasingly strived to regroup them into coordinated programmes, leading on occasion to some 10 projects being carried out simultaneously in different laboratories.

A deliberate effort has been made to assist certain new technical developments: continuous casting of thin products, production of cast iron without using coke, artificial intelligence, etc.

Furthermore, it was deemed necessary to make a greater effort in supporting the development and industrialization phase of techniques arising from research. This led to the creation, mentioned above, of the steel pilot and demonstration programme aimed at contributing to the development of new techniques.

The results of the ECSC steel work are published in reports which are widely diffused within the Community. Some of these results are grouped together in the form of summary reports. In addition, annual congresses, which are held on specific subjects, allow specialists to learn of recent work being carried out and to compare their experiences.

The aim of this report is thus not to list the information already available concerning the work carried out between 1981 and 1990, but to present a certain number of significant results obtained for the different stages of steel production and in the research work carried out into the properties and uses of steel in its various fields of application.

A special chapter has been devoted to a review of the research programmes carried out in parallel by several of the ECSC programmes in the fields of the environment, and social research: safety, health, ergonomics, industrial medicine.

Introduction

In 1989, world production of raw steel attained 780 million tonnes, of which three-quarters were through the 'integrated' route of blast furnace/convertor, the remaining quarter being produced by the scrap/electric arc furnace route.

Progress made over the last few decades in operating blast furnaces has meant that the size of these units has increased considerably, currently exceeding 14 metres in hearth diameter, with production per unit exceeding 10 000 tonnes of hot metal per day.

In the industrialized countries, this has meant that the production of hot metal in a steel works is concentrated in a limited number of units, often numbering between one and three, which means that the regular operation of each unit becomes vital for satisfactory operation of the whole works.

One further specific characteristic is that the blast furnace alone consumes half of the energy requirements of the whole of the integrated works.

The integrated works is subject to increasing environmental restraints, of special concern to its associated operations of coke and sinter production.

These characteristics help to explain the importance of the hot metal sector in the ECSC research and pilot and demonstration programmes. These programmes are illustrated by a series of examples in the fields of coke plants, sinter plants and sand blast furnaces, while environmental aspects are covered in the chapter dealing with the whole of the steel industry.

1.1. Coke plant

Research work on metallurgical coke constitutes a significant part of the ECSC coal research programme, involving more than 10% of the budget of this programme over the last decade. A full report on this research will be published by the Commission in 1991 and observations in the present report will be limited to a résumé of this work.

The main objectives of this research financing were and continue to be:

(i) increasing the capacity and efficiency of coke ovens;

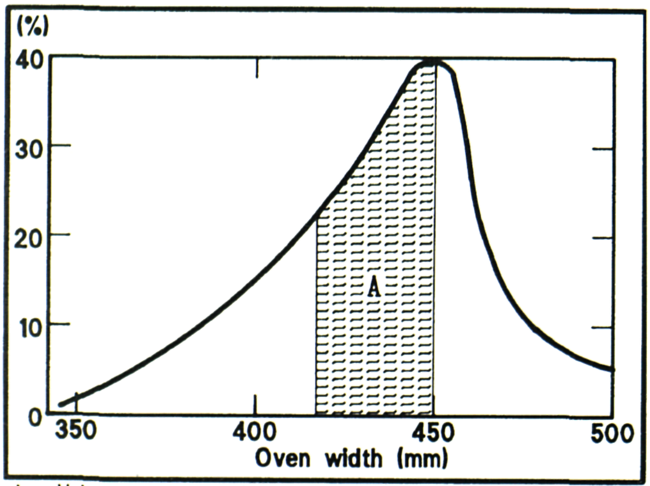
(ii) extending the range of coals suitable for coking;

(iii) maintaining and improving the quality of metallurgical coke;

(iv) solving problems of air and water pollution which result from coke plant operations.

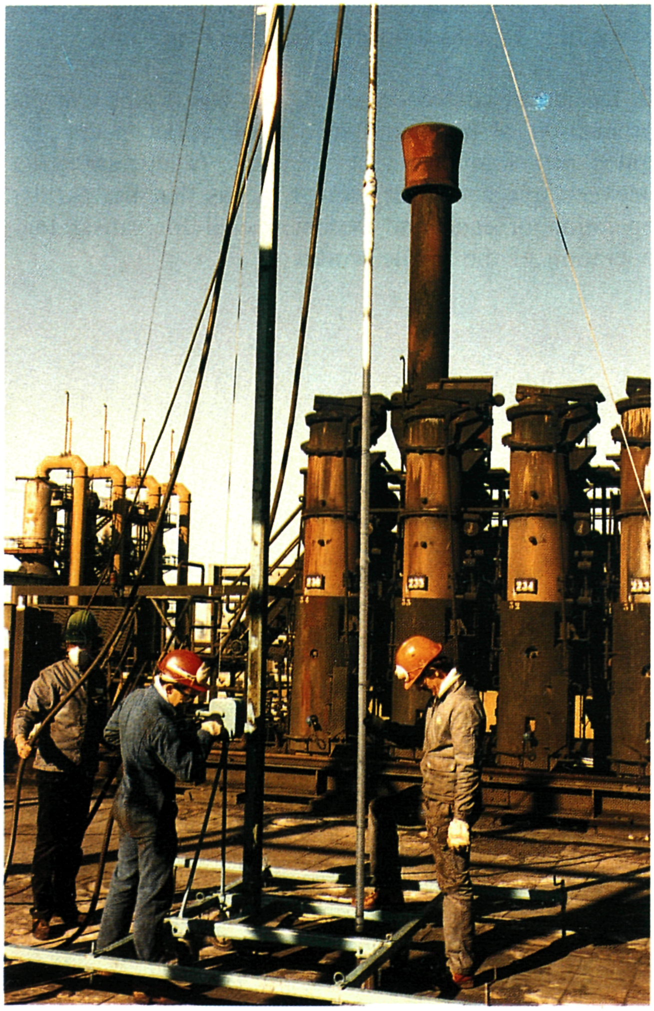
In view of the improved availability of coal supplies, less emphasis has been placed on the second of these objectives than in the past. Thus, for example, at the beginning of the decade concerned, the programme still included work involved with the production of formed coke from non-coking coal, a subject which is currently in abeyance. There is a continuing requirement to modify oven operating conditions to accommodate the different qualities of coal available on the market.

Figure 1-1
Cross section of coke ovens: statistical distribution world-wide
Ref. 1st International congress on the coke plant – Essen – 1987



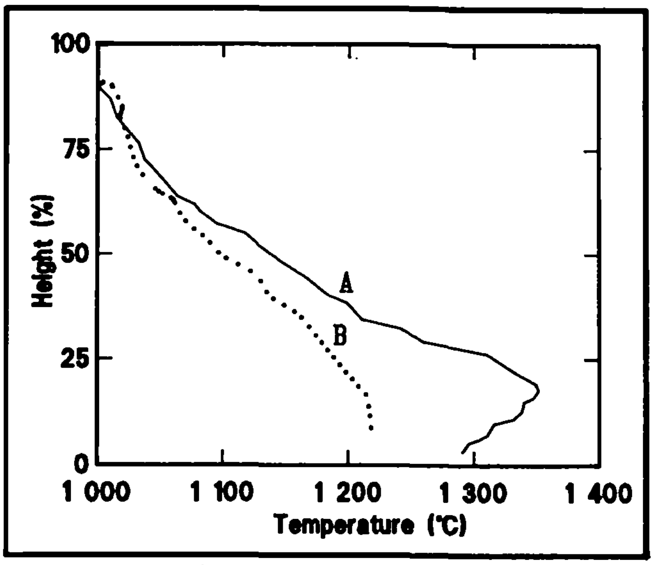
A – Main range.

Figure 1-2
Measurement of flame height using suction pyrometer

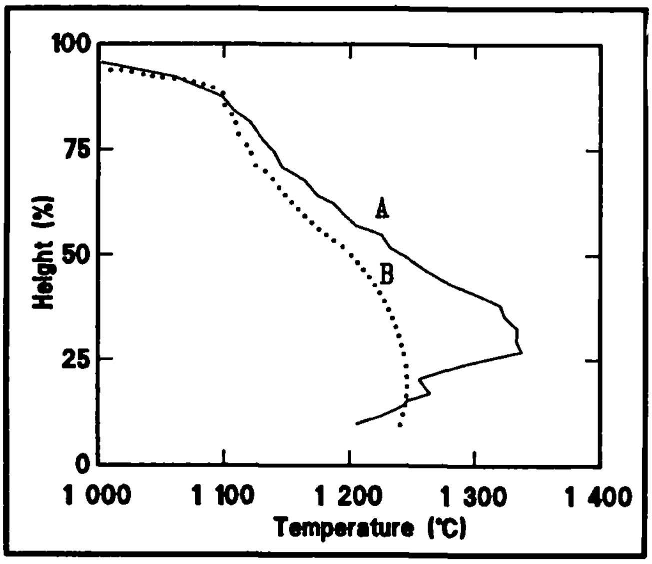


It goes without saying that pollution prevention constitutes a major aspect of research in the field of coke oven technology. It also forms an important part of other ECSC research programmes involving health

Figure 1-3a
Pyrofil probe: Measurement of vertical profiles — major fault in height regulation



A – T° flame. B – T° flue gas.



A – T° flame. B – T° flue gas.

.**Figure 1-3b**
Pyrofil probe: measurement of vertical profiles — correct regulation

and safety in the coal and steel industries, as discussed in Chapter 4 of this report.

Most research in the ECSC programme over the last decade has attempted either to improve economic aspects of coke production or to adapt the characteristics of metallurgical coke to user requirements. These activities may be considered under four closely linked headings:

(i) operation of coke works;

(ii) preparation and pre-treatment of coke mix;

(iii) coke quality;

(iv) by-products.

The trend towards using ovens which are taller and also of increasing width has led to major changes in the design of ovens. Whereas previously a width of 450 mm was considered standard, ovens with widths of 590 mm are currently being used (Figure 1-1). Research has been carried out into the effects of these changes on the quality of coke produced and into the operation of the coke ovens. It has, for example, been shown that wide ovens charged with pre-heated coal intended to complete their coking time within 24 hours can be operated without a night shift, leading to important reductions in production costs despite a certain decrease in specific production per oven. (1).

Work aimed at increasing capacity has included the fields of high conductivity refractory materials and research into methods of increasing the charging density using briquetting or by pelletizing part of the coal being used (2). Attention has also been paid to the problem of improving the homogeneity both of the charge and, as a consequence, of the coke produced. To achieve this, improved charging techniques have been investigated and a probe which is able to measure densities in an oven in operation has been able to be developed (3).

In previous years, pre-heating of coal has been studied extensively with the aim of increasing oven production and widening the range of coals suitable for coking. Less effort has been devoted to these developments over recent years, although its application in incorporating coals with low volatile content into continuous charging operations has been studied (4).

Attention has also been paid to various aspects of instrumentation and automation of oven operation. For example, the problem of ensuring that coking of the charge in the oven reaches the desired final temperature has been studied and, among other techniques, systems have been developed based on optical measurement of the temperature of the incandescent coke either directly on the coke cake when discharging, or in the quenching car (5). Industrial application of this method of checking the level of heating in the oven has considerably reduced scatter of the final coke temperatures (Figures 1-2, 1-3a, 1-3b, 1-4, and 1-5).

We should also mention the development and the validation of several simple and reliable tools for measuring the vertical thermal profile in coke ovens:

(i) the very long, suction pyrometer for measuring flame height directly in the flue (Figure 1-2);

(ii) the new flexible probe not requiring cooling for measuring the vertical profile on the inside of the flue, allowing the quality of the thermal regulation throughout the height of the oven to be evaluated (Figures 1-3a and 1-3b);

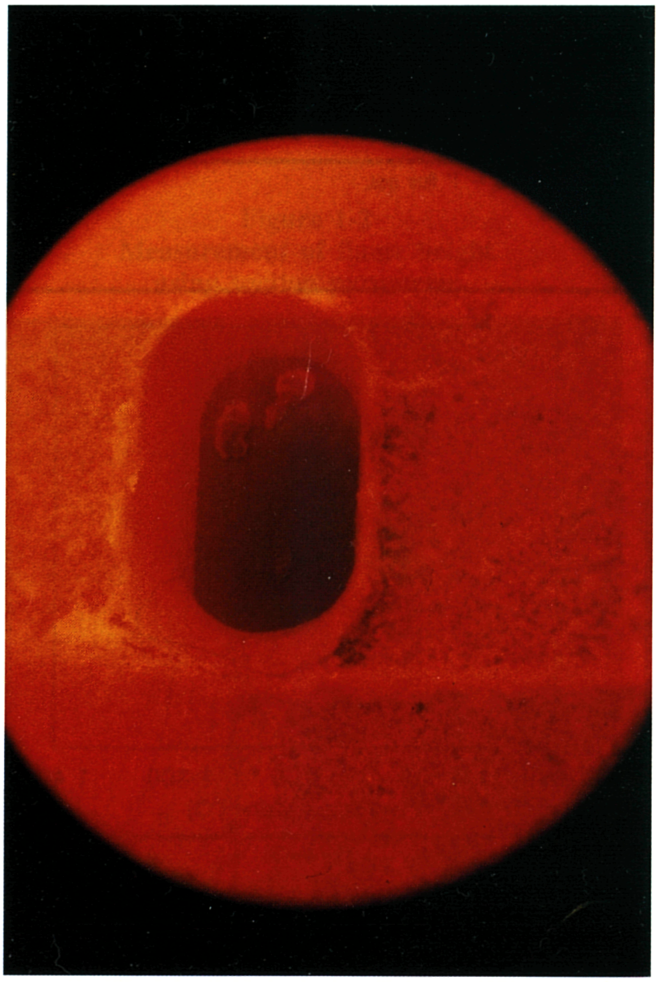
(iii) the application of rigid endoscopy techniques developed in power stations to the inspection of hot, incandescent components of the coke plant (Figures 1-4 and 1-5).

Part of the work has also been applied to improving material and energy balance in the coke works with the aim of improving production costs, especially through energy savings. As an example, dry quenching of coke (CDQ: coke dry quenching) provides advantages over traditional wet quenching techniques, not only in terms of energy recovery but also in the reduction of atmospheric emissions. The potential coke loss due to chemical reactions during dry quenching was studied together with the possibility of using heat recovered during this operation for pre-heating the coal charge (6).

Figure 1-4
Rigid endoscope

Due to the high investment costs for coke ovens, particular attention was paid to maintenance aspects. Research in this field covered repairing ovens while they are still hot, either by replacing refractory lining bricks, or by ceramic welding (7). Certain developments in the domain of coking technology have raised the problem of swelling and shrinking of the oven charge. It is known that excessive swelling, due mainly to the use of certain coals, creates thrust loading on the walls of the oven which can cause damage. On the other hand, insufficient shrinkage of the coke cake in the final stage of coking, or fracture of coke which is not strong enough at the moment that the oven is charged, can give rise to difficulties in discharging, such as damage to ovens and interruption of operations. A series of research projects led to a better understanding of the forces developed and the manner in which such problems can be predicted and avoided (8).

Figure 1-5
View from top of flue



A basic problem in a coke plant is to know what properties the coke must have in order to behave satisfactorily in the blast furnace, and how to produce a coke with these characteristics on the basis of the properties of the mix and of coking conditions.

In view of the intricacy and the heterogeneity, of both the raw materials and the end product, as well as the complexity of the physical and chemical processes of coking, it is probable that a complete answer to these questions will never be found. Nevertheless, substantial progress has been made through a series of research projects both at laboratory and larger scales.

One of the ultimate aims is to be able to predict both the behaviour during coking of new coal mixtures and the properties of the coke obtained, on the basis of a knowledge of the properties of the coals used in the mix.

While fundamental research into coking, including the study of phenomena in the plastic layer, has provided indications on the development of unwanted thrust forces in the ovens, on the shrinkage of the charge during the final phases of coking, as well as on the formation of coke and its end properties, it is nevertheless still necessary, in practice, to carry out pilot coking tests in a pilot oven, which is costly in terms of both time and money.

It is recognized that these pilot tests cannot exactly reproduce the conditions prevailing in industrial ovens and this problem of extrapolation of the results from pilot ovens has been the subject of a research project (9).

The test results depend to a large extent on the operating techniques and the coking conditions employed, and a project which commenced towards the end of the decade is intended to carry out a detailed comparison of thrust values measured on the walls by using the various pilot ovens available within the ECSC (10). At the same time, another project is aimed at developing a test at laboratory scale which is able to provide firm and reliable indications of this phenomenon (11).

Later on in this chapter there is a description of the results of research carried out during this decade within the framework of ECSC steel research into the complex problems involved in the behaviour of coke in the blast furnace.

The fourth line of research, that of by-products, is of less direct concern to the subject of this report. Information on this subject will be provided in the forthcoming publication on ECSC research in the domain of coke.

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(9) 7220-EB/134 — StBV: 'Verfahrenstechnische Grundlagen zum Scale-up halbtechnischer Verkokungsversuche'.

(10) 7220-EB/838 British Steel: 'Comparison of wall pressures developed in different test ovens'.

(11) 7220-EB/833 — BCC: 'Small-scale assessment of coking charges'.

1.2. Sintering

Strand sintering has undergone major changes over the last decade, driven by several objectives:

(i) the need to decrease fuel consumption in order to improve sintering production costs;

(ii) the wish to increase the proportions of fine and ultra-fine ore used in the sinter mix, in order to reduce charging costs;

(iii) the need to produce sinters which are richer in iron, of high reducibility and having excellent mechanical properties, under hot or cold conditions.

During the decade, the ECSC has supported a series of projects along the lines of these requirements, studies carried out with coordination between a large number of participants: CRM, VDEh with Thyssen, Mannesmann, and StfE, Lurgi, British Steel, Hoogovens, CSM with Italsider, Irsid and Arbed.

Some examples will demonstrate the interest of this programme.

1.2.1. Energy savings in sintering

The parameters which influence energy consumption during sintering are numerous and they have been studied in several projects dealing mainly with mixes using rich ores and concentrates available on the European market, as well as into mixes based on ores from Lorraine with their particular chemical and mineralogical characteristics.

A study by Nuova Italsider (1) concerning mainly the repartition of total energy consumption between ignition energy and solid fuel energy in the sinter mix, provided a decrease in the overall energy consumption as well as an optimization of costs as a function of the respective prices of the various fuels available.

A joint project of Arbed and Lurgi (2) demonstrated the effect of adding oxygen to the ignition furnace.

A British Steel project (3) showed that recovery of sensible heat from the sinter mix for reheating combustion air at the ignition furnace could provide savings of over 30% in gas consumption (Figure 1-6).

Measures that could be undertaken during the preparation phase of the mixture were examined according to the possible combinations based on the constituents available in the stockyard. The effects of micro-pelletizing on the permeability of the sinter cake were evaluated as well as the importance of the way in which the mixture is deposited on the moving strand.

The influence of other parameters: thickness of the layer, basicity, addition of lime were also take into account. These projects were carried out on rich ores (Mannesmann, Lurgi-StfE projects [(3) and (7)] and on mixtures based on Lorraine ores (Arbed, Irsid [(8) to (9)]).

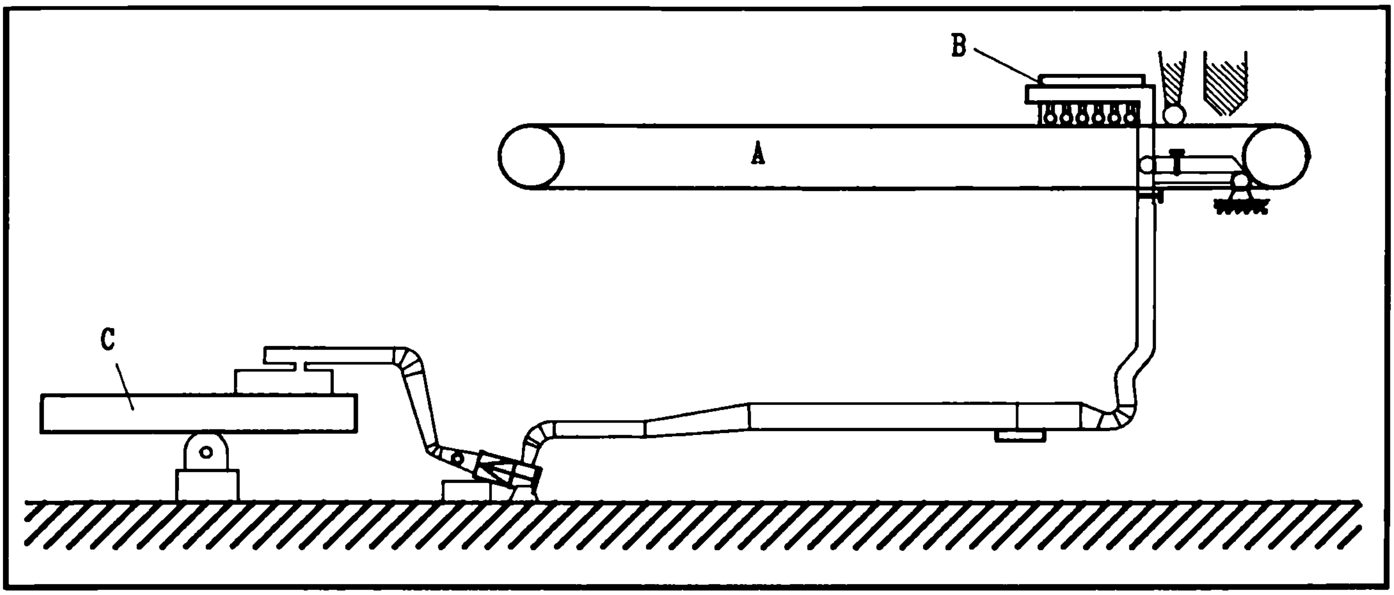
Several projects paid special attention to aspects of the solid fuel, and in particular its grain size.

A British Steel project (3) thus demonstrated that the proportion of the very fine coke fraction (less than 0.25 mm) must be kept very low.

A systematic study by Thyssen (10) on the influence of coke grain size was carried out using two-stage crushing equipment fitted with roll crushers. This installation allowed the grain size of the coke to be controlled by the total crushing effort as well as the flow between the two rolls.

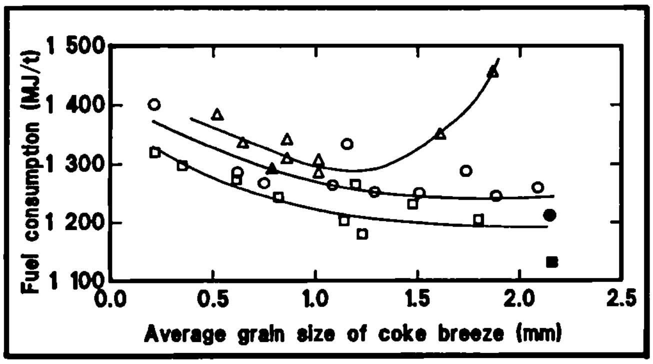
Sintering tests were thus able to be carried out on the basis of precise and varying ranges of grain size. These tests showed that, compared to the usual grain size of 0 to 3 mm, increasing the size of the coke fines led to both technical and economic advantages (Figure 1-7).

Figure 1-6
Heat recuperation system installed at the Redcar sinter plant



A – Sinter strand. B – Ignition furnace. C – Cooler.

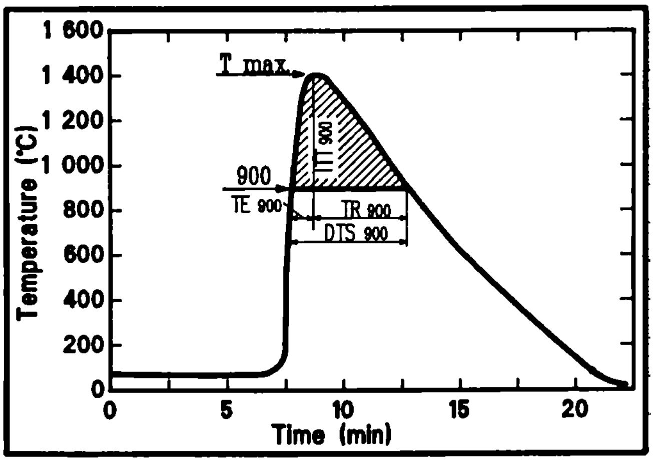
Figure 1-7
Relationship between fuel consumption and average coke fines grain size



△ 203 kg concentrate/t sinter
□ 106 kg concentrate/t sinter
○ 320 kg concentrate/t sinter

C – Flue dust = 5.5 kg/t
Fe^{2+} = 4.5 %
CaO/SiO_2 = 1.9
Layer height = 500 mm

Figure 1-8
Schematic representation of temperature profile



These tests also showed that changing from a grain size of 0 to 3 mm to one of 0 to 6 mm led to a saving of 30 to 50 million J per tonne of sinter (equivalent to 1 to 1.7 kg of coke fines per tonne). At the same time, sinter production increased by 5 to 8% and, furthermore, the properties of this sinter (wear resistance, reducibility) were improved.

1.2.2. Cohesive zone and vertical and horizontal heterogeneities

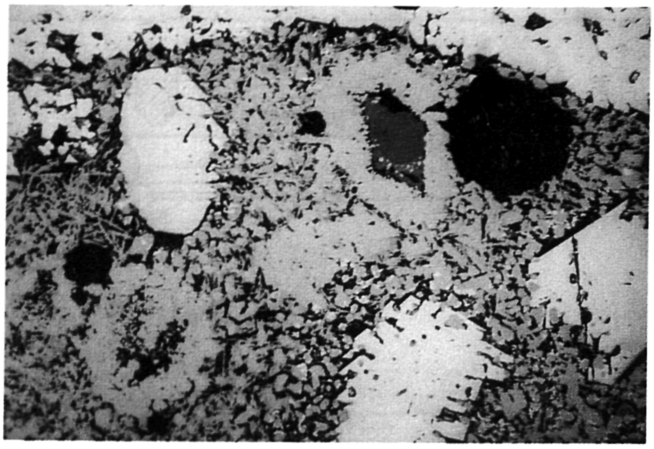
Several projects, including those of CRM, BFI-Thyssen and Italsider, were involved in the study of the cohesive zone. This zone, where the phenomenon of sintering itself occurs, plays a major role on the performance of the sintering plant and on the quality of the sinter [(11) to (14)].

Those factors which influence the shape of the cohesive zone have been subjected to systematic studies, on both the pilot and industrial scale, based on measurements of temperature and pressure at different points in the bed and under the strand.

The temperature profile during sintering has been defined using several parameters (Figure 1-8), including the maximum temperature reached by the mixture and the integral of temperature/time above a given temperature.

This profile varies according to the position being considered in the layer height: the maximum temperature is lower and the profile is narrower in the upper layer, which gives rise to a difference in quality of the sinter between the upper and the lower layers.

Figure 1-9
Microphotograph of good sinter



It is, nevertheless, possible to modify the temperature profiles in the different layers, for example by providing an additional source of heat after ignition, or by modifying the suction under the first wind boxes just after ignition.

These actions correct the vertical heterogeneities of the temperature profiles and improve the uniformity and quality of the sinter.

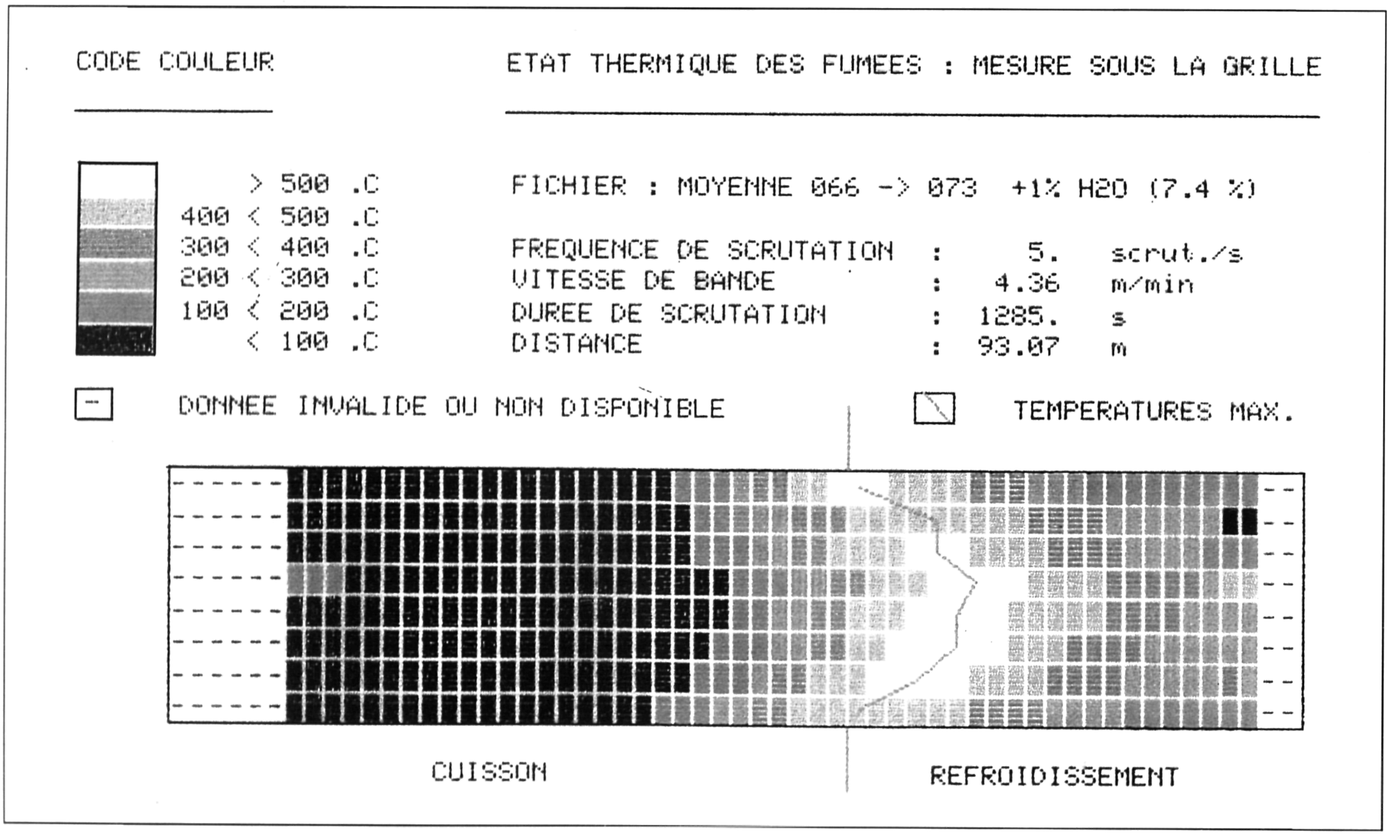
These tests have shown that very good sinter was achieved with a narrow temperature profile and a maximum temperature that was not too high. Such a sinter contains large grains of partially melted hematite surrounded by a network of ferrites of acicular lime ferrites which provide a satisfactory compromise between cold strength, reducibility and hot strength, while at the same time requiring less fuel (Figure 1-9).

The types of ores and additives employed also affect the sintering temperature as a function of their softening and melting-point temperatures. It was possible to demonstrate the advantages of including acid additives in the form of large grains which promoted the formation of acicular lime ferrites.

Research in this field is being continued into the influence of the charge density on the sintering process, productivity and sinter quality. Perfecting certain measurement techniques at an industrial scale: gas permeability, flue gas temperatures, position of the sinter front, temperature profile, all provide information to the operator concerning vertical, and horizontal (both longitudinal and transverse) heterogeneities caused, for example, by a lack of uniformity in charging or in ignition conditions. Figure 1-10, which shows flue gas temperatures across a section of the strand provides an impression of the transverse heterogeneities in the cake.

The operator can then employ suitable methods to reduce these heterogeneities, thus improving the sinter quality while at the same time reducing fuel consumption.

Figure 1-10
Flue gas temperature states as measured beneath the grate



1.2.3. Behaviour of sinters with low SiO_2 content

A current research project being carried out by Thyssen on the influence of SiO_2 content in the sinter (15), shows that when SiO_2 is decreased from 6 to 4.8%, for the same basicity and iron content of the sinter, there is a drop in the ISO mechanical strength, a drop in the reducibility, and an increase in the RDI hot deterioration.

Using this sinter in blast furnaces with respective hearth diameters of 10.8 and 14 m, with the quantity of slag decreasing from 300 to 250 kg per tonne of hot metal, has led to an increase in coke consumption and a drop in the production of hot metal.

1.2.4. Intrinsic properties of ores and additives

In order to assist the operator in defining charge compositions, taking into account the economic constraints in supplies, a CRM research project (16) based on the study of the mineralogy and the structure of iron ores attempted to establish the parameters for the relationships of sinter mixture composition in order to achieve optimal operating results both in quality and in the reduction of production costs. This new information is of use in explaining certain variations in the technological qualities of the raw materials, while the conventional chemical and grain size analyses used in selecting constituent materials for the sinter do not show any notable changes.

A study of the suitability of the mix grain size has revealed physical dimensions which allows the cold permeability of the sinter mix to be estimated: grain size distribution, quantity of potential binder, tendency of fines to adhere.

Another project by CRM (17), currently being undertaken, is intended to link the intrinsic properties of the mix to its hot behaviour. In fact, it is not sufficient just to obtain a well granulated mix with good cold permeability, since the rate of sintering and the temperature profile depend upon the hot permeability. Thus the hot behaviour of mixes with identical cold permeability values differs as a result of the phenomena associated with the passage of the flame front. It can be demonstrated that the behaviour of the mix particles under thermal shock conditions can greatly affect the gas flow and simple tests for measuring decrepitation have been developed.

Many laboratory tests have been carried out on the sinter quality as characterized by its hot behaviour, its softening and its melting under conditions to be found in the blast furnace. This difficult subject will be examined later together with the blast furnace itself.

References

(1) EUR 9328 IT 1985 — Nuova Italsider: 'Ottimizzazione termica del processo di agglomerazione'.

(2) EUR 8694 FR 1983/EN 1986 — Arbed-Lurgi: 'Enrichissement en oxygène des gaz d'allumage en l'agglomération DL'. 'Oxygen enrichment of the combustion gases for sinter bed ignition'.

(3) EUR 9433 EN 1985 — British Steel: 'Optimization of the sintering process with particular reference to energy saving'.

(4) EUR 10583 DE 1986 — Mannesmann: 'Untersuchungen zur Senkung des Energieverbrauches in einer Sinteranlage'.

(5) EUR 12610 DE 1990 — Lurgi-StfE: 'Senkung des Energieverbrauchs beim Sintern von Eisenerz — Verbesserung des Reduktionsverhaltens'.

(6) EUR 11105 IT 1987 — CSM: 'Agglomerazione di miescele di minerali di ferro parzialmente pellettizzate'.

(7) EUR 10582 IT 1986 — Nuova Italsider: ' Alta riducibilità dell'agglomerato a bassa degradabilità'.

(8) EUR 12977 FR 1990 — Arbed: 'Réduction des besoins thermiques pour le frittage des mélanges à base de minerais lorrains'.

(9) EUR 8701 FR 1984 — Irsid: 'Étude du processus de frittage d'agglomération de minerais lorrains'.

(10) EUR 12614 DE 1990 — Thyssen: 'Einsatz unterschiedlicher Koksgrußkörnungen zur Verringerung des Brennstoffverbrauches bei der Eisenerzsinterung'.

(11) EUR 10829 FR 1987 — CRM: 'Facteurs déterminant la zone cohésive lors de l'agglomération des minerais riches'.

(12) 7210-AB/105 — BFI/Thyssen: 'Verbesserung der Prozeßführung in Sinteranlagen insbesondere durch Weiterentwicklung und Betriebseinsatz eines Meßrostwagens'.

(13) EUR 8993 IT 1984 — Italsider: 'Controllo in linea della permeabilità dello strato di agglomerazione per ridurre la variabilità dell'agglomerato e i consumi energetici'.

(14) 7210-AB/203 — CRM: 'Amélioration des techniques de dépôt du mélange d'agglomération'.

(15) EUR 13477 DE 1991 — Thyssen: 'Erzeugung und Verhüttung von SiO_2-armen Sinter'.

(16) EUR 11460 FR 1988 — CRM: 'Étude des propriétés intrinsèques des minerais de fer et des mélanges d'agglomération'.

(17) 7210-AB/204 — CRM: 'Comportement au séchage et aux chocs thermiques du mélange granulé'.

1.3. Blast furnace

The main objectives of the ECSC research and development programme undertaken in the field of the blast furnace over the last decade concerns three main points:

(i) decreasing the production costs of hot metal, in particular by decreasing total energy consumption and through flexibility in the selection of energy sources;

(ii) improving the constancy of hot metal and its average composition, essential factors in regular operation of the plants;

(iii) taking into account the increasing number of environmental regulations.

Some examples of this programme will be presented in brief.

1.3.1. Aerodynamics and behaviour of iron burden

The behaviour of a blast furnace is extremely complex and it has become clear that the best way in which high performance may be obtained is through improved understanding of the process itself occurring within the unit. Experience shows that gas distribution within the unit is an essential factor in correct operation, since it governs reduction efficiency, zinc removal, control of heat loss and the behaviour of the refractory materials.

From an aerodynamic point of view, the blast furnace may be divided into three zones:

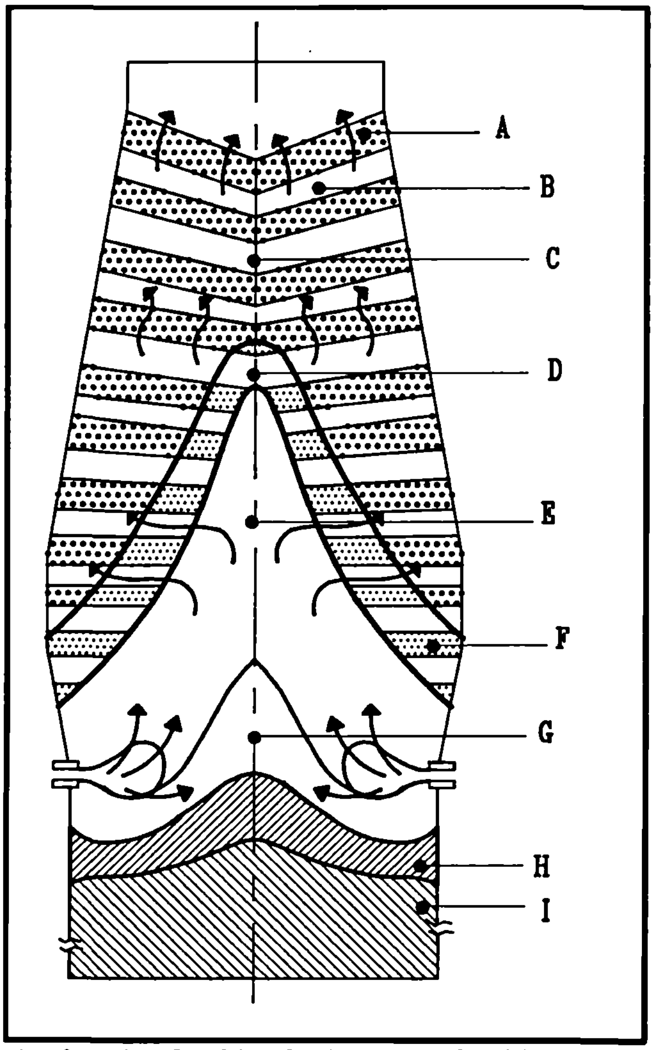
(i) an upper zone with two phases: gaseous and solid, called the dry zone;

(ii) a three-phase zone: gaseous, solid and liquid where the iron-bearing materials start to soften and melt, called the cohesive zone;

(ii) a three-phase zone: gaseous, solid and liquid where the hot metal and the slag drip down through the coke grid, called the wet zone.

Earlier investigations have provided an improved understanding of the operation of the hearth of the blast furnace, the dry zone. On the other hand, the lower part had hardly been explored and theories concerning its operation were based on hypotheses which need to be checked by direct experimentation.

Figure 1-11
Schematic representation of the cohesive zone



A – Ore sinter. B – Coke. C – Lumpy zone. D – Cohesive zone. E – Dripping zone. F – Cohesive layer. G – Stagnant coke zone. H – Slag. I – Hot metal.

In this field, which is so important in controlling the production of hot metal, the ECSC has provided support for a series of large-scale research projects coordinated between Irsid, CRM, VDEh, British Steel, CSM, Hoogovens and Arbed, with the aim of increased understanding of the cohesive zone and the wet zone.

The cohesive zone is composed of layers of iron-bearing materials which soften and then melt, together with layers of coke known as windows since the gases traverse the cohesive zone selectively via these openings, and good gas distribution is essential as stressed above (Figure 1-11).

Furthermore, the level of the cohesive zone determines the extent of the upper dry zone, as well as the lower wet zone. We can thus understand more easily why the cohesive zone largely determines blast furnace performance.

Work funded by the ECSC has been carried out on three parallel and complementary lines of research:

(i) direct determination of the position of the cohesive zone in the blast furnace;

(ii) ascertaining this position through indirect measurements based on mathematical modelling;

(iii) laboratory measurements, under specific conditions, of softening and melting temperatures of the iron-bearing materials.

In addition, work has been undertaken on the behaviour of coke, to which a separate chapter has been devoted.

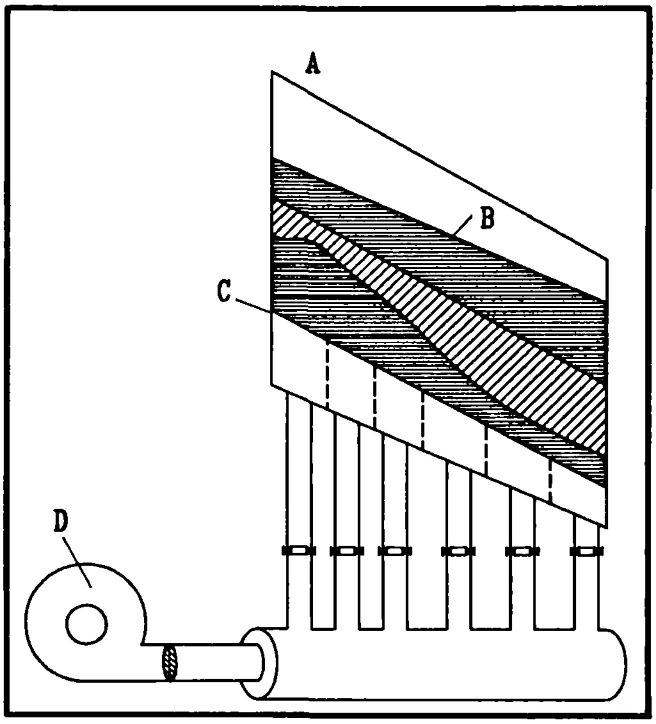
Since it is not possible to give details in this report of all the projects carried out, in view of their number and scope, we shall limit ourselves to a summary of some of the more typical examples of work carried out.

It should be emphasized from the beginning that developing new measurement systems on the blast furnace itself, despite the experimental difficulties on this type of installation, was a decisive contribution in advancing our knowledge concerning the cohesive zone.

In this field, the furnace bell-less top fitted with a rotary chute provides great flexibility in the distribution of materials. This flexibility is also the root cause of some of the problems encountered in attempting to determine the optimal settings. Several research contracts have investigated this question on a full-size scale.

As an example, in the Hoogovens equipment (1), the column of gas rising through the charge is simulated by blown air (Figure 1-12). Different types of charge (spiral, annular, mixed) were thus able to be tested for coke and the iron-bearing burden, thus providing a means of optimizing the effect of a central chimney and the thermal protection of the furnace walls. Correlation was established with the results of industrial operations.

Figure 1-12
General diagram of the test model set-up with ventilator for air supply



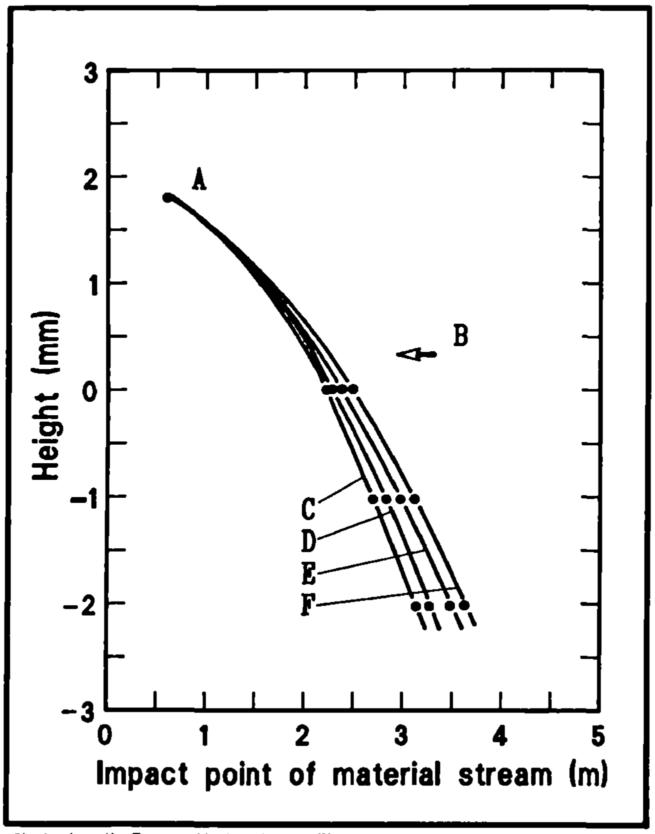
A – Circular segment. B – Burden. C – Perforated base. D – Fan.

Similarly, with a Dillinger project (2), evaluation of the characteristics of materials flow in a model, from leaving the distribution chute up to the point of impact on the circumference of the furnace top, allowed methods of correcting irregularities in the distribution of materials at the periphery to be developed (Figures 1-13a and 1-13b).

Several studies carried out on two-dimensional models at various scales, such as those of CSM and Irsid [(3) to (5)] have provided a means of studying materials flow, as well as deformation of the coke and sinter layers during their descent in the hearth. The phenomenon has been able to be modelled, thus providing a useful guide to blast furnace operators.

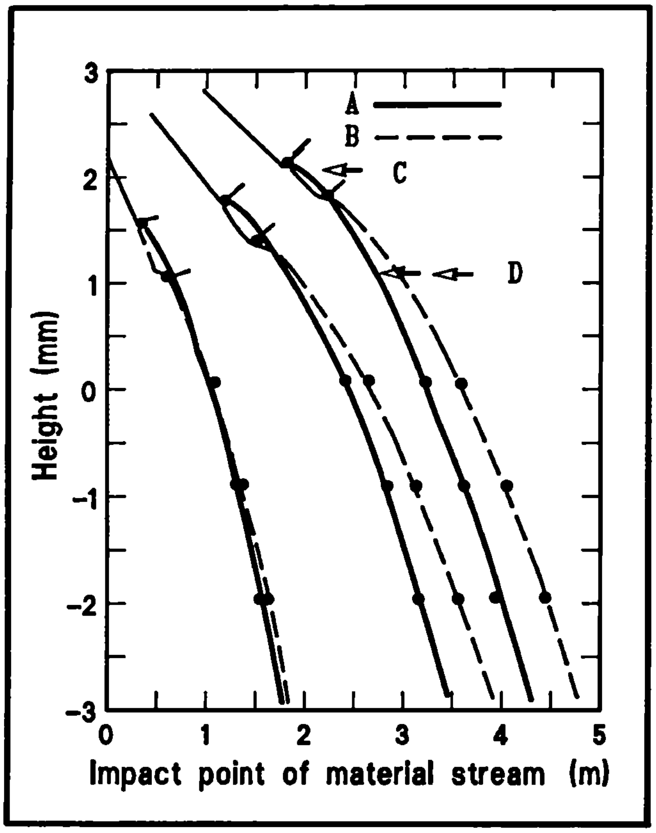
It has been shown that materials flow at the wall depends on their grain size and the condition of the wall. Thus, when the wall is smooth, the materials adjacent to this wall flow in a similar manner throughout the model. When, however, the wall is rough a mixed coke-sinter zone occurs, the formation of which has been described above. The importance of this phenomenon in controlling heat losses and the behaviour of the refractory lining is evident. As mentioned above, direct measurements made on the blast furnace have provided decisive help in determining the cohesive zone and in understanding the phenomena taking place in the bottom of the hearth.

Figure 1-13a
Fall curves of different components for an offset feed chute



Chute length 3 m. Chute slope 45°.
A – End of chute. B – Average stream of material flow.
C – Granulated ore. D – Sinter. E – Pellets. F – Coke.

Figure 1-13b
Fall curves of sinter for different lengths of chute and for offset chute



A – Chute length 3 m. B – Chute length 3.5 m.
C – End of chute. D – Average trajectory of material stream.

The existing range of methods (radial beams above the charge, horizontal and vertical probings, thermography, etc.) has been completed by new techniques which provide vital information to both researcher and operator, examples of which are:

(i) the measurement of the electrical resistance between water-cooled electrodes inserted at different levels in a Thyssen-RWTH (6) project. This provided information on the thicknesses of the layers of materials, their rate of descent, the periods during which material sticks to the walls, information of interest to the blast furnace operator concerning the operating state of his unit;

(ii) optical measurements of the charge profile in the Irsid project (7). This provided, among other data, the variations in the slope angle of the materials, as well as other information essential in the exploitation of charging models;

(iii) the vertical CRM probe method (8). This consists of introducing capsules fitted with a thermocouple, a pressure and gas sampling tube which descends with the charge;

(iv) the Irsid process (3) consists of introducing a capsule containing radioactive xenon 133 at a specific location around the radius of the blast furnace. The capsule is sealed by a fusible plug with a known, precise melting temperature T. When the capsule reaches the temperature isotherm T°, the xenon is released into the blast furnace gases and can be detected by measuring radiation levels. The profile of the T° isotherm may be determined by repeating the test at different radial positions (Figure 1-14).

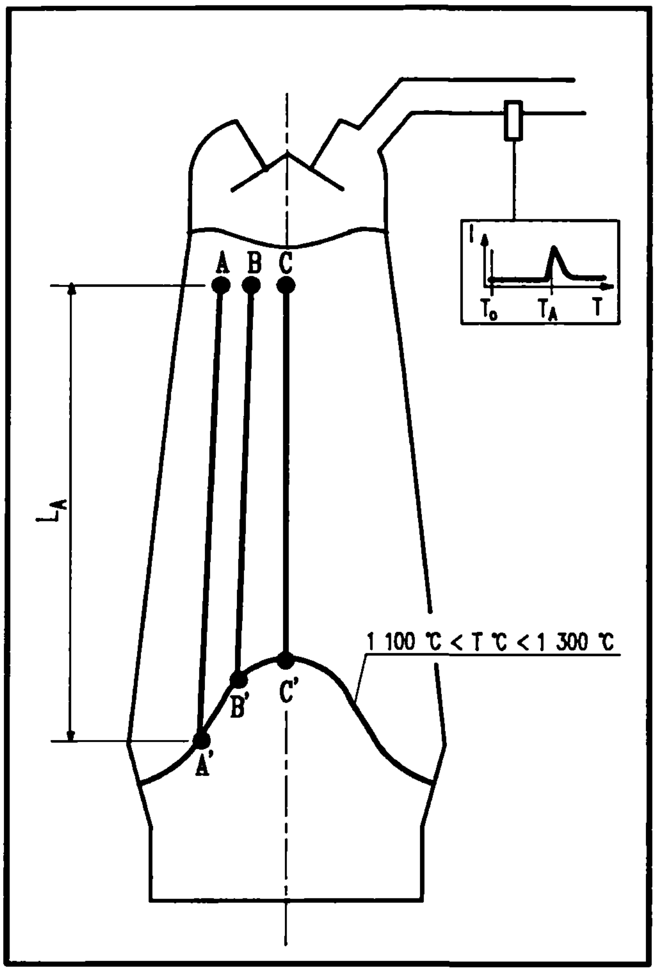
Comparison of the 800°C isotherms measured using xenon capsules with the results of horizontal probings shows good correlation (Figure 1-15).

The measuring techniques described above, together with conventional methods such as thermal losses through the walls, provide high levels of precision in determining the thermal map of the blast furnace at a given moment and the position of the cohesive zone.

Nevertheless, these direct measurement methods are costly and time-consuming and cannot be adopted as standard production techniques.

The preparation of simulation models, according to certain simplified hypotheses, allows predictions to be made of the evolution of the position and the shape of

Figure 1-14
Principle of the system for measuring isotherm shape in a blast furnace charge using xenon capsules



V = Rate of burden descent. T_o = Introduction.
T_A = Rising edge of Xe^{133} pulse. Distance: $L_A = V(T_A - T_o)$.

the cohesive zone following modifications to the operating parameters of the blast furnace: blast temperature and flow, oxygen and water vapour content, properties of iron-bearing materials at high temperatures, etc.

The influence of these parameters on the cohesive zone has been the subject of a series of contracts, of which certain are cited in the references [(9) to (18)]. It is impossible to provide full details in this report in view of the large amount of experimental data collected for extremely varied operating conditions, for both blast furnace and laboratory tests. We shall thus limit ourselves to some examples.

One of the Nuova Italsider projects (9) demonstrated the manner in which the height of the cohesive zone varied with the radial gas distribution and the flattening effect on this zone when increasing the proportion of iron-bearing materials. The distortions of the cohesive zone occur gradually due to the phenomenon of thermal lag.

A CRM project (10) carried out on two blast furnaces with differing conditions led to algorithms being established for determining the extent of the cohesive zone on the basis of indirect measurements.

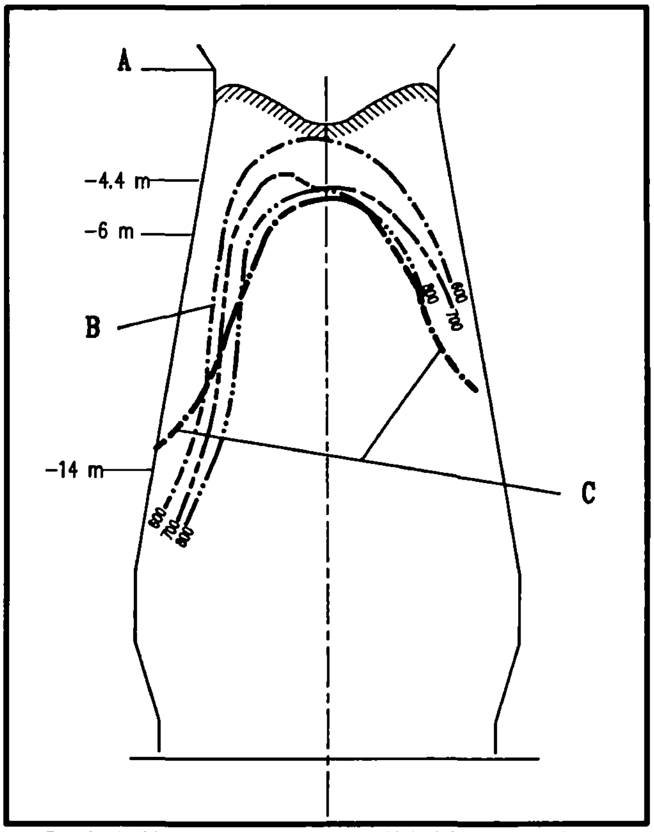
Elsewhere, it was demonstrated that, in the central part of the furnace, the height of the cohesive zone depends largely on the volumetric ratio of the charged coke, while at the periphery of the blast furnace it is mainly dependent on the flame temperature.

The materials studied concerned ores, sinters with varying indexes of basicity and FeO content, and acid and basic pellets. They were sampled either at the charging point or during studies of the cohesive zone carried out on blast furnaces.

Detailed examination of this work provides a great variety of results which can be explained by the diversity of the laboratory equipment used and the operating conditions employed.

A large VDEh project [(11) and (12)] carried out in six laboratories and five different blast furnaces increased our knowledge of the softening and melting phenomena of the components of the burden bed, and experimental techniques were improved.

Figure 1-15
Comparison of tbe 800°C isotherm values obtained using xenon capsules and horizontal probes



A – Zero level of burden. B – Isotherms established from horizontal probing.
C – Xenon isotherm.

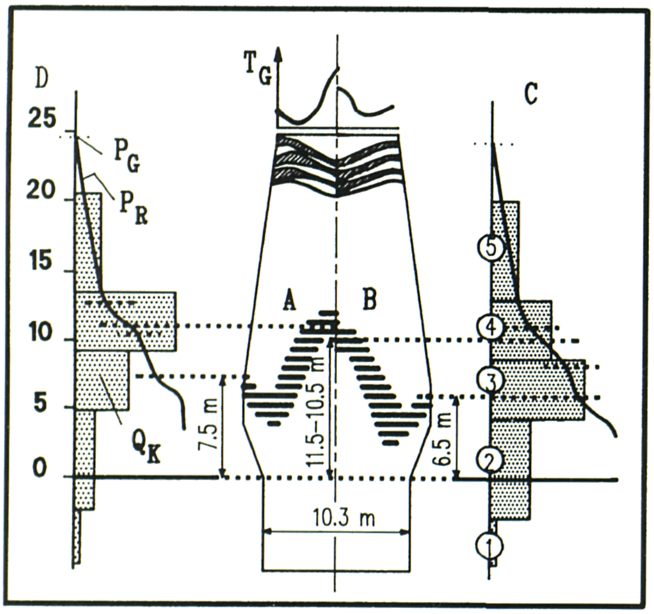
Nevertheless, for blast furnace operation, it is not enough to consider the softening and melting properties of the raw materials, we must also take account of sulphur and other materials circulating within the blast furnace which by accumulation can profoundly modify the high temperature properties, as is the case with potassium.

The cohesive zone is shown to be largely influenced by the properties of the burden bed, although the greatest effects are due to the operating conditions of the blast furnace: charge distribution, conditions at the tuyères, etc. (Figure 1-16).

In a British Steel project (16) concerning the study of high temperature reduction, softening and melting of the burden constituents is based on the development of an experimental technique at laboratory scale which simulates the entire blast furnace process from the top level of the charge down to the cohesive zone where the temperature is of the order of 1 530°C.

The softening and melting characteristics of acid pellets were found to be relatively constant regardless of their type. These properties can be improved by adding magnesia, but deteriorate above a certain threshold level.

Figure 1-16
Model of the cohesive zone for two differing blast furnace burden distributions



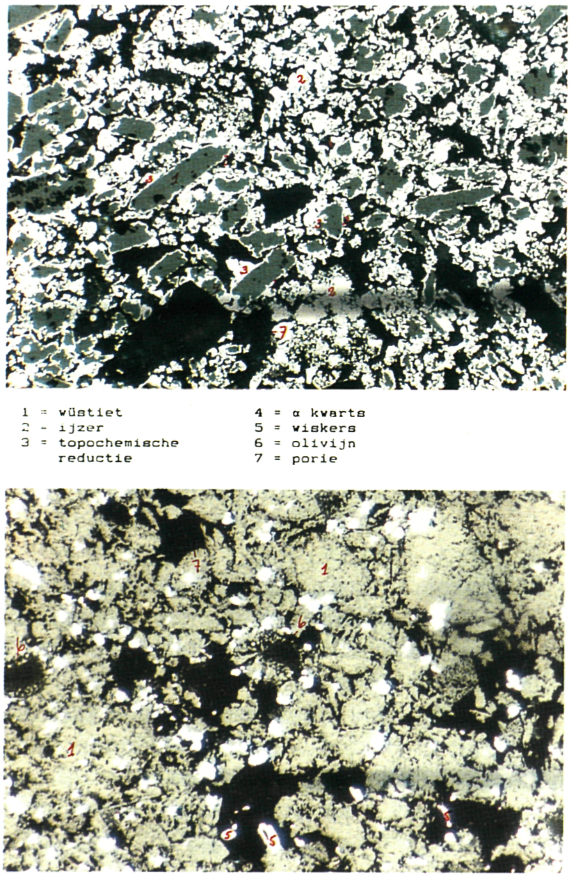
P_G – Furnace top pressure.
Q_K – Heat losses.
A, B – Top of cohesive zone.
D – Height above tuyères.
P_R – Wall pressure.
T_G – Gas temperature.
C – Cooling zone.

On the other hand, sinters show very variable softening and melting characteristics which result from the formation of viscous slags which extend the melting zone. Most sinters were found to be gas-tight at 1 300°C, although some of them, depending upon their basicity, were not entirely melted even at 1 570°C.

The presence of sulphur in the blast furnace reducing gases can have a considerable effect on the softening and melting properties of some of the charge components. Its effect on the acid pellets is disadvantageous since it lowers the rate of indirect reduction and increases the range of melting. On the other hand, the sinters do not appear to be greatly affected.

A recent Hoogovens project (18) carried out reduction experiments on pellets and sinters, using various time-temperature programmes in order to reproduce the conditions to be found in the blast furnace, and the tests were then completed with mineralogical examinations (Figure 1-17). This study also looked into the degradation of the sinter grain size and the beneficial effects of hydrogen.

Figure 1-17
Sinter reduction



The whole of this ECSC research programme has contributed to a greater understanding of the complex phenomena involved in the softening and melting of iron-bearing materials in the blast furnace charge.

1.3.2. Coke behaviour in the blast furnace

Coke fulfils three important roles in the blast furnace:

(i) it produces the reducing gas necessary for reducing the iron oxides;

(ii) it supplies most of the energy requirements of the blast furnace;

(iii) it is an important factor in the aerodynamics, ensuring that the charge is of suitable permeability, particularly in the zone of the bosh and around the tuyères.

This latter function is vital: in fact, in these high temperature zones, the coke is the only material to remain in the solid state, through which the gas can rise to the furnace top and the liquid materials can descend to collect in the hearth.

The distribution of the reducing gas issuing from the tuyères is thus governed by the mechanical behaviour of coke in these zones, and its grain size: a lack of permeability will limit the blast that can be blown through and will cause irregular gas distribution in the hearth.

The importance of good control of the permeability in these zones is increased even more by the development of coal injection at the tuyères, which leads to a reduction in the quantity of coke charged in the blast furnace. Good permeability must be ensured despite the decrease in the quantities of coke.

It has been shown in the past that the conventional criteria for coke characteristics, grain size and cold mechanical strength, are insufficient to describe its behaviour in the blast furnace.

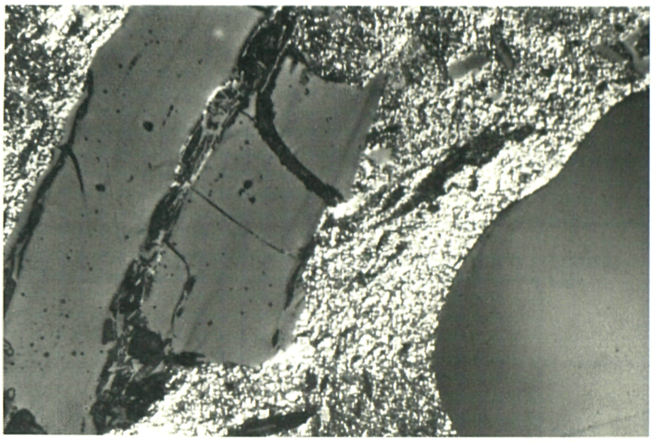
The Community research programme, already started in the previous decade, has been actively pursued over the last decade with the support of the ECSC, in the form of several important projects of which some examples are presented in brief.

In projects undertaken by British Steel/BCRA (19) and British Steel (20), the degradation of coke in the blast furnace was studied on the basis of samples obtained from seven different countries: Germany, Belgium, France, the Netherlands, Italy, the United Kingdom and also Canada.

These samples were examined in order to determine their physical, chemical and mineralogical characteristics. It was found that the change in coke size between the charging line and the bosh depended to a large degree on the wear resistance of the coke in the bosh, and that the decrease in this resistance was related to attack by alkaline elements circulating in the upper part of the blast furnace.

Additional work carried out on a single tuyère in a pilot tower showed that coke submitted to similar temperatures and conditions encountered in the raceway also underwent a marked deterioration in its resistance and dimensions. The study also demonstrated that the dimensions and the resistance of the coke in the bosh determined the size and stability of the raceway. Figures 1-18a and 1-18b show the evolution of the coke microstructure between the zone of the furnace top and the tuyère raceway.

Figure 1-18a
Microstructure of blast furnace feed coke



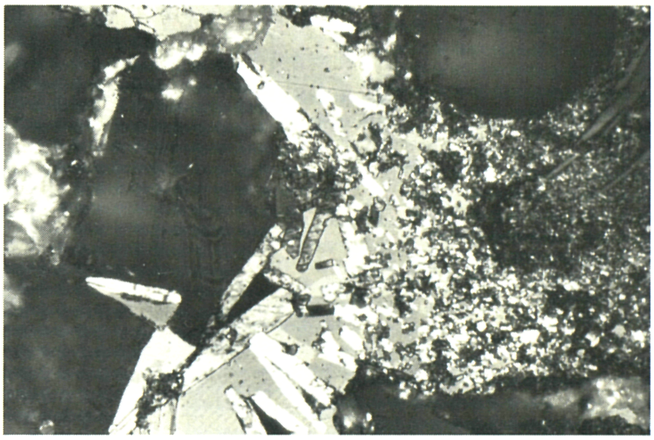


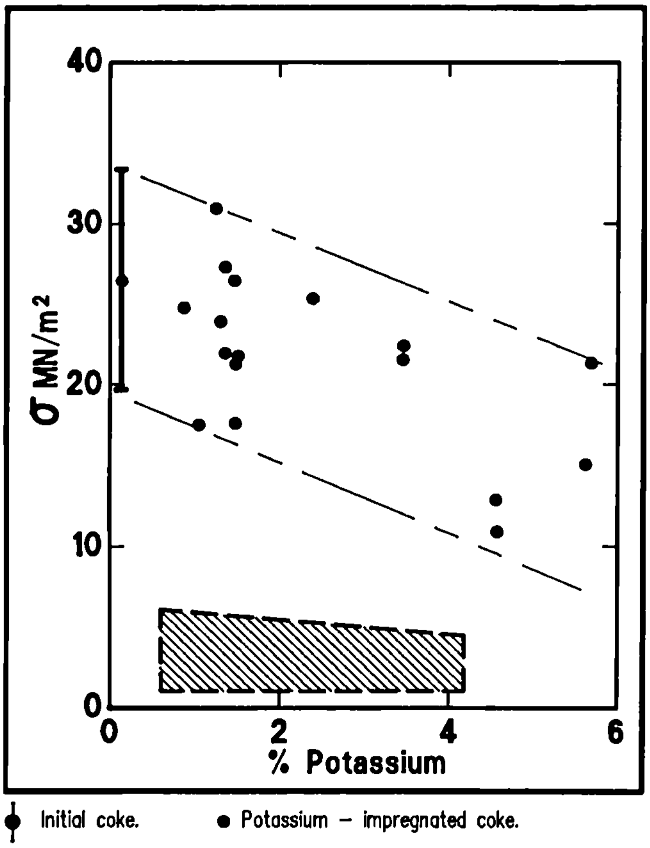
Figure 1-18b
Microstructure of blast furnace raceway coke

A CRM project (21) examined the operation of 17 blast furnaces in Belgium where samples of coke before charging and at the tuyère were also subjected to a series of measurements. The forces encountered by the coke as it descends the blast furnace are both mechanical (friction, pressure, impact), chemical (alkaline elements, gasification) and thermal. It was not possible to establish the relative importance of each of these factors in the observed reduction of coke size, but this decrease was linked to the quality of coke that was charged and the operating conditions of the blast furnaces, especially the blast velocity in the tuyère and the retention of alkaline elements.

In an Irsid project (22) a technique was developed for describing the mechanical behaviour of coke under physico-chemical conditions (temperature, gaseous environment, nature of mechanical forces, etc.) which simulated conditions in the high temperature zone of the blast furnace. The mechanical strength of coke was measured, in uniaxial compression and in tension, up to 1 600°C and for samples which had previously been exposed *in situ* to various physico-chemical treatments at high temperatures: partial gasification by carbon dioxide, and, in particular, with potassium.

This reactivity appeared to be very sensitive to the properties of the carbon phase and to its level of organization in the original coal. The level of degradation caused by potassium would appear to be proportional to the quantity of this element absorbed by the coke (Figure 1-19).

Figure 1-19
Variations in coke yield strength as a function of final potassium content



At the same time the methods of taking samples from the tuyères were perfected.

Several areas in the lower part of the blast furnace were examined in a VDEh project (23).

Knowledge in using mathematical modelling was confirmed through measurements taken from inside the blast furnace.

For the first time, thermocouples were installed around the tapping hole in order to measure the temperature distribution.

During relining operations on a blast furnace, strain gauges were fitted into the graphite blocks and provided information concerning the behaviour of the refractory lining following firing of the blast furnace.

Inserting various probes radially at the level of the tuyères provided temperature profiles and details of coke, metal and slag distribution as well as changes in coke size.

The adoption of an analogue electrical model confirmed the importance of the heel in the hearth for the life span of refractory linings.

In an Irsid project (24) a special probe was installed, in a 5 000 t/d blast furnace at Sollac-Fos, which allowed materials and gases to be sampled at the height of the tuyères across a whole radius right to the centre of the deadman zone (Figure 1-20).

An examination of samples taken across a radius shows three distinct zones:

(i) the raceway, where the average dimension of the coke is small and there are less coke fines;

(ii) the bird-nest zone, at the base of the cavity, where the particles tend to be larger with a greatly increased proportion of coke fines;

(iii) higher up the deadman zone where the coke has similar dimensions to when it was charged.

When the blast was stopped these samples showed a large variation in silicon content in the hot metal, very high opposite the tuyères (6.5%) and low in the axis of the blast furnace (0.7%). This variation in silicon content can be linked to the gasification of the silica in the coke ash in the cavity. Large irregularities in the distribution of alkaline elements in the hearth were also observed.

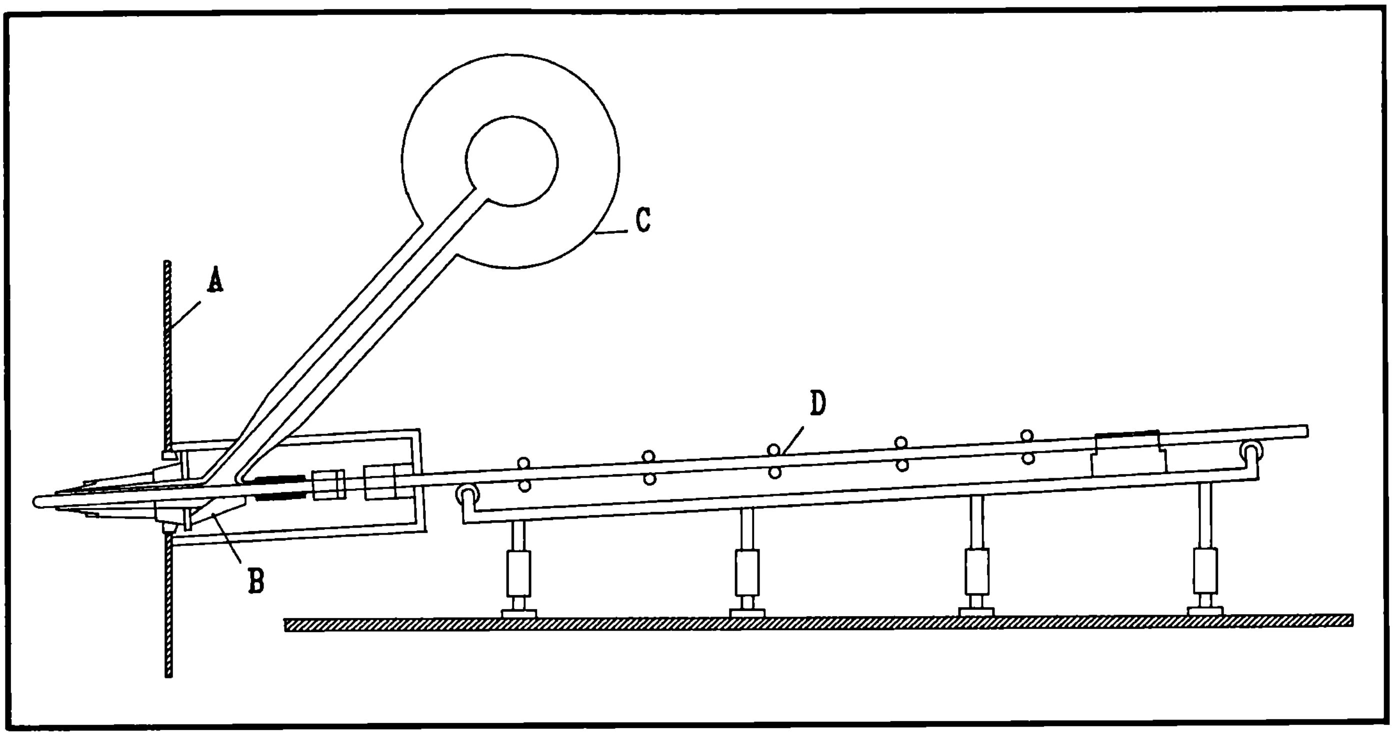
When the blast furnace is operating, these samples can show, across the radius, large variations in temperature and nitrogen content in the gases which are characteristic of the differences in gas flow in the melting zone, demonstrating the valuable information concerning the internal conditions of the blast furnace that can be provided by this type of sampling.

As a result of all this work, our understanding of the behaviour of coke as it descends within the blast furnace has increased greatly over this last decade.

Further progress needs to be made in order to understand this behaviour more completely, especially in the high temperature zones of the bosh, the tuyères and the hearth.

This is exactly the aim of current projects, including a Thyssen project (25) concerning the modifications that different types of coke undergo in the high temperature zones when large quantities of coal are injec-

Figure 1-20
Schematic diagram of the measuring probe



A – Blast furnace. B – Tuyère. C – Bustle. D – Probe.

ted, British Steel (26), Hoogovens (27) and CSM (28) projects on the behaviour of the raceway for high rates of coal injection, which is examined later in detail, and a shared CRM-Irsid project (29) which will model the behaviour of coke by including upstream parameters such as the mixtures of coals used in cokeworks and coking conditions.

1.3.3. Achieving low silicon levels in the hot metal

The increased demand for steels containing very low levels of impurities together with the need to reduce costs in hot metal and steel production mean that the blast furnace operator is required more and more to keep silicon levels in the hot metal to very low and stable levels.

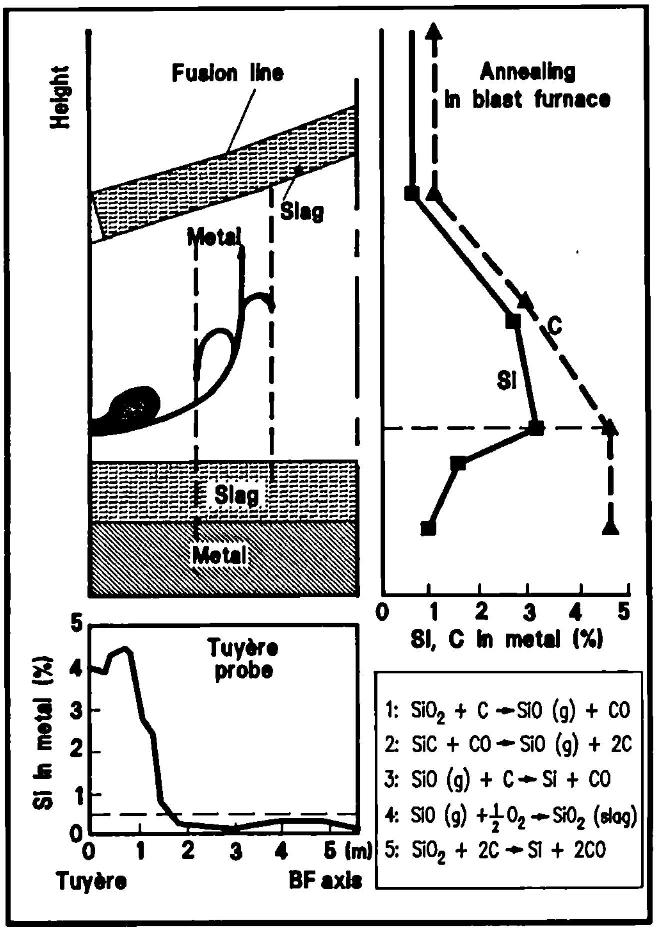
This correction can be achieved in several ways:

(i) either, inside the blast furnace by controlling the silicon transfer phenomena, or, by injecting iron oxides through the tuyères; or

(ii) outside the unit, by applying pre-treatment processes to the hot metal.

The ECSC has provided support for several projects involving these two approaches. The results concerning blast furnace techniques are summarized in the following paragraphs, and those for the pre-treatment of hot metal in Chapter 2.

Figure 1-21
Schematic representation of silicon transport phenomena in the blast furnace



An Irsid project (30), involving fundamental aspects, analysed the physico-chemical aspects of silicon transfer in the blast furnace and defined operating conditions which provided hot metal with low and stable silicon levels.

Figure 1-21 provides a diagrammatic representation of the phenomena involved in silicon transfer within the blast furnace.

A thermodynamic model of the silicon equilibrium between slag and hot metal has been developed. It has been shown that at the tuyère level, the silicon content at equilibrium is high, while in the hearth there is potential for silicon removal.

The essential role played by gaseous silicon monoxide, SiO, in the phenomenon of silicon pick-up by the hot metal, was studied in the laboratory.

The equilibrium model of silicon between slag and hot metal is now being used as a means of checking the quality of the hot metal in several blast furnaces.

The Thyssen project (23) mentioned above, concerning the 'wet' zone in the blast furnace, employed a thermal balance to look at methods of reducing silicon. Tests on the model showed the importance of the slag-hot metal interface on the partition coefficient of silicon.

In this same field, a study currently under way at CRM (31) is aimed at determining the limits and factors involved in the production of hot metal with low silicon, sulphur and nitrogen content, and then, on the basis of predictive algorithms, to optimize conditions of blast furnace operation.

The projects summarized above have demonstrated that the oxygen potential and the availability of oxygen at the slag-hot metal interface appear to be the major parameters which determine the transfer of silicon to the hot metal.

Based on this concept, Irsid is carrying out a project (32) aimed at removing silicon from the hot metal inside the blast furnace, involving the injection of iron oxide fines through the tuyères.

This injection provides a means of preventing silicon levels in the hot metal from rising as it passes through the hearth.

Two routes have been explored:

(i) the injection of a powdered coal-iron ore mixture through all the tuyères of the Sollac-Dunkirk blast furnace (9.2 m diameter hearth). A total of 1 578 tonnes of iron ore (23 kg per tonne of hot metal) were injected continuously over 20 days;

(ii) the injection of 20 kg per tonne of hot metal of iron ore slurry (85% ore in water) via four tuyères surrounding one of the tapping holes in the No 1 blast furnace of Sollac-Fos (10.4 m diameter hearth).

These injections caused a 0.1% decrease in the silicon content at constant temperature. At the same time, the degree of oxidation of the slag tends to increase which leads to a deterioration in the sulphur partition coefficient.

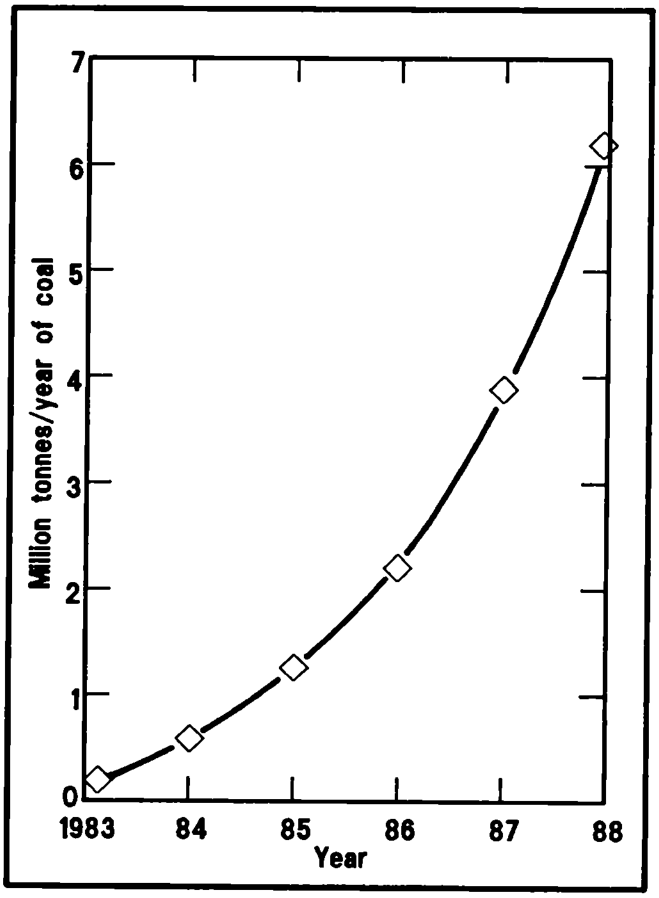
1.3.4. Diversification of energy sources: injection of powdered coal

The blast furnace alone consumes over half of the energy required in an integrated steelworks. It is thus not surprising that blast furnace operators have strived hard not only to reduce the energy requirements of these units, as shown by the examples cited above, but also to diversify sources of energy that may be used in order to benefit from price differentials.

Over this decade, efforts at diversification have, in the main, concerned powdered coal-injection techniques.

We should remember the CRM project (33), carried out at pilot-plant scale some 10 years ago, in which a gas was cracked in a plasma environment and injected through the tuyères at 2 000°C. Tests showed that the metallurgical mechanisms involved obeyed the same laws as in the operation of a traditional blast furnace, and that reaction rates were very high.

Figure 1-22
Increase in coal injection at the tuyères of the European blast furnaces



The first industrial applications of coal injection via the tuyères was seen in the beginning of the 1960s. However, at that time the price of oil-based products together with their ease of use were such that coal injection was abandoned in favour of the almost universal adoption of hydrocarbon injection, except at Armco and most blast furnaces in China.

The energy crisis in 1974 created the well-known rise in prices of both gaseous and liquid hydrocarbons, such that coal injection became economically attractive and underwent spectacular development especially within the Community (Figure 1-22). The ECSC has encouraged many projects, whether in industrial operations, pilot-plant testing or laboratory research.

Some examples of all this work will now be examined.

Arbed (34) carried out a series of comparative tests on a blast furnace which was producing phosphorus-containing hot metal, which involved the injection of different types of coal: steam coal, lignites, coke breeze, with levels of volatile matter ranging from 5 to 50% and ash values of 4 to 18%. All these fuels were employed in the blast furnace without any problems, under existing operating conditions.

Irsid (35) carried out a study, at the Dunkirk site of Sollac, which looked into the effects on the internal parameters and the behaviour of reduction in the blast furnace caused by injecting large quantities of powdered coal. This injection led to a marked improvement in blast furnace operation: reduction in fuel requirements, greater regularity of operation, improved uniformity and quality of the hot metal.

Monthly averages of 140 kg of coal injected per tonne of hot metal were achieved, and in 1990 a monthly average of 180 kg of coal injected was reached, using only 290 kg of coke, on a blast furnace with a diameter of 14 m.

Initial problems of tuyère wear as a result of the injection were examined and resolved by combined theoretical and practical techniques.

This project also comprised a fundamental approach to the combustion of coal particles, which will be discussed later.

The aim of decreasing the cost of injecting coal led British Steel (36) to develop the technique of granulated coal injection at its Scunthorpe works. The grain size that was adopted: less than 2 mm, with only 2% between 2 and 5 mm, with not more than 20% less than 75 microns, for a surface humidity less than 1.5%, corresponded to optimal preparation and transport costs combined with good injection conditions. Coals with medium and high volatile matter contents, covering a wide range of ash contents, were injected.

Blast furnaces operated more regularly during the periods of coal injection, and both hang-ups and slips during operation ceased. Production records were achieved on these blast furnaces with rates of injection of 120 kg of coal per tonne of hot metal, without any soot being apparent in the top gas.

The injection equipment proved to be robust, reliable and easy to maintain.

The project included a study of powdered coal combustion which is also mentioned later in this report.

The use of plasma is one of the methods which should allow the injection of large quantities of coal into the blast furnace.

On the basis of the previously mentioned studies carried out by CRM, Irsid and CRM, in collaboration with Lorfonte and EDF (37), investigated the industrial development of the use of plasma torches simultaneously with high coal-injection rates in a 2 000 t/d blast furnace operated by Lorfonte at Uckange.

The plasma equipment supplied by Aérospatiale was based on the first plasma torches used to superheat the blast of a ferromanganese blast furnace operated by SFPO in Boulogne-sur-Mer. It was the first system in the world to be installed on a steelmaking blast furnace.

Six plasma torches, with a maximum unit power rating of 1.9 MW, were arranged symmetrically. Their specific operating rate exceeded 99%, with thermal losses at the blast furnace-plasma torch interface limited to 2% (Figure 1-23).

For a blast temperature of 1 307°C, values of 329 kg of coke, 122 kg of coal and 115 kWh per tonne of hot metal were achieved.

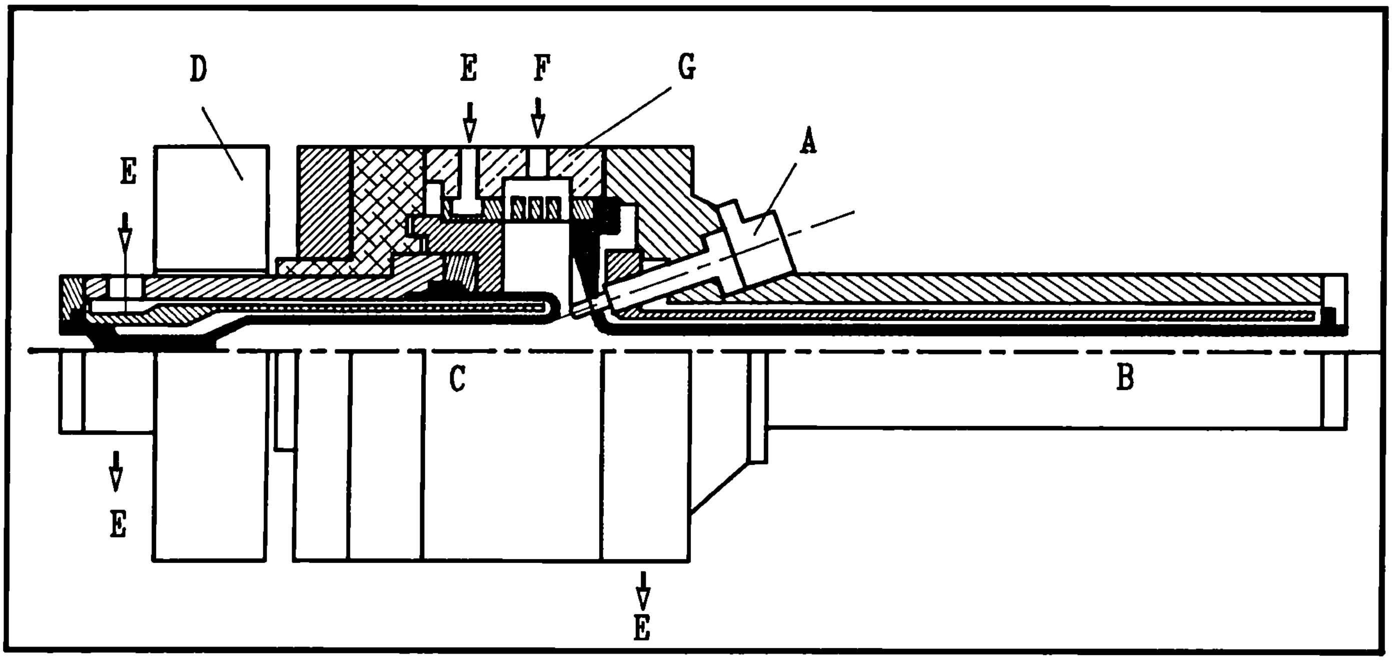
On tuyères fitted with plasma torches, injection rates of more than 200 g of coal per m^3 at standard temperature and pressure (STP) of blast were achieved (it should be noted that 1 g of coal/m^3 at STP of blast corresponds to 1 kg of coal per tonne of hot metal) without any problems of unburnt materials in the top gas occurring.

One of the main objectives of this study was thus achieved.

Combustion of powdered coal injected at the blast furnace tuyères constitutes one of the fundamental aspects of injection, since an understanding of this phenomenon provides the possibility of pushing back the limits of injection, one of these limits being the production of soot in the top gas.

Despite the difficulties, direct measurement through the blast furnace tuyères (introduction of thermocouples, probes, etc.) provided initial information of interest concerning conditions of heating and combustion of coal particles.

Figure 1-23: Cross-section of the Uckange plasma torch



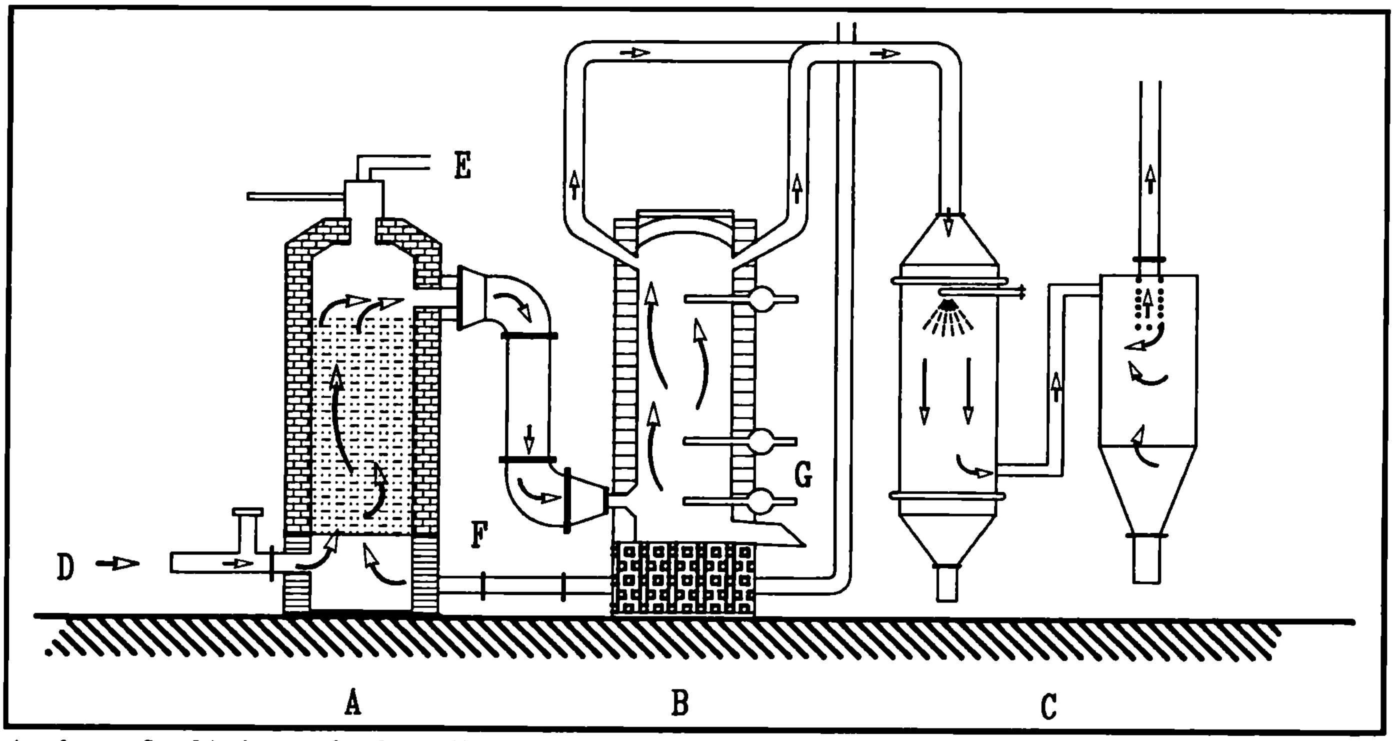
A – Starter electrode. B – Downstream electrode. C – Upstream electrode. D – Field coil. E – Water. F – Air. G – Air injector.

Nevertheless, the difficulties encountered during direct experimentation and the high costs, justified the effort devoted to laboratory and pilot-plant-scale experiments into the combustion mechanisms of powdered coal and attempts to model combustion phenomena.

Hoogovens (38) used the pilot scale furnace of the International Flame Research Federation (IFRF) to study the combustion of powdered coal with different volatile matter contents, demonstrating among other things the high rate at which volatile matter is driven off, in proportions much greater than had been indicated from laboratory analyses. Conversely, the combustion of the cokeified residues is relatively slow.

Another Hoogovens project (27), currently being carried out at laboratory scale, is aimed at determining the maximum injection rates possible before unburnt products appear in the top gas.

Figure 1-24: Pilot installation for studying the raceway

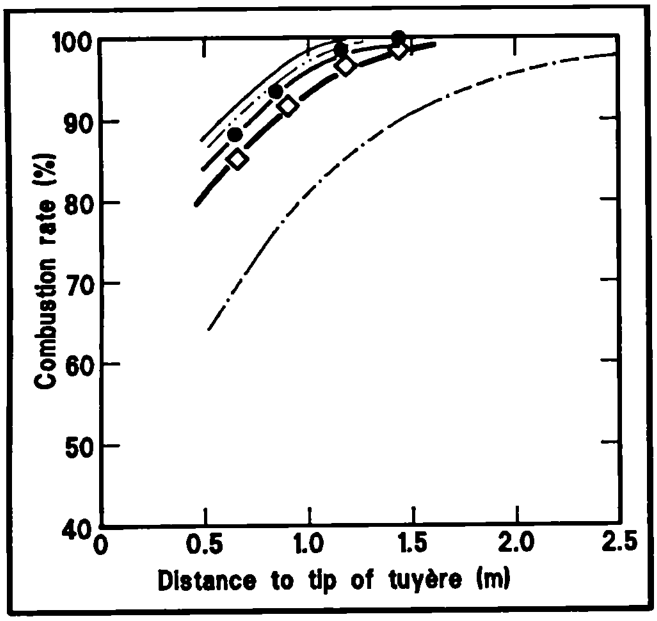


A – Cowper. B – Coke furnace. C – Gas scrubbers. D – Compressed air. E – Burner. F – Tuyère. G – Probes.

British Steel, following an initial project (39) involving a tunnel furnace, has used a pilot tuyère coupled with a coke column (Figure 1-24). The behaviour of a wide range of coals of differing grain sizes was studied under varying injection conditions which influenced the size and stability of the raceway in front of the tuyère.

A project by CSM (40) also employed a pilot tuyère to compare combustion conditions of powdered coal injected pneumatically, or in the form of a liquid suspension either in water (70% coal), or in tar (40 to 50% coal) (Figure 1-25). The results showed decreasing combustion efficiency in the following order: tar suspension, pneumatic injection, water suspension.

Figure 1-25
Comparison of combustion efficiency of coal-tar mixtures with that of powdered coal



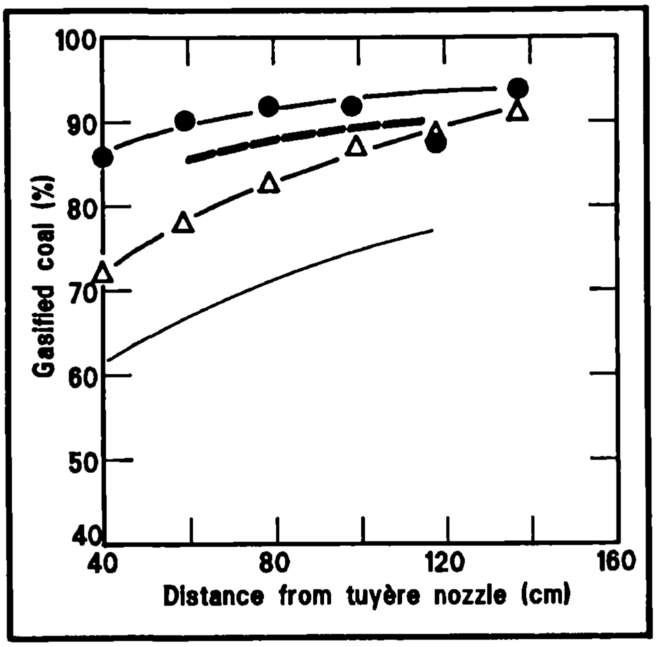
Fuel	Volume (%)	R S	Solids (%)	Size (µm)
Tar	–	1.7	0	–
Coal-Tar	–	1.7	41	42
Coal-Tar	–	1.7	46	58
Coal-Tar	–	1.7	50	148
Coal	21.1	1.7	100	38

Wind characteristics:
T = 1 200 °C
V = 220 m/s
O_2 = 21%

Another CSM project (28) which has already been mentioned is currently being carried out into the effect of high injection rates on the raceway.

A CRM project (41) is using a combustion chamber to simulate the raceway. These tests, which cover a wide range of operating conditions, confirm the three stages of coal combustion (Figure 1-26):

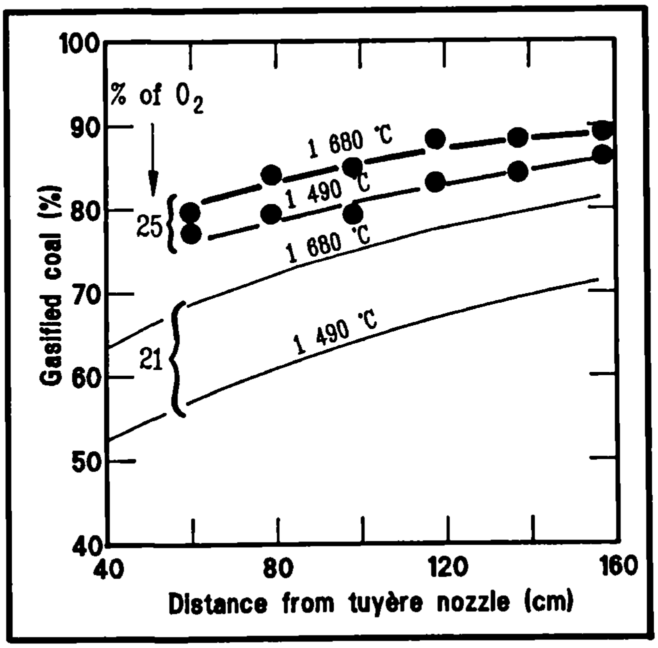
Figure 1-27a Influence of injection rates on combustion efficiency



Type of coal: 40
Air temperature: 1 700 °C
Percentage of oxygen: 21 %

Injection rate (gm of coal/m^3 of air at STP).
73 (●——●)
85 (▬▬▬)
110 (Δ——Δ)
140 (———)

Figure 1-27b
Influence of temperature

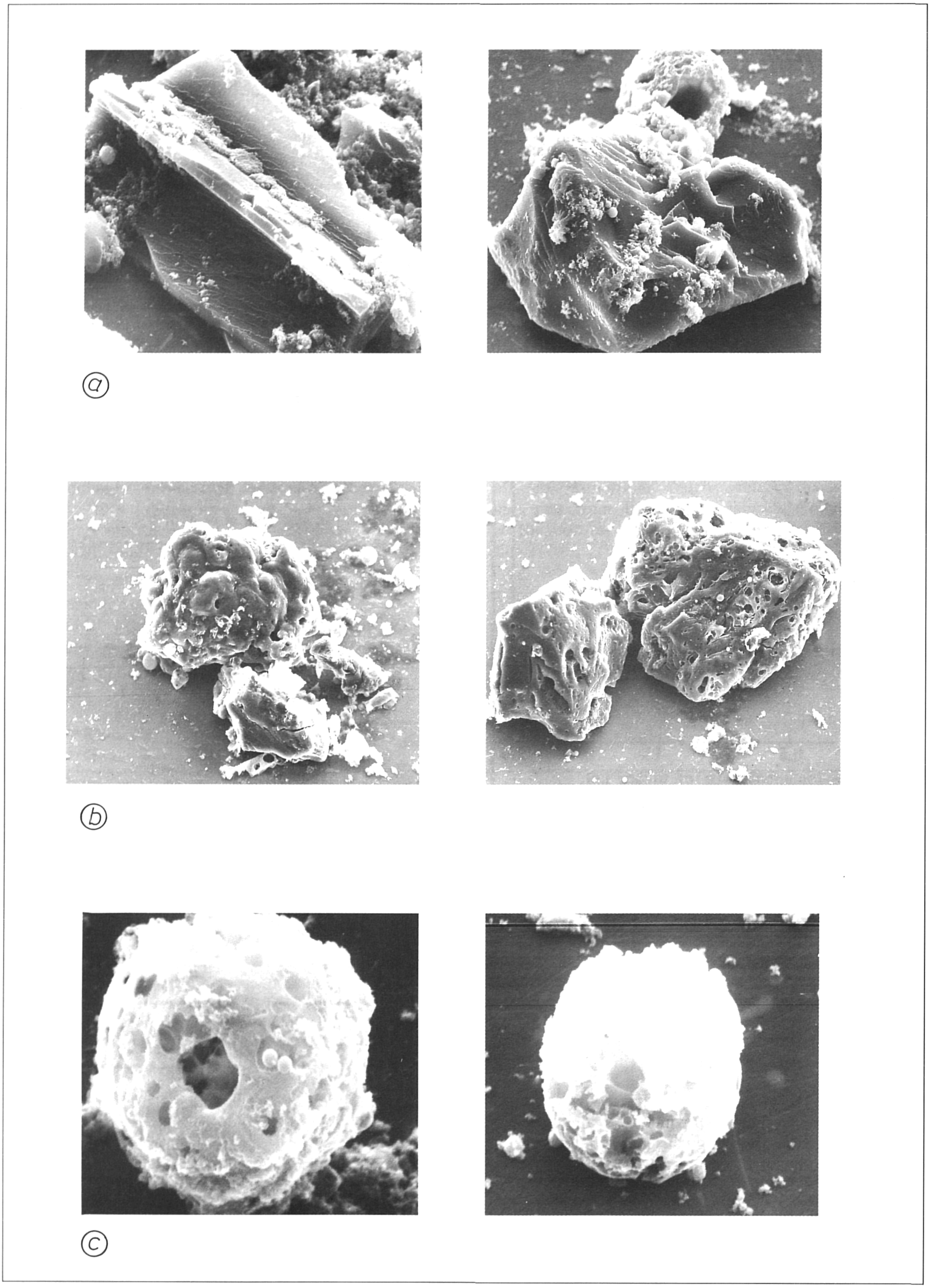


Type of coal: 40
Injection rate: 700 g of coal/m^3 of O_2 at STP.

The first corresponds to the expulsion and combustion of volatile matter: it is very rapid.

The second corresponds to the combustion of the semi-coke with oxygen: depending upon the type of coal, it can be up to 10 times as slow as the first stage.

Figure 1-26
Various behaviour characteristics of coal during combustion



The third corresponds to the gasification of the semi-coke with CO_2 and H_2O: it is very slow.

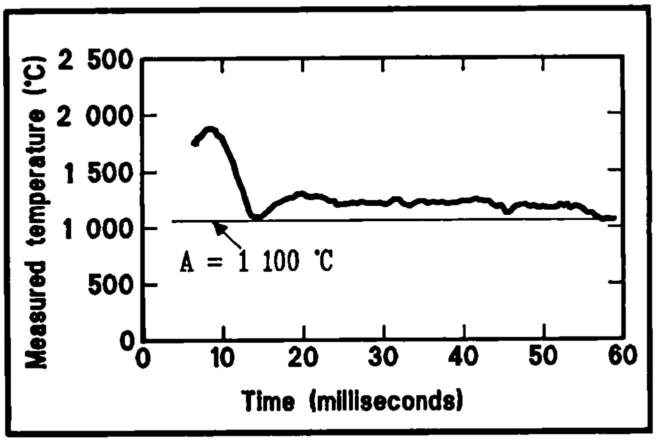
Important factors include the composition of the coal (especially the hydrogen and oxygen content), its grain size, and the air temperature and its oxygen content (Figures 1-27a and 1-27b).

Tests have also shown that the use of a plasma accelerated coal gasification.

In an Irsid project (35) a drop furnace developed by CNRS was used in a precision study of the combustion of coal particles released one by one into a high temperature, lamellar air flow. An example (Figure 1-28) shows the combustion of a 100 micron, low-volatile coal particle in air at 1 000°C.

The temperature peak is due to the volatile matter being driven off and burnt, the quantity being twice that determined by analysis carried out according to the ASTM standard.

Figure 1-28
Thermal history of a coal particle



A – Furnace temperature.

These results confirm that with the injection of low-volatile coal fines into tuyères, the release and combustion of volatile matter is only completed towards the middle of the raceway, and that the semi-coke formed, while very reactive, has no possibility of achieving total combustion in the cavity in front of the tuyère. It is consumed by gasification by the CO_2 and H_2O around the edge of the cavity and higher up in the blast furnace.

All these projects have meant that considerable progress has been made in our understanding of the phenomena involved in coal injection in the blast furnace. Nevertheless, in view of the fact that the results of experiments carried out at pilot-plant or laboratory scale are greatly influenced by the experimental techniques adopted, the direct application of these results to the blast furnace must be made with care because of differences with the actual operating conditions.

On the basis of these pilot-plant and laboratory-scale results, projects were started in order to further increase the amount of coal injected at the tuyères. This is the case with a current CRM project (42).

Also within the framework of the ECSC pilot and demonstration programme, British Steel, Hoogovens and ILVA (43) have started a project at Cleveland (UK) aimed at increasing coal injection in a blast furnace to levels well beyond rates currently employed using simultaneous oxygen injection at the level of the tuyères. At the same time, coke consumption should be reduced to well below 250 kg per tonne of hot metal.

1.3.5. Progress in blast furnace operation

Intensive use of information technology has spread rapidly in the field of the blast furnace: equilibria, prediction mathematical models, use of databases, on-line calculations, etc. It is thus becoming increasingly difficult for operators to utilize the mass of information at their disposal.

This need to take into consideration a large and increasing amount of data is at the root of a study into blast furnace operation by expert systems, that is to say by computer programmes capable of making logical decisions.

Two projects are currently being undertaken in 1990, by British Steel (44) and CRM (45).

As a brief example, an expert system, not currently being used in real-time, has a principal function of checking data reliability, and then of examining the coherence of all the data using criteria derived mainly from thermal and material balances, and applied over long periods of operation.

Important phenomena such as those involving the descent of the charge and gas partition have been described quantitatively and can be handled by software.

Thus blast furnace malfunctions, as well as the formation of skulls, can be identified and predicted.

Improvements are still necessary, but it would already appear that the use of expert systems in blast furnace operation is particularly promising.

1.3.6. Smelting-reduction

Over numerous decades, many attemps have been made at replacing the blast furnace by smelting-reduction processes which require neither coke plant nor sinter plant.

In 1985, the Commission published an investigation into the techniques available or foreseeable in the field of smelting-reduction. Since then an industrial installation with a capacity of 300 000 tonnes of hot metal per year, based on the Corex process has been commissioned at Iscor in South Africa and a pilot plant of 15 000 tonnes per year is projected in Australia based on a new process known as Hismelt.

Within the ECSC steel pilot and demonstration programme, Hoogovens, British Steel and Ilva (46) have started investigations involving the simulation and construction of a pilot plant known as CCF (cyclone converter furnace). The coal and the oxygen which are injected inside a convertor on a heel bath of hot metal reduce and melt the iron ore fines which have previously been pre-reduced in a cyclone situated above the converter, using the reducing gas resulting from the reaction.

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Introduction

Three-quarters of the steel in the European Community is produced in oxygen converters, while the remaining quarter is made in electric arc furnaces.

Following spectacular increases in productivity in these units during the 1970s, and a slowing down in production due to the energy crisis, the steelmakers in the Community concentrated on reducing costs and improving quality in order to comply with increasingly severe customer requirements. The ECSC provided financial support for a large programme of research in these fields.

Increasingly, strict environmental protection considerations have posed problems in employing by-products from steel to the full, especially slags.

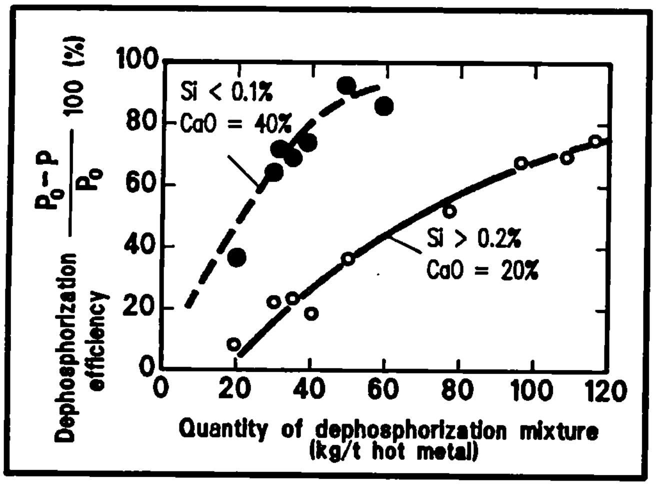
2.1. Oxygen steelmaking

2.1.1. Obtaining low phosphorus contents

Increasing quantities of steel must be suitable for more and more difficult conditions of forming and use, in the case of both flat and long products. These conditions often require, depending on their end-use, low sulphur and phosphorus contents in the liquid steel.

Even if the methods of obtaining low sulphur contents are well established, the same is not true for phosphorus. For this reason, a large effort has been devoted to investigating this problem within the Community in order to evaluate all the different techniques available: pre-treatment of the hot metal, dephosphorization in the converter, secondary metallurgy.

Figure 2-1
Influence of the quantity of dephosporization mixture on the level of dephosporization



2.1.1.1. Hot metal pre-treatment

Removing part of the phosphorus through pre-treatment of the hot metal is a solution that has been widely developed in Japan. The application of these techniques to conditions prevailing in Europe is not obvious, in view of the high investment costs. It was thus felt necessary that the technical and economic characteristics of the various processes for hot metal pre-treatment should be studied in detail.

An Irsid project (1) which was carried out successively at the laboratory (300 kg), pilot (6 t), and industrial (140 t in Dunkirk) stages, demonstrated that it was possible, after desiliconization and the removal of slag, to obtain levels of phosphorus in the hot metal that were below 0.010% by injecting approximately 20 kg of sodium carbonate per tonne.

Krupp (2) also demonstrated on both laboratory (25 kg) and then industrial (80 then 300 t) scales that after desiliconization and removal of slag, phosphorus levels could be reduced by 85% using a mixture of limescale-fluorspar (Figure 2-1). The project, which removed silicon using a rotary reactor installed in the floor of the blast furnace, proved not to be economically viable.

A CSM project (3), which was tested on the 10,000 tonne/day No 5 blast furnace in Taranto, required desiliconization in the runner and removal of the slag by the taphole, following which the addition of a lime-based mixture at the moment of tapping the ladle provided 50% dephosphorization (Figure 2-2).

Hoesch (4) investigated the possibilities of using converter slag and dusts on a 200 kg scale.

Stirring phenomena during lance injections in torpedo ladles was studied by Irsid (5).

In order to achieve phosphorus contents of less than 0.005%, other techniques must be employed, in the converter and in the steel ladle, as demonstrated by the mathematical model developed by CRM (6) which was later confirmed during industrial-scale tests.

Detailed studies were made for industrial installation projects in various countries, but none have yet been adopted on an industrial scale (7).

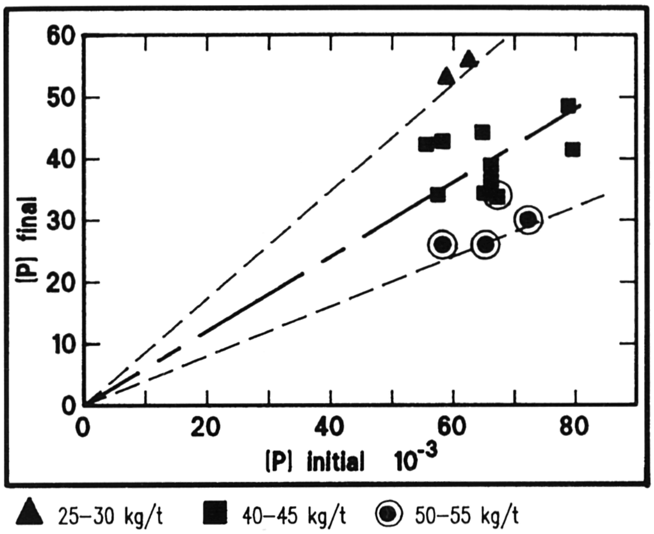
This ECSC research programme has thus completely achieved its initial objective which was to determine the technical and economic aspects of the pre-treatment of raw steel.

2.1.1.2. Dephosphorization in the oxygen converter

Phosphorus levels obtained in an oxygen converter depend upon the silicon and phosphorus content of the hot metal that is charged and also the operating conditions utilized.

Using a desiliconized but not dephosphorized hot metal, Krupp (2) showed, on a 300-tonne converter, that it was possible to obtain levels of phosphorus in the steel of 0.015%, with a small amount of slag.

Figure 2-2
Results of dephosporization treatment



Research at CRM (6) showed, using hot metal with optimum composition (Si 0.3 to 0.4%, Mn 0.2 to 0.3%, P 0.08 to 0.10%), that it was possible to obtain phosphorus levels of less than 0.010% in the converter while still maintaining the iron content of the slag at values of approximately 16%.

Based on similar concepts, British Steel (8) carried out a systematic study of a 3-tonne pilot-scale converter to examine the effect of different lime-based slag compositions on removing silicon and phosphorus during refining.

Reducing converter slag carry-over during ladle tapping operations, by limiting pick-up of phosphorus by the steel, is another method of reducing phosphorus levels in the steel.

The steel industry has for a long time tried to avoid, or at least limit this slag carry-over during tapping. Nevertheless, the procedures employed are not sufficiently reliable. Several research projects have been undertaken, with the support of the ECSC, aimed at improving our understanding of this phenomenon and providing a solution.

In a VDEh project (9), tests were carried out on models and in a steelworks in order to determine the flow characteristics of the liquid phases at the end of tapping, in converters, ladles and continuous casting tundishes.

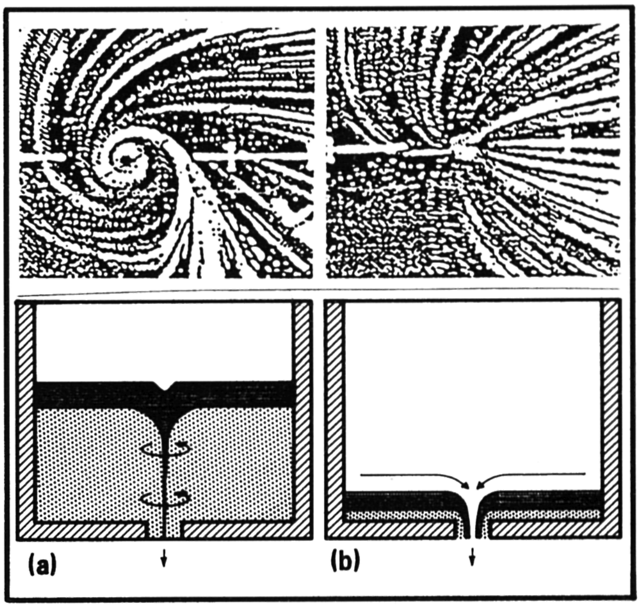
It was demonstrated that three types of phenomena could cause slag carry-over, forming, according to the situation:

(i) a metal-slag emulsion;

(ii) a vortex (Figure 2-3);

(iii) a drain sink (Figure 2-3).

Figure 2-3
Definition of a vortex sink and a drain sink



(a) Vortex sink. (b) Drain sink.

This drain sink phenomenon which had hardly been studied until now, occurred at the end of tapping when the flow rate was less than the capacity of the nozzle.

It is possible to draw a certain number of important practical conclusions from this study. For example, for converter tapping, it was demonstrated that injecting gas near to the nozzle ran the risk of increasing the amount of slag carried over into the ladle.

The results are also applicable to tapping from ladles and tundishes.

A third way in which low phosphorus may be obtained is by treating the steel in the ladle, as discussed in the chapter on secondary metallurgy.

2.1.2. Flexibility and regularity of converter operations

Stirring conditions of the bath of liquid metal play a vital role in steel manufacture, and these metallurgical advantages explain the generalization of bottom-stirring techniques in top-blowing converters.

2.1.2.1. Bottom-stirring metallurgy and technology

A British Steel project (10) consisted essentially of using a 3-tonne pilot-scale converter to compare different bottom-stirring techniques. The stirring efficiency and the metallurgical results obtained in steels covering a wide range of carbon contents were examined.

A current VDEh contract (11) is aimed at obtaining minimal nitrogen levels in the final steel by controlling the evolution of this element throughout the whole manufacturing process, from liquid metal production to steel tapping.

Nitrogen content in the hot metal has only a small effect on obtaining low nitrogen contents in the raw steel.

During desulphurization treatment of the liquid metal, argon blowing reduced nitrogen levels slightly.

A significant effect may be obtained in converter refining operations, and nitrogen levels of less than 20 parts per million (ppm) may be obtained.

Many projects concerning physico-chemical aspects of refining slags will be discussed later in association with secondary metallurgy.

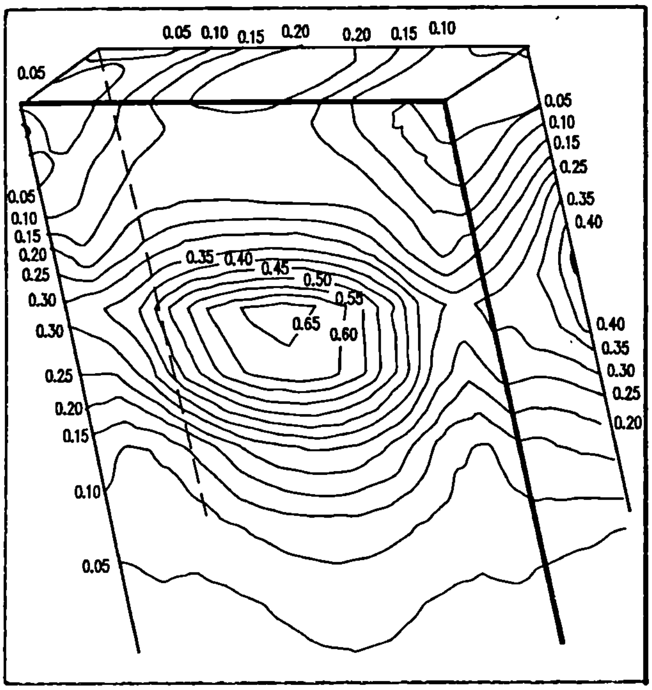
The need to be able to ensure gas injection, under the required operating conditions, for the whole refractory life of the converter lining led operators to improve the life span of stirring elements installed in the bottom of the unit.

Two projects which investigated this theme were carried out through close collaboration between CSM, British Steel and Hoogovens.

CSM investigated several systems intended to measure the wear of porous plugs fitted in the bottom of the converter (12). Temperature measurement using thermocouples fitted at various levels, in combination with a mathematical model, provided predictions of plug wear in the first part of the campaign.

British Steel and Hoogovens carried out a joint study of factors influencing spalling of refractory stirring bricks due to thermal shock (13). A mathematical model and readings from thermocouples installed in various positions allowed the thermal profile as well as the internal stresses of the bricks to be calculated (Figure 2-4). This showed the importance of preheating and the slag covering after tapping. Both steelworks improved the life span of the stirring elements.

Figure 2-4
Stress diagram of a refractory stirring brick



2.1.2.2. The use and melting of scrap

Depending upon the specific conditions encountered in the steelworks and the economic situation, the use of scrap in oxygen converters can represent an important improvement in production costs.

A project by Klöckner (14) attempted to develop the KS process for manufacturing steel in a bottom-blown converter of 125 tonnes, using a solid charge composed mainly of scrap, the energy being supplied by the combustion of coal fines injected in combination with pure oxygen.

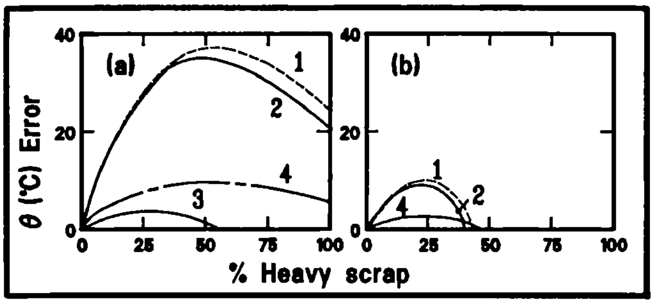
The aim of producing steel without hot metal was achieved, although improvements remain to be made in aspects of energy consumption and the life of refractory linings.

An Irsid project (15) comprised two fields of investigation:

(i) An understanding of the gaseous phase in the converter and the mechanism of post-combustion of CO to CO_2. A mobile probe provided a means of mapping the temperature and composition of gases in the converter and of confirming quantitatively those factors which favoured post-combustion.

(ii) An understanding of the melting mechanisms of cooling additions. Measurements of melting times of pieces of scrap and solid pig iron, and development of a mathematical model provided values for the amounts of unmelted parts according to operating conditions (Figure 2-5). The unfavourable effects on the melting time of mixed charges of heavy and light scrap, as well as the weak influence of pre-heating heavy scrap, were demonstrated.

Figure 2-5
Errors in bath temperature due to unmelted material



(a) Sublance deeping. (b) End of blowing.

Charge without ore End θ 1 650 °C { 1 – Blocks of 2 t; 2 – Blocks of 1 t

Charge with 30 k/t ore { 3 – End θ 1 650 °C; 4 – End θ 1 620 °C

2.1.2.3. Automation of oxygen steelworks

The need to ensure high productivity of steel-producing units while at the same time maintaining flexibility in order to meet the increasingly strict commercial constraints, has led steel producers to develop automation of oxygen steelworks, as was widely discussed in a previous report.

This led to a joint research project involving Arbed (16) as coordinator, together with Irsid, CRM and Hoogovens, each participant having a precise programme to be carried out on converters fitted with suitable measuring equipment.

This study advanced concrete conclusions concerning the advantages and limitations of automation at the current state of our knowledge.

In order to extend these limits, a current CRM project (17) is intended to determine with greater precision, with the help of probes, the settings for various parameters of oxygen blowing operations.

A current Irsid project (18), in collaboration with Sollac at Fos and Dunkirk, is intended to model the metallurgy in the final phases of blowing and during stirring in the after-blow period. This project is aimed at improving both productivity and the regularity of temperatures as well as composition of the steel in the tapping ladle.

A current British Steel project (19) consists of applying expert systems in order to improve metallurgical results, to develop automated operations and increase the reliability of design technology of oxygen steel plants.

As regards metallurgy, a large quantity of data was already available and its analysis revealed methods of optimizing the results, especially concerning temperature, and carbon and phosphorus levels.

As a comparison, the engineering data available was limited, and it proved difficult to extract this type of information from steelworks' operation. Nevertheless, the data obtained during this project was more precise and more suited to the application of statistical methods intended to predict equipment failures and to plan any required preventive maintenance.

The initial industrial results indicate a tightening of scatter in temperature values and final steel compositions when tapping the ladle.

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2.2. Electric arc furnace

During the 1970s, progress was achieved mainly in transforming the electric arc furnace into a high technology piece of equipment, with hourly production rates multiplied several times over, and greatly reduced operating costs, especially in the generalization of water-cooled panels.

The electric arc furnace has thus become essentially a rapid scrap melting process, associated with secondary metallurgy.

The last decade has seen the collective research effort of the ECSC concentrated on mastering scrap melting operations, reducing energy costs and improving environmental protection.

2.2.1. Behaviour of the electric arc

During the phase involving melting of scrap, instability of the electric arc causes a range of unwanted effects: transfer of varying power levels to the charge, creation of 'flicker', increased electrode consumption.

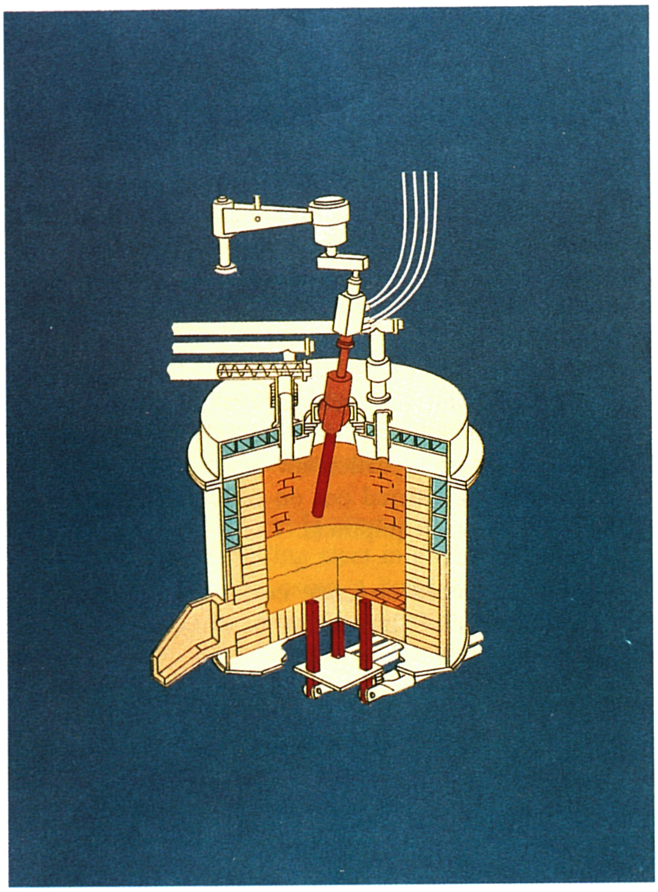
Several projects supported by the ECSC and carried out by British Steel, VDEh and Irsid [(1) to (3)] involved electric arc behaviour during the melting phase: fundamental research into arc properties, industrial development of an instrument to measure flicker, tests on doped electrodes and hollow electrodes, analysis of power fluctuations, mathematical modelling of the electrical behaviour of the arc, etc.

On the basis of the knowledge acquired during these experiments, further projects are under way at VDEh, Irsid and British Steel, aimed at optimizing the use of electrical energy and metallurgical factors in the operation of modern electric arc furnaces, and the use of expert systems [(4) to (6)].

2.2.2. Electrode consumption

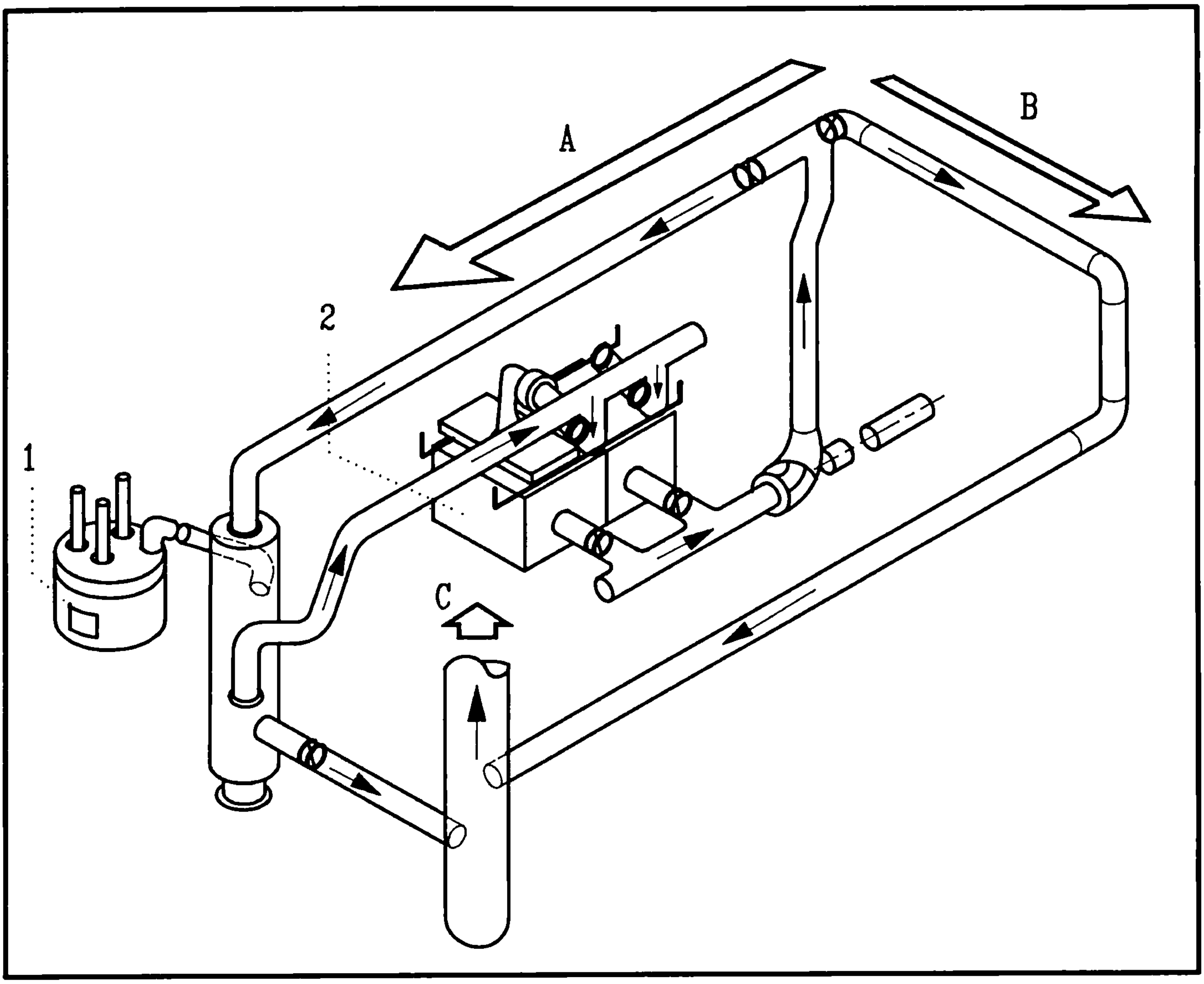
Under normal economic conditions, the cost of electrodes, together with electrical power costs, represent the most important single items in the manufacturing costs of steel produced by an electric arc furnace, with the exception of the cost of the charge; which explains the interest of steelmakers in reducing electrode consumption.

Figure 2-6
General layout of a plasma torch



VDEh undertook a huge project covering several plants, which was intended to establish the relationships between electrode consumption and their properties as well as operating conditions, a difficult subject as shown by previous attempts (7). The tips of the electrodes were filmed after each campaign using a video camera connected to a computer which was able to calculate the amount of tip and lateral consumption that the electrode had suffered. This allowed significant correlation to be made between tip wear and the square of current intensity, as well as between the lateral consumption and the rate of oxygen blowing.

Figure 2-7
Scrap steel pre-heating installation



A – Recirculation circuit. B – Direct circuit. C – To flue gas dust removal.
1 – Electric arc furnace. 2 – Pre-heating chambers.

Plasma also appears to be an answer to reducing electrode consumption. In fact, there do exist furnaces which use plasma torches exclusively, but this technology cannot be considered, for the moment at least, as an alternative to the UHP arc furnace for the mass production of steel.

On the other hand, it is interesting to pose the question as to whether plasma could be used as an additional source of heat in a conventional electric furnace. Following pilot-scale tests, British Steel (8) showed that this solution is technically feasible (Figure 2-6), but requires modifications to the furnace which are overly expensive.

Nevertheless, addition of heat by plasma sources would seem to be of interest for secondary metallurgy, in the ladle and in the continuous casting tundish, as discussed later in this text.

2.2.3. Energy recovery from gases

The most important source of heat losses in electric arc furnace operation is constituted by the gases which escape from the furnace. Their composition and temperature vary greatly during operations and, as a result, it is not possible to apply the same solutions as employed in oxygen converters, i.e. energy recovery without combustion.

The most usual technique is to burn off this gas in a combustion chamber situated at the furnace gas outlet. The gases thus provide a heat saving of some 100 kWh per tonne of steel produced which can be used for scrap pre-heating.

In this field British Steel evaluated the technical and economic feasibility of the Brusa process for scrap pre-heating in a rotary furnace, improvements being due to the installation of an intermediate hopper (9).

Large increases in productivity and savings in kWh and electrodes were realized, although they were unable to compensate for the additional investment and operating costs.

Irsid carried out a world-wide investigation into scrap pre-heating in the basket (10). A mathematical model and the setting-up of a pilot-scale operation provided the means of determining heating curves for the scrap according to its characteristics, the influence of hydrocarbons contained in the scrap, and the effects of other variables.

On the basis of this data, an industrial unit was installed on a 60-tonne, 40-MVA furnace (Figure 2-7). Savings of 20 kWh per tonne were attained by pre-heating 65% of the metal charge (two baskets out of three).

Studies concerning pre-heating scrap in electric arc furnaces are continuing with special regard to environmental aspects.

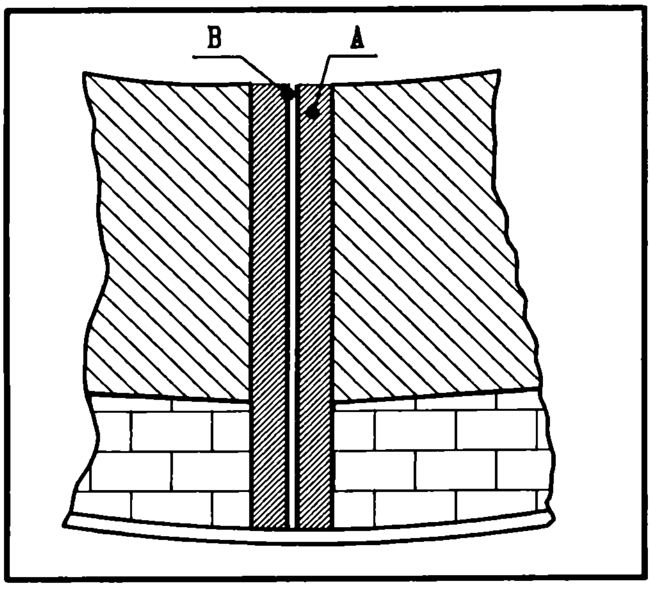
2.2.4. Bottom stirring

Electric arc furnace operators, as well as those of oxygen converters, are attaching ever-increasing importance to the quality and consistency of their steel products.

This is why mention must be made of the application of bottom-stirring to the electric arc furnace.

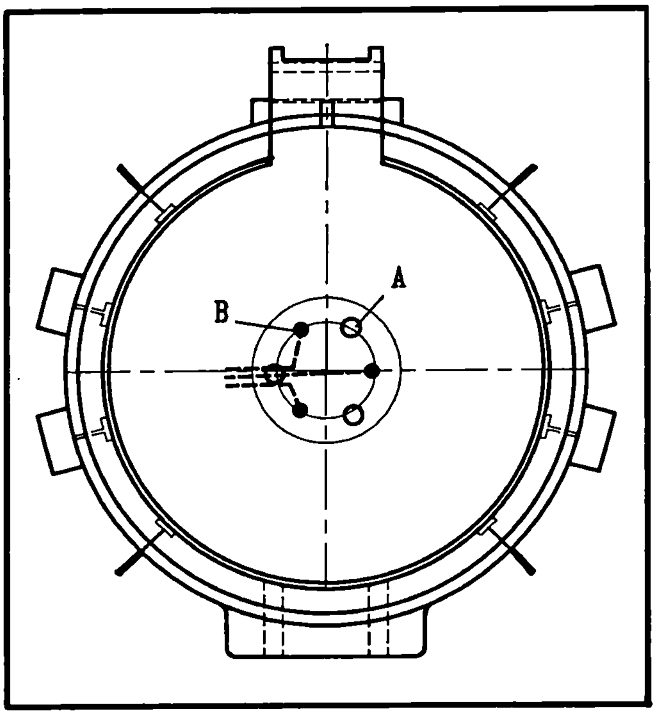
Studies by Thyssen Stahl (11) on a 130-tonne UHP furnace (Figures 2-8a and 2-8b) and Krupp (12) on a 140-tonne UHP furnace, have demonstrated the improved productivity and metallic yield which results from approaching slag-metal equilibrium. These projects have developed industrial technological solutions which are suited to electric arc furnace operation.

Figure 2-8a
Tuyère installation in furnace bottom



A – Pierced bottom brick. B – Steel tube.

Figure 2-8b
Layout of tuyères in furnace bottom



A – Position of electrodes. B – Base tuyère.

2.2.5. Development of a UHP electric arc furnace operating on direct current

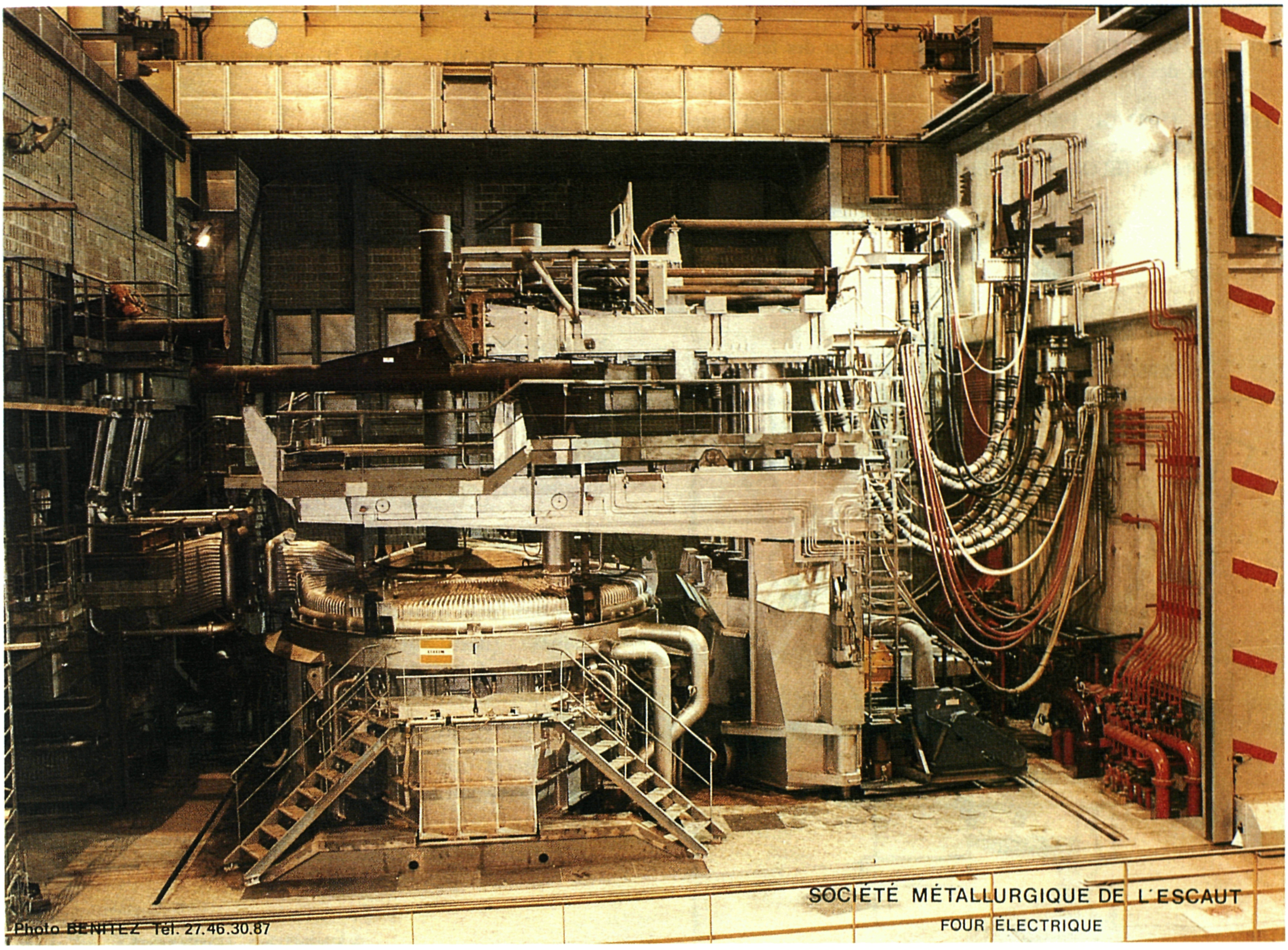
The Société métallurgique de l'Escaut (SME) has installed an 80-tonne, 70 MW, UHP electric arc furnace operating on direct current (d.c.), in its new shop at Trith-Saint-Léger (Figure 2-9). This furnace is equipped with three electrodes, since the designers wanted to keep open the option of returning to alternating current (a.c.) if d.c. operations did not prove successful.

The main reason which led SME to select this concept was the expected reduction in electrode consumption. Should the expected 50% reduction in consumption be realized, this would be translated into an economy estimated at FF 80 per tonne at the time of the research work. Other reasons for this choice include: a reduction in investment costs due to the lack of flicker compensation circuits (FF 12 million), reduction in noise, total energy consumption and in refractories consumption.

The ECSC pilot and demonstration programme supplied funds towards many delicate aspects of fine tuning of the operating conditions of this furnace (13):

(i) the thermal and electrical insulation of the bottom electrodes, together with the design of mechanical components;

Figure 2-9
Direct current arc furnace at SME



(ii) an increase in the diameter of the electrodes axes circle, necessitated by the high heat concentration in the centre of the furnace;

(iii) the modification of the path of the power supply circuits which were influencing arc behaviour.

In 1990, after four years operation, the performance figures of the d.c. furnace at SME are equivalent in cost per tonne of steel and productivity to the performance figures of the best a.c. furnaces. In particular, electrode consumption has dropped to 1.2 kg per tonne. This recent d.c. furnace technique has also revealed a number of further promising avenues for investigation: the continuous charging of scrap iron to the centre of the furnace is one which is being studied under a further contract in the ECSC pilot and demonstration programme (14).

Thus, the main Japanese steelmaking companies have decided to incorporate the most advantageous aspects of this technology in their mono-arc version: 10 units are to be converted from d.c. to a.c. operation before the end of 1992. An agreement has been reached between Usinor-Sacilor, the main shareholder in SME, and the Nippon Steel and Daido Steel companies to coordinate the expected developments of this new technique.

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2.3. Secondary metallurgy

The increasing demands being made of steel quality — chemical composition, cleanliness, mechanical characteristics and surface appearance — have conferred a vital role on secondary metallurgy, by which we mean those metallurgical operations carried out in the steel ladle, and more recently in the continuous casting tundish.

Fully aware of the importance of this domain in ensuring the competitiveness of the European steel industry, the ECSC has provided support for many research contracts of both a basic and an industrial nature.

In view of the size of this programme and the diversity of the subjects covered, it is not possible to describe each research project, but representative examples of the metallurgical and thermal aspects of this Community programme of work will be presented.

2.3.1. Thermal aspects

Ladle or tundish metallurgy may require the provision of heat to compensate for heat losses caused by the additions and the increased time for which the liquid metal has to remain in the ladle.

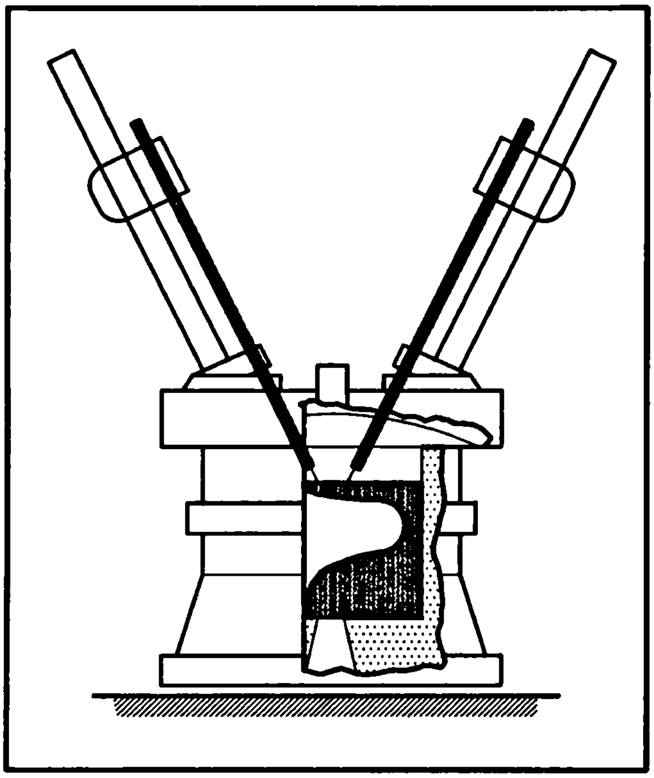
This additional heat may be furnished by exothermic additions (Al) but is most often supplied by an electric arc, resulting in some recarburization of the liquid metal by the electrodes, which can be undesirable for certain grades of steel.

Several contracts have investigated different methods of supplying additional heat:

(i) Irsid has developed an inductively heated ladle on a 7-tonne scale (1) in which the shell, in order not to shield the inductive field, is fragmented and composed of tie rods which hold the refractory lining in place. This solution, which also provides stirring of the liquid metal, would seem to be able to be extrapolated in this form up to 50 tonnes;

(ii) Krupp (2) has studied heating by plasma arc in a 30-tonne ladle fitted with three 4 000 A torches. The initial metallurgical results demonstrated the absence of any changes in carbon or nitrogen content in the bath during heating (Figure 2-10);

Figure 2-10
Thirty-tonne plasma ladle furnace



(iii) CSM (3) investigated the use of the plasma arc in maintaining the temperature of the liquid steel in the tundish, an essential factor in ensuring the quality of continuous cast products. The use of a system employing three plasma torches allows the temperature of the steel to be maintained within a predetermined temperature range of 10°C throughout the cast. An ECSC demonstration project is to be undertaken in order to make the process fully suited to industrial operating conditions.

2.3.2. Metallurgical aspects

2.3.2.1. Dephosphorization by steel ladle treatment

Ladle treatment — secondary metallurgy — is another method for reducing the phosphorus content in the final steel. British Steel (4) has developed, on a 3-tonne pilot plant, a mathematical model for predicting dephosphorization and desulphurization according to certain parameters: time, stirring, residual slag, etc.

On an industrial scale, CRM has tested a ladle addition technique capable of achieving phosphorus levels after slag removal that are below 0.005% (Section 2.1, reference 6).

CSM (5) has, in turn, studied ladle dephosphorization under oxidizing and reducing conditions.

Under oxidizing conditions, the addition of 20 kg of lime-fluorspar mixture with added iron oxide or gaseous oxygen can provide final phosphorus levels of less than 20 ppm for structural steels.

In a reducing environment, dephosphorization for stainless steels has been achieved by injecting metallic calcium. A solution was found for deactivating the slag produced, since under humid conditions this slag produces PH_3 gas which is extremely poisonous.

A basic research project conducted by VDEh on the composition of dephosphorizing slags in secondary metallurgy is described later.

2.3.2.2. Thermodynamic studies of metal-gas-slag systems

Secondary metallurgy involves operations which are becoming more and more accurate and complex. These operations cannot be successful unless they are based on a sufficiently precise understanding of the thermodynamic data concerning the constituents involved. The same is true of the process control of the converter and electric arc furnace.

These thermodynamic studies thus play a vital role in the successful production of steels which are required by the customers to conform to ever more rigorous quality and consistency parameters.

The importance of these studies extends to sectors other than steelmaking, as we have seen concerning the control of silicon in the blast furnace.

In this particularly difficult field of high temperature physical chemistry, the ECSC has supported a large research programme, of which some typical examples are presented.

An RTWH project in Aachen (6) concerns many binary iron-based metallurgical systems. It consists of critically evaluating the validity of thermodynamic data: heats of formation, entropies, specific heats, and of defining phase diagrams with precision.

Irsid (7) coordinated work involving inorganic compounds, mainly oxides, and complex slags, carried out in four laboratories in France and the United Kingdom. A complete collection of valid thermodynamic data was established which has been approved by all the European experts and can be universally applied.

Particular attention has been given to the CaO-Al_2O_3 system in view of its importance in understanding the formation of inclusions during calcium treatment of steel.

An NPL project (8) carried out a critical assessment of the physical properties of refining slags based on CaO, SiO_2, FeO and MnO, with minor constituents P_2O_5, Al_2O_3 and Cr_2O_3. The properties that were studied included: viscosity, density, electrical conductivity, surface and interface tension, thermal properties, heat content and phase diagram.

In industrial slags, the large number of constituents present in appreciable quantities meant that their thermodynamic properties were unable to be determined experimentally. Mathematical modelling must be used in order to predict their properties and corresponding states of equilibrium.

As an example, an Irsid contract (9) has provided an analytical description of the liquidus surfaces of several quaternary systems, allowing phase diagrams to be read by computer.

The model based on statistical thermodynamics, developed during this Irsid project (9) allows both the phase diagrams and the thermodynamic activities of complex slags to be described. It correlates well with experience over a wide range of temperatures and compositions covering basic and acid slags (Figure 2-11).

Figure 2-11
CaO-SiO_2-Al_2O_3 system at 1 550°C: comparison between experimental and theoretical values

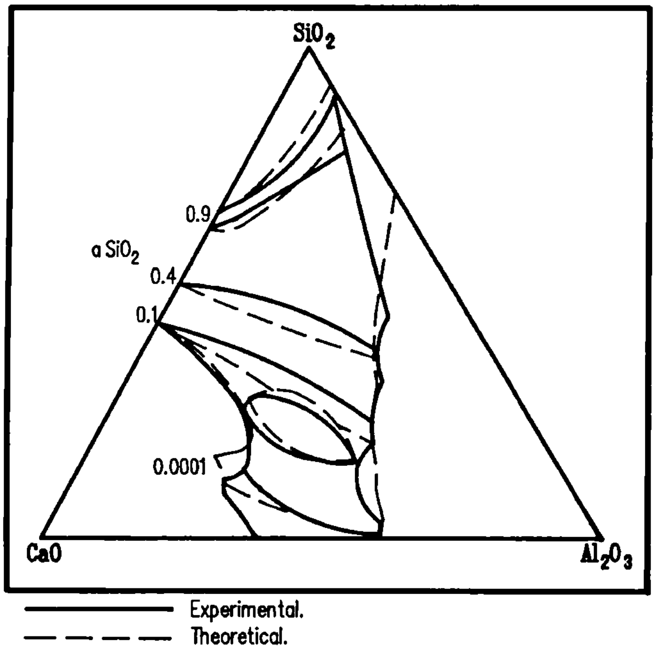
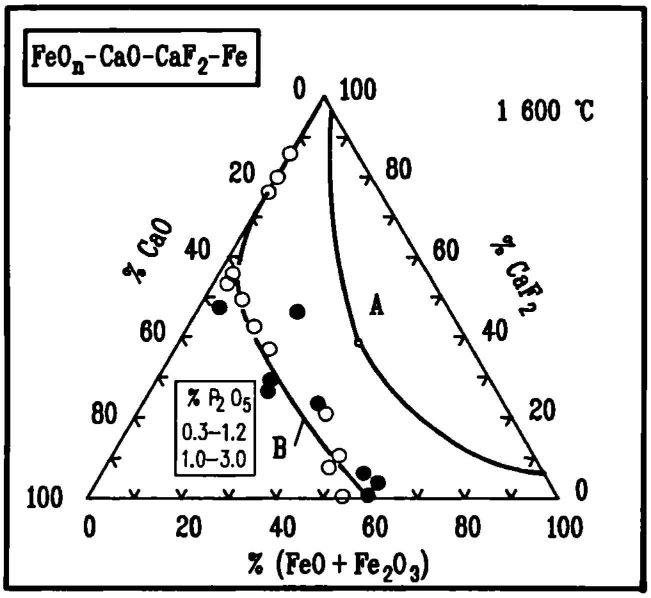


Figure 2-12
CaO-CaFe$_2$-FeO equilibrium phase diagram in liquid steel at 1 600°C



A – Two-liquid zone.
B – % (P$_2$O$_5$)/% (P) ~ 2 000 to 4 000 (50% CaO, 20% FeO)

This model provides a powerful tool for describing metal-slag reactions and the formation of inclusions.

Among those models used in the projects, the Monte Carlo method has been applied in a CSM project (10) aimed at estimating the thermodynamic properties of slags.

A VDEh project (11) concerning dephosphorizing slags, which was mentioned in the previous chapter, investigated ternary diagrams of CaO, FeO$_n$, X (where X may be CaFe$_2$, Al$_2$O$_3$, SiO$_2$, etc.) and showed that the highest partition coefficients for phosphorus are always obtained with lime saturation. By adopting extremely rigorous operating conditions it is possible to obtain very low phosphorus levels with values below 10 ppm in the final steel (Figure 2-12).

A study by MPI (12) looked at the solubility of calcium in the liquid metal bath in equilibrium with lime-saturated slags, for different temperatures and alloying elements.

A recent contract with VDEh (13) has provided greater details on the thermodynamic conditions concerning the solution of alkaline earth elements in liquid iron and Fe, Ni and Cr alloys, and has also determined the influence of these elements on the elimination of tramp elements Sn, N, P, As and Sb from liquid iron and its Ni and Cr alloys.

These studies have thus demonstrated that the addition of metallic calcium under reducing conditions is a promising way forward for dephosphorizing chrome alloy steels.

Metallic calcium added to liquid steel acts as a deoxidizer, desulphurizing agent and modifies the oxides already present in the liquid metal bath.

A CSM study (14) is aimed at improving our knowledge of the behaviour of calcium in association with aluminium and silicon during deoxidation of steel.

Following the theoretical part of the study involving equilibrium phase diagrams between liquid steel and slags in the CaO-Al$_2$O$_3$-SiO$_2$ system, the experimental part investigated the transformation of alumina particles as a function of time following calcium addition.

Another part of this project concerning the Fe-Ca-O and Fe-Ca-S systems at 1 600°C has been entrusted to the Royal Institute of Technology in Stockholm.

The previously mentioned Irsid project (9) investigating oxide systems also involves the measurement of interface properties, especially the angles of contact between the liquid metal and various oxides and sulphides.

Laboratory experiments have shown that the angles of contact between the liquid metal and the solid aluminates depend largely on the oxygen content.

As a result, the formation of a cluster of alumina (which favours settling) can be inhibited if the oxygen potential is kept high. This phenomenon may occur during late reoxidation of aluminium-killed steels.

The field of electrochemical processes has also been the subject of several projects.

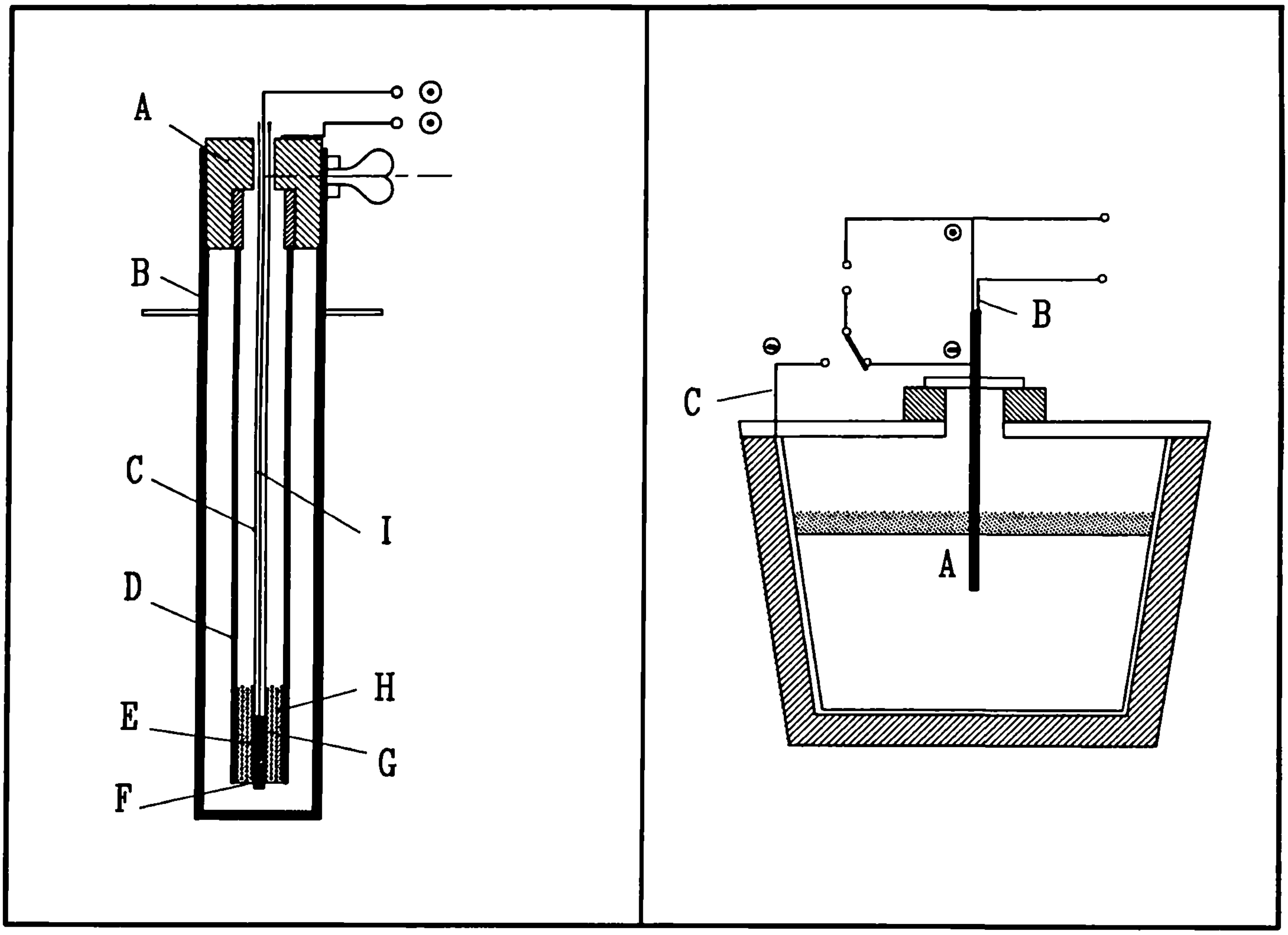
We may recall the Irsid project (15) concerning oxygen and sulphur extraction by electrochemical means, which was very promising on a laboratory scale but which proved to be economically unviable at the semi-industrial scale, due to insufficient mass transfer of these elements from the metal to the slag.

Two VDEh projects [(16) and (17)] were aimed at developing continuous measurement of dissolved oxygen in the liquid steel bath using solid electrolyte cells. The results are promising, especially for continuous casting tundishes where valid measurements were obtained for up to two hours (Figure 2-13).

Two current contracts, VDEh (18) and CSM (19), concern the use of electrochemical cells for measuring silicon, aluminium and manganese in liquid steel.

For further details on these physico-chemical projects, see two recent combined reports [(20) and (21)].

Figure 2-13
EMF immersion probe for continuous measurement of oxygen content



A – Steel plug. B – Steel tube. C – Al_2O_3 tube.
D – Cermet tube. E – Cr/Cr_2O_3 reference.
F – ZrO_2 electrolyte. G – Ir wire. H – Al_2O_3 powder. I – Pt-Rh wire.

A – Cermet sheath with probe.
B – Thermocouple.
C – Steel rod.

We would like to close this chapter by emphasizing the secondary metallurgical treatments which we wish to see increasingly developed in the continuous casting tundish. This new field is the subject of a coordinated programme of current research [(22) to (27)]. Among these projects we may cite a VDEh contract concerning the non-stationary flow and cleanliness of steel, a CSM study on hydrodynamics, a British Steel project involving fine gas bubble injection, and also CSM, CRM, Krupp and Irsid projects on improving steel cleanliness using novel metallurgy techniques and experiments with ceramic filters for trapping inclusions.

References

(1) EUR 9628 FR 1985 — Irsid: 'Traitement métallurgique de l'acier en poche chauffée par induction'.

(2) EUR 13423 DE 1991 — Krupp: 'Untersuchung der metallurgischen Bedingungen in einem Drehstrom-Plasma-beheizten Pfannenofen'.

(3) EUR 13364 IT 1991 — CSM: 'Impiego del plasma per il controllo della temperatura dell'acciaio nel corso del colaggio in colata continua'.

(4) EUR 11222 EN 1988 — British Steel: 'Phosphorus and sulfur removal from liquid steel by secondary steelmaking operations'.

(5) EUR 12665 IT 1989 — CSM: 'Sviluppo di trattamenti di defosforazione spinta dell'acciaio'.

(6) EUR 6432 DE 1980 — RWTH: 'Aufstellung eines Datenprogrammes auf dem Gebiet der metallurgischen Thermochemie'.

(7) EUR 7820 FR 1982 — Irsid: 'Données thermochimiques pour la sidérurgie (Phases 1 et 2)'.

(8) EUR 10434 EN 1986 — NPL: 'Physicochemical properties of BOS slags'.

(9) EUR 9428 FR 1985 — Irsid: 'Données thermochimiques et cinétiques relatives à certains matériaux sidérurgiques'.

(10) EUR 7618 IT 1982 — CSM: 'Il calcolo delle proprietà chimico fisiche delle scorie siderurgiche secondo il metodo Montecarlo'.

(12) EUR 10090 DE 1986 — MPI: 'Thermodynamische Grundlagen der Calciumbehandlung von Stahlschmelzen'.

(13) EUR 12252 DE 1990 — VDEh: 'Raffination von Stahlschmelzen mit Erdalkalinetallen'.

(14) EUR 9815 IT 1985 — CSM: 'Trattamento dell'acciaio mediante tecniche di iniezione di materiali contenenti elementi alcalino-terrosi'.

(15) EUR 7408 FR 1982 — Irsid: 'Désoxydation et désulfuration électrochimiques à l'échelle industrielle'.

(20) EUR 12118 EN 1989 — Irsid/VDEh: 'Fundamental research in the ECSC — Review of previous work and future trends'.

(21) Actes Gijon 1989: 'La CECA dans la recherche technologique et la prévention — Amélioration de la pureté de l'acier'.

(22) 7210-CA/321 — Irsid: 'Amélioration de la propreté de l'acier pour une métallurgie efficace en répartiteur'.

(23) EUR 11420 IT 1987 — CSM: 'La paniera di colata continua come recipiente di postaffinazione'.

(24) 7210-CA/420 — CSM: 'Dispositivi in paniera di c.co. per l'eliminazione delle inclusioni'.

(25) 7210-CA/214 — CRM: 'Amélioration de la propreté de l'acier par une nouvelle métallurgie en répartiteur'.

(26) 7210-CF/106 — MPI: 'Stahlfiltration'.

(27) 7210-CA/144 — Krupp: 'Filtern von Edelstahl beim Knüppel-Strangguß'.

2.4. Continuous casting

The proportion of steel produced in the Community by continuous casting has risen from 30 to 90% between 1980 and 1990 and represents a key link in the chain of steel production due to the positive metallurgical and economic aspects it provides.

In fact, casting and solidification of steel involves many complex physical and chemical processes. These processes must be understood and mastered in order to optimize operation of the strand, economically produce steels of consistently high quality, extend the range to include those grades of steels that are considered to be difficult to continuously cast, or even to develop new processes.

Among the most important phenomena that need to be mastered are the reactions between the liquid steel and the slags, the refractory materials and the atmosphere, the heat transfers which determine the rate of solidification and the thermal profiles of the products in the strand, the solidification structure and the segregation which condition the thermal and physical uniformity of the products, the shrinkage and thermomechanical deformations along the whole of the path of the bar of steel through the machine, which affect the quality of the products.

The ECSC has supported and coordinated a huge programme of research and pilot and demonstration work on these various subjects, which will be illustrated with a series of examples.

2.4.1. Liquid steel treatment

We should recall that the application of secondary metallurgy techniques to the tundish has opened new horizons for improving steel properties, as shown in the previously described ECSC projects: studies of tundish hydrodynamics, protection of liquid metal against contact with the air, argon stirring, the use of plasma arc or induction heating to maintain steel temperature, development of new types of refractories, study of inclusion filtration techniques, etc.

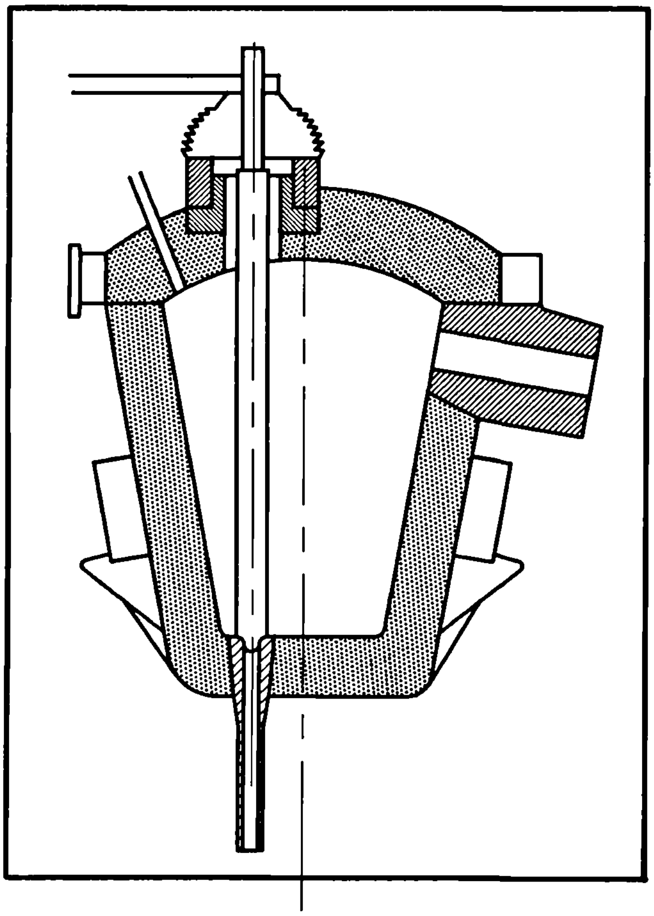
As an example, an Irsid project involves:

(i) improving the settling of inclusions in the continuous casting tundish using techniques for filtering inclusions through refractory walls and argon stirring through porous plugs fitted in the bottom of the tundish;

(ii) fighting against reoxidation using solid carbon dioxide in the tundish before starting the cast;

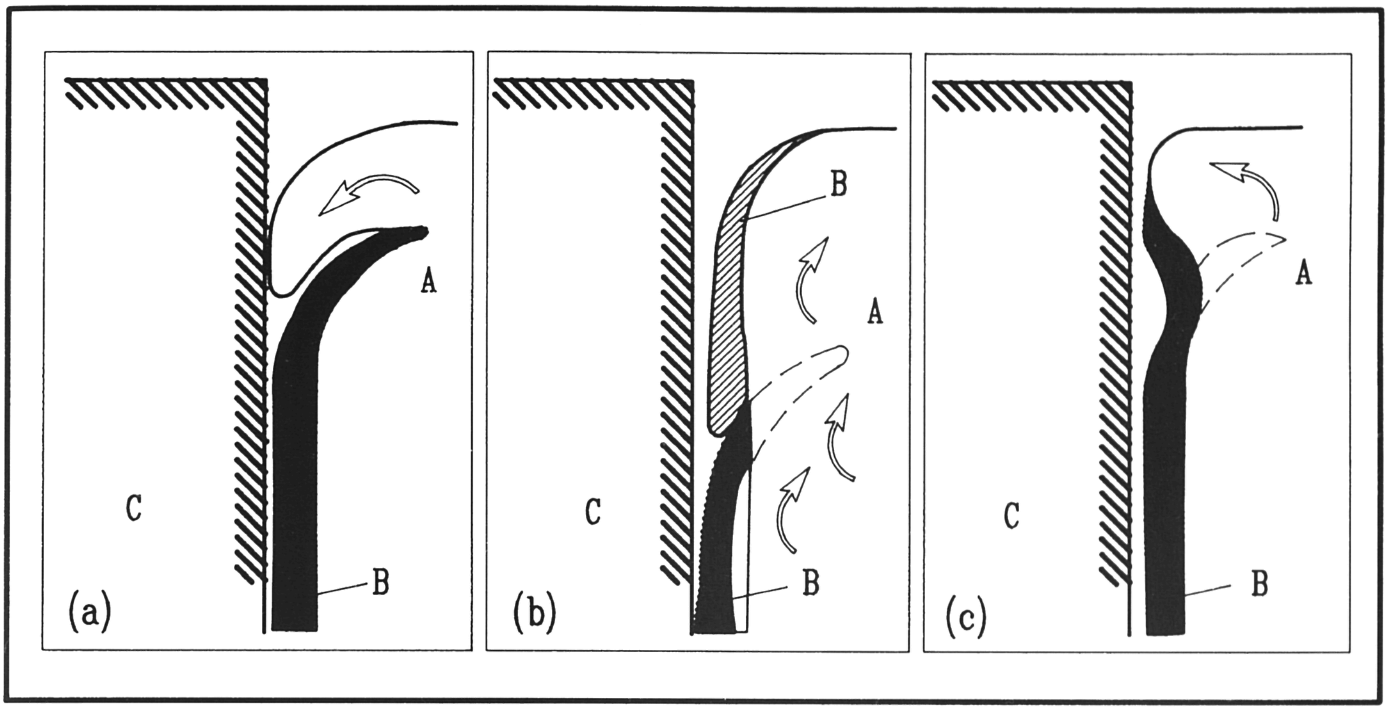
(iii) investigating techniques based on a tundish that is completely sealed and rendered inert with argon gas (Figure 2-14) which would appear to be the most effective solution to reducing the quantity of inclusions in the liquid steel.

Figure 2-14
Cross-section of covered tundish



During casting between the tundish and the mould, the submerged nozzle, provided that it is correctly sealed, protects the steel against pick-up of oxygen and nitrogen from the surrounding atmosphere. Submerged nozzles have been the subject of several ECSC studies

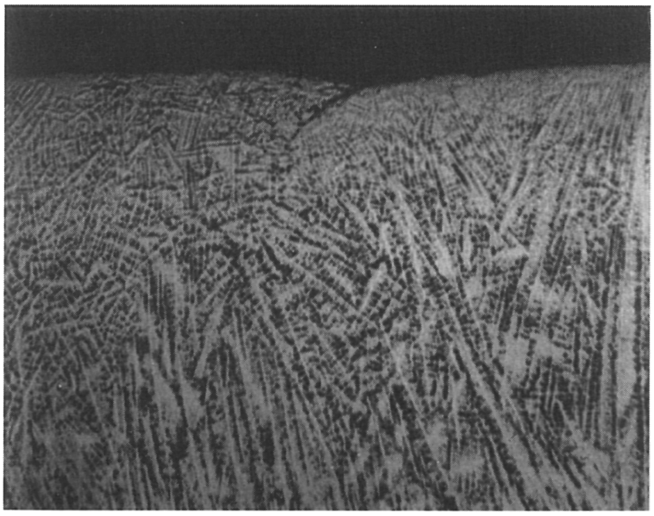
Figure 2-15b
Initial skin formation mechanisms



(a) Overflow. (b) Overflow + remelting. (c) Deformation of the solid hook.

A – Liquid steel. B – Solidified shell. C – Mould.

Figure 2-15a
Microstructure of zone around an oscillation mark



in the past, which have been extended to investigate the more complex aspects such as nozzle clogging during the casting of aluminium-killed steels.

While this phenomenon has certainly become less significant than in the past due to technological improvements up-line, as described above — mixed blowing in the converter, casting with minimum slag, ladle metallurgy and especially calcium and calcium alloy treatment, argon bubbling, etc. — difficulties are still encountered in this area.

A British Steel project has confirmed that the deposits consist of accumulations of sintered alumina (1). Prior to sintering, the alumina inclusions are usually between one and five microns in size. Analysis of steel flow characteristics shows that the alumina inclusions are driven by centripetal forces towards the walls of the nozzle, where they agglomerate.

A CSM project has in turn demonstrated that nozzles with a high lime content (2) avert clogging over a wide range of aluminium-killed steel compositions, and that they may provide an industrial solution to this problem providing that certain simple precautions are taken against moisture pick-up.

2.4.2. Mould and surface quality

Experience shows that those phenomena which occur in the continuous casting mould have a decisive influence on the productivity of the machine as well as on the quality of the steel produced. Thus the surface quality of the steel depends to a large degree on the regularity of the initial skin as it solidifies in the mould. This in turn is conditioned by the amount and homogeneity of heat exchange between the mould and the solidification skin. For these reasons, a whole series of research projects have been supported by the ECSC in this field. Several projects [(3) to (8)] have been devoted to investigating the influence of mould shape (especially in the corners), its length, its vibration, the materials used in its construction, on the casting speed and the quality of the products obtained.

We shall examine the example of oscillation marks.

Oscillation marks which occur on the surface of continuous cast products are preferred sites for non-metallic inclusions and transverse cracking, following positive segregation of existing elements (P, Mn, S, etc.) and the stress concentrations resulting from the gouging effect (Figure 2-15a). Reduction of the depth of oscillation marks represents a positive contribution to product quality.

The phenomena which occur in the area of the meniscus play an important role in the formation of oscillation marks, as shown in the diagram depicting the three main mechanisms of formation of the meniscus (9) (Figure 2-15b).

An initial method of mastering the depth of the oscillation marks and their spacing is to optimize the mould oscillation parameters. In a British Steel project (10), a servohydraulic mechanism has been developed which allows a wide range of frequencies to be employed (up to 1 000 oscillations per minute), as well as an extended range of amplitudes. It has thus been demonstrated on a prototype scale that the depth of oscillation marks is decreased by increasing the frequency and decreasing the amplitude of oscillation.

An Irsid project (11), using a novel type of hydraulic oscillator, showed that up to a frequency of 300 oscillations per minute, the depth and the spacing of the marks decreased as the frequency increased (Figure 2-16). The use of a triangular rather than a sinusoidal oscillation pattern, in combination with a short negative stripping time, decreased the depth of the marks as well as the frictional force between the solidified skin and the mould.

Irsid studied another method for reducing oscillation marks which consisted of installing thermal insulation in the walls of the mould in the zone of the meniscus. This insert decreased heat extraction at the level of formation of the solid metal tooth which is the cause of the oscillation mark (Figure 2-15b). It was shown that a reduction in the depth of the oscillation marks by 20 to 50% was possible.

Mould powder is an essential element in continuous casting, in view of the many functions that it provides:

(i) protection of the steel against oxidation;

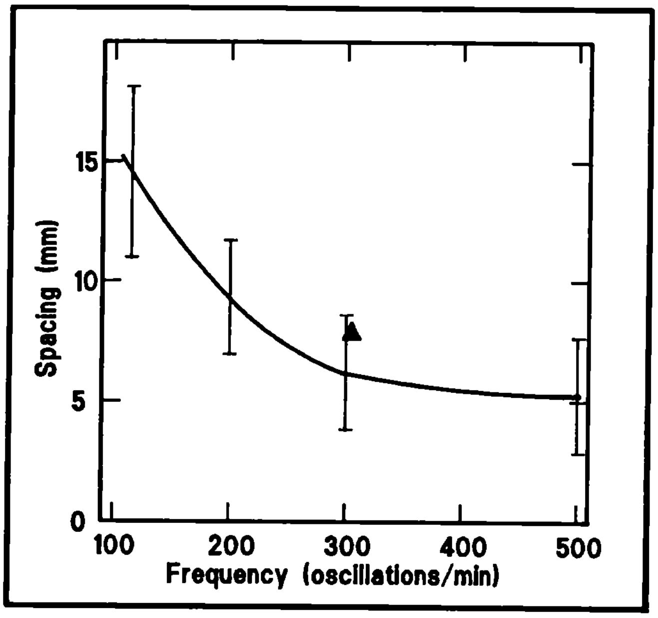
(ii) thermal insulation, preventing partial solidification of the surface of the liquid steel pool;

(iii) absorption of the inclusions present in the liquid steel;

(iv) mould lubrication;

(v) homogeneous heat transfer from the solidified skin to the mould wall.

Figure 2-16
Changes in oscillation mark spacing as a function of frequency in continuous casting of billets



▲ Amplitude: 14 mm   Ɪ Amplitude: 10 mm

Experience has shown that the surface quality of the steel produced is greatly influenced by the characteristics of the mould powder employed.

Some 15 projects involving mould powder were supported by the ECSC over the last decade [(12) to (23)], which in turn formed the bases for many further research projects undertaken by various laboratories and plants throughout the Community.

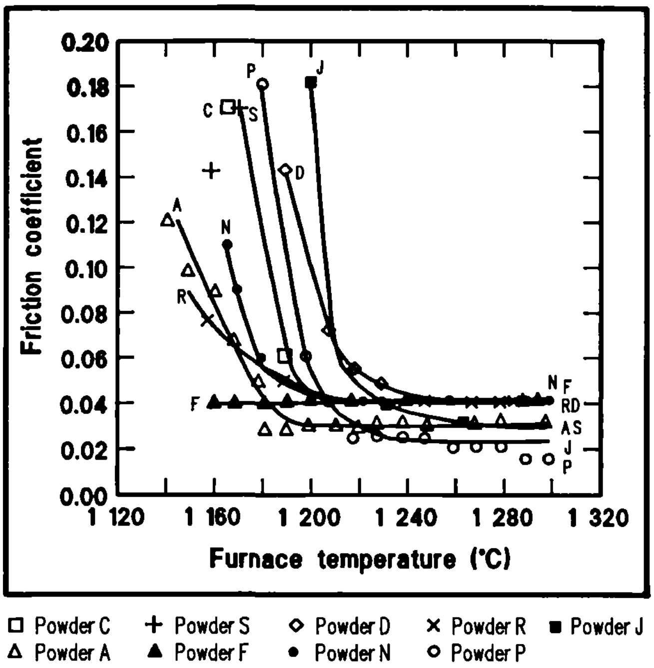
It is not possible in this report to discuss all of this work which was particularly fruitful, but a summary is to be found in a recent ECSC publication (12).

We shall restrict discussions to just a few examples.

One method of a fundamental nature, which was investigated jointly by TU Clausthal, Irsid and NPL (13), was employed to measure the principal characteristics of mould powders providing the vital functions described above: heat transfer, lubrication and the possibility of infiltrating between the skin and the mould wall, and the behaviour of powders was simulated in the laboratory (Figure 2-17).

Experience shows that mould powder behaviour may be at the origin of several types of surface defects: longitudinal cracking, star cracks, oscillation marks, transverse and corner cracking, skin inclusions, crack lines, skin carburization; and several projects undertaken, especially by British Steel [(14) and (19)], CRM (15), VDEh (16), Saarstahl (17), etc. have investigated this field.

Figure 2-17
Variations in coefficient of friction values as a function of temperature and composition



During operations, the powder melts on contact with the liquid steel and forms a liquid slag which infiltrates the space between the solidified skin and the mould wall (Figure 2-18). This thin liquid layer of slag creates a thermal barrier which regularizes heat transfer from the solidified skin to the mould. It is essential that this transfer be homogeneous; if not, longitudinal cracking appears in the solidified skin. Furthermore, this slag layer provides lubrication for the mould which means that it must remain liquid for a sufficiently long period of time.

Several methods have been suggested for measuring the rate at which mould powders melt [(13) to (16)]. Although none of these tests are entirely satisfactory, they have, nevertheless, allowed conclusions to be drawn.

Thus the rate of melting decreases with:

(i) an increase in the free carbon content of the powder;

(ii) an increase in the proportion of fine carbon particles relative to large particles;

(iii) an increase in the melting point and viscosity of the slag;

(iv) an increase in the grain size of the components of the mixture.

A British Steel project studied the causes of break-outs due to mould sticking (19).

Different theories were examined: increase in the basicity and powder crystallization index, thermal hysteresis of the mould during changes of casting speed, high frictional forces due to unsuitable powders, formation of pseudo-menisci extending towards the bottom of the mould.

Examination of the solidified skin resulting from break-outs showed that the pseudo-meniscus theory was in the main correct, provided that the solidified slag skin was also taken into consideration.

It was also shown that the accumulation of alumina, attached to carbon-rich refractory fragments played a significant role in the occurrence of break-outs.

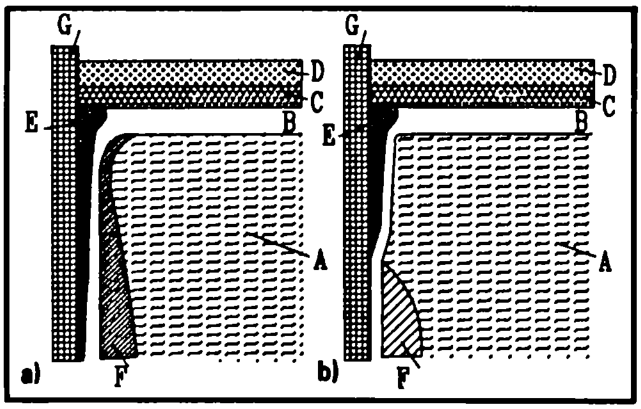
These examinations, completed by plant tests, meant that it could be concluded that break-outs by adherence occur when, simultaneously, a carbon-rich agglomerate blocks the supply of liquid slag along the length of the mould and carburizes the meniscus to create a skin which does not heal during periods of negative stripping.

2.4.3. Solidification and segregation structures

Each year demand for steels of increased quality and consistency increases which in turn requires that improvements in solidification structure have to be pursued, especially in decreasing micro-segregation and semi-macro-segregation or spot segregation, whether for slabs, blooms or billets.

A Community programme has been set up covering this field, in which CSM, VDEh, British Steel, Irsid, and CRM are associated in a detailed study of segregation structures and in determining practical methods of overcoming the problem.

Figure 2-18
Diagram demonstrating initial skin formation: (a) where the skin forms at the steel meniscus; and (b) where the skin solidifies below the slag ring



A – Liquid steel. B – Liquid slag. C – Sintered slag.
D – Sintered powder. E – Ring. F – Solidified shell. G – Mould.

For example, investigations have been carried out into the influence of electromagnetic stirring in the mould and at various points in the solidification well, in particular for steels which demonstrate a large solidification interval [(24) to (26)].

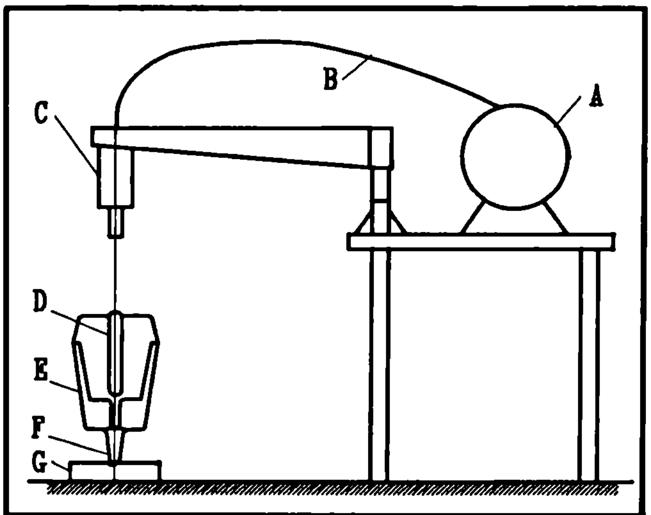
A current British Steel project, continuing from previous research work [(27) and (28)], is looking into the possibility of refining the solidification structure in a billet using vibrational energy transmitted by a vibrator coupled to the mould.

In the FAST process developed by CSM [(29) and (30)], solidification is accelerated and the primary structure is refined by the addition of solid materials directly to the mould, using cored wires passing through the stopper rod and the nozzle, which also allows alloying elements to be introduced *in situ* (Figure 2-19). Two current projects, at CRM (31) and at British Steel (32), are aimed at supplying the mould with steel at a temperature below that of the liquidus.

Several contracts [(33) to (39)] are intended to determine quantitative parameters of segregation and solidification structures, and to describe them objectively using macroprobes, image analysers and suitable mathematical models.

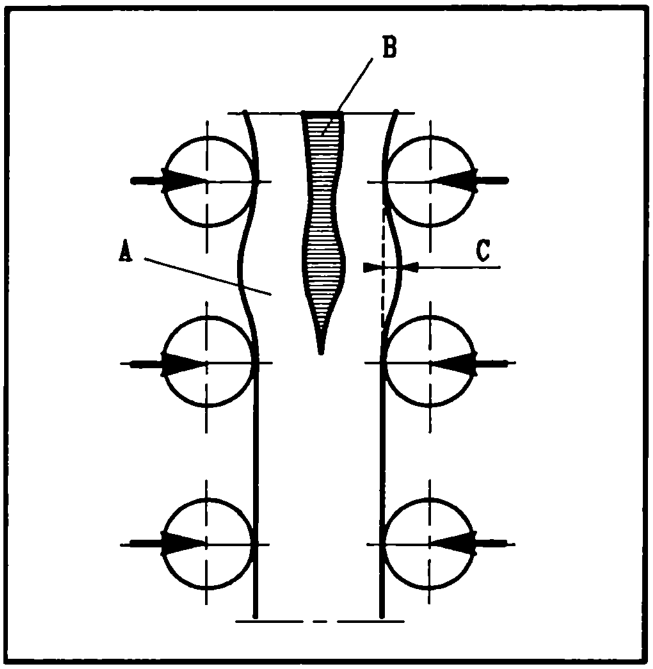
Parameters of great interest to both the operator and the metallurgist alike involve knowing the thickness of solidified steel below the mould, the evenness of each face, and the growth rate. In this complex field, a VDEh-BFI project (40) is investigating, on both laboratory and industrial scales, a system based on eddy currents for contactless measurement of the solidified thickness.

Figure 2-19
Wire feed installation for continuous casting with submerged nozzle



A – Wire uncoiling. B – Cored wire. C – Wire injector. D – Stopper rod. E – Tundish. F – Submerged nozzle. G – Mould.

Figure 2-20
Diagram to demonstrate phenomenon of bulging



A – Shell. B – Liquid core. C – Bulging.

2.4.4. Behaviour of the continuous casting installation

Improving both the internal and external condition of continuously cast products depends upon understanding and mastering the deformation to which the bar of steel is subjected, especially when only partially solidified, during its path through the machine, and especially in the bending and straightening zones.

Accuracy in the geometry of the machine therefore becomes an essential factor in product quality. One of the main deformation phenomena of the product during casting, particularly in the case of slabs, is the bulging caused by ferrostatic pressure on the solidified crust between pairs of rolls (Figure 2-20). This bulging is directly responsible for the formation of internal defects such as the central line of segregation and segregated internal cracks (Figure 2-21). For slabs which undergo a high level of reduction, such as in the manufacture of tubes for gas pipelines, these defects are critical and mean declassification, and the steel may have to be scrapped.

This bulging phenomenon has been studied in a research programme funded by the ECSC and coordinated between Irsid, VDEh, British Steel and CRM [(41) to (47)].

Different methods have been developed for measuring deformations of the support rolls and bulging of the slab between them during casting (Figure 2-22). At the same time, sophisticated mathematical developments based on finite element theory have meant that it is possible to model the phenomenon of bulging

Figure 2-21
Bulging in slabs:
internal cracks and axial segregation

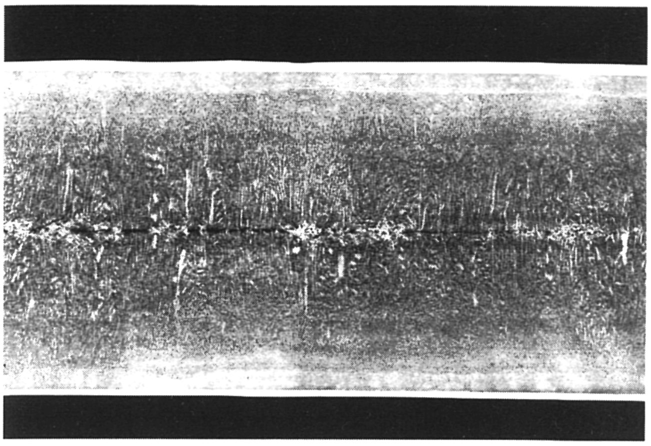
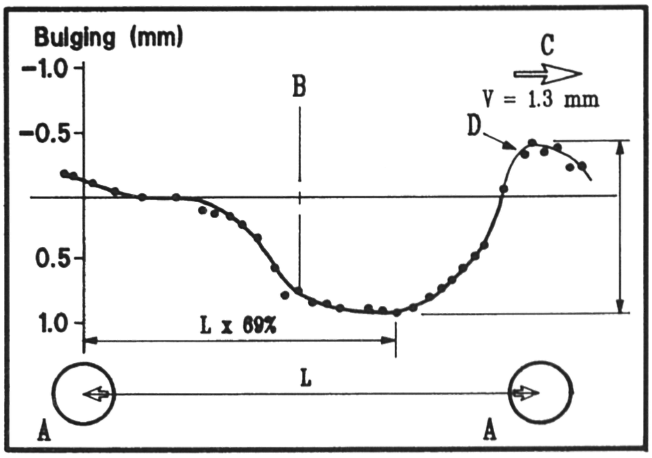


Figure 2-22
Measurements of slab bulging between rolls



A – Roll. B – Centre of roll pitch. C – Withdrawal speed. D – Negative bulging.

which occurs at a set of rolls during strand operation. It has thus been possible to quantify the influence of parameters such as varying the distance between rolls, their lack of alignment in a section or between different sections, their eccentricity, cooling conditions, and also to correlate this bulging with the development of internal cracking.

The formation of these cracks also depends, to a large extent, upon the mechanical properties of the steel at the successive high temperatures to which it is subjected as it passes through the strand.

Several contracts [(48) to (52)] have been carried out or are under way to determine the properties of different qualities of steel at high temperatures, especially their ductility. The structure of the sample used has been shown to be of critical importance in the results obtained.

It is easy to understand that this information is of use in improving understanding of the continuous casting of critical grades of steel and to extend the range of application of continuous casting. It is with this aim that contracts with Irsid (53) and CRM (54) were signed concerning the continuous casting of extra mild steel with very low aluminium and silicon levels (pseudo-rimming steels) and the contracts with Acenor (55) and Saarstahl Völklingen (56) involving free-cutting steels. Other contracts are being carried out in this field to extend the range of application of continuous casting.

A current VDEh project (57), which is on a large scale, is intended to increase the range of those steel grades which can be cast in small sections and rolled to final product without any intermediate operations.

This study which is being carried out in several factories and laboratories includes test casts and metallurgical and other specific investigations on various grades of steel (boron steels, tool steels, martensitic and ferritic chromium steels), as well as measurement of the regularity of the axial structure during solidification of quality alloyed steels.

Among the results obtained should be mentioned:

1. The development by Hamburger Stahl of a method of casting boron steels, with Ti and Al levels of 0.02 to 0.05% and B levels up to 0.005%, cast in the form of billets without using submerged nozzles. The billets show an acceptably low level of non-metallic inclusions, together with excellent surface quality as a result of the care taken with the mould (taper, oscillation parameters, etc.).

2. The extension of the billet programme carried out by Saarstahl to include tool steels.

   Tests performed on a machine with a 10.5 m radius, casting 150 x 150 mm billets, were carried out on unalloyed, low-alloy and high-alloy tool steels. With casting rates of 1.5 m per minute, the temperature of the bar at straightening was sufficiently high to avoid surface damage. Development also examined the choice of mould powders and the positioning of the electromagnetic stirrers.

   On the basis of the positive results of these tests, Saarstahl has set up production of unalloyed and low-alloy tool steels with up to 1.4% C and 5 to 8% Cr, cast as 150 x 150 mm billets.

3. The development by Krupp-Siegen of a continuous casting process for near net-shape sections of high-alloy steels, including rolling these products in a single stage into wire and bar.

   The systematic study of operating parameters from ladle metallurgy through to the bar cooling at the strand exit, together with extensive metallurgical research have enabled optimal operating conditions to be defined.

   It is in this manner that special austenitic steels such as X 53 Cr Mn Ni N 22 9 and other alloys, as well as chromium steels such as X 20 Cr 13 can already be reliably produced as billets on curved machines and/or horizontal casters. It is thus possible to replace the two-phase production process including partial forging, with a single operation in a single low-cost phase.

4. The study of central porosity in 177 mm round bars undertaken by Mannesmannroehren.

The results obtained on specially developed equipment based on the Archimedes principle of displacement has revealed the most important factors (mainly composition, casting speed) and the effect of electromagnetic stirring.

As a general rule, in order to ensure correct operation of the plant, continuous casters must operate without unplanned shutdowns, at rates approaching the limits of their capacity, while at the same time ensuring a consistently high product quality.

This combination of conditions demands excellent operation of the elements involved in the installation, as has been shown by the research projects described above.

It is easy to understand the vital role played by maintenance problems, and their cost. Several projects supported by the ECSC have been carried out over the last few years, or are currently active, in this field, in particular by British Steel, Arbed, VDEh and Irsid [(58) to (61)]. They are employing modern methods of detecting faults and their frequency, managed by an expert system, thus allowing an efficient conditional maintenance policy to be established.

Positive results have already been achieved in this very promising field.

2.4.5. Continuous quality control of hot slabs

Despite the progress made in mastering continuous casting techniques for slabs during the 1970s, it remained of interest for a large proportion of orders to detect incidents concerning slab quality at the moment that they emerge from the strand.

Over this last decade, a series of ECSC projects has been devoted to studying quality control procedures of hot slabs, both for internal quality (solidification structure and defects) as well as surface defects.

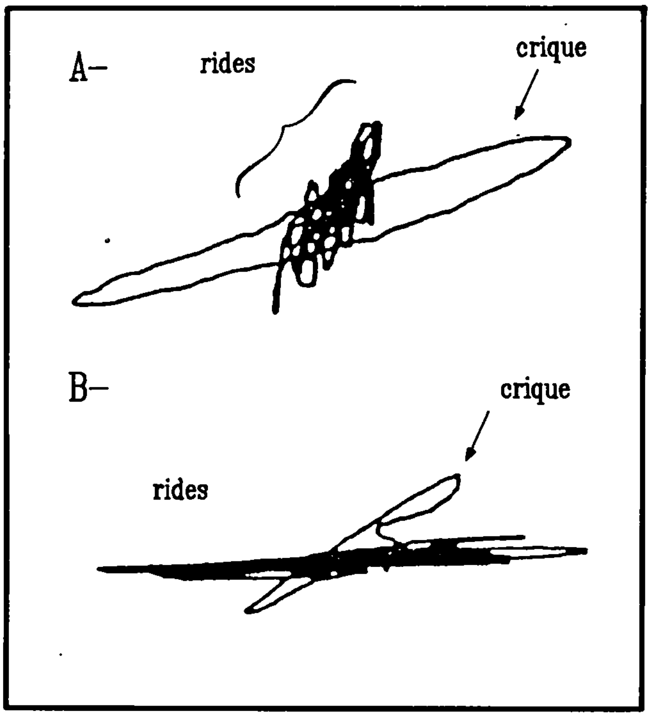
Concerning the internal quality, it should be remembered that at the beginning of the 1980s Irsid had developed and industrialized an ultrasonic contact probe system for use under hot conditions to determine piping in ingots, and that in cooperation with Hoogovens (62) this process had been applied with success to the continuous determination of piping in slabs leaving the slabbing mill.

In parallel, Tube Investment in Great Britain (63) was developing a new contactless probe system, electromagnetic-acoustic (EMA), which was applied initially to warm checking of large, round-rolled products.

CRM adopted this EMA technique for continuous, hot detection of internal defects in continuous cast slabs, with the intention of competing with the conventional Baumann print method which is discontinuous, slow and costly. An initial prototype (64) was installed experimentally on a continuous casting line. In a second stage (65), a new EMA transducer was tested which was more powerful and better protected against radiant heat.

A project of Nuova Italsider and CSM (66) was based on the principle of differential absorption of a highly focused ultrasonic beam, with regard to solidification structures, by recording the voltage of the peak of the return echo. It is thus possible to obtain ultrasonic macrophotographs of slab cross-sections.

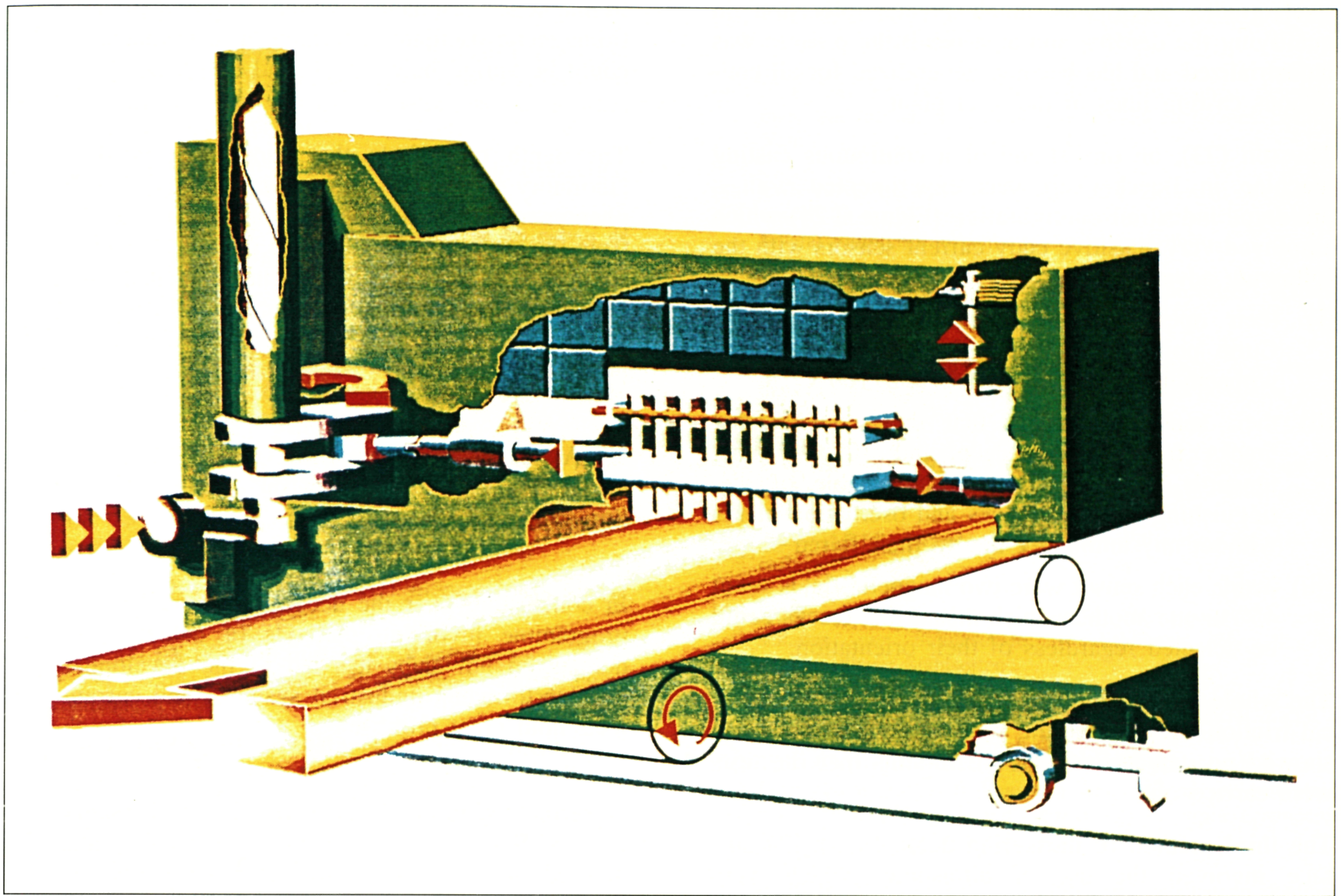
Figure 2-23
Sample of probe with anisotropic geometry
Comparison with a conventional probe



A – Differential probe with geometric anisotropy
Frequency: 20 kHz
Gain: 45 dB
Phase: 0°
Sensitivity: 0.2 volts/cm
Lift-off: 2 mm

B – Traditional ferrite core probe
Frequency: 12 kHz
Gain: 35 dB
Phase: 170°
Sensitivity: 0.5 volts/cm
Lift-off: 2 mm

Figure 2-24
Detection of surface defects on slabs



A current project at BFI (67) is aimed at perfecting new electromagnetic heads for hot checking internal health, as well as surface aspect. In this field, the IZFP project at Saarbrücken (68) concerning structure analysis should also be noted.

Despite the progress made by these projects, further development is still required before industrial application in this difficult field of continuous determination of the internal health of hot slabs.

Three main measurement principles for the continuous measurement of surface aspect have been systematically evaluated on a laboratory scale and on industrial continuous casting lines:

(i) optical sensors,

(ii) eddy currents,

(iii) electro-magnetic-acoustic (EMA) methods.

Projects involving optical sensors, carried out by British Steel, Irsid and CRM [(69) to (71)] initially employed video sensors, then CCD arrays. Industrial results were obtained, although they were limited in the size of defect that could be detected, and also by the need to descale the whole surface prior to inspection.

The use of eddy currents was examined in two industrial projects, one by Irsid and another more recent project by Thyssen. The Irsid project (72) was intended to detect corner cracking of the slab as it left the strand, to differentiate it from oscillation marks and also to define the defect, its geometry and its importance within the framework of a reliable and automated system.

Since it is impossible to probe an area which is near to the Curie point, due to the strong variations in magnetic permeability, and since certain products already had surface temperatures along the edges which were below the Curie point, it was decided to cool the surface in order to ensure that the surface temperature was always below 650°C.

It was also decided right from the start to descale the edges; however, experience showed that this scale did not affect the signal quality.

A total of eight sensors are suspended at a distance of some 5 mm from the surface of the slab.

The sensors were extensively developed and the final configuration involved sensors which display anisotropic geometry, in an attempt to improve differentiation between cracks and oscillation marks (Figure 2-23).

The installation that was set up on a Sollac-Fos continuous casting line demonstrated that for high-risk steel grades there was much greater precision in qualifying the defects, and as a result the process was industrialized and has become generalized for all continuous casting lines of the steel plant.

Thyssen (73), on one strand of a continuous casting machine in Beeckerwert, has experimented with a prototype industrial configuration (Figure 2-24) which employed very sensitive eddy current sensors with the following advantages:

(i) their operating range was situated above the Curie point (770°C) and they were capable of withstanding temperatures up to 1 100°C;

(ii) their sensitivity meant that they could detect cracks from 1 mm deep and 10 mm long upwards, and they were also capable of distinguishing between cracks and oscillation marks without any ambiguity due to their flared shape;

(iii) inside each sensor were two magnetic fields set at 45° to one another which meant that cracks could be detected regardless of their orientation.

The whole system operated with hardly any mechanical friction and, as a result, with hardly any wear and showed no defects over the 12 months that the tests were carried out.

The third method of measuring defects on a hot surface involved the use of ultrasonics which were generated and detected without any contact using EMA principles.

A CRM project (74) investigated the mathematical model which derived the conversion of an electromagnetic wave into a surface wave and vice versa.

The technological problems involved in constructing such sensors were analysed and a solution was adopted using silicon nitride ceramics.

In the same field of research, CSM (75) developed a new, high-performance sensor based on electromagnetic resonance which comprised an electromagnetic oscillator operating at a frequency which could be varied between 50 and 300 kHz.

The depth of defects that can be detected in the laboratory is 0.5 mm. Using the resonance phenomenon, the sensor can operate up to 18 mm from the surface rather than the usual 5 to 8 mm. This advantage is especially interesting in that it markedly improves the thermal protection of the sensor. Measurements are not, in principle, affected by the presence of scale.

ILVA, in collaboration with CSM (75), decided to experiment with this sensor on a continuous casting line in the Tarento works.

In conclusion, over the decade concerned, the ECSC programme involving methods of detecting surface defects on hot slabs has led to the development of high-performance industrial systems, and current projects hold great promise.

Nevertheless, it should be noted that at the same time the continuous casting process itself underwent marked improvements during the same decade, and that in 1990 steelworks were regularly achieving a rate of 70 to 80% of good slabs ready for reheating without conditioning and which, furthermore, did not require cold inspection.

On the other hand, special grades of steel such as medium-carbon steels with or without microalloying are still liable to develop cracks.

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2.5. Continuous casting of near net-shape products

Over the last 10 years, Europe has played a very active role in developing new techniques for continuous casting of thin slabs or strips. In January 1987, an *ad hoc* group of the ECSC Steel Technical Development Committee stated its proposals concerning the setting-up of a coordinated programme in this field.

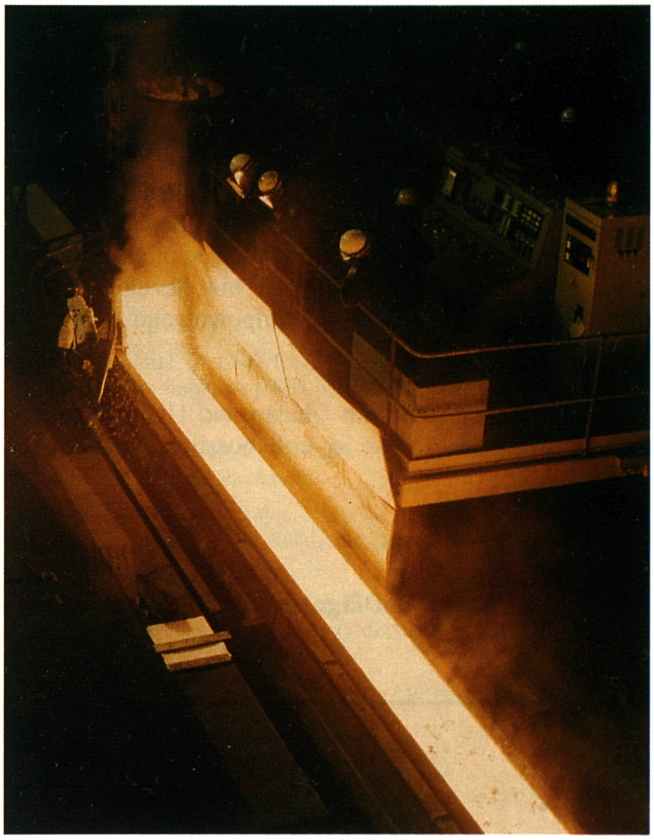
It was considered to be useful to distinguish in these new technologies those that involved the continuous casting of thin slabs or near net-shape semi-products but which required a further hot-rolling operation, and those which involved direct casting of strips or bars that were either directly usable, or which only required further cold transformations.

In the field of continuous casting of thin slabs, Schloemann-Siemag (CSP process), followed by Mannesmann-Demag-Hüttentechnik (ISP process), Danielli and Voest-Alpine, showed that high-speed casting of thin slabs opened up the possibility of economically producing flat products on a mini-steelworks scale. Since then, five installations belonging to this type of technology entered the constructional or operational phase: two at Nucor in the United States, two in Italy (at Arvedi in Cremona and at Ilva in Terni) and one in Sweden at Avesta.

The efforts made on the pilot scale by Krupp Industrietechnik, for over six years, to adapt the 'Hazzelett' mobile strip casting machine to casting mini-slabs of 180 x 70 mm and 180 x 35 mm came up against the emergence of new thin slab techniques (1). Certain aspects required to achieve an industrial stage of exploitation were not compatible with those of a short-term commercialization of this process. British Steel (2) with its horizontal caster employing a moving channel (Figure 2-25) and the Thyssen/Usinor-Sacilor/SMS consortium with the casting-pressing-rolling (CPR) process are exploring new avenues.

The ECSC has supported the project involving the ISP thin slab caster at Arvedi (3), as well as a research project at ALZ in Belgium concerning the castability of stainless steel in a pilot CSP thin slab caster (4).

Figure 2-25
Casting thin slabs in a moving channel at British Steel



There are many programmes in the field of continuous casting of strip, that cover most foreseeable technologies, from simple rolls through to twin or mixed rolls, bands or rolls intended to produce strip from 0.4 to 25 mm thick.

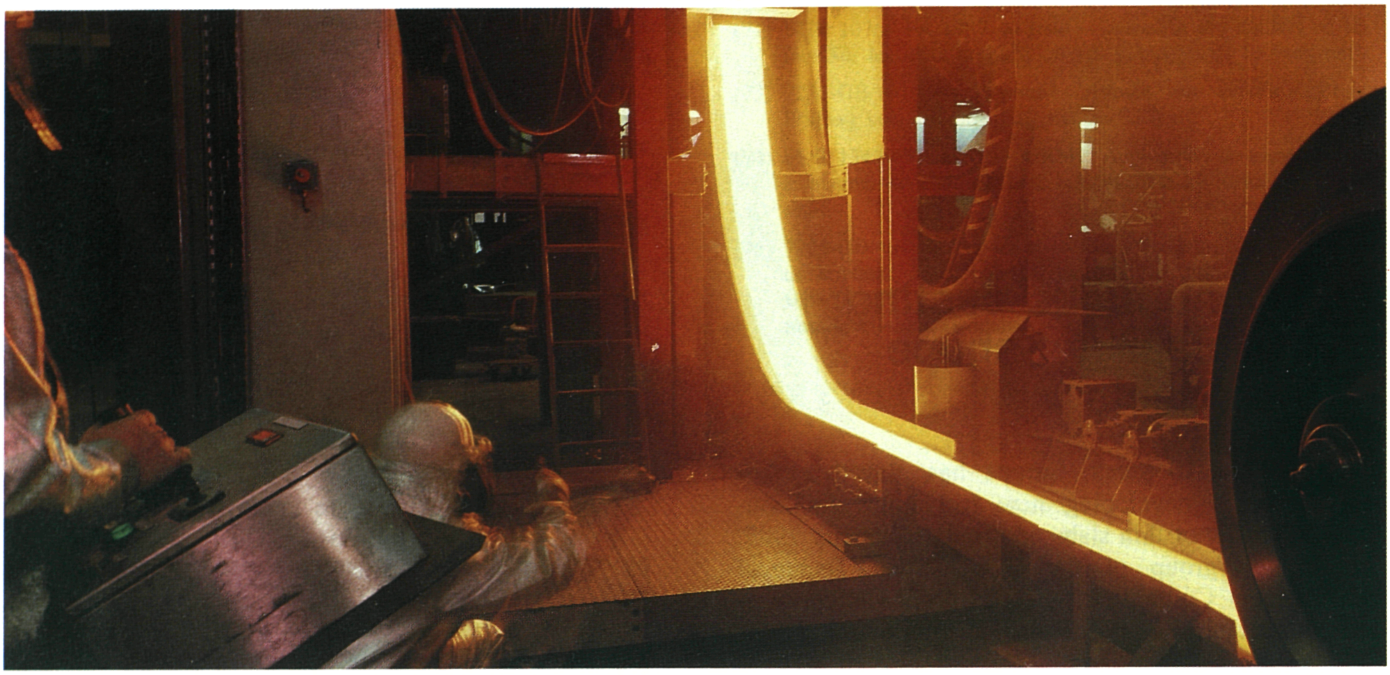
The common problems of this type of machine are to be found in:

(i) the supply of liquid metal in a uniform manner across the whole length of the thin flow section;

(ii) the lateral confinement of the liquid metal;

(iii) the maintenance of stable conditions at high casting speeds.

Figure 2-26
Irsid pilot-plant producing ribbon of steel

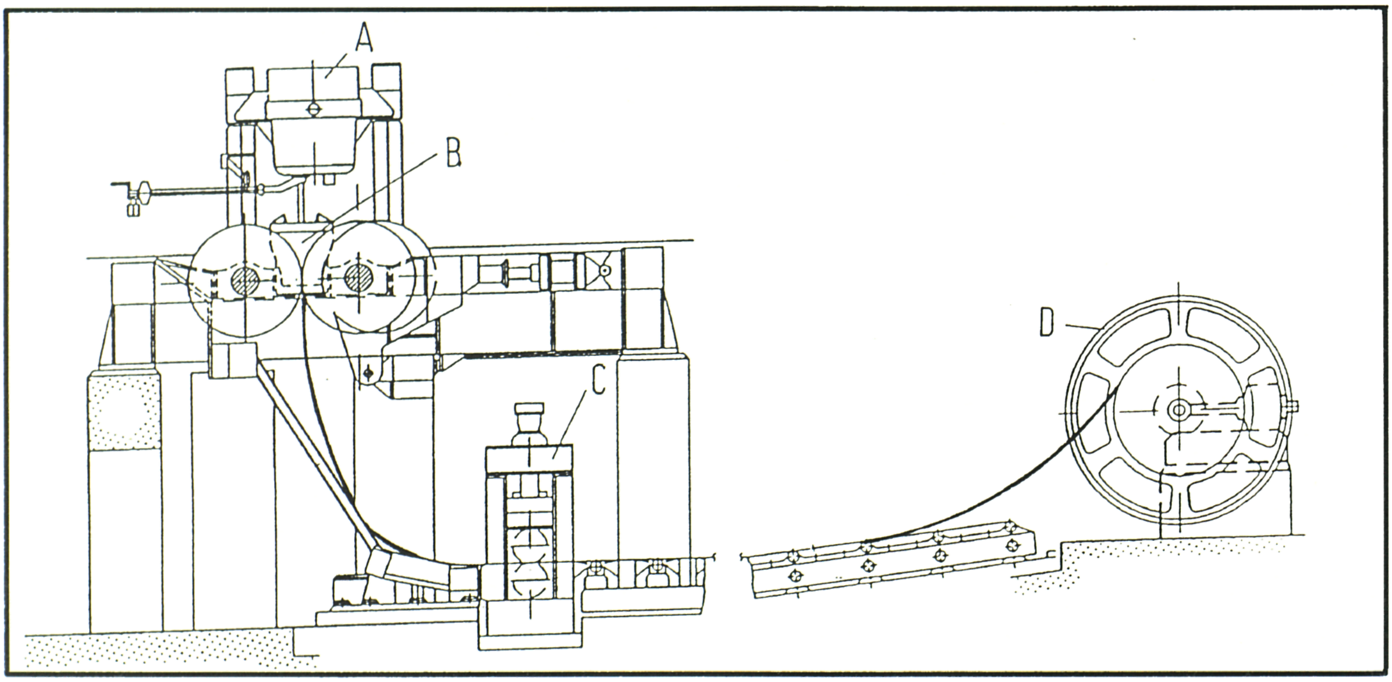


In fact, a 10 mm-thick strip solidifies in 4 seconds, and the exit speed is 3 metres per minute, while a 2 mm-thick strip solidifies in 0.2 seconds and travels at a speed of 70 metres per minute. Operating this type of machine can thus only be envisaged through the development of extremely precise measuring equipment and computer-controlled operations.

Irsid, in collaboration with Clecim and Ugine Aciers in France (5) and CSM, in collaboration with ILVA in Terni in Italy (6) have obtained sufficiently encouraging results to enter into the semi-industrial pilot-plant stage (Figures 2-26 and 2-27).

British Steel is developing a pilot plant for narrow strip intended for manufacturing small diameter tubes by casting steel in the pasty state between rolls to which is applied a strong axial reaction (7).

Figure 2-27
Diagram of the pilot twin-roll strip caster installed at ILVA in Terni



A – Ladle. B – Mould. C – Withdrawal stand. D – Coiler.

Figure 2-28
Continuous strip caster in operation at VDM-Nickel Technologie AG in Unna

The 'melt-drag' supply system is used at Krupp/VDM at Unna (Germany) in the horizontal feed to a cooled, rotary drum. The steel meniscus formed by contact with the drum is carried round by its rotation and the thickness of the film depends upon the speed of drum rotation: a 1 mm-thick strip, 1 metre wide can thus be produced using a peripheral drum speed of 40 metres per minute (Figure 2-28).

To limit wear of the lower lip of the supply nozzle which rubs on the drum, Krupp Stahl (8) is testing, with AEG, a system of electromagnetic levitation created by an electromagnet housed immediately below the lower lip, which leaves a 'gap' of some 0.5 mm between the nozzle and the drum.

Spray forming is also a new process which allows products of near-net shape to be formed in several shapes such as flat products — Mannesmann; small billets — Osprey Metals (UK) and DDS in Denmark (2); or tubes — Sandvik in Sweden. Multilayer or metal-ceramic composite deposits are also being developed using various special techniques, in particular at the University of Swansea.

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2.6. Evolution of chemical analysis techniques

The progress made in steel quality has led steel manufacturers and metallurgists to increase their criteria in two difficult areas of chemical analysis:

(i) measurement at very low levels, necessitated by steel compositions (very low levels of sulphur, phosphorus (<50 ppm), carbon (50 ppm), nitrogen (20 ppm));

(ii) separation and analysis of inclusions.

To this should also be added the need for a reduction in analysis times.

The programme involving the many research projects supported by the ECSC over the last decade has attempted to answer these needs.

To cover point (i), two physical methods have been very extensively developed:

(i) inductive coupled plasma spectrometry (ICP), a very powerful, multi-element method which was investigated during a study coordinated between British Steel, CRM, Hoesch and Irsid [(1) to (7)];

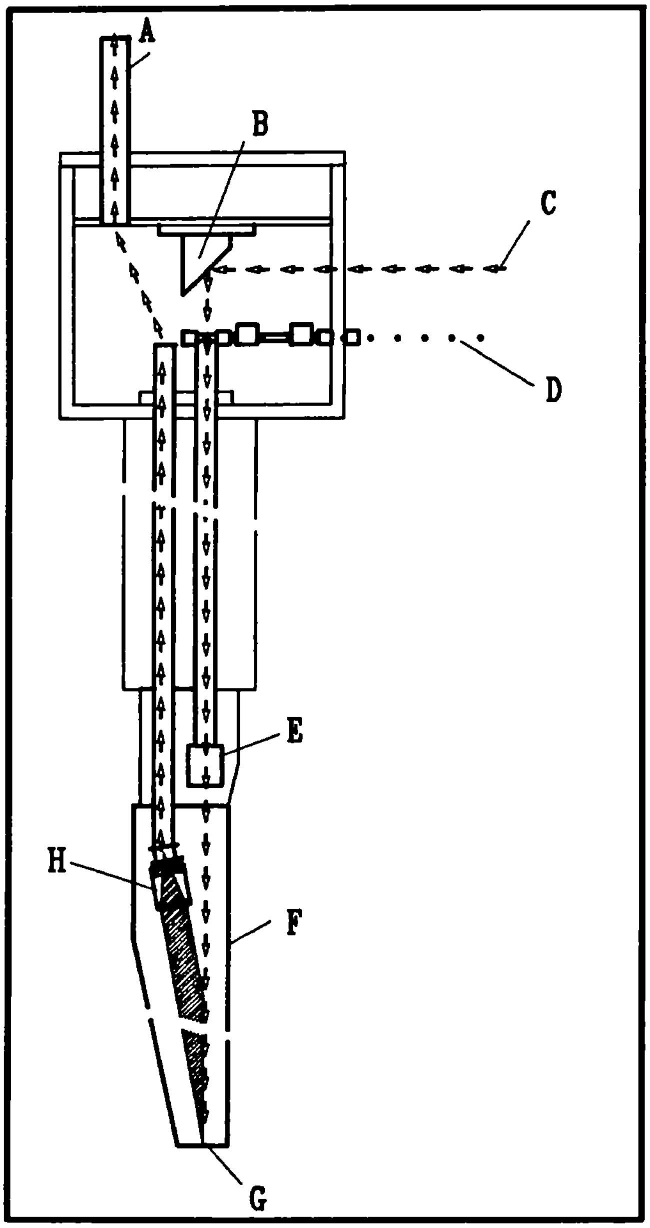
(ii) atomic absorption spectrometry (AAA) for which developments allowing the analysis of trace elements were provided by Creusot-Loire, Unirec, CSM, CRM and Arbed [(8) to (12)].

The field of phases remains difficult. To distinguish between soluble Al and total Al, a solution involving optical spectrometry resulted from contracts between Irsid, CRM and the Dilling works [(13) to (15)].

The separation and analysis of inclusions gave rise to coordinated research between the main steel laboratories throughout the Community, especially concerning electrolytic dissolution of the matrix [(16) to (22)].

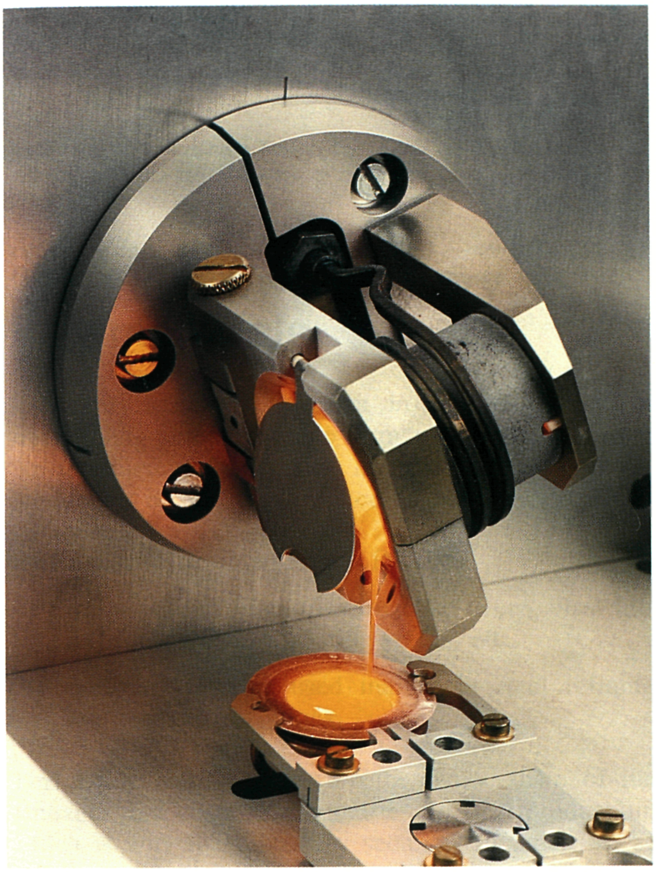
A new process is in the course of being studied by British Steel, and is aimed at melting a button of steel so that the inclusions accumulate at the surface, and which can then be weighed to be able to measure the inclusions in the steel.

Figure 2-29
Diagram of probe for direct viewing of liquid metal



A – Optical fiber. B – Mirror. C – Laser beam. D – Aerosol.
E – Focusing lens. F – Ceramics tip. G – Focused laser image 2 mm
H – Converging lens.

Figure 2-30
Photograph of the PBRLX equipment



Research has been conducted in several fields in an effort to reduce analysis times. The Thyssen project is investigating the direct analysis on the product with the development of mobile spectrometry (22).

Three British Steel research projects [(23) to (25)] and a Hoesch project (26) are concerned with direct analysis of the liquid metal in the ladle and in the oxygen converter using laser spectrometry. A demonstration project has been set up by Krupp (27) for direct carbon analysis (later for phosphorus and sulphur) of liquid steel during refining in the converter, which is also based on laser spectrometry (Figure 2-29).

The automation of laboratory preparation of molten samples has led to the development by Irsid (28) of PBRLX (Figure 2-30) and Plasmasol equipment for supplying a series of samples which can be used by ICP X-ray spectrometers.

Laborlux (29), in collaboration with the company Spectro, have developed a shop-floor laboratory in which the preparation, the spectral analysis of samples and periodic calibration of the spectrometer are entirely robotized and can be used by the personnel in the steelworks. Arbed and British Steel have adopted this principle in several of their plants.

Finally, we should mention the increasing interest being shown in surface analyses [(30) to (33)].

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2.7. Role of refractory materials

Refractory materials represent an important aspect of steelmaking since they help in maximizing profit from the production tools and in ensuring the regular production of high quality steel at competitive prices.

It is usual to distinguish two families:

(i) long-lasting refractories for coke ovens, blast furnaces, cowpers, reheating ovens, etc.;

(ii) wear refractories used mainly in steel refining and casting operations.

This latter family represents the major share of the tonnages and costs of refractories, in steel production, which is why the refractory sector is included in the chapter on steelworks.

Over the last decade, the ECSC has greatly increased its support for studies concerning refractories to such a degree that they account for a quarter of the research budget in steel manufacturing.

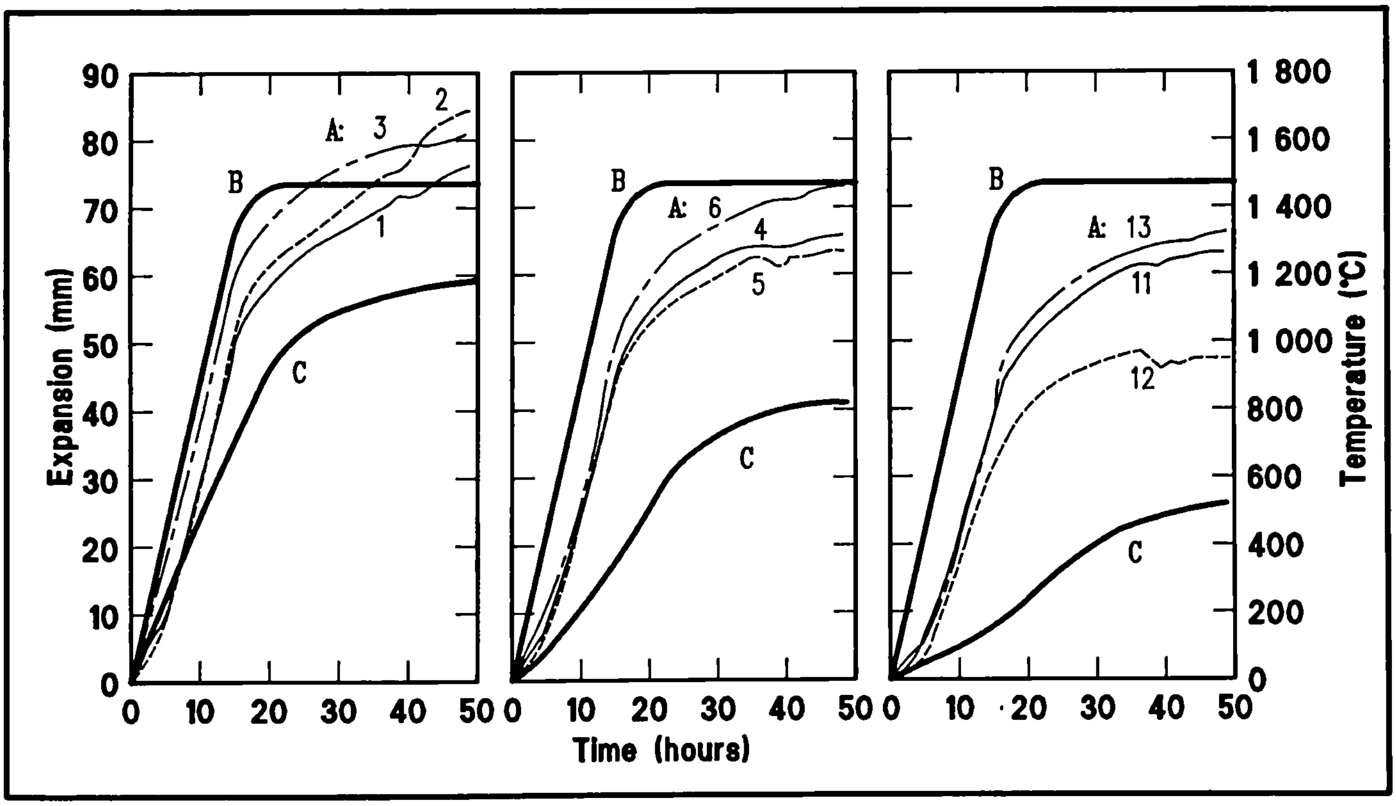
The following examples will help to demonstrate the interest of this Community work programme.

1. A Thyssen study (1) was aimed at determining the optimal rate for heating refractory linings.

The use of a large-scale pilot furnace (5 m in length and 2.5 m in diameter) allowed the relationship between heating rates and the specific behaviour of refractory materials to be studied.

These experiments showed that the heating times could be reduced in comparison with current practice (Figure 2-31).

Figure 2-31: Temperature increase curves



A – Press unit. B – Average temperature of furnace. C – Average temperature of magnesite brick.

Nevertheless, too high a thermal gradient is not desirable: relative movement of the various layers of refractories must be kept as low as possible, and precautions must be taken to avoid forces which could damage the insulating layers and the furnace shell.

Wear refractories cover a wide range of applications and their wear mechanisms vary according to their uses.

Particular attention has been paid to thermomechanical phenomena.

2. Hoogovens (2) studied spalling of refractories as a result of thermal shock, by calculating the forces involved using finite element techniques and by establishing the limiting loads on the basis of properties measured in the laboratory.

The model was then tested industrially on the life of silica burners in coke ovens. Replacing the silica in the inlet piping by corderite was effective in limiting breakage of these components.

Another application performed in conjunction with British Steel, which concerned the resistance of refractory elements for converter stirring has already been described.

3. Two Irsid projects [(3) and (4)] were concerned with the wear mechanisms of converter and steel ladle linings, as well as the improvement of repair techniques.

Among the 20 or so parameters which were involved in the bottom life of a bottom-blown converter, major temperature variations in the tuyère bricks were the main cause of damage.

A series of actions which were instigated to diminish the thermal shock resulted in a spectacular improvement in the life of the bottom concerned.

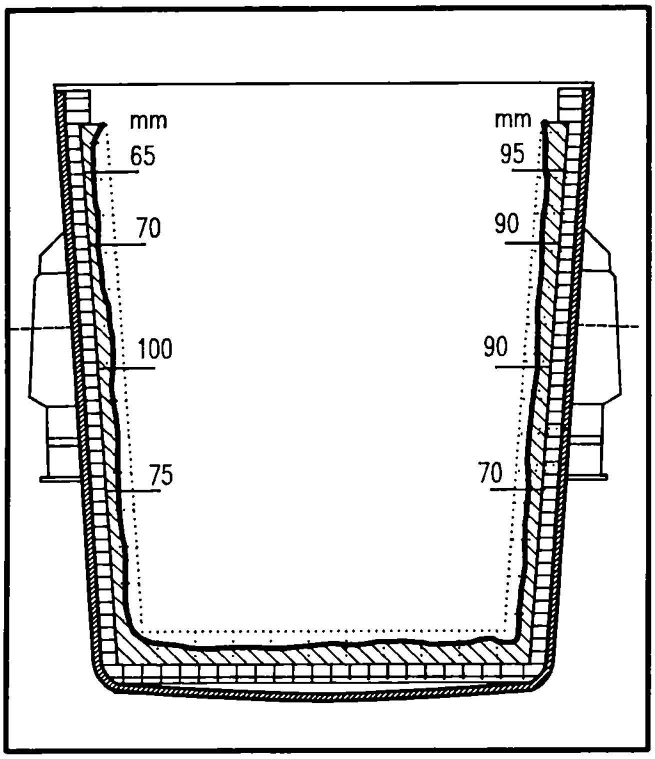
Steel ladles were submitted to thermal cycles which caused fracturing and spalling of their lining.

Laboratory and industrial-scale testing provided improved understanding of the fracture mechanisms involved in different refractories and allowed their life in the ladle to be increased.

The project has also provided improvements to lining repair techniques based on gunning, by both the wet process and by spraying through the flame of a specially designed burner.

4. The complex problem of wear due to chemical reaction was investigated by CRM (5) who developed a test to simulate accelerated attack in the slag phase, leading to notable improvements in the life of submerged nozzles.

Figure 2-32a
Lining remaining after completion of second campaign



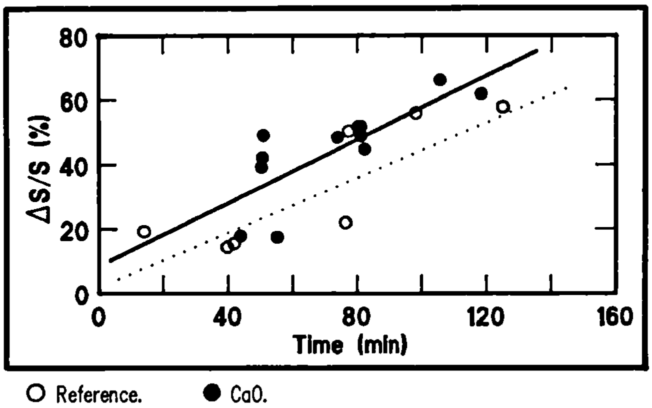


Figure 2-32b
Desulphurization efficiency as a function of final treatment time

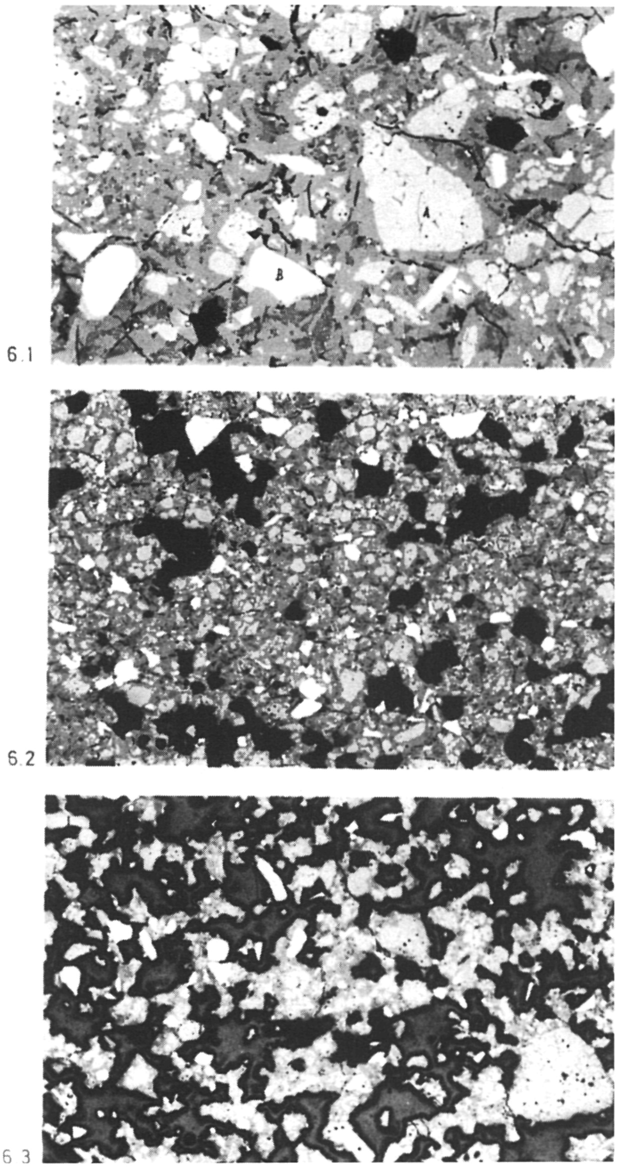
Reduction in refractory costs per tonne of steel is a necessity in view of the existing international competition.

5. A Hoesch project (6) studied the possibilities of using unfired silico-alumina bricks which were compared with fired bricks, for torpedo ladles and steel ladles.

For the base of basic ladles, it was found that unfired andalusite bricks with phosphate binder provided the same lining resistance as fired andalusite bricks.

The potential savings are a function of the evolution of prices of energy and binders.

Figure 2-33
Microphotograph of gunned material



6. With the same objective of making savings, a British Steel project (7) examined wet gunning of thin layers of basic refractories, on to an acid lining in steel ladles. Tests were carried out in the laboratory and on a pilot scale using different materials and different thicknesses of gunned layers.

The industrial application on a scale of 300 tonnes demonstrated that potential savings were greater than 10% of final costs of refractories, compared with the use of a basic refractory lining.

Problems of refractories and of steel quality are becoming more and more intimately involved and several research projects have been directly concerned with this aspect.

7. Studies carried out by CSM [(8) and (9)] have demonstrated that stabilized calcium oxide can provide a refractory that is of interest to the steelmaker.

An initial project was to look at the manufacture of stabilized calcium oxide for use as refractory bricks for ladles and experimental studies on them during several campaigns at the Dalmine steelworks.

The behaviour of the CaO bricks was satisfactory and provided better desulphurization than is found with alumina bricks (Figures 2-32a and 2-32b). These calcium oxide bricks can be stored without any deterioration due to humidity, provided very simple precautions are taken.

A second project involving submerged nozzles manufactured from calcium oxide was described in the chapter concerning continuous casting.

8. In a CRM project (10), the technique of gunning using an oxygen/natural gas flame was employed to build up, by successive layers, the protective lining of continuous casting tundishes.

Compared to cold tundishes, using an internal insulating protection, this method displays amongst other advantages, those of providing an insulating lining with a ceramic bonding, i.e. totally hydrogen-free in the binder and leading to lower thermal losses for the liquid metal bath, especially at the start of casting (Figure 2-33).

The proceedings of the Journées réfractaires at Luxembourg (11) organized jointly by the ECSC and the Fédération européenne des fabricants de produits réfractaires (PRE) provide further details on these projects, and on others that have not been mentioned.

This joint gathering is an eloquent witness to the excellent technical cooperation which exists between the ECSC steelmakers and the European refractory manufacturers.

Most of the current projects concern the influence of refractories on steel quality, mainly in the field of secondary metallurgy performed in either ladle or tundish. As an example we can cite the following projects:

(i) the use of plasma-coated nozzles in continuous casting (VDEh) (12);

(ii) the control of recarburization of low-carbon steels (Hoesch) (13);

(iii) the refractories for very high purity steels (CSM) (14);

(iv) the optimization of refractories for continuous casting of stainless steels (Ugine-Savoie) (15).

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3.1. Reheating furnaces

Reheating furnaces in rolling mills are intended to supply a product at the correct temperature with low-scale formation, thermally homogeneous, at the required moment, while ensuring optimal energy consumption.

Several Community projects have been undertaken to attempt to comply with these multiple criteria.

In the field of burners and energy savings, Arbed (1) has developed an improved burner using an air/gas mixture which can be operated with less excess air, which means that there is a decrease in energy consumption.

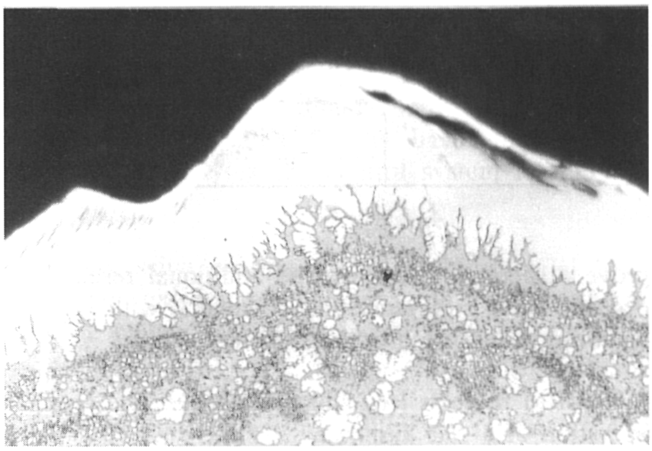
A VDEh project (2) was aimed at eliminating pulsation in large multifuel burners, and was successfully completed on a laboratory, pilot and industrial scale. This project allowed phenomena of resonance between the burner free space and the combustion chamber to be demonstrated, as well as air/fuel mixture conditions. Modifications in the geometry which were then made to the burners and their fluid supply led to the elimination of pulsations and improvements in combustion, with consequent energy savings.

Managing the continuous reheating of products of varying size, steel grade and loading temperature has become an extremely complex operation. The operator, however skilful he may be, is no longer capable of making all the fine adjustments required and furnace operation now requires automated control.

The CSM project (3) was aimed at optimal operation of a furnace for reheating niobium microalloyed steel slabs. It is well known that the quality of the final strip depends upon the reheating phase: state of oxidation and microstructure of the slab when removed from the furnace.

The project was composed of several different areas of investigation: developing a mathematical model on the basis of industrial data for reheating slabs, the analysis of parameters involved in determining the growth of oxide layers, and determining the relations between reheating parameters and the characteristics of the microstructure of the slab when removed from the furnace.

Figure 3-1
Microstructure of low-carbon steel scale



It was thus possible to perfect a reheating model capable of defining the optimal operating cycles as a function of the desired results.

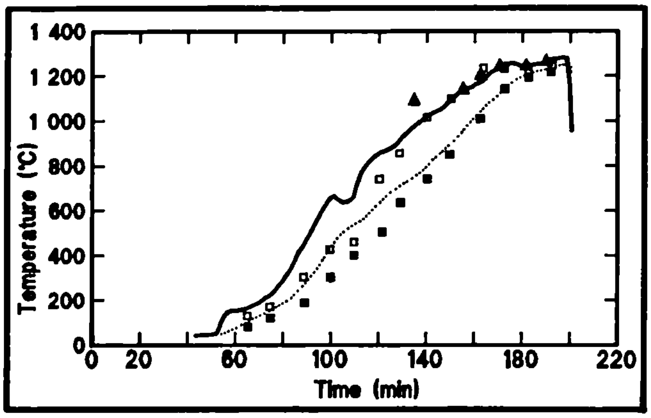
In the field of scale formation, a CSM project (4) described a method of laser spectrometry for the direct determination of temperature and composition (CO, CO_2, O_2, N_2 and water vapour) of the furnace atmosphere.

A current project at British Steel (5) concerns the formation, constitution and properties of the scale formed in reheating furnaces and during hot-rolling operations (Figure 3-1). It suggests that air heating to rolling temperatures leads to the formation solely of wustite, and not, as is generally thought, to a structure with a triple layering of wustite, magnetite and hematite. While the last two oxides are certainly present in many scale formations, it appears that they have been formed by transformation during cooling and not beforehand at rolling temperatures.

It has been observed that low levels of oxidation lead to 'active' scale formation, with rapid growth, which poses problems both for hydraulic descaling and during final rolling operations.

'Passive' scale formation, saturated in oxygen, produces scales which are hard, compact, which resist thermal shocks well and which are able to transmit rolling forces without failure. Nevertheless, they can

Figure 3-2
Slab fitted with thermally insulated microprocessor



	Calculated	Measured between two beams
Top surface	▫	——— by thermocouples
		▲ by pyrometers
Mid-thickness	▪	········ by thermocouples

prove difficult in pickling, and additional research is necessary to link atmospheric factors with surface metallurgy during hot-rolling operations.

Two CRM projects [(6) and (7)] concern the optimal operation of a slab furnace:

(i) In one case, the rolling mill only operates at full capacity, the aim being to save energy while still maintaining production quality. The method consists of establishing the relationships between the temperature on leaving the furnace and reheating and rolling costs, then to define the optimal temperature for removal from the furnace, with regard to the overall constraints of the programme (Figure 3-2). Industrial application of this optimization has led to important savings in production costs.

(ii) In the other case, steel production, continuous casting and rolling operations are to be integrated into a single line. Campaigns of data measurement have allowed the modelling coefficients to be identified and the validity to be checked for various cases of hot charging.

Another example concerns the Irsid project (8) for reducing temperature heterogeneity in slabs on removal from the furnace. These transverse temperature heterogeneities, which can be of the same order of magnitude as those of the skid marks (50°C), cause defects in the finished steel: surface defects, dimensional defects, defects in metallurgical characteristics.

The study carried out on a model and on an industrial furnace demonstrated that a reheating furnace can be the source of flue-gas flows which are impossible to regulate solely through burner control, and that these flows must be channelled. The installation of guide walls in the furnace led to an 80% reduction in this problem.

In this field, a current study at VDEh-BFI (9) concerns the optimization of flow phenomena in the furnace and its impact on improving the thermal efficiency of the furnace.

Among other current projects, we should cite the VDEh project (10) concerning the improvement of heat transfer in furnaces fitted with high-emissivity linings and adiabatic heated walls, those of CSM involving experiments with oxidation inhibitors (11), and the project involving the design of novel furnace types for reheating thin semi-finished products produced by new continuous casting processes (12).

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3.2. Rolling of long products

The two main objectives in the field of long products are concerned with the desire to improve rolled product quality in order to meet the growing customer demands, and at the same time to decrease production costs.

Some examples will be described from among those projects supported by the ECSC and carried out by VDEh, Arbed, Irsid, British Steel, CRM and CSM in close collaboration with the steel companies.

3.2.1. Tension control

Variations in the longitudinal tensile force on the bar during rolling operations is a source of dimensional variation in the product and several projects have examined this subject.

During continuous rolling operations, it is vital that the speeds are correctly synchronized between one stand and the next: in fact if one stand is running too fast then there is tensile force on the product up-line of the stand with the risk of reducing the diameter, and conversely there is compression down-line of the stand with inherent risks of incidents; even after the initial adjustment phase the settings can drift.

Tension control is vital when one considers that in 1990 Japanese rolling mills could achieve dimensional tolerances of ± 0.1 mm for 50 mm diameter bars.

The VDEh project, based on plasto-mechanical principles (1) has investigated principles of metal deformation in groove rolling and developed models allowing the geometry of the deformation, the rolling torque, and the spread to be calculated with sufficient accuracy. A method of simulating a section rolling mill was developed so that comparisons could be made between the different systems of regulating the longitudinal tension loads, and it was demonstrated that the operating parameters calculated on the basis of the model were in good agreement with the measured values.

The way in which the finished product dimensions are affected by temperature variations and/or the input section is demonstrated by the example of a roughing stand in a small section rolling mill.

Simulation calculations carried out during this project have shown that the best way of improving the final product section lies in direct control of the tension load and that positive results have already been obtained by applying the control system to the first two stands.

Two successive projects at Irsid [(2) and (3)] have examined existing techniques and suggested an original method of tension control which involves measuring slip.

These projects involved modelling the interstand, and various tensile force control systems, and experiments with the froward slip measurement technique, successively on a pilot rolling mill using lead, a beam mill and then a bar mill.

Experiments with this technique are continuing on an industrial scale.

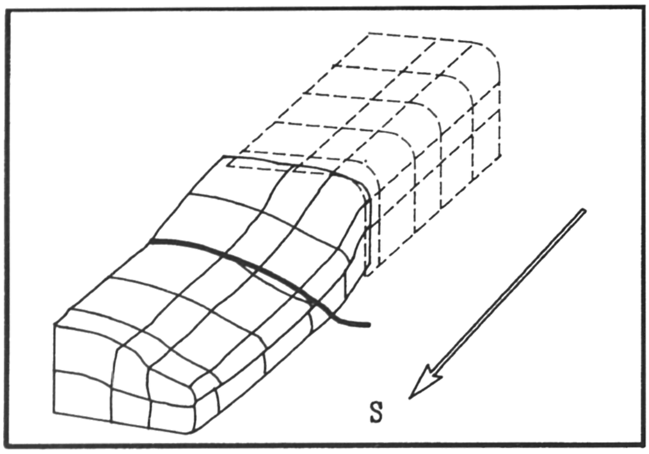
Two other projects carried out in parallel and through association between British Steel and VDEh (4) concerned the development of automated systems for tightening the stands and tension control on merchant steel-rolling mills.

The development of a dynamic mathematical model allowed comparisons to be made between the various regulation techniques. It was observed that direct control of tension loads is the most suitable for improving dimensional accuracy. However, it only allows variations caused by changes in the entry section geometry to be corrected.

The reduction of dimensional defects as a result of temperature variations is possible using automated regulation systems operating on stand load. Until now, however, it was not known exactly as to which of the stands these adjustment systems should be applied in order to ensure greatest efficiency.

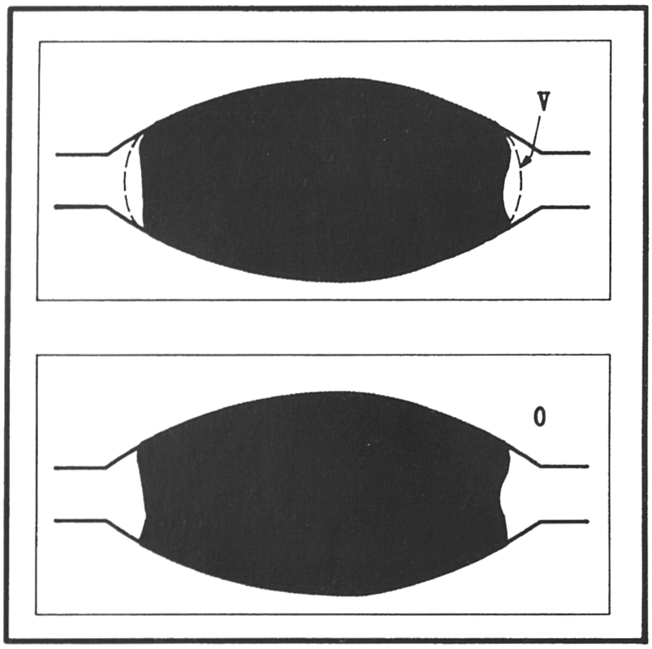
For this reason, different regulation configurations were tested using simulation models. The roughing mill of a small section and bar mill was used to demonstrate how the final dimensions were influ-

Figure 3-3a
Mathematical modelling of the rolling process



- - - - - - - - - Initial finite element mesh.
———— Deformed finite element mesh.
———— Groove contour.

S – Rolling direction.



V – Required section. 0 – Section obtained after test at the mill.

Figure 3-3b
Mathematical modelling of the rolling process

enced by variations in entry section geometry and temperature when the longitudinal tensile force and stand load systems were used, either separately or in combination, on different stands.

3.2.2. Computer-assisted gauging

Until recently, the techniques of calibrating rolls for rolling long products were based mainly on empirical rules. Calibration was carried out by successive iterations, corrections to the shape of the grooves being made progressively on the basis of observations made in the rolling mill. This procedure could be both long and costly, particularly for sections with very complicated profiles.

The problem was further complicated by the use of thermo-mechanical treatments which introduced additional parameters.

Computer-assisted calibration techniques have appeared over the last few years.

This is the subject of an Arbed project (5). A finite element model has been developed in order to predict the results of a rolling pass (Figures 3-3a and 3-3b). The mathematical formulae employed in setting up the model allow the deformation to be displayed at any moment during the operations and to calculate the forces and deformations as well as the thermal condition for each point.

The calibration operator is thus able to predict the shape of the product without going through a series of successive industrial tests. Continuous display of the deformation as work proceeds provides a much improved understanding of the rolling process. In this way it is also possible to simulate and check the feasibility of new techniques which could not be tried out on rolling mills for fear of failure. The new tool is thus a very strong stimulant for creativity on the part of the calibrator.

Following the theoretical developments carried out during this research project, an integrated system of computer-assisted calibration was set up. This system is based on a computer network which integrates the various functions involved in calibration: computer-aided design of the shape of the grooves, numerical simulation of the finite elements of the calibration, generation of the numerical data for the CNC machine tools manufacturing the rolls and the manufacture by electro-erosion of the gauges, etc. All calibration operations are currently carried out in this manner at Arbed.

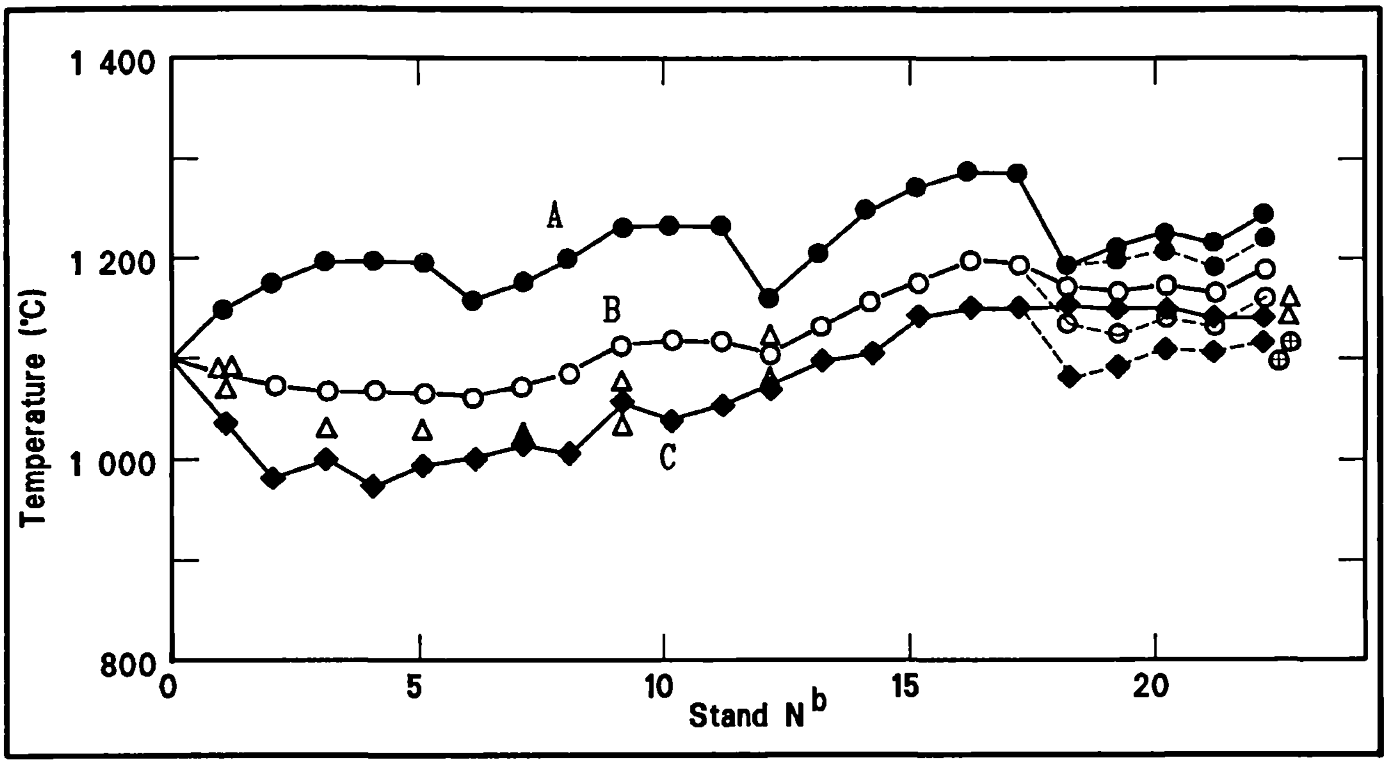
3.2.3. Automation of beam mills

Two projects have been carried out, involving close collaboration between Arbed and Irsid [(6) and (7)], on two different beam mills.

The aim, identical in each case, corresponded to the principal concerns of the mill operators: improvement of quality, especially for dimensional tolerances, increasing production and decreasing production costs.

Measurements taken on site demonstrated the importance of precise understanding of the roll bending curves of the horizontal and vertical stands, on which depends the quality and the dimensional precision of the products.

Figure 3-4
Calculated and measured values of heat development in a wire and bar mill (X5 Cr Ni 18 10 steel: entry speed 260 mm/sec; input dimensions 107 x 92 mm, output dimensions 10.5 mm diameter)



A – Centre. B – Middle. C – Surface.

	Theoretical	Experimental
Without cooling	———	Δ
With cooling	------	⊕

An original method of measuring this phenomenon was developed in an Irsid project and its application was successfully extended to the Arbed project, another example of the efficiency induced by the ECSC.

One of the projects involved computer control of rolling of large beams in the range in height of 200 to 1 100 mm.

Automation was based on a computer system established on several levels allowing the mill to be managed directly on the basis of basic rolling pass sequences. The mill operator is nevertheless able to modify the rolling parameters at any moment.

The rolling pass sequences are first calculated off-line using a ‘generator’ programme which takes into account the various technical constraints: physical limitations of the mill (rolling loads, length of bars, etc.), and any likely rolling defects, etc. This generator calls upon physical models for calculating temperatures and mechanical sizes and makes use of algorithms which minimize the likelihood of defects developing.

The theoretical productivity of the mill is also modelled; this allows the selection of rolling pass sequences which ensure maximum productivity while ensuring satisfactory operating conditions.

The measurement sensors concern mainly temperatures, rolling loads and beam dimensions (thickness and width of flanges). The role of these sensors is, on the one hand, to ensure that the models are respected and, on the other, to operate by controlling the rolling parameters.

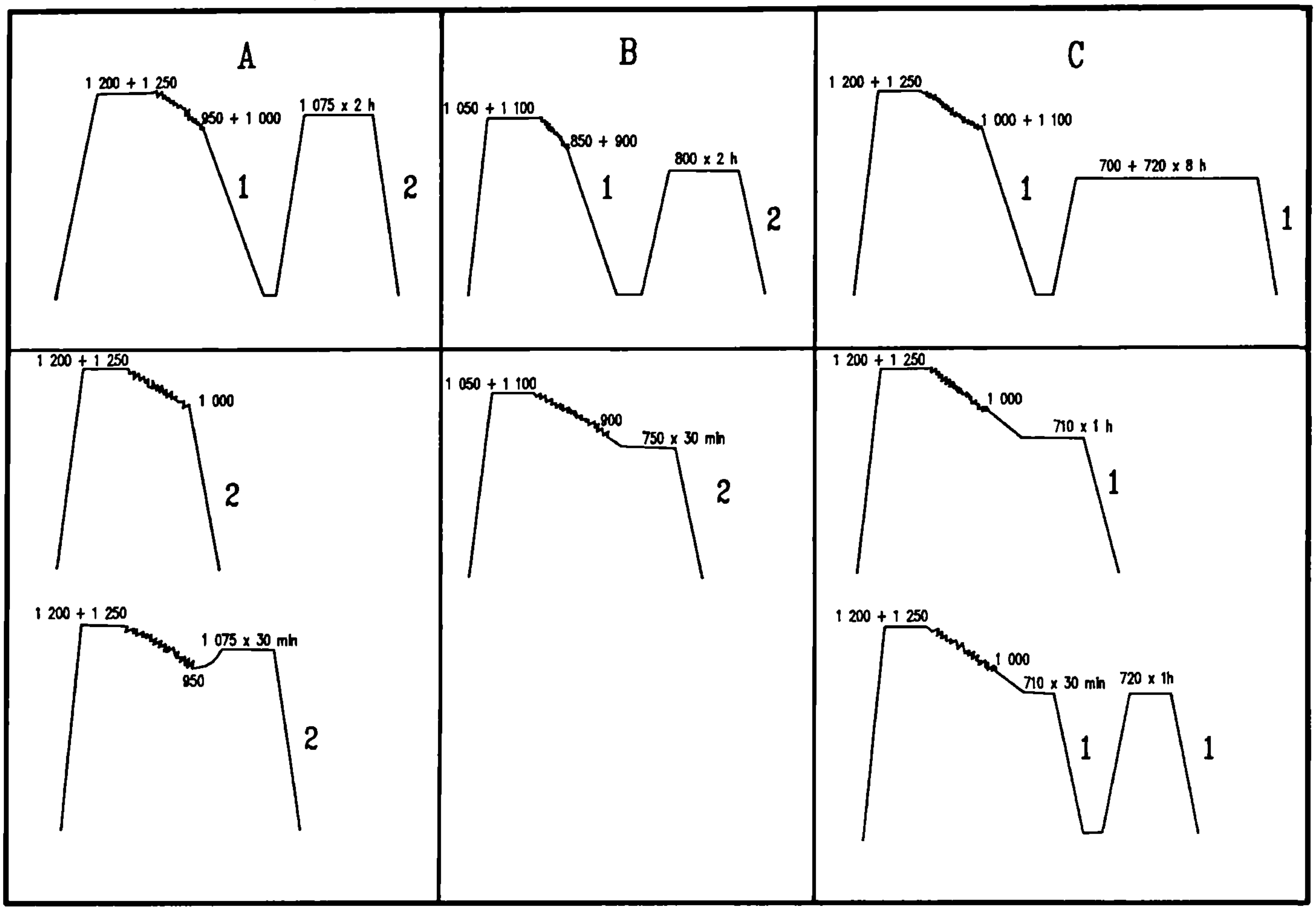
The industrial results confirm the validity of this solution.

3.2.4. Control of temperatures and thermo-mechanical treatment

The VDEh project (8) aims to calculate the temperature distribution in the cross-section of the rolled product during passes through individual stands and in the cooling zones.

Cross-checking the results of the mathematical model with measurements carried out on a 22-stand rolling mill demonstrated excellent agreement between the calculated and the measured values (Figure 3-4).

Figure 3-5
Individual thermal cycles for residual heat recuperation in rolling different types of stainless steel



A – Austenitic. B – Ferritic. C – Martensitic.
1 – Air. 2 – Water.

This model also demonstrated the considerable influence of steel-flow constraints on product temperatures, as well as a marked influence on rolling speeds. A reduction in the entry temperature, while providing a reduction in temperature in the first stands of the rolling mill, means that similar values as can be achieved using a higher entry temperature are obtained throughout the rest of the rolling mill.

In an Irsid research project on the same subject (9), modelling and industrial measurements were performed on different types of products and different cooling systems for a specific application of selective cooling in a wire mill.

This project allowed the rolling temperature to be reduced to 850 to 900°C at the entry to the finishing block, and to reduce variations in temperature along the slab to ±10°C, and also to allow cooling of the extreme end of the slab which corresponds to the first loops of wire.

To provide selective reheating, an analysis of the different technologies available for rapid induction reheating in the rolling line was carried out.

Three CSM projects were directly concerned with the heat treatment of steels in hot rolling.

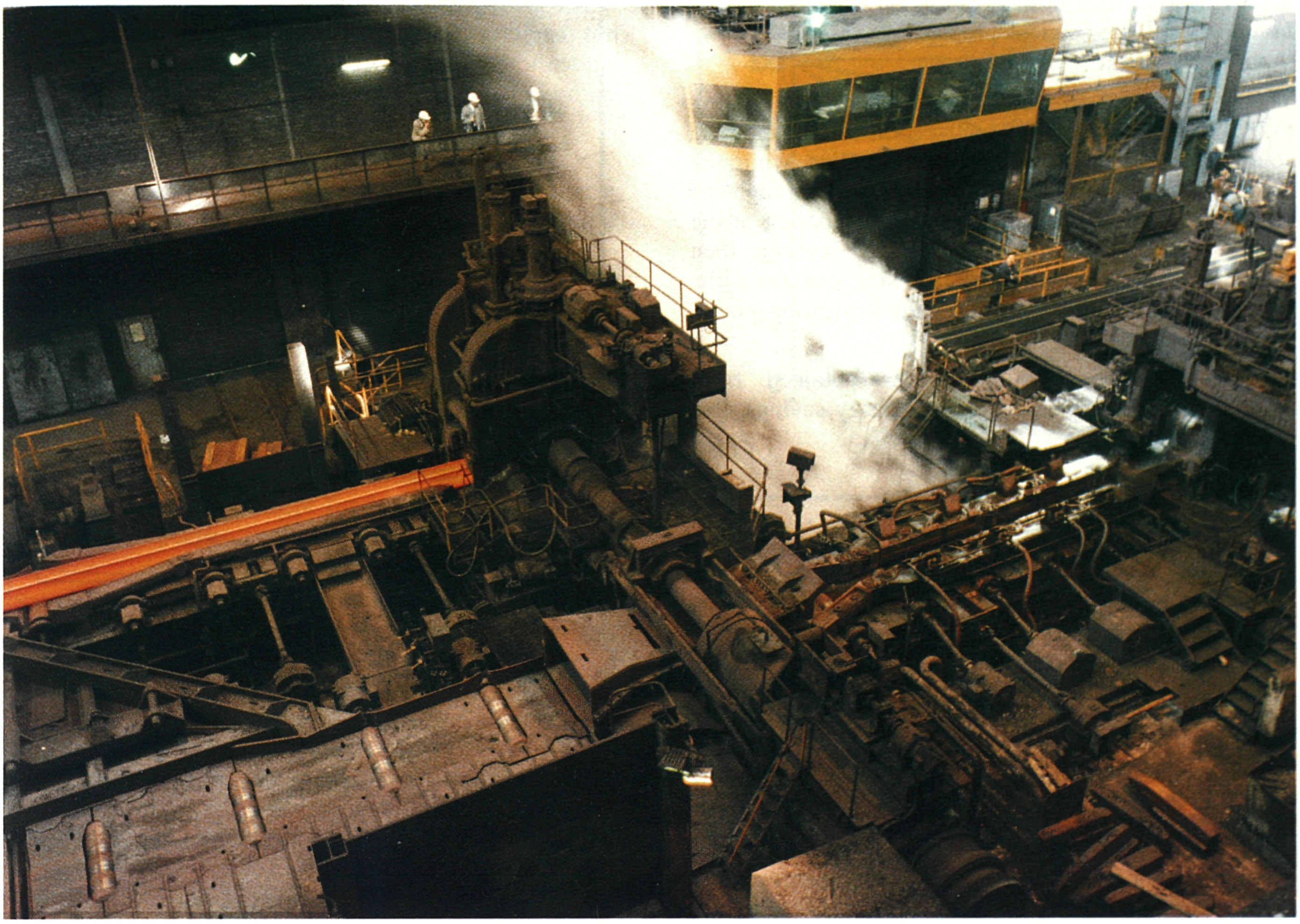
One of them (10) involved a mathematical model for describing structures to be found in carbon steel machine wire in the raw rolled state. The model predicted the development of steel microstructure during the whole rolling cycle and provided useful estimations of the final properties of the product.

The model was tuned following laboratory and industrial testing on a wire mill. The model described growth phenomena of austenite grains during heating, recrystallization during and after hot deformation, and the transformation of austenite during controlled cooling.

The two other CSM projects [(11) and (12)] were aimed at determining metallurgical parameters and formulating industrial techniques which allow coils of stainless steel machine wire to be treated using rolling heat.

In an initial step, the operational parameters of in-line thermal treatment of rolls of austenitic and ferritic stainless steel machine wire were defined. This treatment provided the as-rolled coils from the mill with user characteristics which were fully compatible with coils treated by conventional discontinuous cycles.

Figure 3-6
Application of QST at Differdange



The second stage was aimed at on-line thermo-mechanical treatment of martensitic steels.

On the basis of laboratory tests, including hot deformation tests, two solutions were adopted.

The first consisted of controlled cooling down to a temperature of 700 to 720°C after rolling, maintaining this temperature in a tunnel furnace for one hour, and finally air cooling. The second solution reduced the holding time to 30 minutes, but after air cooling the coils required further treatment for one hour at 720°C (Figure 3-5).

The end-use characteristics obtained were equal to, or better than, those of materials treated using conventional discontinuous methods, which provide significant economies in both time and energy.

Three demonstration projects were aimed at carrying out heat treatment within the rolling line itself, subjecting the product to a suitable selective cooling, and using the residual heat for annealing. This technique was applied successively to railway lines at Rodange (MMRA-CRM) (13), mining props (Unimetal) (14) and to Grey beams (Arbed) (15).

Besides the interest accorded to the quality of the product, the economic advantages of this type of process are considerable in terms of both productivity and energy savings, especially when compared to competitive products treated 'off-line'.

The MMRA, with the help of CRM, developed a heat treatment process for rails at the exit of the rolling mill, known as CHHR (continuous heat hardened rails). It consists of accelerated cooling of the rails in order to increase the hardness above a required minimum value (HB > 341 or 351) by refining the perlite while avoiding the formation of undesirable structures such as bainite or annealed martensite. Rails manufactured using this method have improved wear, fatigue and deformation resistance compared to untreated rails of the same composition.

At Arbed's Grey mill in Differdange, the quenching and self-tempering (QST) process — already developed for plates — was applied to a whole range of sections up to 1 100 mm high and 140 mm thick (Figure 3-6). Developed through collaboration between CRM and British Steel, the process is aimed at maintaining minimum temperature differences across the sections during rolling in order to ensure homogeneous mechanical properties.

This is obtained by selective water pillow cooling (WPC) of the core/flange intersection as it leaves the roughing and intermediate stands in the line, while the QST treatment applied after the final pass through the finishing stand involves intensive water cooling of the whole surface. The quenched surface layer is then annealed using residual heat diffusing out from the core of the product during the homogenization phase.

Besides the economic advantages obtained from improvements in productivity and energy savings, this treatment ensured:

(i) a marked increase in strength;

(ii) excellent cold temperature impact strength;

(iii) good weldability due to the possibility of lowering the equivalent carbon content;

(iv) a decrease in production costs through the decrease or removal of alloying elements.

The CHHR and QST processes are now part of standard production procedures in the MMRA and Arbed Differdange works.

3.2.5. Dimensional control and straightening of products

An Arbed project (16), aimed at improving the quality of beams, investigated automatic dimensional checking of this hot product in the process flow. Positive results were obtained by using a head fitted with multiple sensors and controlled by a robot.

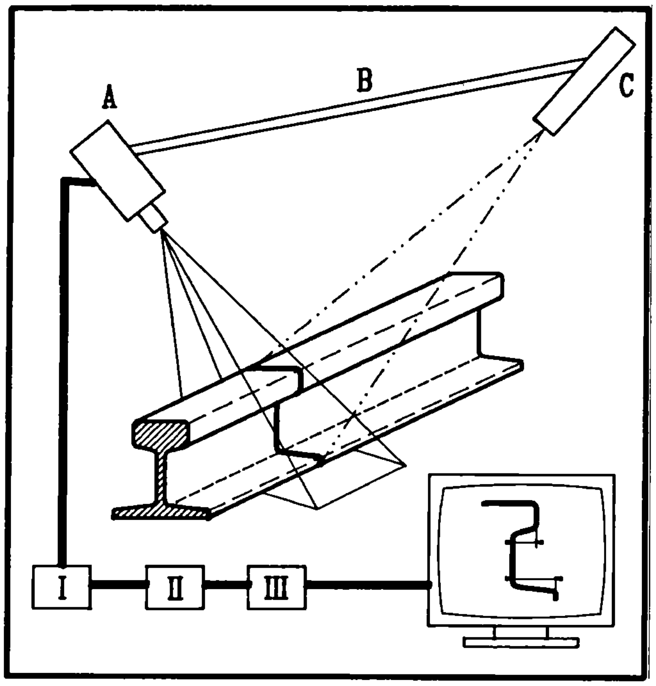
The Irsid-Cirep project (17) was aimed at developing a continuous, real-time measuring technique for the shape of long products.

The technique adopted was that of optical sectioning which provided a true three-dimensional image of the rolled product.

The principle entailed viewing the cross-section of the product using a laser (Figure 3-7) and observing the intersection with a sophisticated camera connected to a computer-imaging programme.

Tests on simple-shaped products (billets, square tubes) were completed with success. Understanding the possibilities and the current limitations of the equipment provides a path to developing an industrial system.

Figure 3-7
Principle of optical cross-section determination



A – CCD camera. B – Beam. C – He-Ne laser
I – Video interface. II – Computer. III – Visual display.

Several projects having this same objective of quality of finished products investigated the deformation of products during cooling operations and their cold straightening.

The Arbed project, studied in conjunction with CRM, concerned products with single asymmetric sections. In fact, U-shaped piling, which has a much more solid core, was studied. During natural cooling this piling has a tendency to develop a curvature which hinders hot sawing and feeding the product into the rotary straightener (18).

A device for selective core cooling was developed in order to considerably reduce temperature differences prior to natural cooling. This device provided a marked improvement in the straightness of the piling without introducing any harmful side-effects which had an effect on the use of the product.

Another Arbed research project of a more general nature investigated the mathematical modelling of the deformations which long products undergo during natural or accelerated cooling, either during or after rolling (19).

This model was developed in order to be able to predict the phases formed, the deformations, and the residual stresses during any type of cooling process. This mathematical model, based on finite elements, combined the thermal, metallurgical and mechanical phenomena and meant, for example, that the quantity of martensite, bainite, perlite, and ferrite present after accelerated cooling on leaving the rolling mill could be predicted. It was of particular use in setting up the QST process.

British Steel, during two successive projects [(20) and (21)] was able to advance the knowledge of cold straightening of sections. This problem is particularly elaborate in the case of asymmetrical sections for which process modelling of elasto-plastic deformation has yet to be perfected before it can be adopted on an industrial scale.

A current study by VDEh (22) is aimed at defining a straightening strategy capable of acting on residual stresses.

3.2.6. Continuous casting and rolling behaviour

The use of continuous cast semi-finished products has become generalized except for certain grades of steel or for very specific applications.

Several projects investigated the minimum reduction ratios, i.e. sufficient to consolidate central porosity and to guarantee the physical and metallurgical properties required in the products rolled from continuous cast steels.

The following are cited as examples:

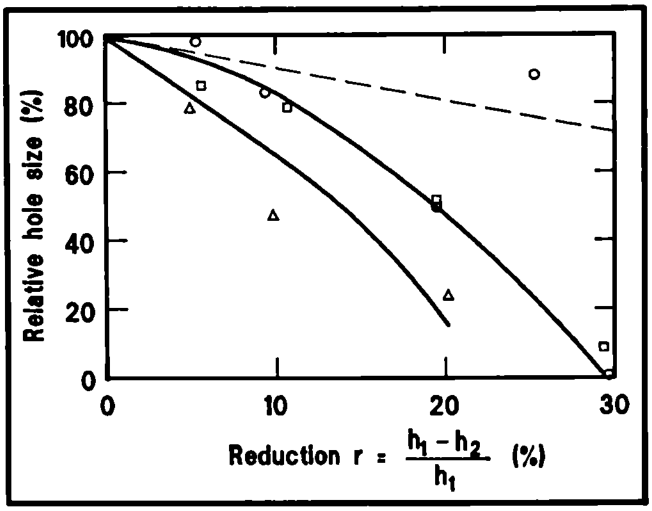
(i) A CSM-Deltasider project investigated continuous casting conditions for eutectoid steels for wire and the characteristics obtained (23).

(ii) A CSM project (24) determined the minimum reduction ratios that could be obtained for carbon and alloyed constructional steels as a function of continuous casting parameters concerning various characteristics: microstructure, strength, ductility, toughness.

Research has confirmed the importance of slightly overheating the steel in the tundish and the advantage of electromagnetic stirring on minimum reduction ratios.

(iii) A British Steel project (25) examined the effects of various deformation parameters on minimum reduction ratios.

Figure 3-8
Comparison of reduction in the dimensions of holes in steel, lead and plasticine



O Steel. □ Lead. △ Plasticine.

ing pilot testing, in which central porosity was simulated by holes drilled in lead used as a simulation material, rolling tests were performed on billets. The minimum reduction ratios were determined, as well as the importance of methods of rolling and closing up the central porosity (Figure 3-8).

Under the testing conditions applied during this project, rolling tests on continuous cast billets demonstrated that reduction ratios of 4 to 6 are sufficient to guarantee homogenization of the ductility. Reduction ratios of 15 must be practised to avoid any risk of remanent central porosity.

A model was developed which was able to predict with sufficient precision the reduction ratio necessary to close up the central porosity according to the calibration sequence adopted.

Research programmes continue into the optimization of deformation processes, while also taking into account the possibilities offered by the new continuous casting processes that are being developed [(26) to (29)].

References

(1) EUR 10140 DE 1986 — VDEh: 'Untersuchung des Werkstoffflußes beim Walzen in Kalibern (I + II)'.

(2) EUR 8892 FR 1984 — Irsid: 'Régulation des tractions sur trains continus à produits longs'.

(3) 7220-EB/303 — Irsid: 'Régulation de la traction intercage sur un train continu à barres'.

(4) EUR 12728/12729 EN/DE 1990 — British Steel/VDEh-BFI: 'Process control system for bar mills (I)' / 'Regelstrategien in Stabstahlstrassen (II)'.

(5) EUR 12252 FR 1990 — Arbed: 'Système intégré de calibrage assisté par ordinateur'.

(6) 7220-EA/319 — Irsid: 'Automatisation d'un train universel à poutrelles'.

(7) EUR 12976 FR 1990 — Arbed: 'Contrôle par ordinateurs d'un train universel à poutrelles'.

(8) EUR 11196 DE 1988 — BFI: 'Walzen hochlegierter Stahlwerkstoffe auf Drahtstraßen bei Erhöhung der Walzgeschwindigkeit'.

(9) 7220-EB/301 — Irsid: 'Contrôle de la température dans la section d'un produit laminé'.

(10) EUR 12813 IT 1991 — CSM: 'Impiego di modelli matematici per l'ottenimento di strutture prefissate in vergella di acciai al carbonio di laminazione'.

(11) EUR 10497 IT 1987 — CSM: 'Utilizzazione del calore residuo di laminazione per il trattamento termico di matasse di acciai inossidabili austenitici e ferritici'.

(12) EUR 12299 IT 1988 — CSM: 'Utilizzazione del calore residuo di laminazione per il trattamento termico di matasse di acciai inossidabili'.

(13) 7225-EA/501 — MMRA/CRM: 'Fabrication de rails par traitement thermique dans la chaude de laminage'.

(14) 7225-EA/303 — Unimetal/Irsid: 'Traitement thermique dans la chaude de laminage des cadres de mine'.

(15) 7225-EB/502 — Arbed: 'Trempe et revenu des poutrelles dans la chaude de laminage'.

(16) 7220-EB/502 — Arbed: 'Développement d'une cellule flexible à intelligence artificielle pour le diagnostic de produits laminés à formes complexes'.

(17) EUR 12530 FR 1990 — Irsid: 'Mesure de la forme des produits longs'.

(18) EUR 12251 FR 1989 — Arbed: 'Refroidissement sélectif de profilés à plan de symétrie unique'.

(19) EUR 12982 FR 1990 — Arbed: 'Contrôle des déformations des produits longs soumis à un refroidissement'.

(20) EUR 10711 EN 1987 — British Steel: 'Studies of straightening and levelling operations for plate and section products'.

(21) EUR 12793 EN 1990 — British Steel: 'Theoretical investigation of problems in straightening of asymmetric sections'.

(22) 7220-EB/103 — VDEh: 'Richtstrategien zur Beeinflussung von Eigenspannungen'.

(23) EUR 10773 IT 1987 — CSM: 'Acciai per vergella di composizione eutettoide fabricati in colata continua'.

(24) EUR 12812 IT 1990 — CSM: 'Influenza del grado di riduzione sulla qualità e proprietà di impiego di barre laminate di acciai di costruzione ottenute da blumi e billette colate in continuo'.

(25) EUR 12957 EN 1990 — British Steel: 'Extending the product size range from continuously cast sections'.

(26) 7220-EB/405 — CSM/Arbed: 'Estensione sagomario prodotti lunghi da C.C.'.

(27) 7220-EB/804 — British Steel: 'Optimization of the deformation process for continuously cast billets'.

(28) 7220-EB/105 — Krupp: 'Walz-Parameter Optimierung für Horizontalstrangguß-Knüppel'.

(29) 7220-EB/931 — Acenor: 'Laminación de la palanquilla de colada continua horizontal'.

3.3. Rolling of flat products

Rolling of flat products covers the whole range of hot-rolled strip, cold-rolled strip and plate.

In all these fields, the objectives over the last decade have, in general, been similar:

(i) the improvement of quality in order to satisfy more and more demanding end-users, and to open up new markets for steel;

(ii) the reduction of production costs especially through progress in efficiency and improved products.

3.3.1. Hot-rolled strip

The research and development activity in hot strip mills supported by the ECSC over the last decade has been aimed at several major targets:

(i) improving the geometric regularity of the strip: its width, thickness profile and flatness;

(ii) increasing the flexibility of the plant, rolling without any width restrictions, and, in the field of integrating continuous casting and strip mills, rolling with large width reductions of the blank;

(iii) obtaining mechanical characteristics that are more and more consistent and continuously improving with the development of thermo-mechanical treatments, i.e. rolling lines that are ever more highly developed;

(iv) studying rolls for use in strip mills and their lubrication systems.

Some examples will provide an insight into the amount of progress made in this very wide field, with the support of the ECSC.

3.3.1.1. Guiding the strip during rolling operations

During hot strip mill rolling operations, lateral variations in the position of the strip are sources of costly problems: deterioration in strip quality, premature wear of guides, drops in production.

Research carried out by VDEh and British Steel has been specifically devoted to improving strip tracking during rolling operations [(1) and (2)].

At the roughing stand, measurements taken have shown that the shape of the saw of the strip head is mainly caused by eccentric entry of the slab into the horizontal roll entry during the first pass. It would thus appear to be essential to ensure that the slabs enter symmetrically.

In the finishing stand, several types of measurement were made: transverse loading of the strip on to the lateral guides, load of the strip applied to the looper, monitoring the passing strip using diode cameras, thermal profile of the strip using infra-red cameras.

These measurements meant that the influence of lateral movements on the profile of the finished strip were able to be determined, together with the influence of thermal heterogeneity.

It was shown that the position of the strip in the finishing stand is identical to the position of the roughed strip, and that, of all the lateral guides in the finishing mill, it is the first stand that has the greatest influence on the position of the rolled strip.

This means that preventing lateral movement of the strip as it enters the finishing mill is the best means of reducing lateral movement of the strip during rolling operations, and thus of decreasing the resulting thickness variations in the edges, and also of limiting the risk of problems during coiling.

3.3.1.2. Determining strip width

Users of hot-rolled strip, who are mainly cold-rolling mills, order products which are sufficiently oversize to allow for edge shearing to be carried out.

Furthermore, when leaving the strip mill, the product exhibits three main types of width variations: insufficient width at the start and finish of the strip, variations in the average width, fluctuations in width at skid marks from reheating furnaces.

In view of these variations, the strip mill must aim for an oversize that is even greater than that described above in order to be certain that the strip does not at any point drop below the minimum width ordered by the user.

Another factor that is involved is the need to limit the number of times the width of the slabs has to be changed at the continuous caster in order to ensure maximum productivity.

Changes in width must therefore be carried out in the strip mill. Nevertheless, these large changes in width, when they are carried out using the traditional processes, cause high metal losses due to the unfavourable geometries at the ends of the strip, and to major width variations along the whole strip.

The importance of these economic factors means that the ECSC has actively encouraged several projects which have investigated this subject.

These projects have been carried out on plant equipped with precise and reliable methods of measuring the width, and have been backed up by pilot and laboratory tests, especially using plasticine, as well as mathematical modelling.

In a Hoogovens project (3), which was aimed at producing large changes in width in a hot strip mill, experiments were carried out on a laboratory strip mill using plasticine on a one-tenth scale.

These experiments provided an excellent understanding of the effects caused by edger passes, and the development of a formula for predicting the final width for various combinations of width and thickness reductions.

Offcuts from the head and tail of the strip can be minimized by using edger stands.

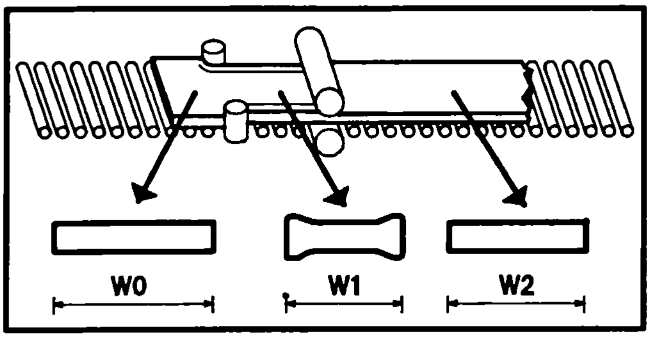
The results of tests on hot steel displayed good correlation with those obtained using plasticine.

The Irsid project (4) examined phenomena of fishtailing during rolling in the Dunkirk roughing stand and showed that the appearance of fluctuations in width cannot be explained solely by the phenomenon of roll bending in the vertical stands, even those that are less rigid as in the case of the roughing stand.

Fluctuations in width over the body of the strip are due to thermal heterogeneities and their effect on the formation of laps and spread in vertical edger stands.

Based on these factors, a system for controlling the width of the blank was made which employed the following principles (Figure 3-9):

Figure 3-9
Principle of slab width rolling operations



W0, W1, W2 = Widths at successive stages.

(i) compensation for shortfalls in width limited to the edges, a priori through the opening of the vertical stands, at the start and end of the blank;

(ii) width control over skid marks using hydraulic screwdrive in the final vertical stand, based on the determination of rolling loads in the previous stand and the measurement of the width.

This system has found industrial application in the strip mill at Dunkirk.

The resulting improved regularity of width, fluctuations of only ±1 mm across the strip body, meant that there was also a marked decrease in the number of coils to be repaired due to localized under-width, repair rates dropping from 4 to 1.5%.

A VDEh contract (5) examined the decrease in variations in width along blanks at the roughing stand and the offcuts at the ends of the slab, including those cases where there was heavy width reduction.

Different methods were initially tested on a pilot-scale mill and those that showed promise were then tested on an industrial scale:

(i) the method of forming a bevel or edging the corners was not shown to be economically viable;

(ii) relatively positive results were obtained by the edging method combined with a simultaneous horizontal pass;

(iii) the method involving controlling the position of the vertical stands during the edging pass proved to be the most efficient both in achieving a uniform width along the whole of the slab, as well as ensuring an improved configuration for the ends of the slab.

The controlling curve is calculated individually for each slab according to the number of horizontal and vertical passes. Since important differences often exist between the nominal and the effective widths of slabs, the width along the whole length of the initial slab has to be measured. Furthermore, since the width gradients that have to be compensated are large, the method requires a good understanding of both the dynamic response of the plant as well as the position of the blank in the stand.

We have seen elsewhere that in the finishing mill the phenomenon of tension between stands influences the width of the strip.

It follows that a system intended to overcome the problems of strip width must integrate the roughing and the finishing stands, in order to take account of all the parameters which are involved in the width of the strip, from feeding in the slab right through to coiling of the strip.

CSM (6) undertook a study of the different parameters involved in order to master variations in the width of strips and the automation of such a system. The system was being installed on the No 2 strip mill at Taranto during 1990, and hot torsion tests were being carried out in the laboratory at the same time. It is intended to operate on the roughing mill, in the position of the vertical stands and on the finishing mill by controlling the inter-stand tension.

A VDEh project (7) has studied coiling operations in detail on an industrial scale and demonstrated that the main factors influencing the lateral offset of the turns are the displacement of the coiler chuck due to increasing coil weight, and the geometry of the pinch rolls. Modifications to the design of these assemblies and to the positioning of the material guides have improved coil quality.

3.3.1.3. New control methods for metal flow

A Peine Saltzgitter project (8) involves a new method of controlling metal flow in a hot strip mill.

Hydraulic screwdrive of the stands is remarkable for the high rates at which speed and acceleration values may be varied. They may be used to compensate for flow-rate variations of the metal, visible as changes in the looper, while the gear ratios of the stand drive motors remain constant.

This novel concept of regulation provides a much more efficient means of respecting strict thickness tolerances than using conventional regulation methods:

(i) the disturbing parameters: errors in calibrating the roll gap, roll wear, thermal warping of the rolls — fields in which several projects have been involved [(9) to (11)] — and eccentricity, are integrated with the closed servo loop and thus do not have to be allowed for in the complex mathematical models;

(ii) the strip thickness is already directly regulated, right from the very first stand.

In this project, this new method of metal flow regulation has achieved a level of industrial viability for stands 4 to 7 of the Salzgitter hot mill, while the theoretical-base work has been developed for stands 1 to 3.

Rolling tests have revealed that, in the range of thicknesses below 5 mm, the new regulation method means that tolerances of ±25 microns can be achieved along 99% of the strip.

3.3.1.4. Maintaining profile and flatness

The increasingly severe requirements for hot-rolled strip quality has meant that steel manufacturers have been looking even more closely at maintaining the size and flatness of hot-rolled strip, as well as the surface appearance and the properties of the steel itself.

Maintaining size depends upon precise on-line determination of strip profile and flatness.

For the rolling operator there are several types of system available on the market for measuring the width of the strip.

The same is not true, however, for the continuous measurement of the transverse strip thickness profile.

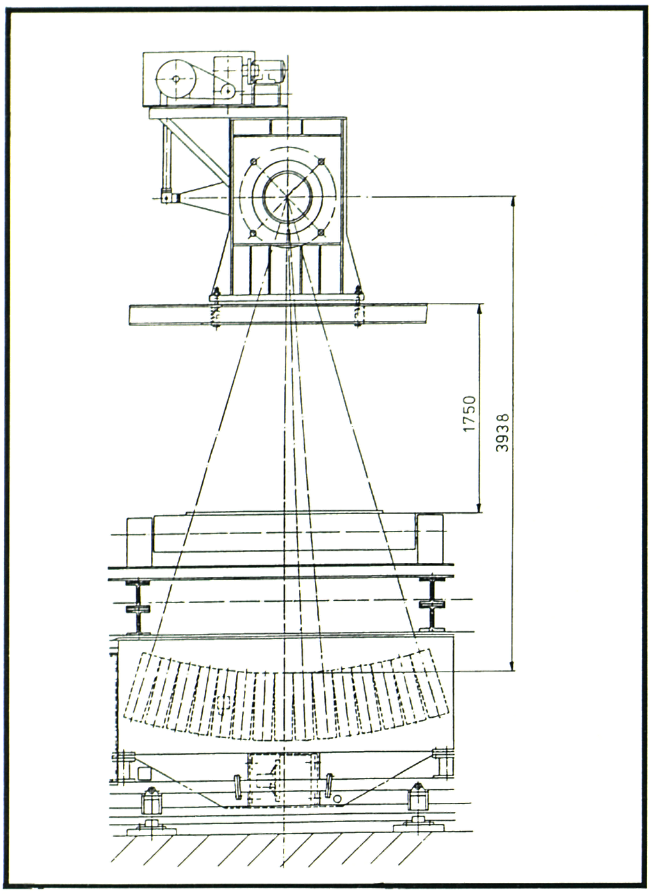
Two research projects by British Steel [(12) and (13)] in the Port Talbot rolling mill have investigated the design, construction and use of a system for measuring the transverse profile.

The equipment is based on measuring the absorption of gamma radiation. A source moves transversely at a speed of 0.5 m per second, which is equivalent to 4 seconds for measuring across the whole of a 2-m wide strip. A scintillation counter, which has been specially designed to measure across a width of 2 metres, measures the radiation which emerges from the strip. Pulses are measured for a period of 20 milliseconds, which corresponds to an incremental step of 10 mm. Measurements can be taken up to 15 mm from the edges and the precision achieved is 0.5% of the width.

A more recent Hoesch project is based on a different concept (14).

The measuring device employed uses an industrial X-ray source modified for energies up to 320 keV in

Figure 3-10a
Diagram of equipment for profile measurement



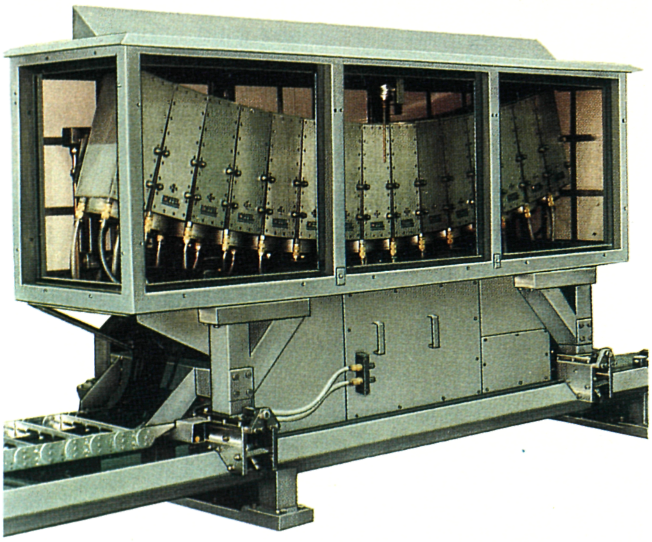
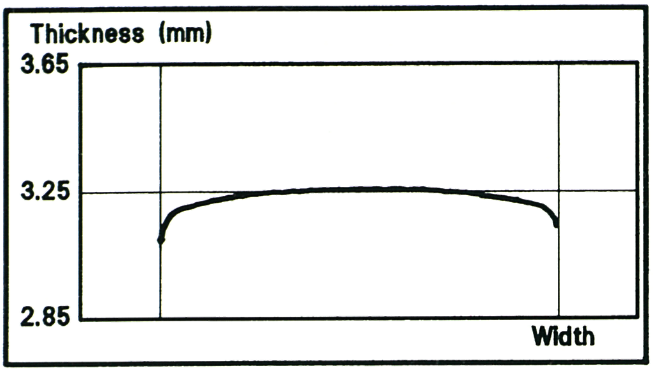


Figure 3-10b
Photograph of detection unit

conjunction with radiation detectors of a new, high sensitivity type. (Figures 3-10a and 3-10b).

A series of 15 detectors allows simultaneous measurement of the whole width of the strip while at the same time ensuring a very high level of spot discrimination, even for most of the edges, together with an extremely short measurement period.

Figure 3-11
Strip profile



The equipment has been installed just after the exit of the last stand of the Hoesch finishing mill in Dortmund. It operates extremely well under production conditions and achieves the precision targets set at the outset of the research work.

The achieved precision is 0.1%, which for a 4 mm-thick strip represents a tolerance of 4 microns, which in turn means that it is possible to achieve a difference of 50 microns tolerance between the centre and the edges along the whole of the strip (Figure 3-11).

Very soon after its installation, the equipment allowed studies to be made of those parameters involved in strip profiles and of the measures to be taken in order to obtain the desired profiles.

This equipment has been used, among other installations, for a project involving thinning at the edges of hot-rolled strip (15).

It has been demonstrated, in a Hoesch rolling mill, that the thinning which starts at 40 to 50 mm from the edges and reaches a value of 120 microns at the edge, can be reduced to 20 microns by modifying the rolling parameters of the final stand in the finishing mill.

Furthermore, asymmetrical rolling relative to the central axis of the mill has a strong influence on edge thinning.

We should also mention the Irsid pilot project currently under way at Sollac-Fos involving induction reheating of the edges of slabs for a hot-rolling mill (16).

In this critical zone, edge reheating is advantageous since it provides a means of reducing thickness variations relative to the body of the strip, and also of improving the metallurgical properties and of decreasing defects. There is also a decrease in roll wear.

An initial pair of 'C' inductors, each with a power rating of 360 kW were installed and are being tested on stainless steel strip (Figure 3-12) and steels for tinplate. The installation of a second pair of inductors

Figure 3-12
Photograph showing edge reheating in operation

that was initially envisaged may prove to be unnecessary if the power rating of the currently installed pair can be successfully increased.

The shape and the profile of the hot strip depend upon the geometry of the work rolls, as mentioned above, and this geometry changes during rolling operations due to mechanical and thermal effects. British Steel has undertaken a major research programme on this subject [(10) and (11)], and has developed an air-cushion sensor (Figure 3-13) for the continuous measurement of these changes and which is also able to predict with precision the effects of cooling the rolls (10). This sensor has proved to be sufficiently robust and reliable to be used industrially and its calculations are communicated to the process control computer.

The success of this project has led to the idea that variations in expansion of the work rolls could be overcome by selective cooling which would maintain the profile and the flatness of the final strip.

The cooling heads have been linked to rapid-acting valves which provide selective and controlled cooling of the work rolls.

It has thus been possible to establish the relationship between the thermal bulging of the roll, the flow rate and distribution of the coolant, and to create a system which maintains the shape and profile of the hot strip.

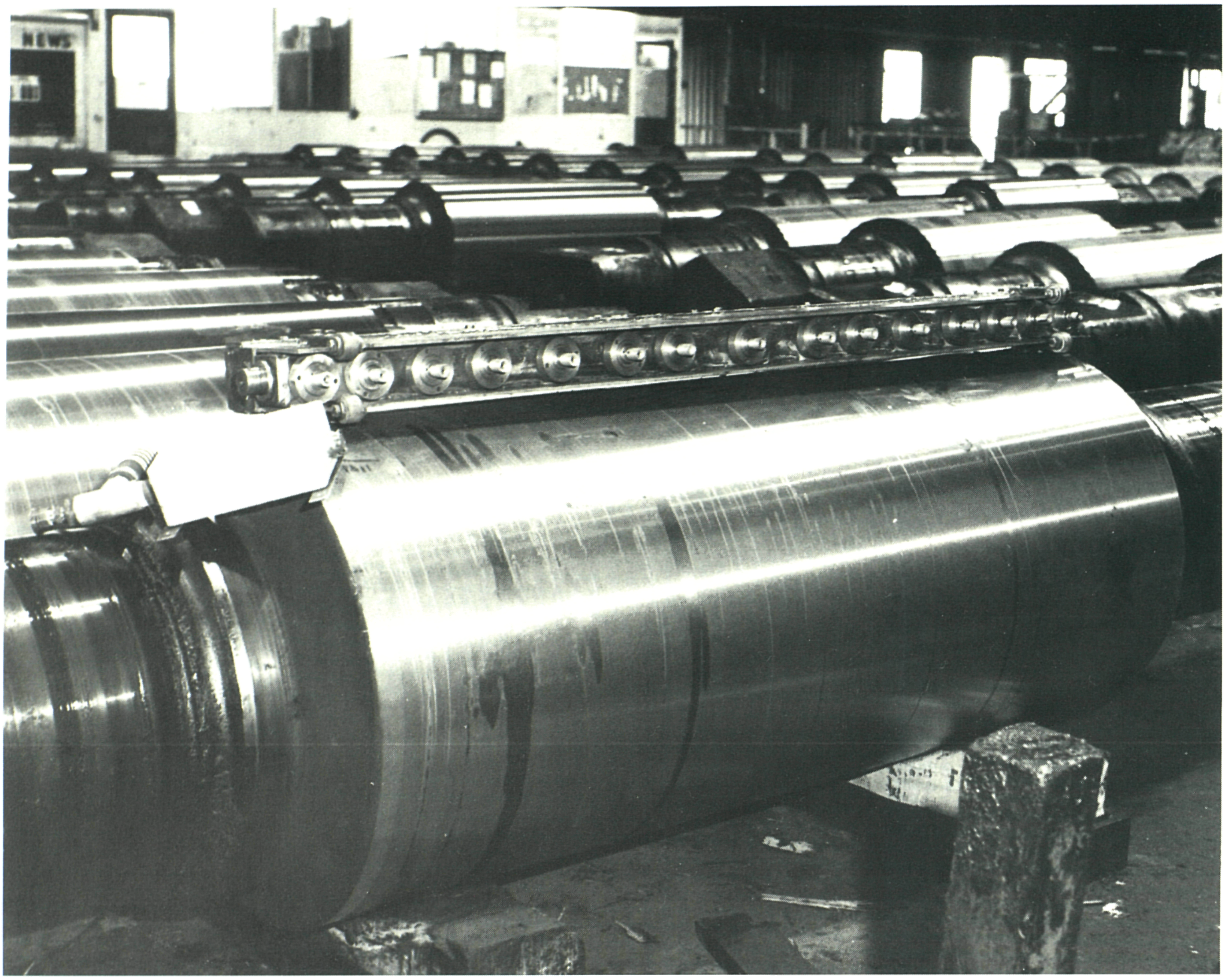
A current VDEh project (17) is aimed at determining the number and the position of stands in the hot finishing mill which need to be controlled by this system in order to maintain the strip profile.

Another aspect concerns flatness. The measurement of flatness has become a priority requirement, especially since orders for hot-rolling mills are extending to ever thinner and wider strip, for which the problems become increasingly acute.

An Irsid project (18) in this field, following on from a modelling project (19), has been carried out at the Sollac-Fos finishing mill.

The Irsid flatness gauge comprises three optical triangulations. Each one consists of a laser which transmits a spot of light on to the strip. Aligned with the reflection of this spot is a camera comprising photographic optics and a linear array of 512 photodiodes, with the associated electronics. The

Figure 3-13
Profile measurement



address of the diode receiving the most light provides a value for the height of the strip at that instant (Figure 3-14a).

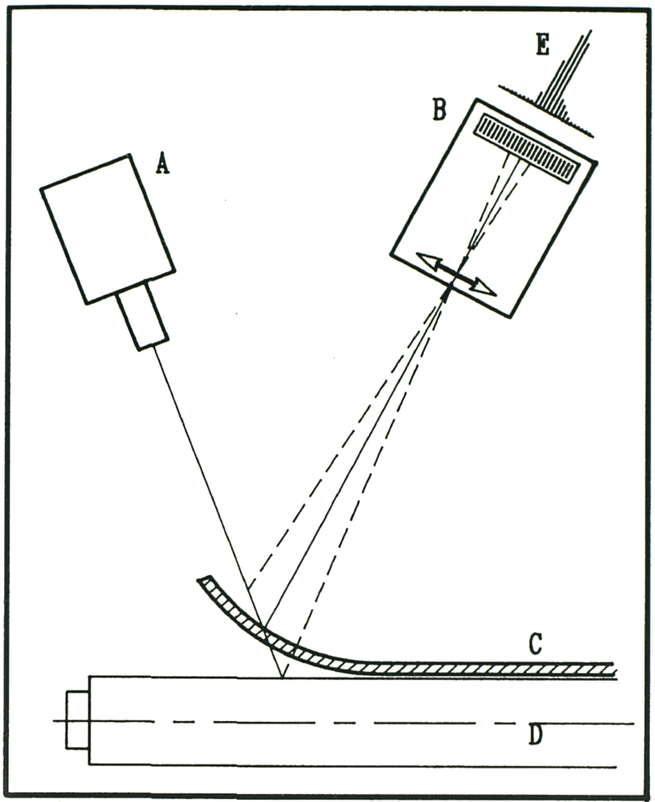
The system provides continuous measurement of the values of the centre and the two edges of the strip (Figure 3-14b). Measurement of the profile is provided by two X-ray gauges: the first is fixed and continuously measures the thickness at the centre of the strip; the other is mobile and sweeps back and forth.

Regulation of the flatness functions as a closed loop circuit based on the flatness measurements provided by the gauge and operating on the two cambers of stands F6 and F7. These stands have been specially fitted with Clecim variable cambering, and the resulting response time of the whole loop is 250 milliseconds.

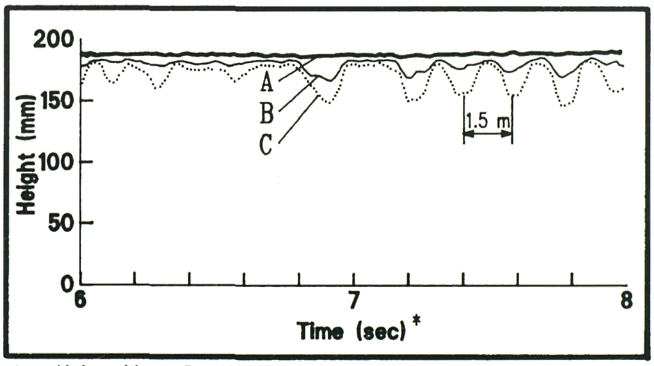
The reliability of the system has been proven industrially. During the initial period of utilization, some 7 000 coils were checked and it was demonstrated that the flatness control system means that the length of the coil which is below the usually acceptable tolerance values (30 UI) is reduced from 8 to 3%. The use of flatness control has also provided a marked decrease in rolling incidents.

As a further example involving flatness, a CRM project (20) was aimed at improving the shape of the strip head on the continuous strip mill at Forges de Clabecq. In an initial phase, the problem of curving of the extreme tip was investigated. This study demonstrated that deformations of the head originated in an asymmetry of rolling geometry, mainly in stand No 1. These deformations are amplified if thermal asymmetry is also present. Improving the symmetry, both geometrical (rolling) and thermal, has resulted in a marked reduction in defects. This allowed cambering to be installed on four stands, and automation of the mill provided the opportunity to develop an algorithm for the a priori calculation of the operating points of the cambering system in relation to the load distribution between stands in order to produce a flat strip. The second part of the research involved setting up a control system, automatic camber control (ACC), which responds to any rolling load variation by altering the cambering in order to maintain constant strip profile.

Figure 3-14a
Principle for measuring strip lift-up using optical triangulation



A – Camera. B – Photodiode array. C – Sheet.
D – Roll. E – Energy curve received by diode.



A – Motor side. B – Middle. C – Operator side.
Strip speed: 8 m/sec.
* From head of strip.

Figure 3-14b
Example of measurements on each of three axes as a function of time

3.3.1.5. Sequence-free rolling

During rolling operations, the surface of the rolls is subject to increased wear in the zone in contact with the edges of the strip. This requires rolling operations to be programmed in a certain order, known as the rolling cone, according to strip widths.

Over the last few years, different methods have been employed in an attempt to remove this constraint and the ECSC has supported several projects in this field.

Figure 3-15
Shifting work rolls: Sollac-Dunkirk

A current ILVA project (21) is aimed at defining the optimum strategy for free rolling, based on the results of the No 1 hot strip mill at Taranto which has been fitted with cambering systems on all its stands and shifting work rolls.

The purpose of displacing rolls is to be able to spread table wear across a wider area thus ensuring that the wear profile is capable of ensuring successive strip-rolling operations, in any order of width, without impairing physical quality — profile, flatness — of the rolled strip.

Sollac, in collaboration with Clecim (22), has developed a technology for shifting work rolls in various four-high stands in the Dunkirk hot strip mill and has set up shifting programmes based on roll wear and the characteristics of the strip being rolled.

The work has involved installing a mechanical system able to shift two work rolls along their respective axes, on either side of the rolling axis, in a symmetrical manner, over a distance of 100 mm (Figure 3-15).

Such an installation on stands F4 to F7 of the finishing mill has reduced the constraints of the 'rolling cone', constituted by the order of decreasing widths rolled, in sequence, due to the following economic advantages:

(i) reduction of stocks of semi-finished products;

(ii) increased hot charging with consequent energy savings;

(iii) reduction in technical delays.

3.3.1.6. Control of microstructure

Optimization of the microstructure of hot-rolled strip has been investigated in a series of projects encouraged by the ECSC, in which the effects of hot deformation and cooling conditions of the strip were studied.

Some examples have been taken from the dozen projects [(23) to (35)] dealing with this subject that is so important in steel quality and its end-use properties.

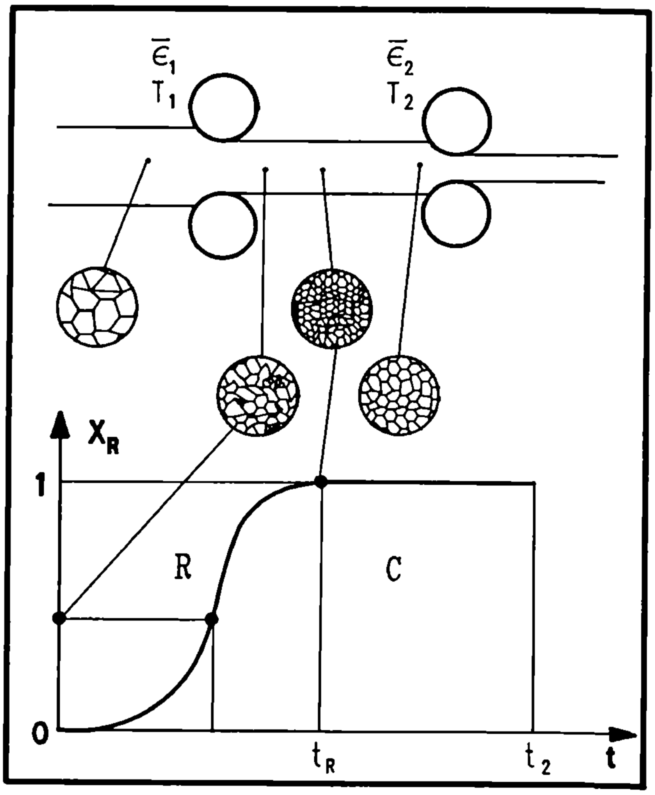
An Irsid project (23) looked into the plastic-flow characteristics of metal during hot-rolling mill operations.

Tests were carried out using hot torsion on C-Mn steels and microalloyed niobium steels. The results were compared with results obtained in a hot strip mill.

The first part of the study was devoted to a quantitative description of the role that certain variables played in yield stress, leading to the development of a static model.

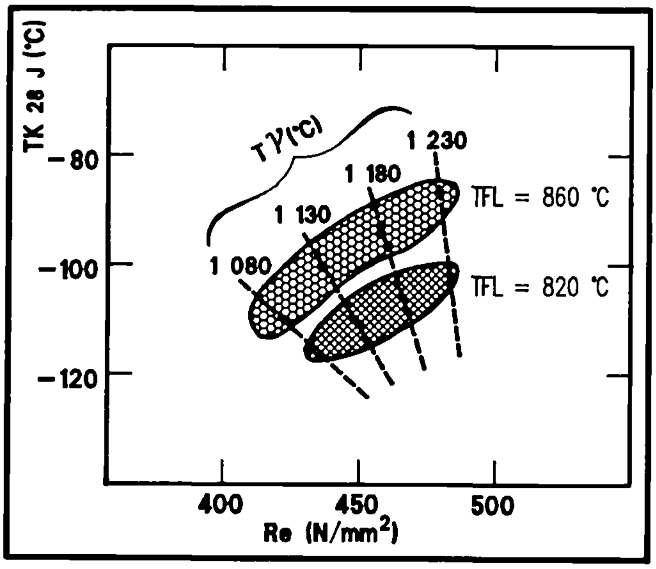
The metal structure has a considerable influence on the yield stress and the evolution of this structure during rolling operations is mainly controlled by static recrystallization which develops during the period between two successive deformations.

Figure 3-16
Diagram showing development of structure between two successive deformations



R – Recrystallization. C – Grain growth.

Figure 3-17
Graph of mechanical strength versus fracture-toughness of C Mn Nb steel: results of experimental rolling tests



The second stage in the research was concerned with studying the influence of deformation conditions on the evolution of the structure: recrystallization kinetics, crystallized grain size, grain growth (Figure 3-16).

The structural model that was developed describes the role played by the metal and rolling parameters on the behaviour of the structure of steels after hot deformation. In combination with the static model, it forms a dynamic model which is able to predict development of the structure and the yield stress during rolling in a strip mill with accuracy, and thus represents a very useful tool for the mill operator and the metallurgist (Figure 3-17).

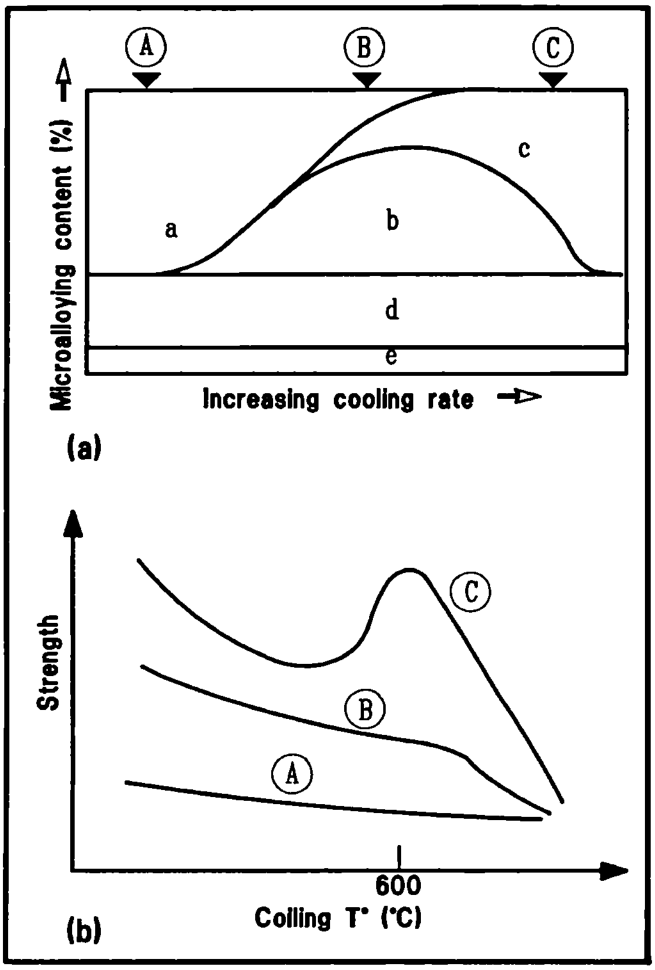
Another project undertaken by CRM (30) was aimed at improving understanding of precipitation hardening and the nature of the precipitates thus formed. The objective was to improve the homogeneity and characteristics of microalloyed steels.

It was possible to quantitatively describe precipitation kinetics of the microalloying elements during hot-rolling operations, using a simulator for hot deformation and the analysis of the precipitated phases, by using selective electrolytic dissolution of the ferritic matrix.

For microalloyed steels, the project demonstrated that the microalloying elements, returned to solution during heating of the slab, later precipitate out during the thermo-mechanical-rolling cycle and are divided into two categories (Figure 3-18):

(i) coarse, incoherent precipitates with little hardening effect which form, either during rolling operations or at high temperature, on the exit table, or within the coil if the temperature is high enough;

Figure 3-18
The effect (a) of the cooling rate on the distribution of microalloying elements between the precipitate phases in the end-product cooled at ambient temperatures, and (b) of coiling temperature on strength depending upon cooling rate



a – Transformation induced precipitation.
b – Coherent precipitation.
c – Element in solution.
d – Strain induced precipitation.
e – Undissolved precipitate.

(ii) very fine, coherent precipitates, with much hardening effect, which form either in the ferrite on the exit table, or within the coil at temperatures between 500 and 650°C.

For these microalloyed steels, cooling and coiling conditions play a vital role in the mechanical characteristics by modifying the distribution between coherent and incoherent fractions.

Several projects were undertaken to look into the structure of steels throughout the whole of the rolling operation in the strip mill, on the exit table and during coiling. These projects have confirmed that the best compromise of mechanical properties is obtained by refining the structure, through reductions in reheating and rolling temperatures. Particularly accurate rolling models have been developed and it has thus been possible to produce new grades of steel with improved and homogeneous properties under optimal industrial conditions. Many examples are given in the following chapter on properties of steels.

One such example, a Thyssen-MPI project (29), examined 0.4 to 0.7% carbon steel, hot-rolled strip. Laboratory tests were carried out on unalloyed and C 45 and C 60 alloyed steels.

Attempts were made to achieve a lower rolling temperature of 550°C for different final rolling temperatures (900, 780, 730°C), by employing different cooling rates.

The phenomenon of hot deformation of austenite greatly accelerates initiation of perlitic transformation, the main cause being the refining of the austenitic grains.

Strength properties are mainly influenced by increasing cooling rates in the transformation zone which results in a decrease in the perlite lamellar space and a lower proportion of ferrite.

Toughness is only slightly influenced by an increased cooling rate.

During tests on a medium-width hot-rolling mill, C 60 steel containing 0.65% Mn was rolled to thicknesses of between 2 and 5 mm with the aim of producing two different strength values, relying on complete transformation either on the exit table and/or within the coil itself.

While the solution of transformation on the roller table, resulting from a high cooling rate in the gamma/alpha range, produced fine lamellar perlite with strengths of between 850 and 900 MPa, a low cooling rate of the austenite being transformed within the coil led to the creation of coarse lamellar perlite with a high percentage of ferrite, which reduced strength values to 650 MPa.

Furthermore, within the range of activities investigating direct rolling, a CSM study (34) involving several different grades of steel for strip mills demonstrated that this approach could provide properties comparable to those achieved in the conventional manner.

3.3.2. Cold-rolled strip

For most users of cold-rolled strip, such as the automobile industry, it is vital to have a range of products which does not cause any problems on their highly automated production lines.

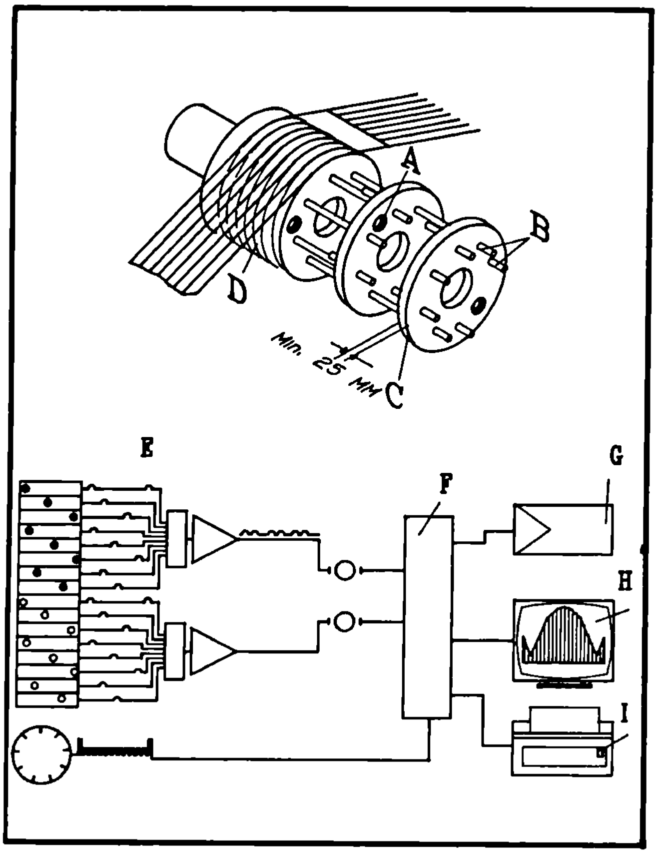
This implies very strict quality criteria for the strip:

(i) flatness and absence of residual stresses;

(ii) constant thickness;

(iii) surface finish.

Figure 3-19
System for measuring flatness



A – Force transducer. B – Tie-rods. C – Measuring element.
D – Measuring roll. E – Equipment. F – Computer.
G – Flatness control. H – Flatness display. I – Printer.

The ECSC has supported many research projects over the last decade, in this vital field of quality, which is of importance to the customers and some typical examples are discussed below.

3.3.2.1. Achieving flatness

An important part of this research concerned flatness, a complex problem for which the difficulties increase as the nominal thickness of the strip decreases.

A series of projects carried out by MPI, CRM and CSM [(36) to (39)] paid particular attention to the thermal bulging of cold-rolling mill rolls following a similar study of hot-rolling mill rolls.

The influence of several factors on thermal bulging was examined in greater depth: cooling conditions of the rolls, deformation conditions of the roll gap, strip width, rolling rate, and an initial simplified model of thermal bulging was used in real-time on a four-stand tandem mill at Nuovi Ligure (38).

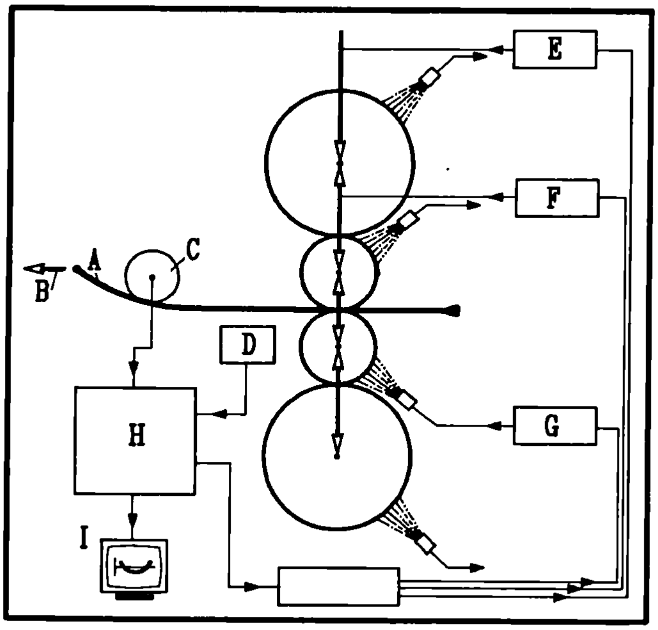
In a later phase, a more complete model including work rolls as well as back-up rolls was used for dynamic thermal control of a five-stand cold strip mill (39).

A Hoesch project (40) was involved in perfecting a real-time control system for optimizing flatness of cold-rolled strip.

The continuous flatness measuring equipment that was employed had been developed by BFI (41). It consisted of a 250 mm-diameter measuring-roll composed of 25 mm-wide elements connected by tie-rods (Figure 3-19). Piezoelectric transducers are positioned at the measuring-roll periphery and connected to a single amplifier. Measurements covered by variations in strip length or tension are displayed on an oscilloscope. Flatness defects with high linear gradients along the strip can thus be detected with greater precision than for any other currently available equipment, and in 1990, some 150 systems of this type were operating in cold strip mills throughout the world. The comparison of these continuous measurements with those discontinuous values obtained on rolled strip samples demonstrated significant differences in results. A laboratory study on a tandem mill showed that these discrepancies were due to thermal gradients in the strip, running perpendicular to the rolling direction, created during rolling operations.

A system was developed for the continuous measurement of this temperature gradient and to integrate the distribution of tensile stresses into the correction of the measurements. It was thus possible to match flatness values measured using discontinuous methods with those obtained from continuous methods. Once this vital step had been accomplished, a flatness control system was able to be developed. It consisted of operating in a closed loop, on the basis of corrected values of measurements of tensile stresses, on the

Figure 3-20
Principle of a flatness control system



A – Strip. B – To coiler. C – Strip tension measurement.
D – Strip temperature. E – Roll position. F – Roll camber.
G – Roll cooling. H – Computer. I – Screen.

parameters for adjusting the geometry of the roll gap in the final stand of the rolling mill (Figure 3-20). This system was used industrially to obtain a notable improvement in the flatness of finished strip.

The Krupp pilot project (42) also involved the flatness of cold-rolled strip in developing the continuous variable crown (CVC) system on a tandem four-stand cold-rolling mill. Investigations were directed at the influence of various rolling parameters, in particular multizone cooling situated between stands 3 and 4 (Figure 3-21).

Additional equipment had to be installed: hydraulic screwdrive on stands 3 and 4, hydrostatic lubrication of the Morgoil bearings of the back-up rolls in the four stands, improved guide positioning system for controlling centring of the strip and back-up bearings for the coiler.

The intention was to set up, in the future, a closed loop flatness control system based on information supplied by the ASEA roll tensioners.

Several BFI research projects [(43) to (45)] investigated flattening operations on cold-rolled strip, and their behaviour as they passed through the tension roll systems used at various steps of cold strip rolling operations.

During unwinding through the mill, the strip is subjected to many alternating bending forces which are superimposed on the longitudinal tensile force and these conditions can cause significant and uncontrolled plastic elongations.

Thus the VDEh project (45) carried out on an S-traction roll test bed demonstrated that the irregular elongations across the width of the strip appeared when it was subjected to a tensile load that was relatively low compared to its elastic limit, and that an initially flat strip underwent marked deterioration of its flatness.

For strip which initially showed major localized defects in flatness, the project demonstrated that, for the grades of steel concerned, by increasing the tensile force to a value of 25 to 75% of the elastic limit depending upon the thickness, the flatness profile was improved. A value of 25% of the elastic limit was sufficient to improve the flatness of a 1 mm-thick strip, while 65% was required for a 0.4 mm-thick strip.

A Hoogovens project (46) consisted of researching into the influence on flatness of the different stages of strip production in order to achieve process optimization. Research was centred on the following stages which did not cause any changes in the dimensional profile of the strip:

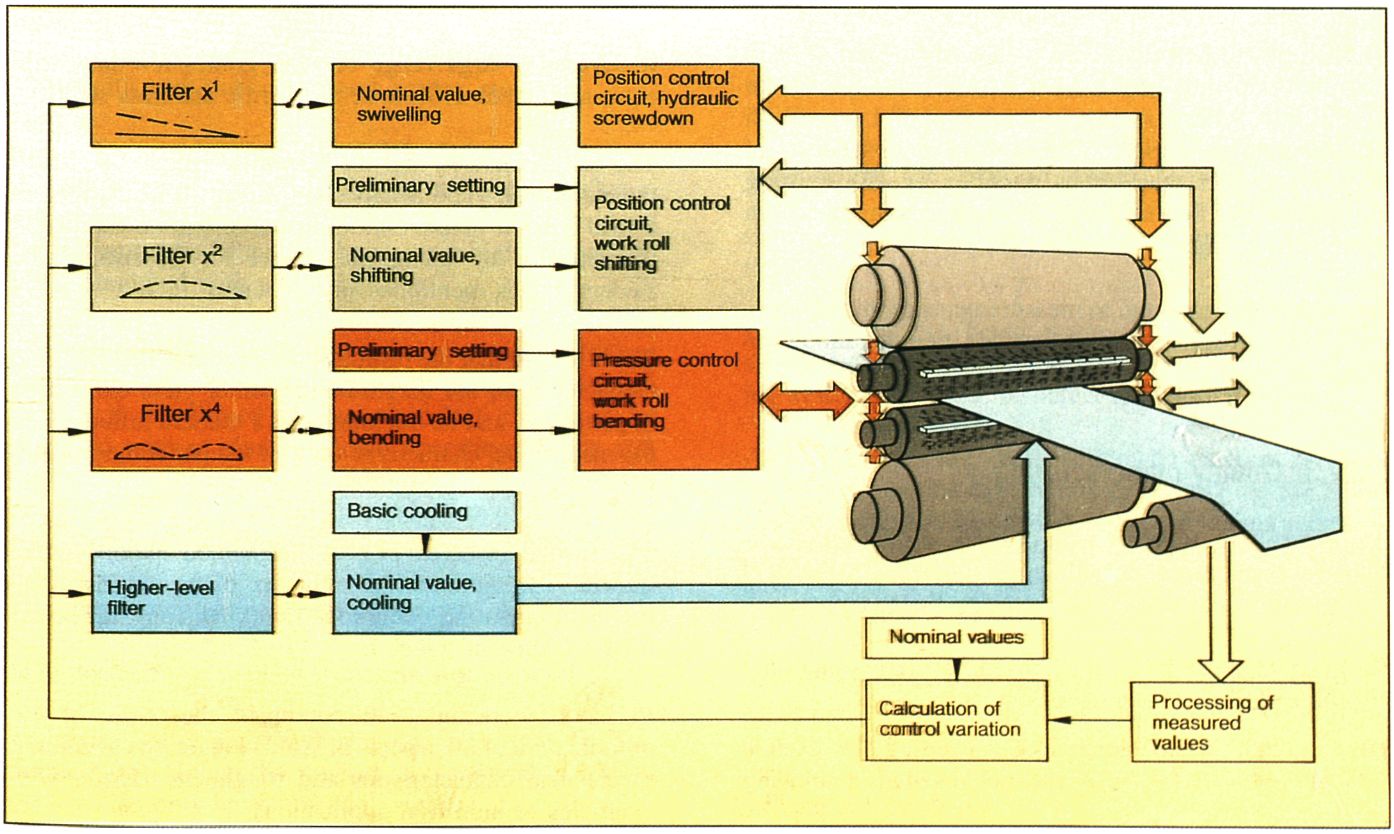
(i) roller tables at the exit of the hot finishing mill;

(ii) coiling of hot strip;

(iii) batch annealing;

(iv) continuous annealing.

Figure 3-21
Complete flatness control system



Two systems were specially developed for measuring flatness off the production line, one for hot-rolled strip, the other for cold-rolled strip before and after annealing.

The principal conclusions may be summarized as follows:

(i) On the roller table, at the exit of the hot strip mill, changes in flatness are substantial. Modelling shows that changes in flatness are produced during cooling within the coil.

(ii) During batch annealing, changes in flatness are very slight.

(iii) In continuous annealing, they are marked. The lack of flatness at the entry (i.e. after cold rolling) is corrected to provide an almost flat shape. This flattening process can be explained by the tensile and bending forces acting on the strip during its passage through the numerous guide rollers, at a relatively high temperature.

3.3.2.2. Measurement of the transverse thickness profile

The increasingly severe end-users' criteria for the transverse thickness profile of cold-rolled strip mean that it is necessary to make rapid on-line measurements, with a sufficiently fine lateral resolution to be able to accurately detect thinning towards the edges.

An Irsid project (47) used a new generation of X-ray detectors — photodiode arrays — allowing simultaneous acquisition from large numbers of measurement points, with the same accuracy, but with greater resolution than for existing equipment.

This prototype was developed on a cold tandem mill and provided thickness profile values for a maximum width of 140 mm, with a transverse resolution of 1 mm. With a measurement period of less than one second, an accuracy greater than 1% is possible, as with existing equipment, but the measurements are accurate to within 3 mm of the edges.

Extension of the system to measurements of thicker strip, especially hot-rolled strip, is possible if certain modifications are made.

3.3.2.3. Quality manufacturing

Temper rolling, together with coating, are the final metallurgical operations carried out on thin strip by the steel manufacturer before it is delivered to the customer.

Its main characteristics are thus particularly important for the end-user. The skin-pass must:

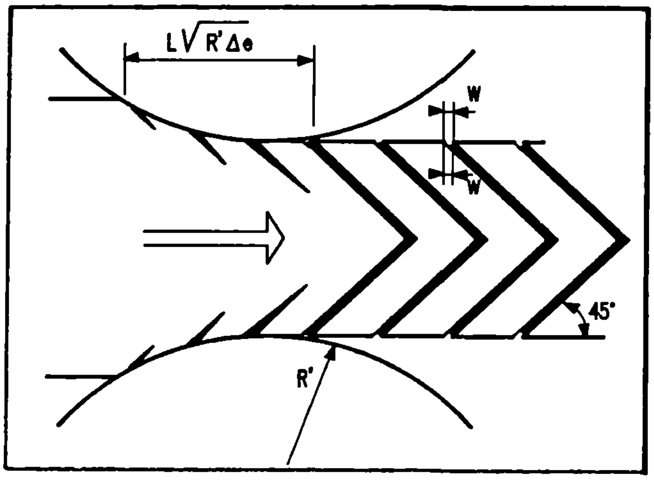
(i) eliminate yield elongation, cancelling the tension curve to avoid band-type defects during drawing operations;

(ii) impress the final roughness on the strip, so vital for good drawing and painting qualities;

(iii) correct the flatness, if necessary.

In practice, temper-rolling operations were carried out manually and were not optimized due to lack of sufficient knowledge of the mechanisms involved in cancelling the yield elongation and the transfer of roughness.

Figure 3-22
Diagram of roll bite: development of Lüders' bands during temper rolling



Two Irsid projects [(48) and (49)] were concerned with improving understanding of temper rolling.

The first project involved the study of metallurgical phenomena and the development of mechanical properties during temper-rolling operations.

It covered a large range of steel grades for thin strip: extra-mild steel, HSLA steels, ferritic stainless steels.

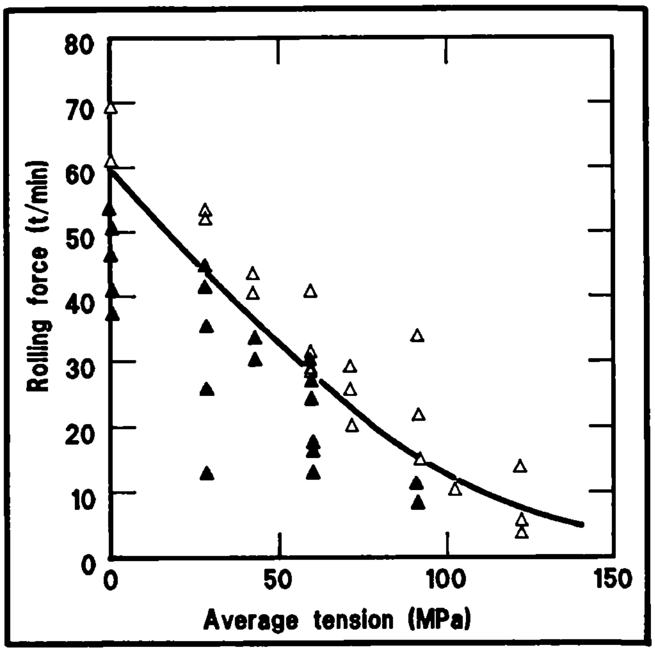
The results showed that the operating range over which the elongation yield is cancelled can easily be defined in a load-tension graph. The limit curve can be calculated theoretically by using the model for describing the Lüders' bands mentioned in this report.

It was shown that the rolling speed, coiling tensions, strip characteristics, the length of the initial yield elongation in particular, and its thickness had a marked influence on the mechanical characteristics after temper-rolling operations (Figures 3-22 and 3-23).

The second research project was aimed mainly at the transfer of roughness: the influence of factors involving rolls and operating conditions (load, tensions, lubricant) on the degree of transfer.

Research work in 1990 continued the study of the optimization of all aspects of yield elongation cancelling, mechanical characteristics and roughness transfer with examples of industrial applications.

Figure 3-23
Experimental determination of elongation yield cancellation in an extra-mild grade of steel



△ Suppressed yield elongation.
▲ Residual yield elongation.
Steel C: e = 0.82 mm σ_y = 198 MPa
Rolling speed: 10 m/min.

3.3.2.4. Integrated installations

The operation of integrated pickling line-tandem mill installations raises new problems of rolling mill operations.

In fact, the application of new models of automation to uninterrupted rolling operations has to incorporate a new factor: optimal methods of modifying parameters such as strip width, exit thickness, steel grades, etc.

This was the objective of an Irsid research project (50) still under way in 1990 which was investigating changing rolling parameters on the fly (CSV) for a five-stand tandem mill (the fifth stand being a six-high), which has been integrated with a pickling line.

The aim of the project was to develop a control strategy which allowed those rolling mill parameters which needed to be altered during a product change to be modified without shutting down operations, while still maintaining the highest possible rolling speeds, without breaking the strip and with the production of a minimum length of strip that is outside thickness tolerance values.

This pre-setting model takes account of the maximum admissible differences of speeds, tension, and screwdriving which can be applied from one strip to another.

The existence of a six-high stand required that the flatness control strategy be revised as compared to rolling mills which only have four-high stands.

The validity of the roll-gap model which had been linearized about its operating point was demonstrated, and current developments are concerned with minimizing tensile forces induced in the first interstand when changing from one thickness to another.

3.3.2.5. Automatic surface inspection

Now that pickling and rolling operations at the Sainte Agathe works of Sollac at Florange have been integrated, a prototype system for automatic inspection of pickled strip has been installed (51). In this case the system will attempt to detect serious defects which can cause strip breakage or roll damage during rolling operations. This detection system must be installed up-line of the intermediate accumulator situated between the pickling line and rolling mill so that the operator can be forewarned and take action without unnecessarily slowing down the line.

The technique employed in this project is that of optical inspection of both sides of the strip using a linear CCD camera developed by Irsid. Using suitable electronics, the image of the strip is reconstituted and processed in real-time to provide fault detection. A computer provides functions for managing the various lists of tasks, the alarms and data transmission to the process control computer and the operator, as well as data acquisition and storage.

The average improvement in strip breakages provided by this system is of the order of ECU 400 000 per year for an operating cost of the same order of magnitude (ECU 300 000) and twice that amount in capital investment (ECU 700 000).

Strict customer requirements and heavy competition have increased the need to perfect surface quality control of thin strip.

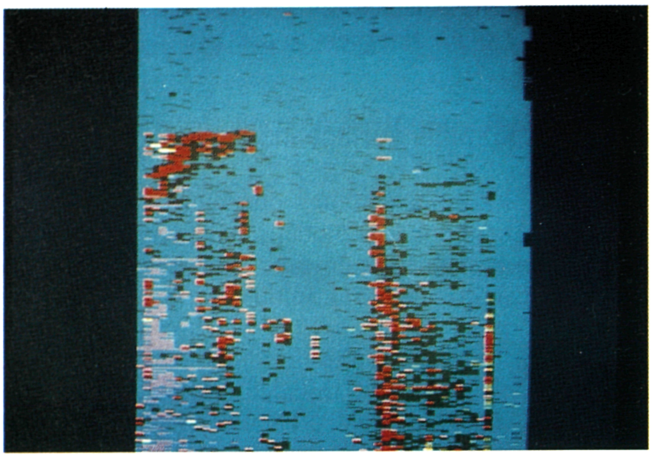
Over the last decade, considerable progress has been achieved in the field of visual inspection, but the automatic systems available were unable to satisfy requirements concerning the detection of types of defects.

Large efforts are being made to determine types of significant defects and to develop the computer-processing systems required for defect recognition.

A BSC contract (52), which followed on from previous work, provided the opportunity of developing the SIRA surface inspection system based on laser beams and computer processing of sensor signals. Progress has, nevertheless, still to be made in the field of on-line inspection at high production speeds.

A later VDEh contract (53) is also further investigating aspects of an earlier study. Thin strip is examined transversely as it uncoils using a high frequency digital laser-imaging system. The four characteristics of a defect, reflection, light dispersion, length and width are filtered.

Figure 3-24
Surface inspection: images of defects at the end of the strip (including surface deposits)



These characteristics have been determined previously for various types of defect by examining strip samples and by observing defects on a sampling line (Figure 3-24).

This information has been introduced into a computer programme which is able to recognize defects according to certain specific characteristics.

Testing on an industrial scale has shown that the probability of recognizing defects reached 65%, at that time, and that higher values were possible.

These automated inspection techniques, modified and adapted to smaller defects, and developed by CSM in Rome and Irsid have been jointly applied by ILVA at Terni and UGACG at Gueugnon (54) for inspecting stainless steel strip. In the first case, the strip is inspected on both faces just before coiling down-line of the first pickling bath, while at Gueugnon one face is inspected after bright annealing.

Ensidesa in Aviles (55) has, in turn, installed automatic inspection of strip at its final production stage after skin-pass. In view of the high strip speeds involved, some 1 200 m per minute, the capacity of inspection that has been developed reaches 20 MHz, a value five times greater than that used in previous applications.

3.3.3. Heavy plate

In the production of heavy plate in a four-high stand, research and development promoted by the ECSC over the last decade has concerned the improvement of the metallic yield (56) and especially those problems involving quality: economic production of plate with improved properties, improvement of profile and flatness, checking of internal condition.

An Arbed project (57) examined the application of the quenching self tempering (QST) process to heavy plate before applying it to beams (Figure 3-25a).

Figure 3-25a
View of a plate during cooling

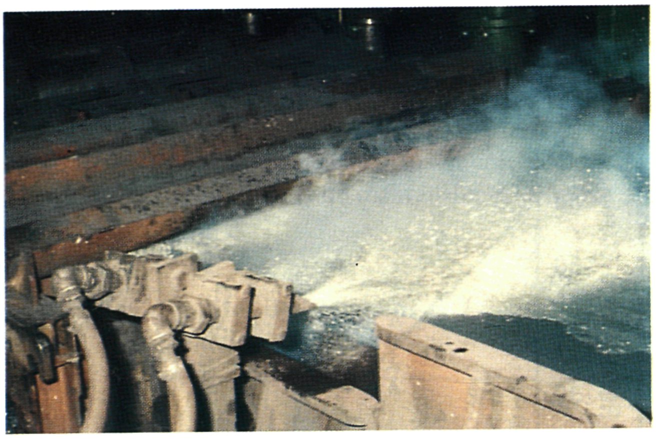
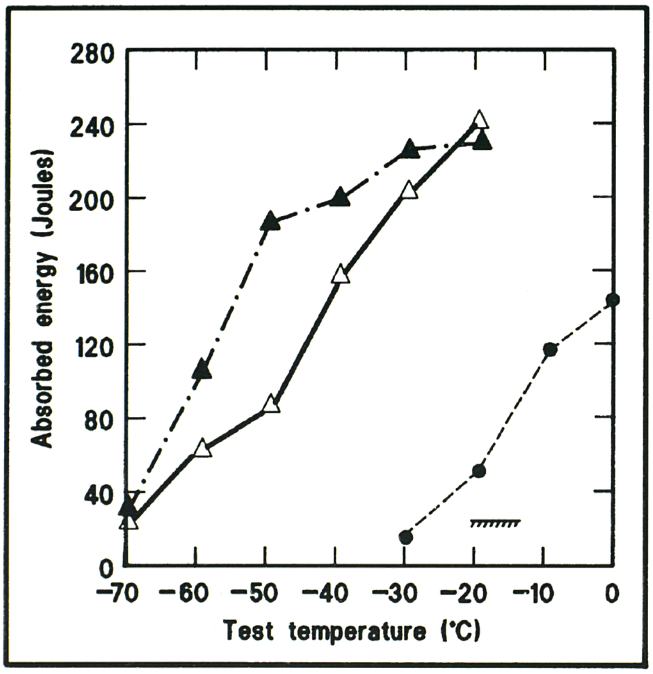


Figure 3-25b
Results of Charpy V toughness tests on QST plate and untreated plate



●-------● Test plate (3 M)
△———△ QST plate (1 M) entrance cooling zone: 820 °C T_{AR} = 600
▲—·—·—▲ QST plate (1 M) entrance cooling zone: 790 °C T_{AR} = 595

●-------● Re = 262 N/mm^2
△———△ Re = 364 N/mm^2
▲—·—·—▲ Re = 357 N/mm^2

Sampling: standard position (beneath skin)
/////// Minimum values for St 52-3N steel according to DIN 17100

It should be recalled that the QST process consists of submitting the hot-rolled product to very rapid cooling for a brief period after the final roll pass.

The peripheral zone of the plate is thus quenched, but since the cooling is rapidly terminated, the heat flow from the core of the product provides for an annealing of the quenched zone. The plate thus acquires a composite structure of annealed martensite on the surface with a core structure of ferrite/perlite and bainite.

The cooling system installed after the final stand of the rolling mill was capable of handling the range of thicknesses from 20 to 40 mm, of St 52-3 N grade steel, with a more economical chemical analysis and with a lower carbon equivalence than for a conventional configuration (Figure 3-25b).

An extensive study concerning homogeneity of QST treatment provided positive results. Furthermore, plate flatness is perfectly satisfactory and reproducible.

Improving the regularity of the thickness and flatness of plate was the subject of an Irsid project (58) which followed on from previous studies in the same field and was carried out at the Dilling heavy plate mill. This project involved:

(i) the installation of a countercamber system on the work rolls of the four-high stand operated by pressure from the balancing rams;

(ii) the development of a mathematical model of the effects of countercamber on the plate profile;

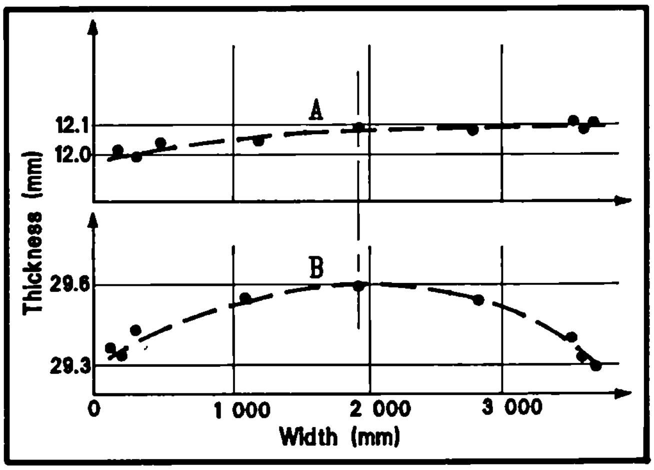
(iii) the integration of this model into the industrial conditions of automated rolling operations.

The progress achieved in modelling the roll bending of the stand and the understanding of the transverse profile of the plate mainly resulted in incorporating, in real-time, the wear and thermal expansion of the work rolls, as well as an improved understanding of the elastic deformation of the roll assembly (Figure 3-26).

The improvements obtained include the following three points:

(i) more uniform thickness across the width of the plate with an average decrease of bow of 0.08 mm for a width of 4 000 mm;

Figure 3-26
Cross-sections of 3 700 mm-wide plate with extreme values for roll bending



A – Calculated camber = 0.0
Burb = 1 375 tonnes
Worb = 288 tonnes
B – Calculated camber = 0.27
Burb = 592 tonnes
Worb = 42 tonnes

(ii) increased productivity;

(iii) improved flatness for thinner plates.

Nevertheless, despite the progress achieved in controlling flatness in a four-high stand, as the previous project demonstrates, heavy plate must generally be subjected to hot flattening.

The traditional concept of hot flatteners has been put into question by several factors: the development of the heavy plate manufacturing process, the increased strength of plate produced, increases in productivity in the rolling mill, new products and the development of flattening methods.

Two research projects carried out in cooperation between Irsid and Dillinger Hüttenwerke [(59) and (60)] investigated hot flattening of heavy plate.

They comprise a description of existing hot flatteners for heavy plate, together with their mechanical operating characteristics under the effects of flattening loads.

The behaviour of the steel under hot flattening conditions was studied and a model of the elasto-plastic bending of a steel plate was developed, leading to the production of a complete uni-dimensional model of hot flattening.

By combining operator experience with the results of this model, an optimal flattening strategy was able to be devised, allowing, among other aspects, control for high-strength plates to be adjusted, the residual stresses to be diminished, and plates with thicknesses which varied along their lengths to be flattened successfully.

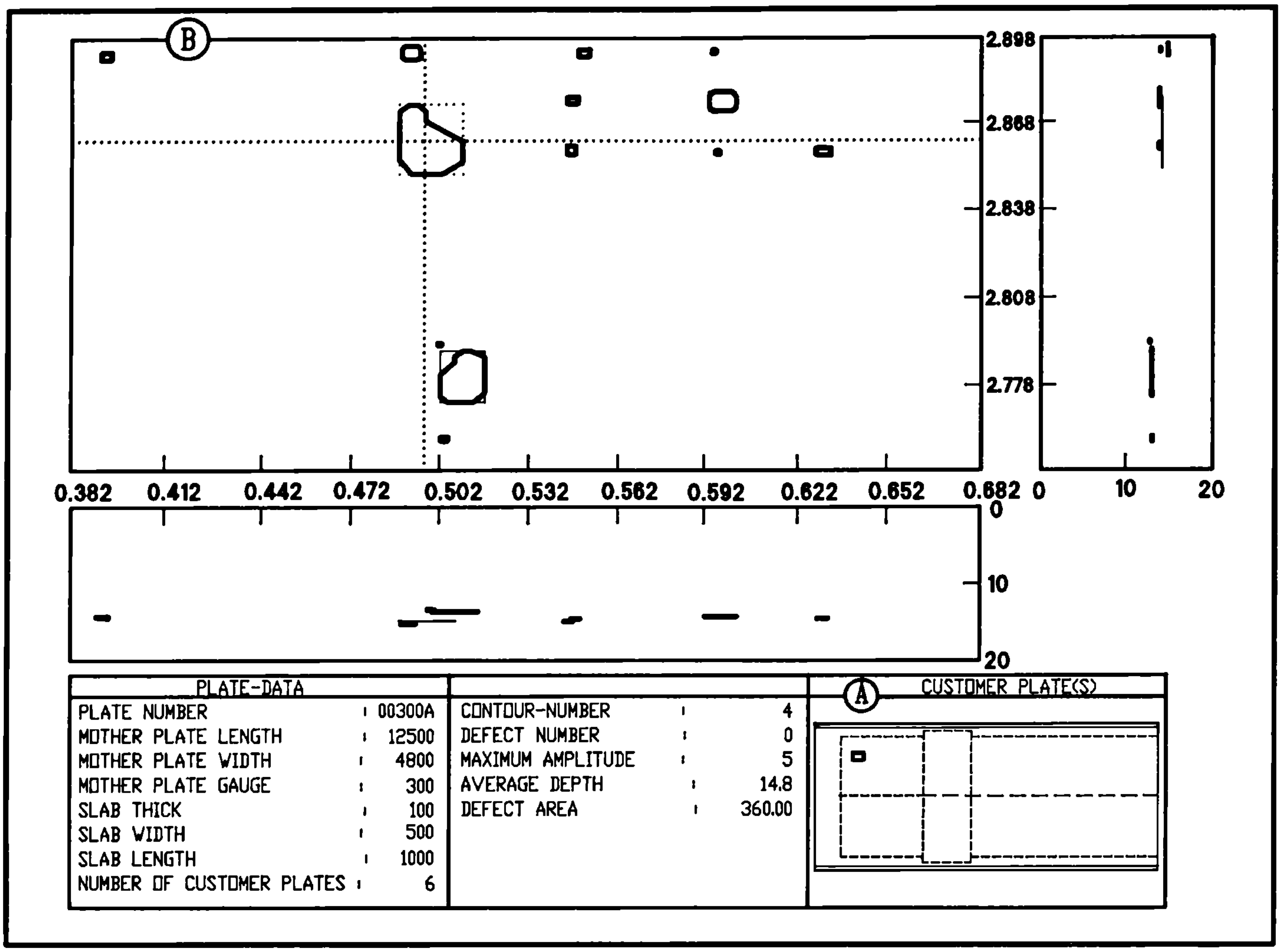
In the field of quality control of products leaving the four-high stand, several projects undertaken by IZFP of Sarrbrücken, in close cooperation with Dillinger, have provided improvements in the performance of ultrasonic systems used in controlling the internal condition of heavy plates.

Two of these projects [(61) and (62)] concerned the industrial application of the Augur system (Automatisch Ultraschal-Grobblech-Prüfung und Rekonstruktion der Reflectoren: i.e. automatic inspection of heavy plates using ultrasonics and the reconstruction of reflectors) on the ultrasonic system installed at Dillinger.

The reflector characteristics (amplitude and echo transit times) are supplied by 288 channels which inspect 100% of the plate, up to a width of 4.8 metres.

They are processed in several stages by 15 controllers which, among other operations, eliminate background noise and reconstruct the reflectors, thus providing

Figure 3-27
On-line Augur inspection
(A) Inspected area of mother plate
(B) Details of the zone of defects



A – Control of the tested surface of mother plate.
B – Details of defect zone.

details of the position and the shape of any defect (Figure 3-27).

This information can provide, directly on-line, an evaluation of plate quality according to the usually employed standards (SEL 072, Euronorm 160, ASTM A 435, ASME SA 578), individually for each customer plate within the mother plate. The results are stored on magnetic tape.

Future developments will initially consist of a centralized system of direct graphic display, later to be extended to the possibility of individual processing of the parameters of a specific channel.

Another project (63) carried out a fundamental study for the industrial inspection of the surface of heavy plate using electromagnetically-induced eddy currents (EMA).

The sensor head was optimized for sensitivity, frequency, axial precision, wear resistance, and compact size. It was able to detect defects that were 0.3 mm deep, 10 mm long at a distance of 300 mm.

Advanced processing of the ultrasonic signals meant that external factors were diminished while defects were pinpointed and described.

The ALOK 4 (Amplituden, Lufzeit-Orts-Kurven: i.e. amplitude, transit time, position and curves) prototype in combination with the EMUS system for processing eddy currents and with an optimized sensor head were employed with success in the laboratory and in individual tests under industrial conditions.

These fundamental principles should lead to the development of automated systems for surface inspection of heavy plates.

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(29) EUR 13113 DE 1990 — MPI: 'Einfluß der Warmumform- und Abkühlbedingungen von Warmband auf das Umwandlungsverhalten perlitischer Stähle zum Kaltumformen'.

(30) EUR 12724 FR 1989 — CRM: 'Précipitations induites par la déformation à chaud au train finisseur'.

(31) 7210-EA/321 — Irsid: 'Amélioration de l'uniformité des bandes laminées à chaud'.

(32) EUR 13620 DE 1991 — Thyssen: 'Aufstellung von Regressionsgleichungen zur Beschreibung des Umwandlungsverhalten beim thermomechanischen Walzen'.

(33) EUR 13935 DE 1991 — Thyssen: 'Metallkundliche Auswirkungen von Energiesparmaßnahmen im Bereich des Warmbandwerkes auf die Eigenschaften von kaltgewalzten Stählen'.

(34) 7210-EA/416 — CSM: 'Aspetti metallurgici della laminazione diretta'.

(35) 7210-EA/213 — CRM: 'Valorisation de la bande à chaud par un traitement thermomécanique en continu'.

(36) EUR 6927 DE 1980 — MPI: 'Thermische Gestaltänderungen von Arbeitswalzen und ihre Ausnutzung zur Steuerung oder Regelung der Planheit beim Kaltwalzen von Band'.

(37) EUR 7755 FR 1982 — CRM: 'Les variations thermiques du bombé des cylindres d'un train tandem à froid'.

(38) EUR 7403 IT 1982 — CSM: 'Set-up autoaddativo di un treno a freddo'.

(39) EUR 11680 IT 1988 — CSM: 'Controllo dinamico del regime termico di un treno tandem a freddo'.

(40) EUR 9083 DE 1985 — Hoesch: 'Regelung der Zugspannungsverteilung und der Planheit an einer Kaltwalztandemstraße für Fein- und Feinstbleche (Phase III)'.

(41) EUR 13338 DE 1991 — VDEh/BFI: 'Untersuchung der Einbau- und Betriebsbedingungen von Planheitsmeßsystemen an Kaltwalzanlagen'.

(42) 7215-EA/104 — Krupp: 'Flatness control in closed loop'.

(43) EUR 9083 DE 1982 — VDEh: 'Regelung der Planheit und der Zugspannungsverteilung an einem 20 Rollen- Kaltwalzgerüst (Phase I)'.
EUR 9083 DE 1984 — VDEh: 'Untersuchung zur Beeinflussung der Bandebenheit an einer Streckbiegerichtanlage (Phase II)'.

(44) 7210-EC/101 — VDEh: 'Einflußgrößen beim Streckbiegerichten'.

(45) EUR 12983 DE 1991 — VDEh: 'Untersuchung der Bandverformung in Spannrollen Sätzen'.

(46) EUR 13628 EN 1992 — Hoogovens: 'Shape and profile throughout the strip mill processing line'.

(47) 7210-GF/306 — Irsid: 'Mesure du profil transversal d'épaisseur des bandes'.

(48) EUR 7601 FR 1981 — Irsid: 'Étude des phénomènes métallurgiques et mécaniques lors du skin-pass'.

(49) 7210-EC/302 — Irsid: 'Optimisation métallurgique de l'opération de skin-pass'.

(50) 7210-EC/301 — Irsid: 'Réglage d'un train tandem couplé'.

(51) 7210-GB/302 — Sollac: 'Contrôle en ligne de la qualité de surface des tôles laminées à chaud'.

(52) EUR 8686 EN 1984 — British Steel: 'Advancement of surface inspection instrumentation for cold rolled steel strip'.

(53) EUR 10767 DE 1987 — VDEh: 'Weiterentwicklung und Betriebseinsatz eines Prüfungsystems zur Erfassung von Oberflächenfehlern'.

(54) 7215-EA/402 — CSM/UACG: 'Automatic surface inspection of stainless steel strips'.

(55) 7215-EB/931 — Ensidesa: 'Expert multisensorial system for quality control of cold strip moving at high speed'.

(56) EUR 9427 FR 1985 — Irsid: 'Amélioration de la mise au mille lors du laminage des tôles épaisses par contrôle des extrémités des produits'.

(57) EUR 11457 FR 1988 — Arbed: 'Fabrication de tôles moyennes et fortes à haute limite d'élasticité par le procédé QST'.

(58) EUR 8591 FR 1983 — Irsid: 'Étude d'un dispositif d'équilibrage à pression variable permettant une contre-flexion des cylindres de travail en tôlerie forte'.

(59) EUR 12016 FR 1988 — Irsid: 'Planage à chaud des tôles fortes'.

(60) EUR 12506 DE 1990 — Dillinger Hüttenwerke: 'Optimiertes Warmrichten von Grobblechen'.

(61) EUR 9062 DE 1984 — IZFP: 'Die Bewertung von Grobblechen nach Ultraschall- Prüfergebnissen und Liefervorschriften mittels elektronischer Datenverarbeitung'.

(62) EUR 10751 DE 1987 — IZFP: 'Qualitätskontrolle durch automatische Ultraschallprüfung von Grobblechen im Produktionsfluß'.

(63) EUR 12415 DE 1990 — IZFP: 'Prüfung der Oberflächen von Grobblechen mittels elektromagnetisch erzeugter Ultraschallwellen'.

Introduction

Within the ECSC research programme, collaborative research activities have been rapidly developed in those fields which have become of increasing importance over recent years: environmental concerns, industrial health and safety, ergonomics and industrial medicine.

It is important to emphasize that by virtue of the objectives of the policies of European collaboration, the Commission of the European Communities has endeavoured to promote concerted research between different teams of researchers throughout the Member States. As is the case for those fields involving the manufacture and treatment of steel dealt with in the previous chapters, these research projects enable researchers and users alike to concentrate their work effort, and become accustomed to working together on the same sites and to pooling technology and ideas.

4.1. Environment

The technical battle being waged by steel manufacturing plants against nuisances created on site and in the environment has been based on four multiannual research programmes, the results of which have contributed greatly to protecting the environment and improving working conditions. The year 1990 is situated in the fifth research programme.

The first three research programmes were aimed principally at controlling atmospheric pollution, developing methods of measuring the pollutants and improving certain areas of work.

The first two research programmes (1964-73) looked mainly at the problems of atmospheric pollution.

The rapid extension of oxygen-based steelmaking then oriented research work towards the struggle to eliminate the emission of red fumes from the converters.

The third research programme (1974-78) (1) covered the problems of solid waste and liquid discharges.

The financial help supplied was able to help in promoting the work involved, mainly in those establishments or institutions which were directly connected with the steel industry. This system of promotion meant that results were rapidly translated into practical solutions, which had a marked effect upon environmental protection, especially in the neighbourhood of steelworks, and upon working conditions within the plant.

The fourth programme (1979-83) (2), in view of the evolution of the technologies concerned, had to confront new problems. Through increased funding, the programme was able to encourage research not only into all the domains described above, but also into those of noise, studies of environmental impact and health at work. This fourth programme has been based upon the recommendations of the Commission of the European Communities and in particular the following four points:

(i) to improve working conditions;

(i) to satisfy the requirements of the administrative authorities;

(iii) to maintain the competitive nature of companies, and as a result to maintain employment;

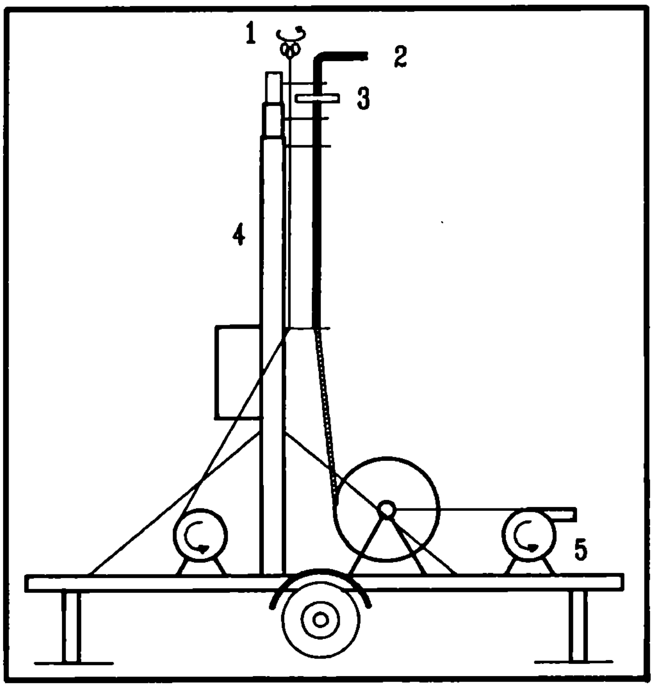
(iv) to economize raw materials and energy.

In total, some 82 research projects were funded under this programme. The research topics were selected according to their chance of success in providing practical solutions. A summary report has been published (3).

The fifth research programme (1984-92) has continued with the concerns of the preceding programmes and has also taken account of the new problems caused by the evolution of manufacturing technologies and by the increase in regulatory constraints. Emphasis has been placed on nine objectives:

(i) conformity with the objectives of the European Communities, especially with Community directives;

Figure 4-1a
Diagram showing principle of sampling equipment



1 – Anemometer. 2 – Sampling nozzle. 3 – Filter holder.
4 – Mast. 5 – Pump.

Figure 4-1b
Photograph showing equipment installed at Sollac-Fos

(ii) research into efficiency, safety in operations and reliability of pollution removal installations at optimal cost;

(iii) promotion of energy and raw materials savings;

(iv) fight against pollution transfers;

(v) development of 'clean' technologies;

(vi) improvement in water-treatment techniques;

(vii) development of waste handling and dumping techniques, providing an improved environment;

(viii) actions involving manufacturing processes;

(ix) application of progress made in the fields of new technologies (biotechnology, robotics, techniques of information dissemination).

The themes to be investigated are:

(a) air pollution, including nuisance caused by odour, in both working conditions as well as external pollution;

(b) pollution of fresh and marine waters;

(c) waste;

(d) acoustic nuisances, including the risks of work-induced deafness;

(e) metrology.

The fact that these different nuisances are listed separately does not mean that these problems should not be attacked together on the factory floor. Avoiding the transfer of pollution from one milieu to another must be a part of all research and development work as well as being incorporated into the design of industrial installations.

4.1.1. Air pollution

The fight against air pollution has been continued through research projects covering the following subjects:

(i) the reduction in emissions of dust, sulphur oxides, nitrogen oxides, heavy metals and organic compounds;

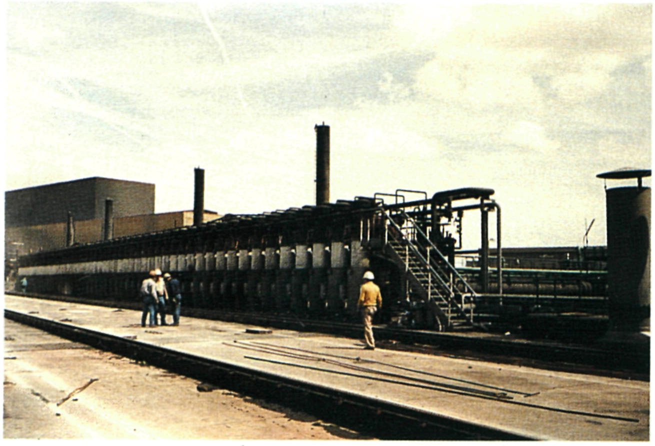
(ii) the elimination of odours;

(iii) the retention and treatment of diffuse emissions from cokeworks, blast furnaces and steelworks;

(iv) the elimination of dust creation during handling, transport, preparation and storage operations in raw materials' storage areas and waste tips.

Figure 4-2
Charging an old coke oven

Figure 4-3
General view of the floor of a modern coking plant in operation



As an example, the system used by Sollac-Fos for taking samples of emissions given off from coal tips is shown in Figures 4-1a and 4-1b.

Among the more remarkable results, the following examples can be cited:

(a) *The control of polluting emissions from iron-ore sinter works has been studied by CSM, Leces, CRM and Mannesmann* [(4) to (11)]

The tests carried out by CRM (9) have led to the improvement of dust removal from sintering flue gases by the industrial application of digital controllers which allow the fields of the electrostatic filters to be supplied with intermittent power and counter-ionizations to be controlled.

A Leces research project (10), still being carried out under the fifth programme of research (Phase II), investigated a pilot installation of bag filters fitted with a pre-coating of lime which should provide comprehensive dust removal and simultaneous sulphur removal of the sintering flue gases, to ensure full compliance with future legislation.

(b) *The fight against polycyclic aromatic hydrocarbon (PAH) and nitrogen oxide emissions from coke plants*

The theme of PAH emissions was treated from the point of view of metrology under the fourth ECSC programme. Tests were carried out on new models of coke oven doors. It is a known fact that these doors constitute a major source of PAH emissions.

This work was coordinated between several countries and the same approach has been adopted for the fifth programme, with the participation of:

(i) Bergbauforschungsinstitut (BBF) in Essen (Germany);

(ii) Ensidesa in Avilés (Spain);

(iii) Laboratoire d'étude et de contrôle de l'environnement sidérurgique (Leces) in Maizières-les-Metz (France);

(iv) Coal Products Ltd (CPL) in Wingerworth (United Kingdom).

The significance of this work is demonstrated by the results obtained in German coke plants for benzo(a)pyrene.

Figures 4-2 and 4-3 compare several remarkable results between modern, clean coke plants in operation, which have undergone technological modifications on the basis of ECSC research work, and old-fashioned coke plants.

Research work undertaken by BBF and Marienau has made it possible to define the influence of various heating and coke oven design parameters on emissions of nitrogen oxides, with the result that there has been improved control of polluting emissions on an industrial scale.

(c) *The elimination of emissions of nitrogen oxides from reheating furnaces*

Continuing coordinated research into nitrogen oxides within the framework of the fourth ECSC programme of research, the Centro Sviluppo Materiali (CSM) in Rome has studied parameters governing the emission of nitrogen oxides during reheating of products to be rolled in a pilot furnace with a power rating of 2 MW installed in Genoa (12) and has issued some practical recommendations concerning burner design for low levels of NO_x production. More recently, British Steel has also undertaken research on this subject with the aim of furthering the necessary industrial understanding in this field.

4.1.2. Water pollution

The fight against fresh and marine water pollution has been based on four themes:

(i) treating coke plant effluents;

(ii) treating rinse water from gas scrubbers such as those for the blast furnace flue;

(iii) treating waste water from rolling mills;

(iv) trapping heavy metals present in waste water from surface treatment.

The most remarkable results on an industrial scale are undoubtedly those obtained during treatment of coke plant effluents. The combined efforts of British Steel, BCRA, DSM, CRM, Cebedeau, CSM, IRH [(13) to (22)] have made it possible to design biological purification installations which are capable of providing very high levels of purification, including nitrification-denitrification. Priority in research projects forming part of the fifth research programme is currently assigned to the elimination of organic micropollutants and to the tertiary treatment necessary to comply with increasingly severe legislation.

Another field in which great progress has been made on an industrial scale is in treating rinse water from blast furnace gas scrubbers. The results of research work carried out by IRH-Cebedeau-CRM [(22) and (23)] on removing cyanides and formaldehydes are already being used industrially.

IRH (24) has also developed a novel technique for removing oil from hot-rolling mill waste water consisting of a particularly efficient pre-treated sand filter, which has been granted a European patent.

4.1.3. Solid waste treatment

Research into solid waste treatment has been aimed at three main topics:

(i) the promotion of cleaner technologies, producing less waste;

(ii) the increased recycling and utilization of waste products, as raw materials or energy sources;

(iii) the organization of the destruction, neutralization and controlled tipping of toxic wastes.

Obviously, the ideal solution is to avoid, or reduce as much as possible, the production of waste at its source. Nevertheless, it has to be recognized that actions taken in the field of 'cleaner technologies' still remain modest.

Waste water from coke plants contains ammonia, phenols and other toxic products, and poses particularly acute problems of disposal. One of the objectives of the ECSC coke plants research programme which was investigated by a series of projects [(25) to (28)] was to develop a coke plant without any waste, producing solely commercial materials and water that is sufficiently clean to be recycled industrially. With this aim in view, an incinerator in which the raw coke oven flue gas, laden with tars, can be burnt under sub-stoichiometric conditions was developed which is capable of producing a clean gas composed only of carbon monoxide and hydrogen, which can in turn, be used for the synthesis of organic chemicals.

Another vital field of research is found in pickling baths. The development of the ugine peroxy pickling process (UG 3) for pickling alloy steels, without using nitric acid, is an excellent example of a technological development which reduces waste at the source (29). Compared to conventional bi-acidic (nitric-hydrofluoric) baths, the improved environmental impact of the mono-acidic bath (hydrofluoric-hydrogen peroxide) is considerable: lack of nitrate in the waste water, elimination of nitrous vapours in the work area, reduction in the number of treatment baths required.

Classic market forces often lead to the conclusion that it is financially more interesting to dispose of a waste product on a waste tip than to try to make use of it.

It is certain that the increasing ecological constraints are slowly eroding this concept. Nor should it be forgotten that tipping of dangerous waste products will be forbidden in the immediate or near future.

Under these conditions, recycling and utilization become more and more attractive. In steelmaking, ferrous dusts and sludges which are rich in heavy metals (Cr, Ni, Mo, Zn, Pb) and oil are particularly concerned by this problem. A study by BFI (30) in 1988 made an extensive inventory of processes that were of interest in this domain.

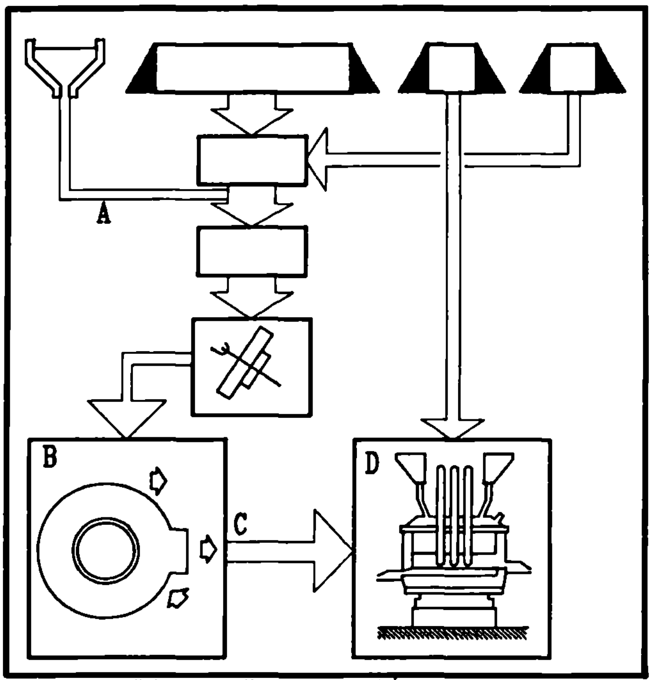
In this field special mention should be made of some of the ECSC research carried out:

(i) On an industrial development scale, the hydrometallurgical process by Cebedeau [(31) and (32)] based on sodium leaching of Zn/Pb-rich dusts. Unfortunately, news received from the SERH plant at Saint-Florentin, with a capacity for treating 12 000 tonnes per year of dusts from electric steelworks, indicates that the process has not been able to survive under the current economic situation.

(ii) On an industrial demonstration scale, the Tetronics [(33) and (34)] electrochemical process based on plasma smelting-reduction of Cr/Ni-rich dusts. An installation with a capacity for treating 8 000 tonnes per year of dusts from electric steelworks and AOD has been constructed by British Steel Stainless near Sheffield (35).

Two other major demonstration projects should be mentioned. The first (36) concerns a pyrometallurgical process (Inmetco process) for treating all recycling materials from steelworks' processes. It is based on the principle of pelletization and direct pre-reduction on a rotary hearth (Figure 4-4). A feasibility study of the process was undertaken by Eisenhütte Südwest-Saarbrücken.

Figure 4-4
Beneficiation of iron-rich waste by the Inmetco process (200 000 t/year)



A – Green pellets preparation: 330 000 t/year.
B – INMETCO rotary hearth furnace.
C – DRI pellets (900 °C): 200 000 t/year.
D – Iron-smelting electric furnace: 200 000 t/year hot metal, 60 000 t/year slag.

The second, starting from a concentrate of the lead- and zinc-rich fraction of blast furnace sludges mixed with fine steelworks' dusts, is aimed at driving off the volatile fraction from a circulating fluidized bed. The residual material can be recycled through addition to the sinter mix. A pilot plant with a capacity of 20 000 tonnes per year, based on this principle, is to be commissioned in 1991 in the region of Duisburg.

(iii) concerning oily residues, British Steel (37) has tested various techniques for recycling oils from stainless-steel rolling-mill scale on a small pilot plant. Vaporization under a vacuum or inert atmosphere was shown to be technically possible but the recovery operation did not appear to be economically viable under current market conditions, especially when compared to destructive techniques such as direct injection into electric furnaces. CSM (38) looked in greater detail at the treatment of scale dusts and oily sludges. Various recovery processes for the metallic fraction were evaluated on a small pilot scale in the ILVA plants. It is intended to burn off the oily fraction. Large-scale projects are currently under evaluation.

In techniques involving internal destruction and neutralization of waste, mention should be made of the CRM-Cebedeau-Sidmar (22) research which, on the basis of tests carried out on a semi-industrial scale, defined a method for the destruction of biological coke plant sludges by reinjection, after suitable treatment, into the coke ovens. An IRH (39) research project investigated the possibilities of neutralizing toxic oily wastes before dumping, especially by suitable treatment based on the use of lime.

In waste dumping, the major pollution risk lies in leaching by water and a good understanding implies that priority be assigned to comprehending the interactions between water and the waste product, on the one hand, and between the leached liquor and the substrate, on the other. Many projects have been devoted to this subject.

The projects [(40) and (41)] by IRH and by Creusot-Loire [(42) and (43)] have investigated a wide range of steelworks' wastes.

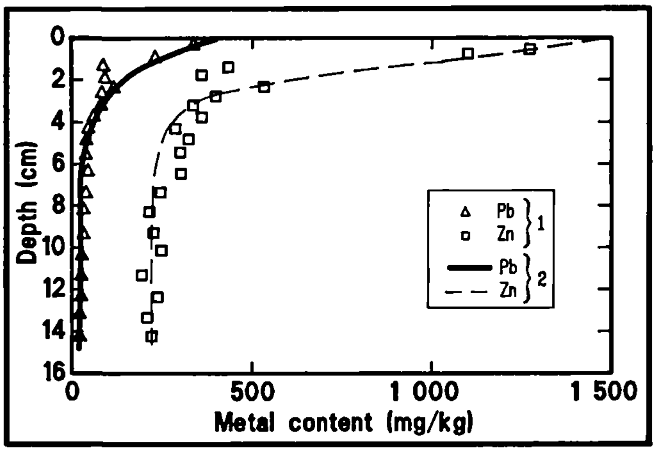
The Leces (44) and the Universität Fredericiania zu Karlsrühe (45) went a step further in attempting to understand the behaviour of waste in tips. The Leces aimed to study the concept of tipping waste in alternating layers with the intention of reciprocal neutralization and fixing of heavy metals. The University of Karlsrühe examined the capacity for retention of metals in various soils and adapted available models of diffusion (Figure 4-5).

There is no doubt that the information that will gradually become available over time will serve as the basis for establishing a 'guidebook' for the rational management of steelworks' tips.

4.1.4. Noise pollution

In the fight against noise, several very successful projects on sound insulation should be mentioned. For example, casing of electric arc furnaces constitutes, where practicable, an efficient method for reducing noise at work sites in the electric steelworks. This was demonstrated by a project undertaken by the

Figure 4-5
Behaviour of Zn and Pb on discharge site



1 – Theoretical. 2 – Experimental.

Betriebsforschung Institut (BFI) (46) with reductions in noise levels of the order of 110 dB(A) by:

(i) 3 dB(A) inside the casing, and

(ii) 18 dB(A) on average outside the casing and within 1 metre of it.

Research efforts directed at perfecting methods of predicting sources of noise pollution and their reduction, specific to steel production, were undertaken by Leces (47) and Cedia (48).

4.1.5. Metrology

In the field of metrology, several projects which were applied industrially should be mentioned. Such a case is the automated operation of coke plant waste water stripping columns based on on-line measurements of ammonia by British Steel, and on-line weight determinations of dust emissions in flues by CRM (9).

Another remarkable project in this field was the control of the energy consumed by dust-extractor fans in the electric furnace bay through the use of a long-distance opacimeter developed by British Steel (49).

Various studies are still under way concerning the measurement of the radioactivity of raw materials and scrap, especially at BFI and British Steel.

4.2. Utilization of by-products

4.2.1. Utilization of blast furnace and BOF slags

The inevitable by-products resulting from the production of hot metal and steel are the blast furnace and BOF slags which represent considerable annual tonnages: in the European Community blast furnace slag production reached 25 million tonnes per year, and production of BOF slag some 8 million tonnes.

This only serves to emphasize the importance of the reuse and utilization of these by-products, now more accurately designated by the term co-products.

A further important reason which requires these co-products to be taken into consideration lies in the desire to maintain the quality of the environment and its appearance.

A major research programme supported by the ECSC, which grouped together some 15 projects concerning the use of blast furnace and BOF slags in civil engineering activities, terminated in 1987.

A technical 'Information Day' held in Liège in 1988 was specifically dedicated to this theme. Several examples of results are summarized below, while for a more complete appreciation of the work achieved in this sector, the reader should refer to the proceedings of this 'Information Day' (50).

In general, it can be stated that blast furnace slag does not present many problems, in view of the wide range of products: raw or crushed crystalline slag, expanded forms, slag wool, granulated or crushed slag. This does not, however, mean that improvements cannot be made.

4.2.2. Projects concerning self-hardening foundations

This subject covers a type of road sub-base treated with vitrified blast furnace slag, which has been researched and used in several European countries (France, Germany, United Kingdom, the Netherlands, Belgium), but with certain variations in composition.

Figure 4-6
Highway graders laying a gravel-slag course on the A31 motorway in France

In France, the first country to use this technique of gravel-slag mixes for road sub-bases (500 million tonnes of material treated with blast furnace slag up to 1990), the work was carried out by the Centre technique de promotion du laitier de haut fourneau (CTPL), and the Laboratoire central des ponts et chaussées. Using a summary crushing of the slag (known as the pre-crushed slag technique), the efficiency was greatly enhanced, thus allowing the quantity of slag that needed to be incorporated into the gravel-slag mix to be cut by half and replaced with sand that could not be used for any other purpose (51) (Figure 4-6).

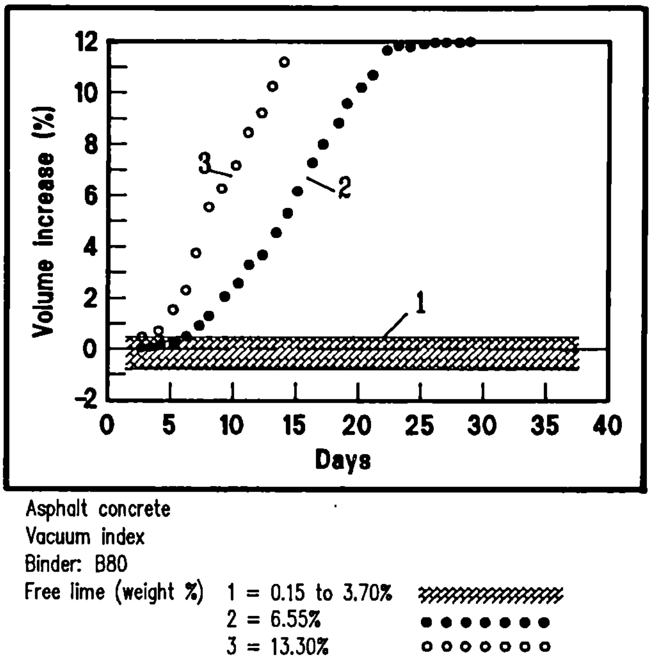
As a consequence, the use of the gravel-slag technique was able to be extended to up to 900 km from the blast furnace site, instead of the previous 300 km maximum.

In Germany, with the FGHS, preference was given to similar gravel-slag mixtures but which contained solely blast furnace slags (80% crushed, 20% vitrified) and without the addition of lime (52).

In the United Kingdom with British Steel, and in Belgium with CRM, the development of mixtures containing BOF slag for which various end-uses were being sought was pursued, the composition being different in the two countries (53).

These examples show that starting with a technique inspired by one partner, at least four other categories of new mixtures promoting the use of other by-products were able to be developed, which, in turn, provided great flexibility in their use.

Figure 4-7
Volume increase as a function of ageing time in air and the percentage of free lime



4.2.3. Projects involving other applications — civil engineering, agriculture

In the field of the utilization of blast furnace slag in cement manufacture, a Usinor project demonstrated the favourable influence of basicity, and alumina, while titanium oxide can pose problems if ilmenite is present in the blast furnace burden (54).

ECSC projects involving the use of BOF slag have meant that it can be used as an effective material in various civil engineering techniques such as backfilling, embankment protection, road surfacing and even in hydraulic concretes.

These projects have been undertaken with close collaboration between FEHs, British Steel, CRM, Usinor and Laitiernor, and the Roads and Bridges Department in France [(55) to (63)].

The BOF slag itself contains a variable quantity of free lime which expands when hydrated. The critical question that arises when BOF slag is to be used as fill in replacing natural fill materials, concerns its dimensional stability.

Currently, it can be demonstrated that slags containing up to 7% of free lime can be sufficiently stable to be employed in most techniques involving normal conditions of use (Figure 4-7). Research projects examined simple and economical ways of ensuring the lowest possible levels of free lime.

Experiments were carried out on several different methods: modifying oxygen converter refining operations, treating the liquid slag in the ladle, ageing on the crushed slag tip.

The technique of ageing on the slag tip followed by a dimensional treatment is the one that is the most used. In particular, it has meant that BOF slag has been able to be employed in road construction techniques which have been developed on the basis of large-scale practical trials.

Systematic and coordinated trials have been directed at the dimensional stability of a large range of slags, the establishment of physico-chemical models of free lime, the development of rapid tests to measure expansion, the comparison of experiments, the influence of MgO content, etc.

Research continues into the comparison of results obtained from laboratory experiments on the stability of BOF slags and their behaviour in practice (64).

An FEHs project, which followed on from previous research by the same organization, studied in detail the risk of pollution of water percolating through blast furnace and BOF slags that had been used as backfill. These studies were based on both laboratory experiments and a full size backfill which incorporated measurement sensors (65).

The results were clear: the only modification observed was a slight increase in the pH of the water, easily neutralized by the action of the CO_2 in the air and the acidity of rainwater.

Concerning heavy metals, the trace levels that were sometimes detected were always below the levels permitted in Germany, and were due more to the rainwater itself than from its passage through the blast furnace or BOF slags.

This project is of particular interest for the use of slag in civil and hydraulic engineering projects.

BOF slags with a high lime content can be an excellent material for use in the campaign against the de-acidification of soils and in keeping them within the range of values which promotes biological activity.

The phosphorus contained in these slags also provides a positive constituent as a fertilizer.

A large ECSC programme has commenced involving three projects [(66) to (68)] to examine the use of blast furnace and BOF slags in agriculture and forestry. It is hoped that additional uses for these slags will be found, while at the same time their use will have a positive environmental impact, and also provide a remedy against acid rain.

4.3. Social research

4.3.1. Health at work

The domain concerning health at work has the same objectives as for the environment, with priority in:

(i) air pollution, in terms of health protection;

(ii) noise and the resulting risk of work-related deafness.

Research involves the following methods:

(a) laboratory studies,

(b) metrology,

(c) pilot installations,

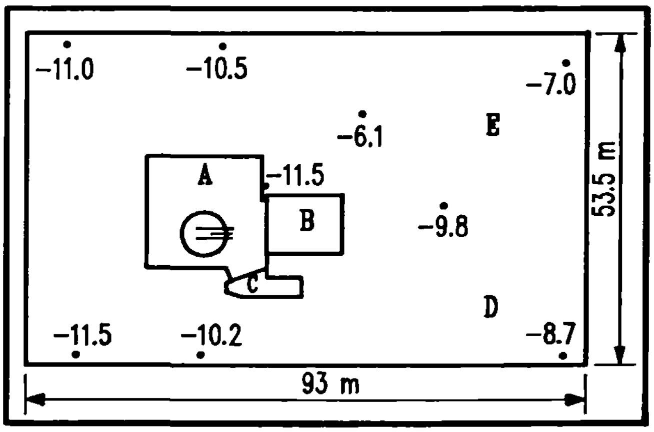
(d) plant experiments,

(e) modelling of the results obtained,

(f) industrial developments.

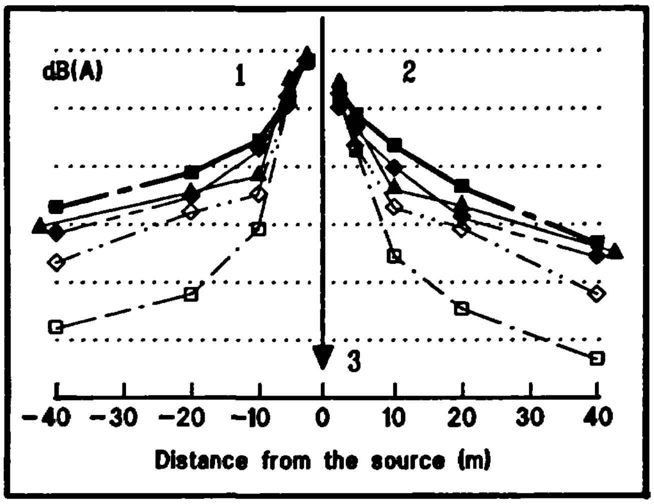
Figure 4-8 shows the decrease in noise levels in an electric arc furnace shop through the use of a casing around the furnace, as described in a previous chapter.

Figure 4-8
Decrease in noise levels (dB) through the use of an electric arc furnace casing



A – Caisson. B – Transformer. C – Control room.
D – Ladle preparation. E – Continuous casting.

Figure 4-9
Comparison of noise reduction techniques on a rail cooling line



1 – Rolling mill side.
2 – Fan side.
3 – Source.

■ Initial state.
◆ Absorbing ceiling.
□ Screen 6 m + absorbing ceiling.
◇ Absorbing screen 6 m.
▲ Reflecting screen 3 m.

Figure 4-9, concerning a rail cooling line, demonstrates the potential improvements offered by various sound insulating techniques.

4.3.2. Safety in steelworks

Safety in the workplace constitutes an essential element in the social pollution programme. A pluriannual research programme set up in the 1980s directed its efforts mainly at the steel manufacturing sector in studying the repercussions of technological changes, especially in continuous casting operations. In 1989, the Commission set up the first joint programme for safety matters in the ECSC industries where the specific and general requirements of the mining and steelmaking industries had been defined (69).

Safety in steelworks requires that the whole of the workforce achieve increased awareness, a major task for each of the work areas.

Technological developments in the field of hot metal production have been put into practice through extensive automation of blast furnace operations. As a consequence, the reliability of the various technical systems as well as the training of personnel, during which they should be made familiar with the different production processes and the risks involved, must be made the subject of preventive research.

The profound changes in technologies and processes employed in steel production have resulted in the problem of potential risks involved in hot metal and steel production being pushed down the line to secondary steel metallurgy operations and on to the site of continuous casting operations. The types and the possible occurrence of risks run by the personnel are the subject of intensive research efforts. Automation and remote control of operations have meant that safety and the repeatability of operations has significantly improved.

Competition in the domain of hot- and cold-rolled products has resulted in even more high performance installations being set up in order to increase competitiveness. In the light of these complex technological changes which have occurred in the cycle of operations, the planned actions are oriented towards incidents involving personnel, in which automation and computer control of rolling mills is implicated, from a safety point of view.

If we compare the finishing shops with other traditional sectors of steel manufacturing, we note that, despite attempts to mechanize, these shops continue to employ a greater workforce than the average for other steel manufacturing shops. Furthermore, simultaneous operation of traditional and automated activities, the diversity of these activities, and the noise produced can increase the risk of accidents. These can only be avoided by setting up major safety schemes which are totally coordinated with the techniques and organization of the work involved.

In the framework of the technical evolution of steel manufacturing operations, the maintenance services hold a key position. Their contribution in the campaign to reduce the accident and health risks is continuously increasing. This is true not only for the safety of the maintenance personnel themselves, but also for the workforce employed in the extremely diverse production sectors. When designing equipment, care should be taken, over aspects of industrial health-care and accident prevention, that optimal conditions for control and maintenance of the equipment are incorporated. Furthermore, particular attention should be paid to permanent training and refresher courses for the maintenance personnel, as well as to the planning and organization of maintenance operations.

4.3.3. Research programmes into ergonomic aspects

Since 1980, the Commission has funded several programmes of applied research in the field of ergonomics in the coal and steel industries. For the 1985-89 research programme (70), the Commission allocated ECU 15 million for carrying out ergonomic studies on the basis of financing assured by itself and the co-contractors. These credits have now been entirely allocated.

The programmes in question are aimed at promoting improvements in the health and safety of personnel in the ECSC industries by defining criteria:

(i) for an integration of human factors which are critical in technological systems in reducing health and safety risks;

(ii) for protection against the sometimes physically hostile environments encountered in the two sectors concerned.

During the period covered by these research programmes, the steel industry has been subject to wide-scale rationalization and restructuring, particularly through the introduction of new computer and automation techniques. New installations have been able to incorporate the relevant ergonomic factors based on the exploitation of the results of previous work and the rapid adoption of applied research projects in the following fields:

(a) continuous casting installations;

(b) wide strip mills;

(c) strip pickling and cold-rolling mill installations;

(d) annealing lines;

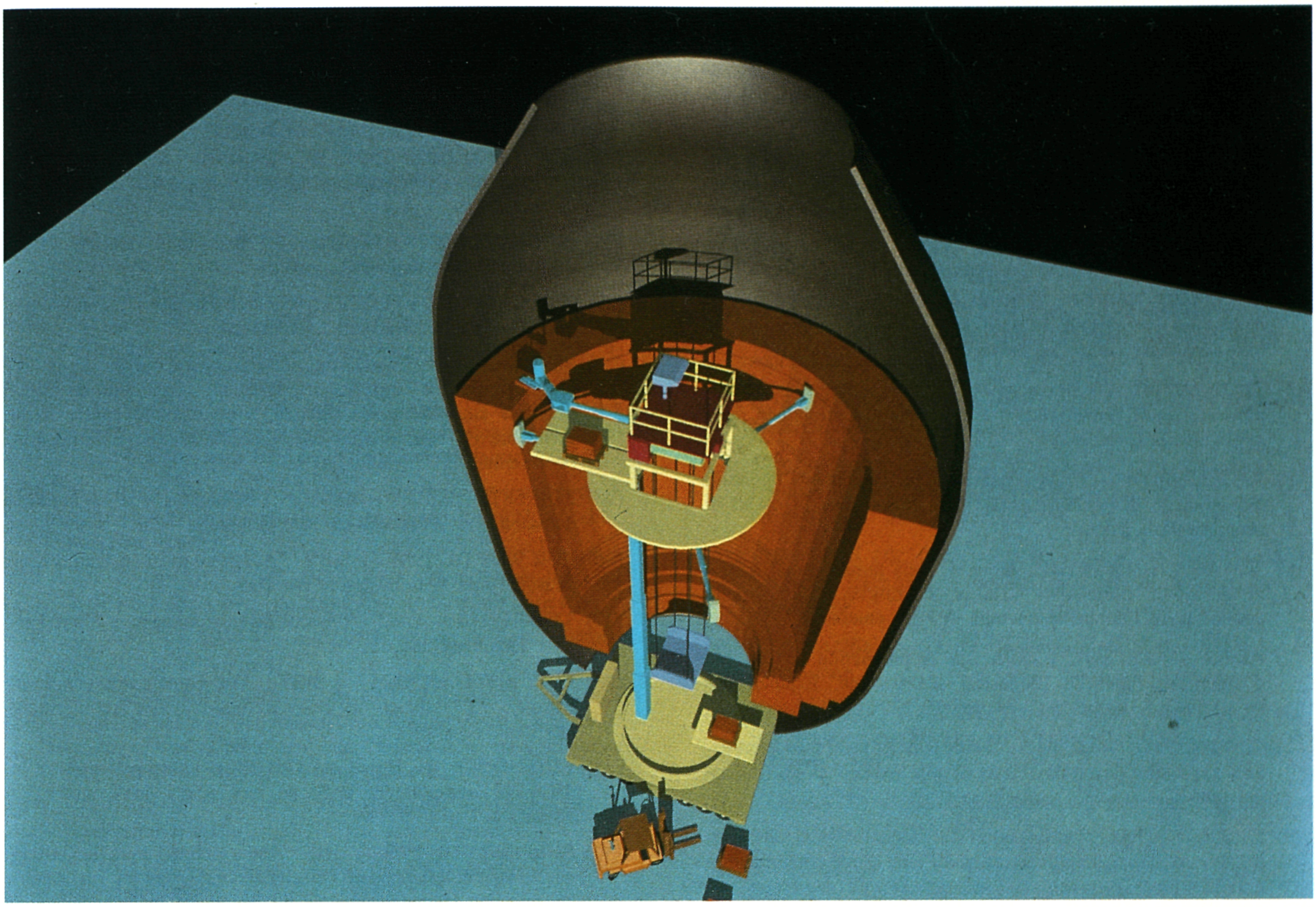
(e) finishing lines.

In other cases, the human factors to be taken into account in design of systems have only become apparent after the installations have been commissioned, even though, once again, efficiently run projects have been able to supply full details of suitable modifications and have provided all the data necessary for improving future designs.

As an example, the automated, remote-control system for controlling the operating conditions of a strip mill has benefited from this approach. In another plant, safety aspects of a computer system for managing rail trucks were improved.

In the second part of the programme, the same approach was applied to technology to be adopted by the steel industry at the beginning of the 1990s. Equally satisfactory results in modern technologies such as combined man-robot or remote-control systems can be expected. These systems are usually intended to replace human effort in carrying out

Figure 4-10
Automatic brick-laying robot for oxygen steel converters at Arbed



boring or dangerous tasks while still maintaining control by a human operator through the use of assisted controls. Such tasks include:

(i) demolition of refractory linings in converters;

(ii) relining converters;

(iii) handling steel products;

(iv) inspecting and cleaning pipelines transporting gaseous by-products of the steel industry;

(v) integrated quality control systems.

As an example, Figure 4-10 shows the automatic robot for refractory relining in oxygen steel converters, which is being developed by Arbed.

The results of these programmes have been diffused throughout the Community as well as on an international scale. For the ECSC, a network of Community ergonomic action based on national ergonomic groups and a central coordination and information unit has been able to rapidly diffuse these results in suitable forms such as manuals, recommendations and reports, European conferences and national information days.

4.3.4. Industrial medicine

The first three programmes (1955-81) of medical research were mainly aimed at the study of lung and respiratory tract ailments in miners and steelworkers.

The fourth (71) and fifth (72) programmes, while still assuring the logical continuation of the primary objectives of the preceding programmes as a function of scientific progress, were characterized by an obvious desire for diversification to include further pathologies.

In particular, we can cite, for the fourth programme, the attention directed towards:

(i) cancerous infections, their early detection and the research into carcinogenic materials in industrial pollution;

(ii) epidemiological, biological and functional research into high-risk operations for workers in the steel industry and coke plants.

Within the framework of the fifth programme, these preoccupations have been extended to ailments of the locomotor system and the protection of workers against the effects of noise.

It should also be noted that the fifth programme further emphasized the intention to promote the practical application in the workplace of the results of scientific research.

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Introduction

Research projects concerned with the promotion of steel cover wide areas in which steel products are used. These fields will serve as the guidelines for this chapter and are identified as follows:

(i) boilermaking and constructional steelwork;

(ii) construction industry;

(iii) mechanical engineering;

(iv) electrical engineering;

(v) automobile bodywork;

(vi) packaging.

Some research projects cover several fields of application at the same time. For example, German steelmakers have united to examine the influence of continuous casting on the characteristics of utilization of the different types of products and different grades of steel that can be produced by this process, in order to answer the preoccupations of certain constructors and approval organizations over the possible presence of a central zone in the metallographic microstructure of steels [1] (Figure 5-1). This is also the subject of certain basic research work.

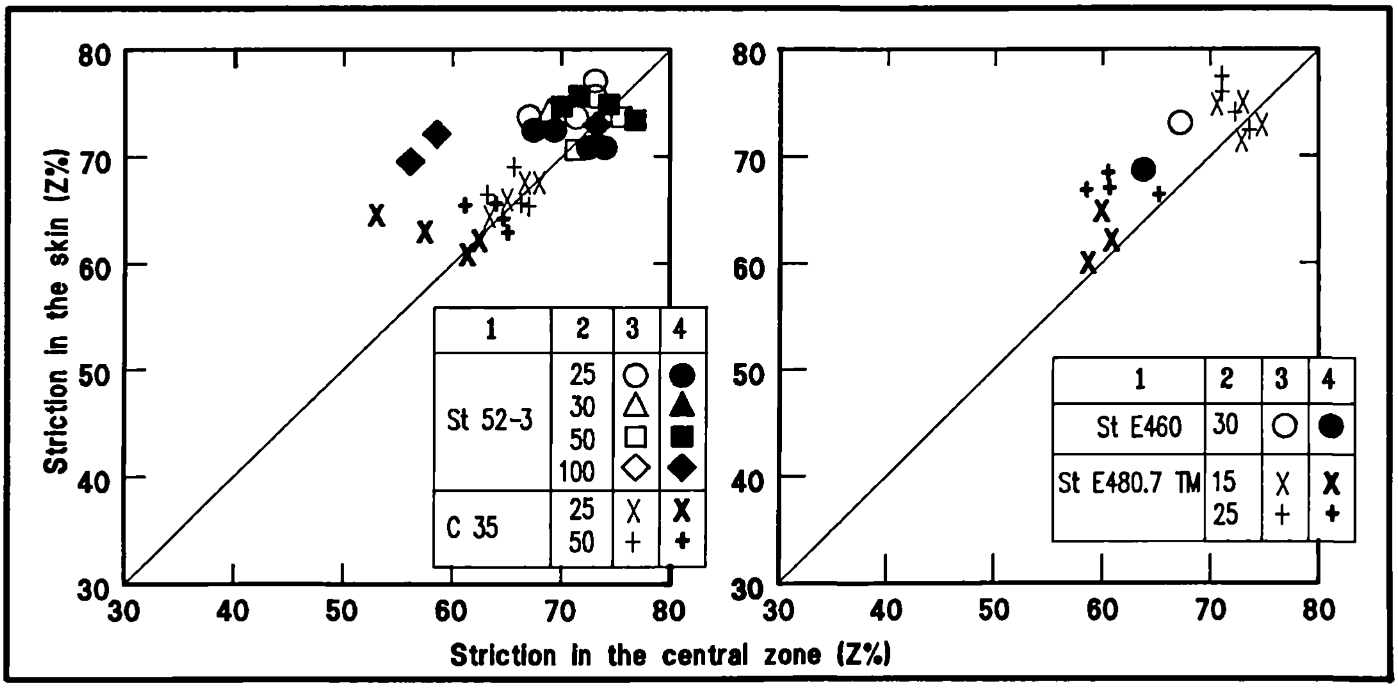
It is not possible to describe each research project as there are over 260, but a very large sample has been taken in order to demonstrate their activities, their spirit and their purpose.

It should also be noted that in each field the subjects have been regrouped according to whether they concern the use of steel, its in-service behaviour and the relations between their properties for use and what are termed metallurgical factors which result from the conception and production of steel products.

[1] EUR 10339 DE 1981 — VDEh: 'Einfluss der Seigerungen bei Strangguss auf die Werkstoffeigenschaften

Figure 5-1

Influence of continuous casting on mechanical properties: comparison of the skin ductility (Y-axis) and the core ductility (X-axis) for different grades and thicknesses of steel strip, the ductility being determined by the Z% striction of cylindrical tensile test specimens



1 – Steel grade. 2 – Thickness (mm). 3 and 4 – Along and perpendicular to the rolling direction.

5.1. Boilermaking and constructional steelwork (bridges, marine construction, pipelines, storage tanks)

The research work grouped under this heading demonstrates the large effort that has been devoted to certain problems, in particular those posed by the dimensioning of offshore platforms for petroleum and gas production, by oil and gas pipelines, by the interpretation of road traffic parameters and their transposition into dynamic loads in metallic bridge structures, and in a more general manner by welded joints.

Resistance to hydrogen is a subject that regularly reappears in the three main fields of research defined in the introduction (construction, in-service behaviour, and metallurgical factors) which will form subdivisions for most of the main headings.

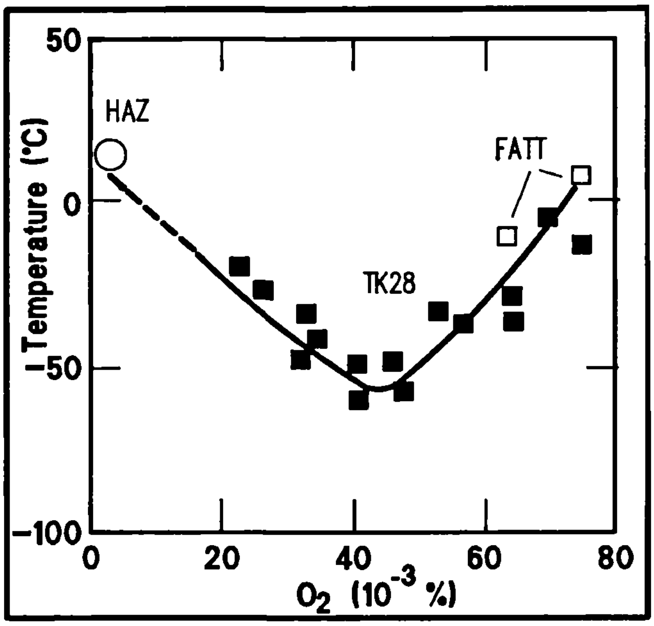
5.1.1. Welded construction

The savings provided by welded construction may be optimized by reducing handling operations. To achieve this objective, it is quite natural to think of decreasing the number of weld passes by depositing greater amounts of metal for each pass. Other possibilities lie in simplifying or even eliminating preparatory operations such as pre-heating or post-treatment operations such as stress relieving. Further research can reveal the qualities of certain recently developed steels.

5.1.1.1. Molten metal

Depositing more metal for each weld pass signifies welding with greater energy input. The molten metal must acquire suitable properties which depend upon the manner in which it is produced, the microstructure which is formed and its composition. The technique of adding filler metal must also make optimal use of the heat produced by the welding arc and thus help to limit the degradation of the heat affected zone (HAZ).

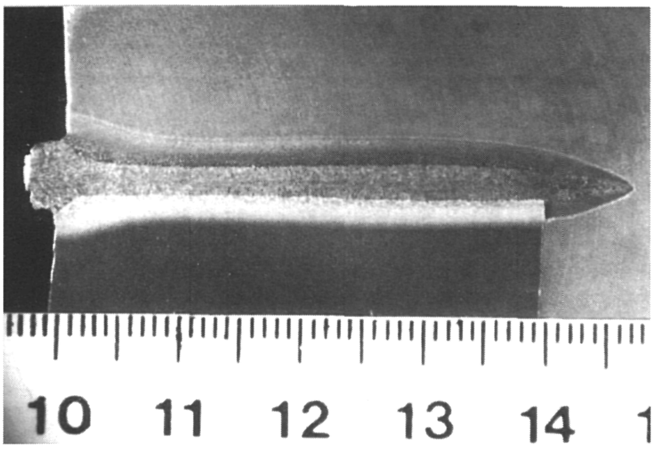
Figure 5-2
Example of the evolution of the transition temperature FATT and the Charpy toughness test (28 J-TK28) of molten metal as a function of oxygen content (1)



Several projects investigated the production and refining of the melt metal. Irsid and Creusot-Loire studied deoxidation conditions of the molten metal in different welding procedures such as submerged arc (1), electroslag (2) and electron beam welding (3) (Figure 5-2).

These projects confirmed the importance of metal refining by the slag, and the favourable effects of certain additives. For electron beam welding (Figure 5-3), since the operation is carried out under a vacuum, the reactions can continue in the molten metal by displacing the carbon-oxygen equilibrium. This has consequences on the characteristics of the welded joints. Important advances were made in the understanding of these phenomena and thus in the choice of quality control criteria for this type of joint.

Figure 5-3
Example of a macrophotograph of an electron beam weld in a dissimilar metal joint
Above – mild steel sheet: Below – 34 Cr Mo 4 steel sheet
(Photo: Soudobeam)



A systematic characterization of molten metal in the assembly of microalloyed steels by techniques using submerged arc, inert gas, or electron beam techniques was carried out by CSM (4) in order to correlate the microstructure components with the strength of the welded joint.

Thyssen investigated the welding of 9% nickel steels for cryogenic applications, and has developed a wire containing 11.5% Ni for joining these steels using the automated MIG process (5).

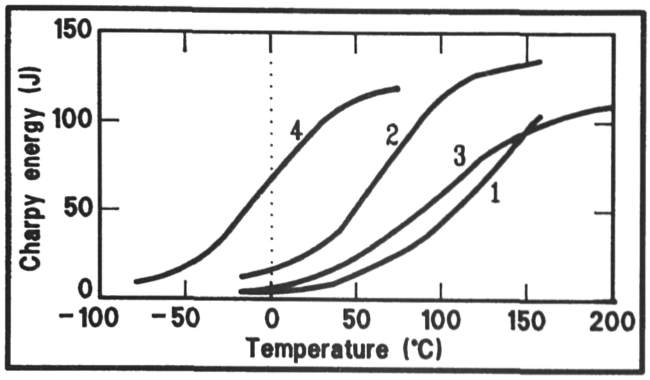
The Welding Institute and the Institut de soudure in Paris have demonstrated the potential of adding metallic powder directly to the molten bath of metal in order to increase the deposition speed of the submerged arc, while at the same time maintaining or even improving metal toughness (Figure 5-4) (6). CSM and Italsider provided precise details of techniques for supplying molten metal using several wires in line for submerged arc welding of thick plates (60 to 100 mm) and plate for pipes (7).

Italsider also demonstrated that it could be of interest to employ a process that is less efficient than those mentioned above, and to use, for example, an inert gas process for welding large diameter pipes because of the high quality of the welded joint which is able to comply with certain specific requirements (8).

5.1.1.2. Hydrogen in filler materials

Pre-heating problems are linked to the risk of cold cracking due mainly to the presence of hydrogen supplied by the electrode coatings or fluxes in the case of submerged arc welding. It is thus of interest to limit the hydrogen content of welding materials and to take advantage of the mobility of this element in the crystalline network of the metal at temperatures up to the order of 100°C in order to eliminate it through

Figure 5-4
Influence of the addition of metallurgical powder on the liquid metal properties: comparison of Charpy toughness testing of liquid metal from single-pass butt welds of 30 mm-thick, niobium microalloyed steels



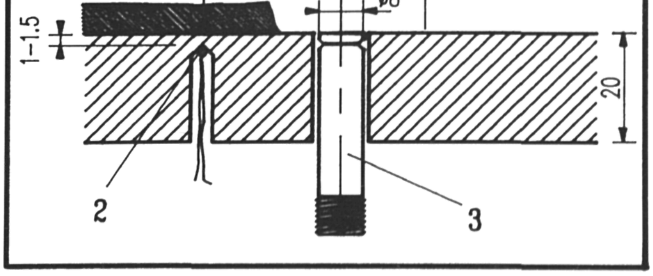
1 and 3 – Reference curves without addition of metallic powder.
2 – Addition of metallic powder to the molten metal.
4 – Welding conditions as in 2 but with ceramic backing plate.

the use of a suitable thermal cycle. CRM had modelled this phenomenon at the end of the previous decade in such a way as to provide quantitative evaluations of safety factors for the risk of cold cracking when using basic electrodes under specific welding conditions.

The Institut de soudure confirmed, for Fe-E 690 steels, the advantages of ensuring low hydrogen levels and control of the thermal regime of the first weld passes in order to simplify the procedure (9) (Figure 5-5).

CRM perfected its prediction model and extended it to the case of cellulosic electrodes and semi-automatic welding. It also adapted it to cover gas pipelines [(10) and (11)]. The model is thus capable of defining welding conditions which provide the best economic compromise while respecting safety aspects. A most spectacular use of this model was in defining the operating conditions for making a new connection to an in-service gas pipeline, without any interruption to the gas flow.

Figure 5-5
Diagram showing layout of implant for cold cracking tests



1 – Direction of welding. 2 – Thermocouple. 3 – Implant specimen.

All the research work carried out into cold cracking has been made available in a common publication by the Institut de soudure, CRM, bureau de ponts du ministère des travaux publics belge who have adopted the predictive model of CRM. This document has been recommended by the Institut international de soudure.

Another research project was carried out by the Institut de soudure and the Welding Institute (12) into the risk of cold cracking of the melted zone in the case of modern C-Mn steels. It gave suggested maximum hydrogen contents in filler materials and the selection of pre-heating temperatures.

5.1.1.3. Base metal

Among the more modern techniques, direct quenching using rolling heat is the preferred method for producing steel products which combine high strength and high toughness. It was important to correctly understand the suitability for welding of these quenched and self-annealed steels. Irsid took on this task and demonstrated the excellent weldability of these products. This is explained by the possibility of realizing a high elastic limit by reducing the amount of alloying elements compared to the usual procedures: the toughness and resistance to cold cracking characteristics are similar to those of more conventional grades of steel with comparable chemical composition, but with lower strength.

A softened area may develop in the HAZ, but this has little effect on the tensile strength due to its small area (13).

A joint Irsid and Unirec project was aimed at promoting cladded plates, by simplifying the assembly procedures for such plates using welding techniques.

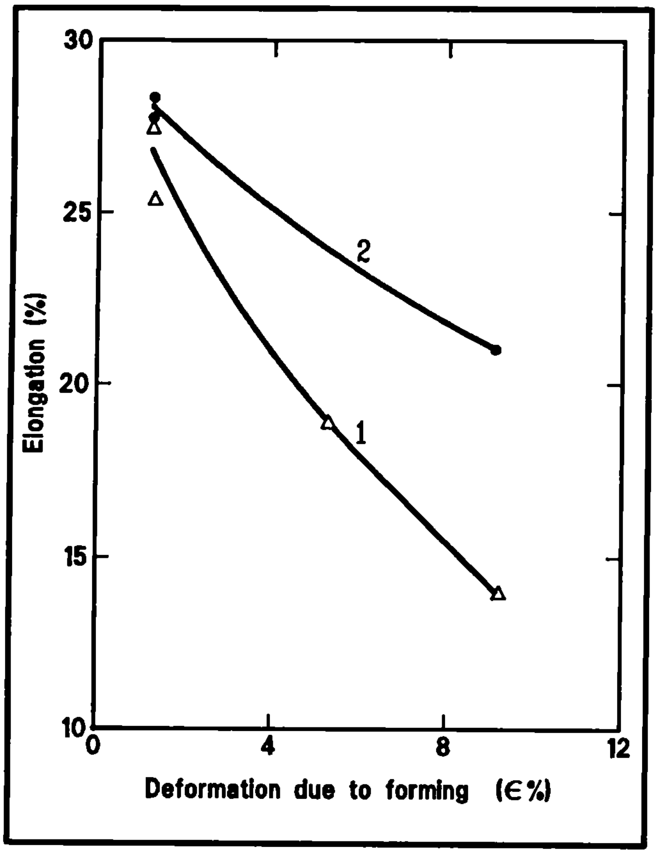
The repercussions of the suggested simplifications on the fatigue resistance of welded joints was examined. It was shown that the bevelling which is part of the classic procedure can be dispensed with without significantly influencing the fatigue behaviour in the case of butt joints (14).

5.1.1.4. Post-welding treatments

Cold forming is often adopted for manufacturing pressure vessels. In view of the progress made in the production of steel products, the question was posed as to whether the published codes covering cold forming of welded plates were, in fact, well adapted to currently produced qualities of plates and welded joints. In particular, the manufacturing codes limited deformations to 5% and required very expensive intermediate stress relieving to be carried out.

Irsid and Creusot-Loire demonstrated that for three steel grades (A 530, 10 CD 910, 14 Mn N D V 5 according to Afnor) the current quality of plates (60 mm thick) allowed deformations of 7% to be attained in a single operation without any problems. A final stress-relieving operation bestowed excellent properties on both the plate and the welded joints (15) (Figure 5-6).

Figure 5-6
Influence of work hardening and relaxation on the ultimate tensile strength of the HAZ in multi-pass welding of A 530 steel
(It should be noted that the guaranteed value for the base metal extension is 21%)



1 – Prior to stress relief. 2 – Stress-relieved state.
The warranted elongation of the base metal is 21%

The necessity of stress-relieving operations was also examined by the University of Stüttgart for 22 Ni Mo Cr 37 steels with thicknesses of between 40 and 200 mm (16) and by the University of Braunschweig for C-Mn-Mo and C-Mn-Mo-Cr steels (17).

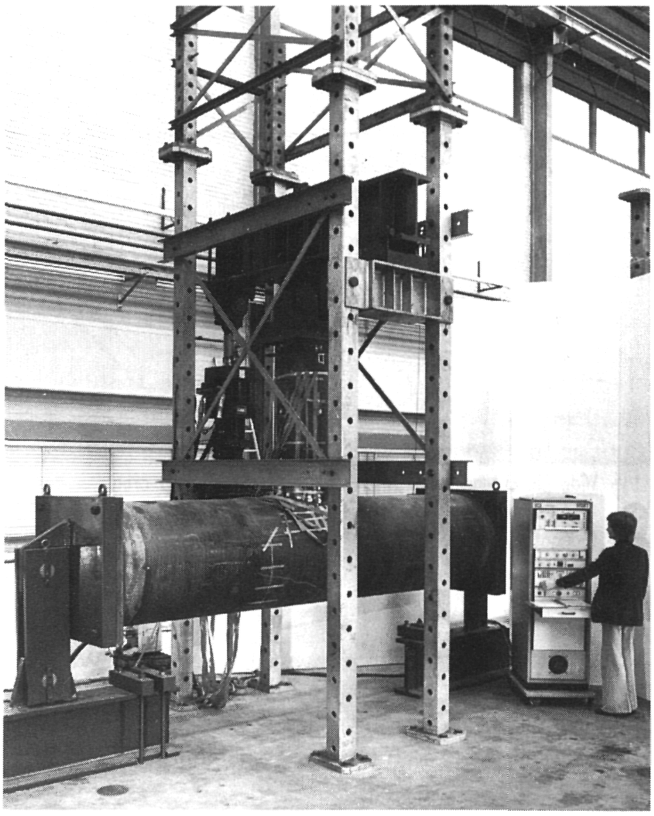
Research into the sensitivity of thick-wall, welded assemblies of 22 Ni Mo Cr 37 and 20 Mn Mo Ni 55 grade steels to reheating confirmed the validity of the criteria based on a limit value of impurities and tramp elements (18).

5.1.2. In-service behaviour

5.1.2.1. Offshore platforms

Research started in the 1970s, which was intended to describe the behaviour of tubular nodes on oil

Figure 5-7
Example of test rig for studying the fatigue behaviour of tubular nodes *(Photo: Delft University)*



production platforms in the North Sea, was continued and the programme was related to the importance of the subject (Figure 5-7).

Working groups coordinated research carried out in different laboratories. Furthermore, the activities of these working groups included contacts with and exchanges between organizations and institutes which had the same objectives but were financed by other sources of funds. These studies provided the occasion for exchanges of contact between steelmakers, platform operators and the approval organizations. The results obtained constituted an important pool of information for establishing design and calculation codes of practice. As well as the technical aspects, the promotional aspect for Community steel which is fostered during these international contacts should be emphasized.

It is obviously not possible to provide full details of all the results achieved by all the contractors: VDEh, British Steel, Irsid, SMOZ, the Danish KC Institute and Cetena [(19) and (20)]. Therefore only one example is given below: the complex interaction of cathodic protection on fatigue resistance of welded joints in seawater, which involves calcareous concretions and biological effects.

The first tests concluded that seawater reduced fatigue life by a factor of two compared to values in free air, but that the situation was redressed by using cathodic protection.

A deeper analysis of the phenomenon demonstrated that the reality was much more complex. In fact, the cathodic protection delays the start of cracks although it may accelerate their propagation. The importance of these effects depends especially on the value of the cathodic protection potential and as a result on the quantity of hydrogen liberated in contact with the metal. The situation is further complicated if we take into account the possible presence of calcareous concretions. When they form within the cracks they tend to keep them closed and to delay propagation. This effect is far from negligible for shallow cracks. The potential difference of the cathodic protection influences the rate of formation of the calcareous and magnesian deposits and their size.

Another interesting phenomenon, which was shown by the Danish KC Institute, concerned the action of micro-organisms living in the sea which could develop on submerged surfaces. They can produce an appreciable quantity of hydrogen, which varies according to the season and which interferes with cathodic protection systems. One of the consequences of this discovery concerned the simulation of the behaviour of tubular nodes in the laboratory (Figure 5-8), due to the fact that synthetic seawater free of micro-organisms is usually employed in laboratory tests. The results of these tests should thus be treated with a certain caution.

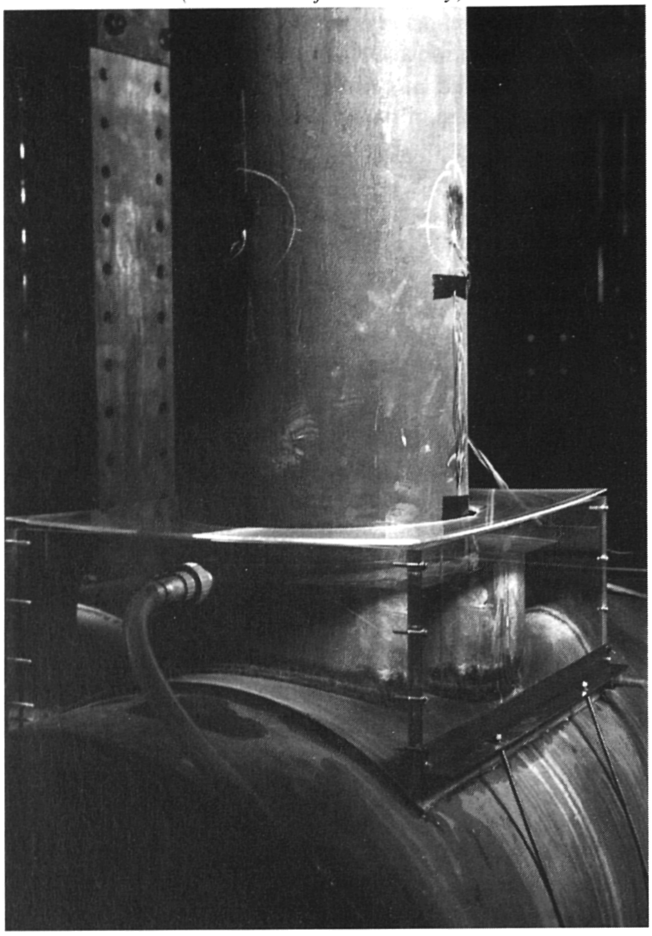
Finally, the best way to improve the fatigue resistance of tubular nodes in seawater is to delay crack initiation as much as possible. This means, on the one hand, achieving weld beads with controlled geometry, using weld finishing techniques and, on the other hand, applying moderate protective electrical potentials in service.

5.1.2.2. Dynamic loading of bridges

Another example of coordinated research between several laboratories concerns fatigue in road and rail bridges. The final aim is to both optimize the calculation and design of metallic bridges and to standardize the rules for calculation. This research was undertaken in several phases. Firstly, the manner in which road traffic and the resulting loads were to be evaluated had to be defined. Research commenced by measuring axle loads, vehicle spacing, the type, the number and the mechanical loads resulting from the traffic, in various parts of the metallic structure of bridges (Figure 5-9). The work was carried out on some 15 bridges throughout the Community Member States. The data was used to select a simulation model for the traffic and its effects, and finally the model was refined and perfected.

Research also examined aspects of orthotropic decks.

Figure 5-8
Test rig assembly for studying the effect of seawater on a welded joint subjected to cyclic fatigue
(Photo: Delft University)



This work was divided between different organizations and laboratories: the Universities of Liège and Pisa, LCPC, Irsid, TRRL, SMOZ and LBF [(21) and (22)].

The results obtained included: improved behaviour of the triangular members compared to the trapezoidal members, the influence of the gap at the weld root and residual welding stresses and finally the applicability of Miner's law to damage accumulation.

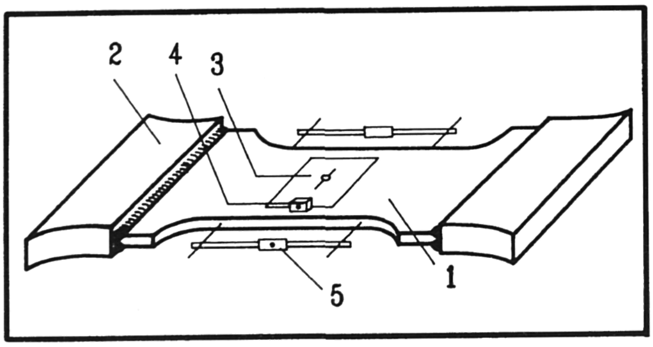
This research has had important effects, especially the methodology developed for evaluating traffic and its influence which was adopted for use on other bridges, and the mass of data obtained forms an important basis for Eurocode, Part 12: action on road bridges.

The design of certain bridge elements has been influenced; such as, for example, in the case of the mobile bridge at Kruischans in the port of Antwerp.

5.1.2.3. Evaluation of the safety of structure against the risk of catastrophic failure

The laboratories in the Community have been very active in determining methods of evaluating these risks on the basis of fracture mechanics.

Figure 5-10
Example of a tensile test specimen with a transverse median defect, fitted with sensors for measuring extension across differing gauge lengths



1 – Wide plate tensile specimen. 2 – Specimen grip area.
3 – Grid for assessing localized strains. 4 – CTOD gauge.
5 – Elongation gauge.

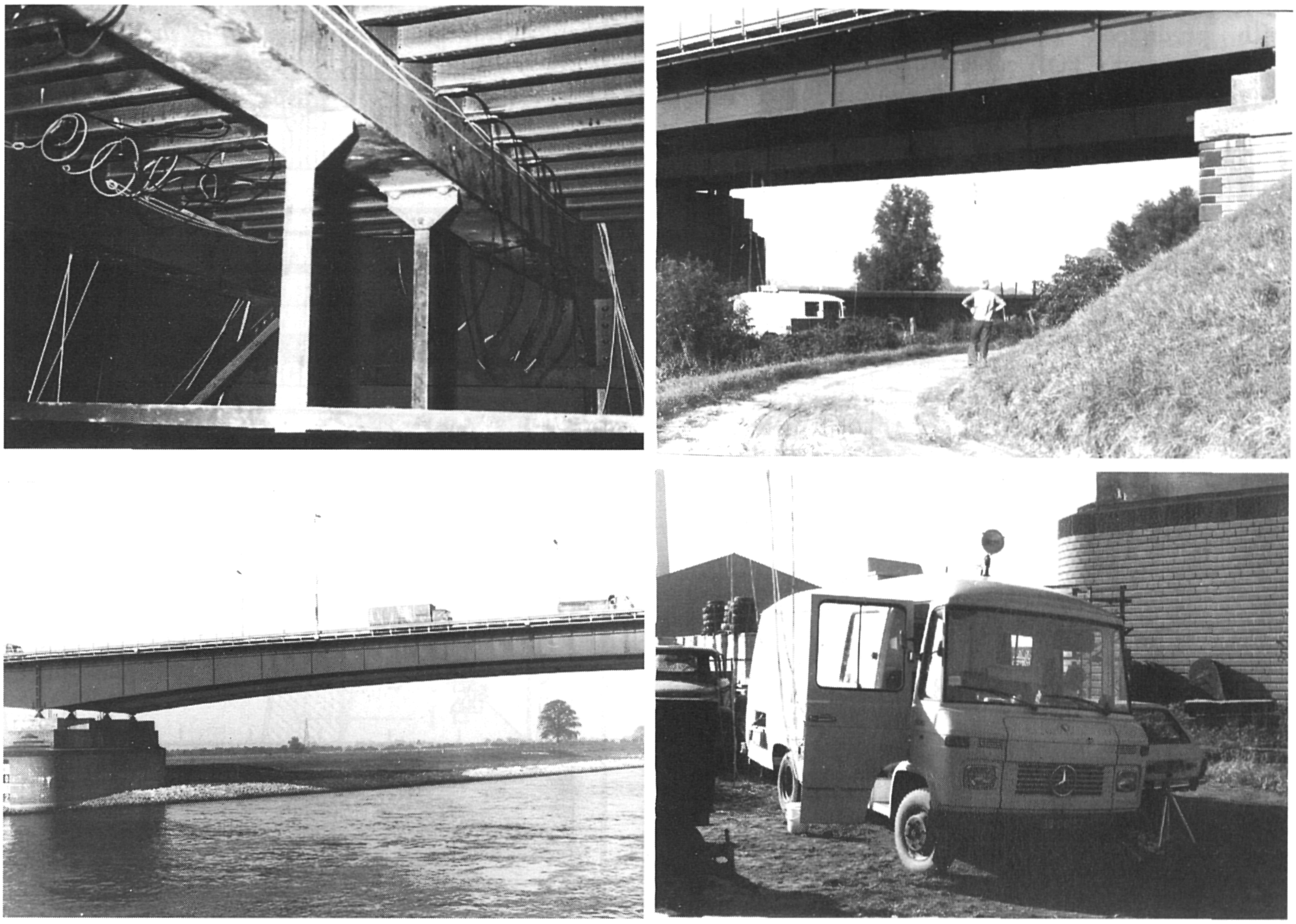
A multinational programme was set up by the Welding Institute (23) to determine the discrepancy between laboratories in measuring characteristic parameters of toughness using fracture mechanics. Fourteen laboratories took part in this comparison and they were supplied with samples originating from the same plates. Tensile tests on wide plate specimens with machined defects were also carried out (Figure 5-10). Samples such as these are considered to be simple elements of construction. Their behaviour was compared to values measured on smaller specimens.

It was demonstrated on a statistical basis that the variation between laboratories was not significant and that the minimum values measured were in agreement. Predictions of wide plate behaviour and critical size of the defect that had been incorporated were shown to be satisfactory on the basis of a CTOD and the J integral measured in the laboratories, if the Soete criteria was used to define the critical state of the large samples, i.e. generalized plastification and an elongation of at least 1%. This study was carried out using plates without any welded joints (Figure 5-11).

Comparison of different fracture mechanics concepts for evaluating the behaviour of large tensile test specimens incorporating defects was a point in common in the case of most research carried out over this decade. Even so, a start had to be made in understanding the behaviour of wide plate specimens incorporating defects under different conditions of stress. Such a research project was carried out systematically by the University of Aachen (24). It demonstrated that the most critical sample was one notched on both sides.

The comparison we have mentioned above was the subject of a coordinated research project undertaken by VDEh. This research was made on steels in the nor-

Figure 5-9
Example of instrumentation of a steel bridge structure.
Also shown is a truck containing the recording instruments



malized or thermo-mechanically treated state for which the nominal strength values reached 530 MPa, quenched and tempered steels, and nickel steels for use at low temperatures. A large part of the tests were carried out on wide plates with welded joints with defects in the melted metal. The participants were: the University of Aachen, Thyssen laboratories, CSM, TNO and British Steel (25).

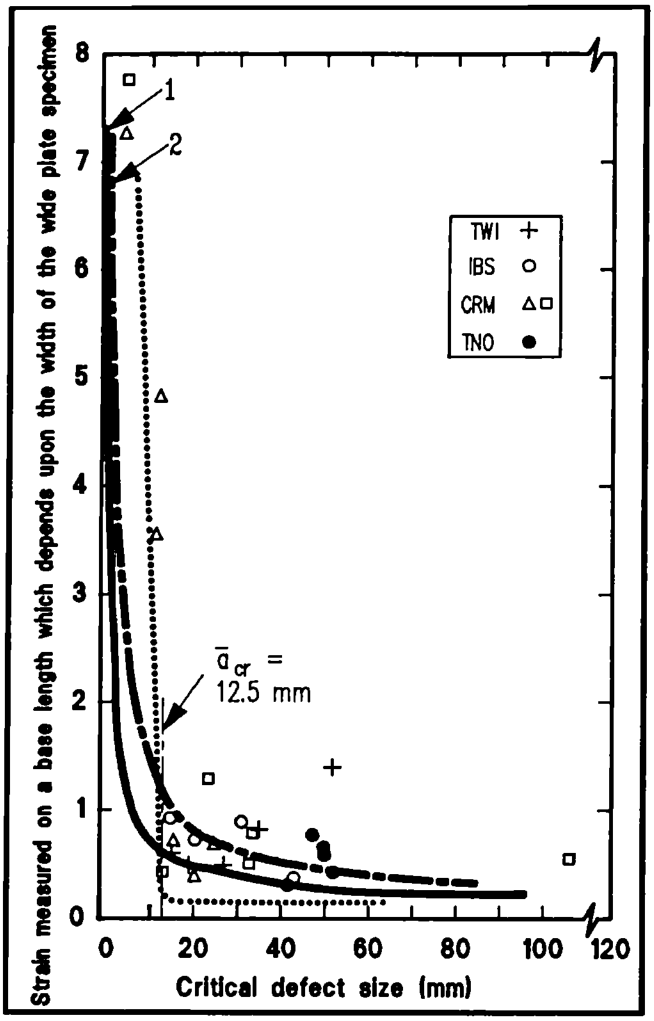
This project commenced at the beginning of the decade and provided results which it is interesting to compare with those obtained by Irsid using X 65 grade plate with submerged arc or electroslag welds (26) and those published by the Max Planck Institute (27) for standard St 52-3 grade steel plate or thermo-mechanically treated St E 480 or St E 500 plates, with and without welded joints. The common conclusion for all, these projects was that the prediction of critical states correlates with experimental results in a certain number of cases, in particular when there is no welded joint. Nevertheless, theoretical predictions are sometimes considerably different to experimental results, especially when the defects are in the welded joints.

In general, the difficulties encountered in those cases where there is a welded joint arise from the fact that it is difficult to obtain data required to evaluate the strength of the metal, such as the tensile properties of the HAZ and the way in which they change with temperature. Residual stresses of the welded joint may also give rise to a certain lack of precision.

The relationship between crack initiation in the HAZ and its microstructure are being actively studied. British Steel has demonstrated the essential role played in this domain by the grain size as well as the elastic limit (28).

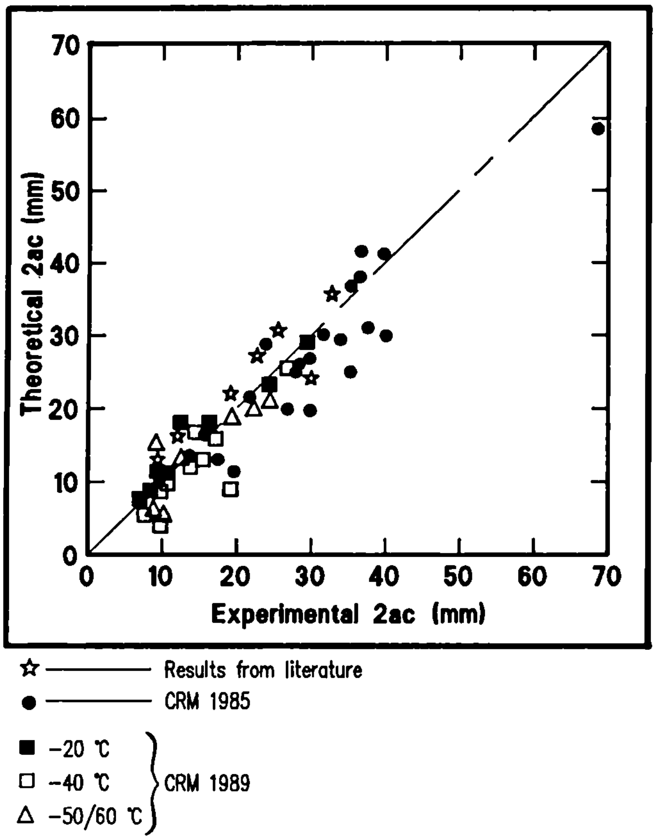
CRM has adopted an alternative approach. Resolutely distancing itself from fracture mechanics concepts, the metal toughness is expressed using two parameters that are considered to be complementary: the Charpy resilience and the ratio σ_u/σ_y between ultimate and yield strengths. According to the CRM theory, a low σ_u/σ_y ratio may be compensated (as is the case with modern thermo-mechanically treated steels) by a higher impact strength. Toughness values measured on this basis allow the critical size of defects running across wide samples to be predicted. This applies to a large range of microalloyed steels or steels quenched

Figure 5-11
Comparison of critical states and catastrophic failure measured in different laboratories on wide plate tensile test samples with transverse defects, with predicted values derived from fracture mechanics and CTOD concepts. The specimens are homogeneous, weld-free, wide plate samples (23)



1 and 2 are the design curves corresponding to critical CTOD values of 0.31 and 0.78 mm.

Figure 5-12
Comparison of theoretical and predicted defects in wide plate tensile test specimens.
According to the CRM theory, the metal has been characterized by its toughness and by the relationship between ultimate tensile strength and the yield stress. The values concern homogeneous weld-free samples (29)



from rolling heat for plates up to thicknesses of 30 mm (29) (Figure 5-12). Going a step further, CRM has modified its theory to include welded joints. The tensile properties and the impact strength of the base metal and the molten metal are taken into consideration, while the HAZ is characterized by a filiation of hardness values which are directly converted into ultimate strength. It is also possible to make reasonable predictions of the critical size of defects in large samples (30) on the basis of the extended theory.

5.1.2.4. Gas pipelines

The principles of fracture mechanics can be applied normally to evaluating the failure risk of constructions such as storage vessels and steel constructions. Gas pipelines are a special case. The metal must be able not only to resist crack initiation but, in the event of an accident, it must not allow the crack to propagate over long distances under the influence of gas decompression. Therefore is important to be able to predict the more or less ductile or brittle failure of the metal at pipeline service temperatures and to quantify its toughness.

Experimental difficulties arise with the speed of crack propagation under real conditions (it reaches the speed of sound), which lead to the need to carry out full-size tests. This has been done in the USA. It was shown that the relatively fibrous aspect of the crack surfaces, according to temperature, could be reproduced using a shock loading test known as the Battelle drop weight tear test (BDWTT) and this has led to Charpy impact strength values being recommended as a function of the wall thickness and the loads to which they are subjected. Unanimity of opinion has not been achieved and the sector is currently faced with three different propositions.

Figure 5-13
The prevention of catastrophic failures in gas pipelines

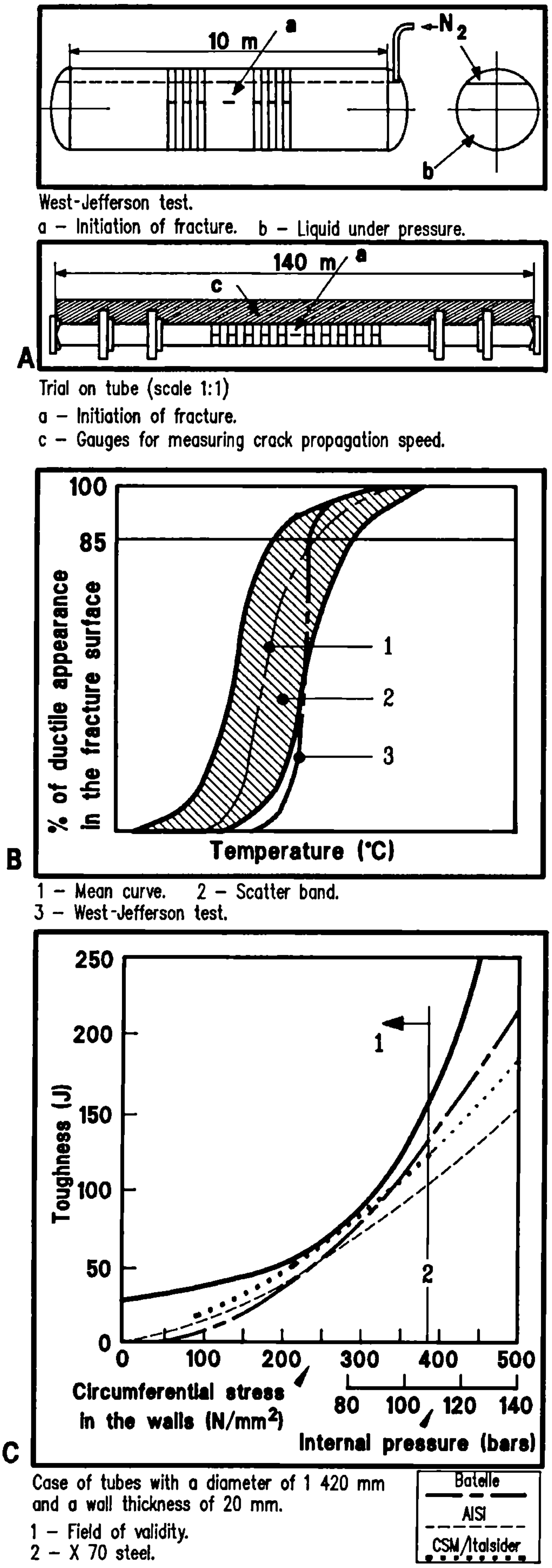


Figure 5-13a shows the two types of large-scale tests involved. The West-Jefferson test determines the manner in which the failure propagates (brittle/ductile) as a function of temperature. The other test determines the ability of the metal to arrest propagation of the crack.

Figure 5-13b compares the more or less ductile characteristics of the failure according to temperature in the W-J test and the BBDWTT laboratory test.

Figure 5-13c is an example of the characteristics used to define the level of tangential strain allowed in the walls and the toughness required to ensure that crack propagation is prevented (Ref.: VDEh and Stahl und Eisen 7(90)).

The European manufacturers of linepipe and the gas distribution and service companies have created a research association (EPRG) and, with assistance from the ECSC, a certain number of failure tests have been carried out on pipelines. In parallel with this action by the EPRG, other tests on pipelines have been carried out by Italsider and CSM. Research which was started in the 1970s concerned X 60, X 65, and X 70 grades of steel. It allowed ranges of validity for each of the three approaches mentioned to be defined, and Italsider and CSM to jointly propose a unified relationship which was also valid in all three domains (Figure 5-13).

By studying the behaviour of gas pipeline failures at 30 metres below water-level, or buried beneath 1 metre of earth, CSM was able to confirm the validity of the Charpy impact strength test to define the strength of pipelines, and suggested a value of 60 Joules/cm^2 as a characteristic of the metal which would ensure that a ductile failure would be arrested for diameters up to 36 inches (31) (Figure 5-14).

Tests carried out by the EPRG and the Italsider-CSM group were continued using tubes of X 80 grade steel and quenched and tempered steels. It became apparent that the predictive models developed up until then and based on Charpy impact strength values were no longer sufficient. New ideas and laboratory studies were required to be able to predict the behaviour of these grades of steel [(32) and (33)].

New concepts were proposed. British Steel suggested using a parameter combining two elements, one characterizing failure energy, the other the energy associated with the plastic deformation. Both were determined in an impact test on the basis of failure energy of two notched samples with different lengths of ligament which had been failed in an impact test. By using samples of steels which had been used in the

Figure 5-14
Example of a dynamic failure test carried out on an experimental buried gas pipeline
(Photos: CSM-Italsider)

manufacture of tubes for EPRG tests, it was possible to predict the behaviour of the full-scale tests in 90% of cases (34).

CSM proposed a new concept called CTODA, which is the crack tip opening angle at the moment of failure, obtained on a laboratory sample. The concept appears promising and it is being actively studied in the laboratory [(32), (35) and (36)].

Another risk connected with service use of gas pipelines is corrosion which may be caused by NaCl-loaded humidity, or by H_2S and aggravated by mechanical loading. The test procedures most often used for evaluating sensitivity of steels to these phenomena are generally very severe, and probably too severe. This was demonstrated by an EPRG research project (37) which attempted to evaluate the risk of failure in the presence of H_2S by full-size tests on gas pipelines. Tubes were subjected to pressure in H_2S-rich seawater and filled with gas containing H_2S. The behaviour of these tubes was compared to that of laboratory samples submitted to HIC and SSCC tests, according to recommended procedures. Not only was it demonstrated that the laboratory procedures were too severe, but divergences in the values of results compared to the full-size test results could not be explained.

There is, nevertheless, no question at this time of revising the test procedure and thus to oblige the steel manufacturers to adapt to the resulting impositions and criteria and to study in consequence the metallurgy and the microstructure of the steel.

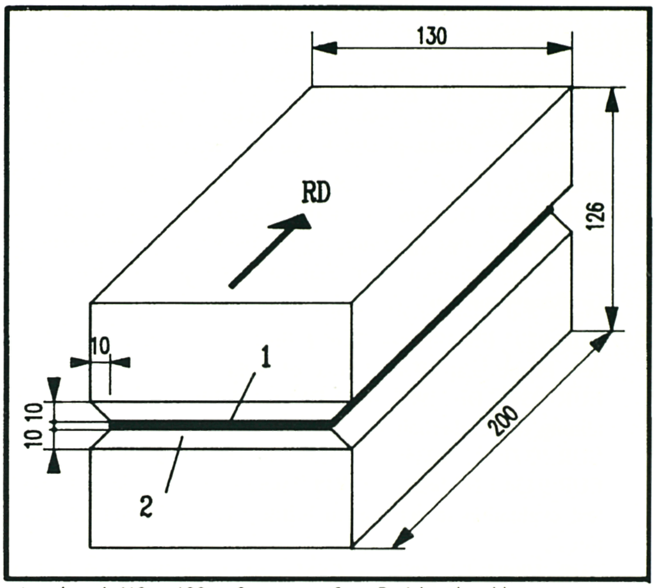
5.1.3. Metallurgical factors, chemical composition and service conditions

5.1.3.1. Hydrogen susceptibility

A great deal of effort has been expended in determining the factors to be considered when developing steels with low susceptibility to the detrimental effects of hydrogen, hydrogen sulphide and other salts, and which are capable of satisfying the criteria imposed in evaluating this susceptibility. This research work concerns not only steel for gas pipelines, but also high-strength steels for the petroleum industry and geothermal applications (38), hydrocracking reactor vessels (39) and more generally in those applications where steel is liable to become charged with hydrogen [(40) and (41)].

It was known that banded microstructures were detrimental to corrosion resistance of steels used for manufacturing tubes. An ingenious methodology was developed by British Steel (42) in which the composition and microstructure of the segregated bands was varied in a controlled manner. The principle lies in preparing a 'sandwich' of which the central part is made up of a strip with segregations (Figures 5-15a and 5-15b). This method was also used in a second British Steel research project on the same subject (43). The results obtained agreed with those published by Irsid (44) and CRM (45). They showed that the susceptibility of steel to hydrogen depends upon the hardness of the segregated bands and local

Figure 5-15a
Example of preparation of a composite test sample in which the insert is able to simulate, as required, the states of the segregated central zones observed in sheets originating from the continuous casting plant [(42 and 43)]
These samples will later be rolled



1 – Insert 110 x 100 x 2 mm. 2 – Peripheral weld.

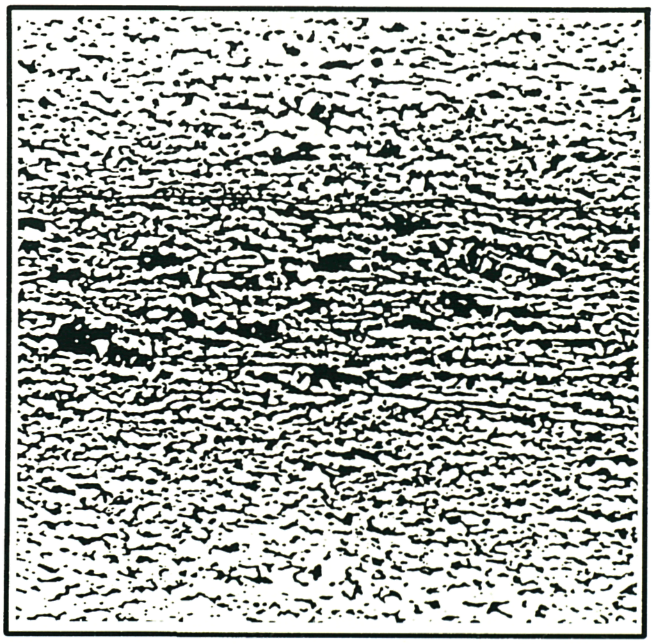


Figure 5-15b
Microphotograph of the artificially induced segregated zone [(42) and (43)] after rolling of the composite test specimen

manganese and phosphorus enrichment. The limits of carbon, manganese and phosphorus analysis must take account of the tendency of these elements to segregate.

5.1.3.2. Seawater-resistant steels

At the beginning of the 1980s, a great amount of confidence was placed in microalloyed steels with small additions of aluminium, chrome and molybdenum, capable of resisting marine corrosion. Extensive research was carried out into developing a suitable chemical composition [(46) to (49)], and care was taken to ensure that the steel could be rolled and transformed by drawing and welding (46). Testing under service conditions were then carried out at marine sites and below sea-level [(50) and (51)]. It became apparent that these steels resisted satisfactorily when they were totally immersed in seawater, but that their behaviour was unsatisfactory in the splash zone where seawater and the atmosphere alternated. The range of application of these steels is thus much smaller than was initially imagined.

5.1.3.3. Miscellaneous

The life span of construction steels is not the only property which can be related to metallurgical factors and chemical composition.

Certain research projects have attempted to correlate rolling conditions to the microstructure and to the mechanical properties of the strip and plate.

CRM (52) provided details of the influence of temperature after rolling and cooling rates on the toughness of X 65 and X 70 grade steel strip and plates with thicknesses of between 8 and 20 mm.

Irsid (53) developed a methodology for simulating and modelling the influence of cooling during rolling and coiling on the microstructural state of the metal which later conditions the behaviour of the metal.

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5.2. Construction industry

In Europe, the use of steel in buildings has not reached the level and degree of development to be found in the USA and Japan. The ECSC has thus continued its efforts in research aimed at providing steel with the position it deserves, from which it has only slipped due to poor appreciation of its possibilities. The main lines of Community action during this decade can be summarized as follows:

(i) Research for data that can be used in adopting a European policy that is more favourable to the development of steel in the construction industry. For example, the comparative study of the respective situations of steel construction in Europe, Japan and the USA, or undertaking studies to compare risks and damage caused by fire in steel structure buildings compared to those using other materials.

(ii) Continuing studies into the behaviour of construction elements, such as those made from hollow sections, cold-formed sections and hot-formed sections combined with concrete, or the efficiency of metallic foundation piles.

(iii) Developing the computerized calculations and predictions for the behaviour of metallic or mixed (steel-concrete) constructions.

(iv) Evaluating the relatively conservative nature of certain codes or regulations.

(v) Promoting activities intended to inform interested constructors and authorities.

5.2.1. Perspectives for increasing the market for steel

We shall commence illustrating these with a comparative study of metallic construction in the United States, Japan and the European Community which was carried out by the Centre belge d'information de l'acier (1). This was a study which showed the similarities and the differences of the respective situations.

Similarities included the modest size of the contractors, the weakness in their technology and their profitability, their position as sub-contractors and the strength of the competition. Differences were established in the geophysical environments, good understanding of steel as a material, architectural design and site planning which provided steel with an advantage through the prefabrication of building elements and finally, in the United States and in Japan an organization of the market and regulations which provide an impartial choice of materials.

We can draw similarities between this study and a more recent one carried out by British Steel (2) in order to bring together all the elements required to define a future marketing strategy for hot-rolled special and structural sections and, in particular, the high-strength grades. Without neglecting other areas of utilization, the construction industry was specially targeted. Once again, the need for ample information was demonstrated, and also for training engineers and those in charge of specifications, and for an action on codes and regulations. Finally, the potential of steels which have been quenched from rolling heat and self-tempered was demonstrated, in particular through the QST process applied to large-sized Grey's beams which is practised in Arbed's plant in Differdange (3). This has produced a new generation of beams with high yield strength and high toughness at low temperatures for use in skyscrapers and offshore constructions.

In this report, two important ideas resulting from these studies are examined: good understanding of steel properties and suitable regulations.

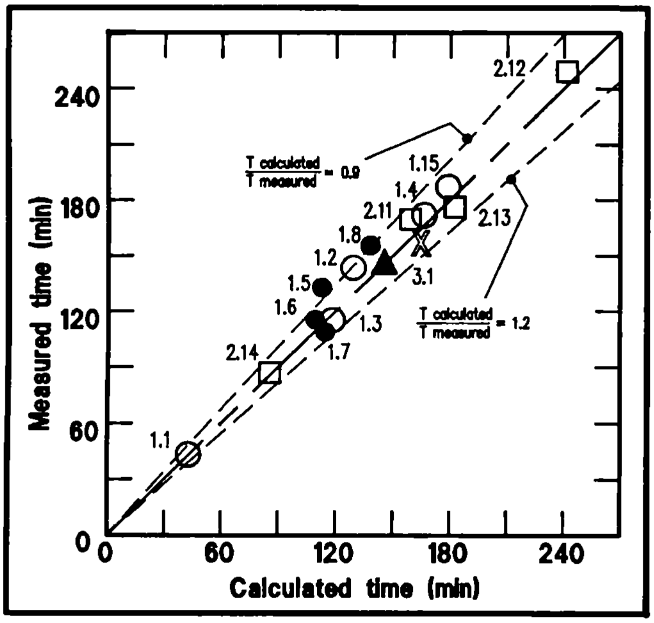
They are to be found in the themes of the research work carried out during this decade into fire resistance of metallic structures.

5.2.2. Fire resistance

We know that there is a certain mistrust, particularly within insurance companies, concerning the behaviour of metallic structures in the event of fire.

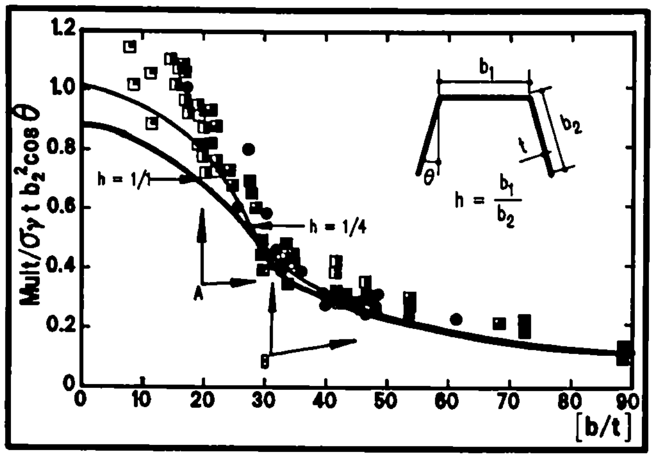
This has justified extensive analyses performed by TNO and CTICM (4) on the conditions and consequences of fires which have gutted one- or two-storey buildings. They mainly concern industrial or commercial buildings. Several hundred cases were examined. It was shown that the type of material (steel or otherwise) used in the structure was not specifically related to the degree of damage caused by the fire. The same is also true for the rate

Figure 5-16
Comparison of ISO fire resistance times
(Arbed — Technical Review 2-87)



	Gand	Braunschweig	Failure criterion
Columns	○	●	Buckling
Beams	□	▲	f < L/30
Frames		X	Buckling

Figure 5-17
Comparison of proposed rules for calculating [(12) and (13)] the behaviour of cold-rolled sections



The curves correspond to elastoplastic or elastic behaviour (A or B regions).

● Final test series Various h values

h = 1/4

h = 1/2

h = 3/4

h = 1/1

of propagation of the fire. In fact, the degree of damage depends on the size of the fire at the moment when the fire brigade arrives, the warning systems installed, the presence of automatic extinguishing systems and fire walls. If statistics often expose steel structure buildings, this is mainly due to the large number of this type of industrial building in existence.

If we now look at a more experimental level, we should mention several studies into the behaviour of metallic elements:

(i) The University of Liège, CRIF and TNO (5) showed that the approach suggested by the Convention européenne de la construction métallique (CECM) was too conservative in a certain number of cases.

(ii) The Studiengesellschaft für Anwendungstecknik von Eisen und Stahl analysed the fire-resistant qualities of hot-rolled sections, hollow or open cold-rolled sections, composites of hot-rolled sections/concrete, in order to draw up recommendations for improving fire resistance and to establish an experimental basis for modelling the phenomenon and developing computer-design programmes (6).

(iii) British Steel has also studied the rationalization and financial savings in fire protection provided by spray coating with fire-resistant products (7).

(iv) The centres de l'information de l'acier have assembled all the available information and published a brochure in six languages, thus providing complete but brief information of all the factors influencing the fire behaviour of steel constructions (8).

(v) A very large programme was carried out under the guidance of Arbed, including several universities (Liège, Wüppertal, Gand, Braunschweig), into computer modelling and analysis of the fire resistance of steel/concrete structures or hot-rolled columns (9). This resulted in a polyvalent programme allowing temperatures and their evolution, as well as the behaviour of the constructional elements over time to be calculated (Figure 5-16).

5.2.3. Design and dimensioning

Efforts to complete the regulations and recommendations and to bring them up to date were not limited to the case of elements subject to fire.

Mannesmann, Cometube, Dalmine, SSN and British Steel have coordinated their efforts in the field of the design of different types of welded joints based on hollow sections (10).

Cometube also studied the buckling of rectangular hollow sections under eccentric loading (11) and by combining these results with other previous research data, was able to draw up an overall theory for thin and thick sections in compression and bending.

Stichting Staalcentrale van Nederland (SSN), TNO, Strathclyde University and CTICM have developed different calculation models for cold-rolled sections [(12) and (13)] (Figure 5-17).

The Steel Construction Institute has presented a computer-based model for calculating the behaviour of three-dimensional structures in the elastic domain (14).

All these studies which are mentioned above have had an impact on the activities and recommendations of the CECM as well as the Eurocodes.

We end this chapter by recommending the British Steel report (15) on the atmospheric exposure tests of metallic- and paint-coated plates. The report includes data on corrosion resistance and evolution of the surface appearance not only for galvanized strip but also for zinc-aluminium coatings, all having been subjected to a whole range of climatic conditions.

References

(1) EUR 6911 FR 1983 — CBLIA: 'Étude comparée de la construction métallique aux État-Unis, au Japon et en Europe'.

(2) EUR 13426 EN 1991 — British Steel: 'Increased use of higher strength steel in structures'.

(3) 7225.EB/EA/502 — Diffusion restreinte — Arbed: 'La trempe de poutrelles dans la chaude de laminage suivie d'un autorevenu'.

(4) EUR 11493 EN/DE/FR — CTICM/TNO: 'Field survey on the role of steel structures in industrial fires'.

(5) EUR 12470 EN 1990 — Université de Liège/TNO: 'The effect of mechanical and structural properties of steel at deviated temperatures on the buckling of fire exposed columns'.

(6) EUR 9514 DE 1985 — SAES: 'Brandverhalten von Stahlstützen im Verbund mit Beton und von massiven Stahlstützen ohne Beton'.

(7) EUR 10713 EN 1987 — British Steel: 'Spray applied fire protection for structural steel — aspects of application techniques'.

(8) EUR 12208 EN — Eurofer: 'Brochure-argumentation on fire safety of steel constructions'.

(9) EUR 10828 EN 1987 — Arbed: 'Computer-assisted analysis of the fire resistance of steel and composite concrete steel structures'.

(10) EUR 10436 EN 1987 — Mannesmann/Cometube/Dalmine/SSN/British Steel: 'The development of recommendations for the design of welded joints between steel structural hollow sections or between steel structural hollow sections and H sections'.

(11) EUR 9198 FR 1984 — Cometube: 'Flambement de profils creux sous charge excentrée'.

(12) EUR 11670 EN 1988 — SSN: 'Research into the mechanical behaviour of cold-formed sections and drafting of design rules'.

(13) EUR 12748 EN 1990 — CTICM: 'Software for the calculations of light gauge cold-formed steel sections'.

(14) EUR 12018 EN 1989 — SCI: 'The development of computer-aided design methods for steel framed composite floored multistorey buildings'.

(15) EUR 10715 EN 1987 — British Steel: 'A study of relationship between design of precoated steel cladding and its environmental behaviour in service'.

5.3. Mechanical engineering

This heading concerns those products for which the manufacturing operations include one or more of the following: hot or cold forging, cold heading, machining.

A large number of mechanical engineering items are manufactured from bars and billets, but components of larger dimensions such as turbine rotors are also included. In general, we can consider two main types of research depending upon whether they are involved in optimizing the production line or with obtaining the optimal combination of steel properties through improving its production and refining or simply by a more judicious choice of type and grade.

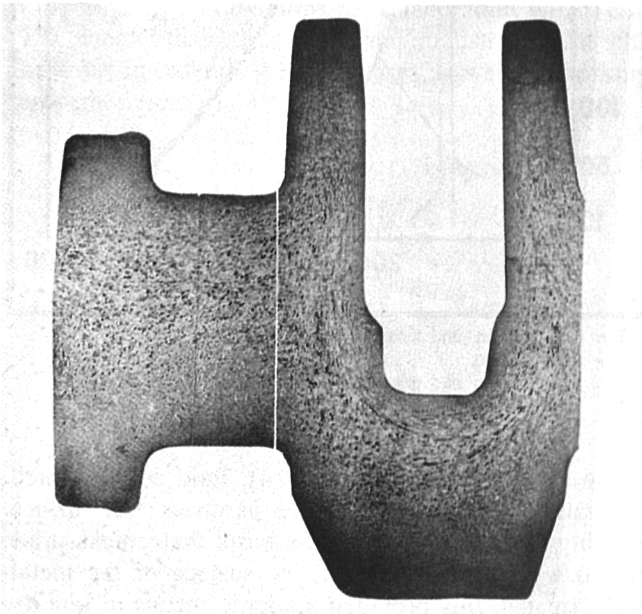
5.3.1. Manufacturing with steel

Decreasing the number of manufacturing operations is an especially efficient manner of reducing production costs. Another way is to simplify or shorten the more costly phases; for example, in the automobile industry some 25% of the total cost of a given component is in transforming the bar or billet into a forging, while machining to final dimensions contributes more than 50% of the final cost. We can thus appreciate the interest in precision forging, which provides a means of obtaining dimensions very close to those of the final machined component. The following two research projects illustrate these concepts.

In the manufacture of many components in automobile mechanical engineering, the diameter of the initial bars is often less than 100 mm, while continuous cast billets commonly have dimensions of 130 to 175 mm across flats. It is therefore necessary, in general, to carry out an initial rough machining.

Krupp demonstrated that billets may be used directly for hot forging (1). Two cases were used in this demonstration: the production of kingpins from 130 mm across flat billets (42 Cr Mo 4 steel) (Figure 5-18) and crankshafts for trucks in 38 Mn VS 6 steel from 150 mm across flat billets.

Figure 5-18
Cross-section macrophotograph of a rocker shaft bearing, hot-forged from a continuous cast billet (1)
(the fibre pattern should be noted)

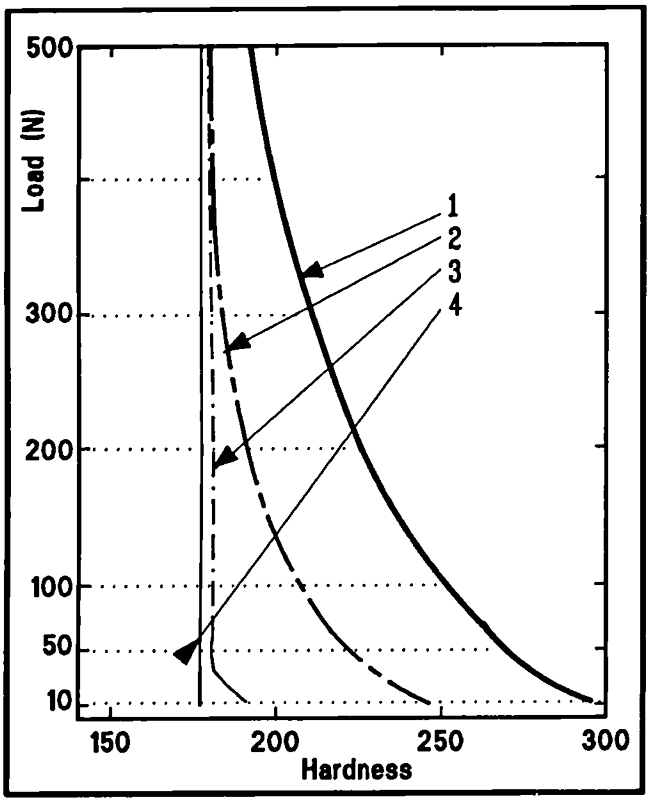


The second example describes a British project (2) based on the optimal limit between cold precision forging and machining. This limit depends upon the characteristics of the steel being worked. This project helps to set this limit according to the suitability of the steel to forming or machining.

Improved quality control checks, resulting in a decrease in the amount of defects and thus of rejects is also a major subject of research.

In this field, two studies are mentioned, both of which are based on cold forming of wire and bar. One of them, carried out by British Steel (3) shows that many defects (cracks) are related to adiabatic shear phenomena of the metal in the plastic phase, which should thus be avoided. In the case of soft boron steel, the project was able to recommend a drawing operation prior to further forming operations.

Figure 5-19
Hardness profiles beneath the skin of a bar after different surface treatments (4)



1 – After peeling and straightening.
2 – After peeling.
3 – After peeling and grinding.
4 – After peeling and electrolytic polishing.

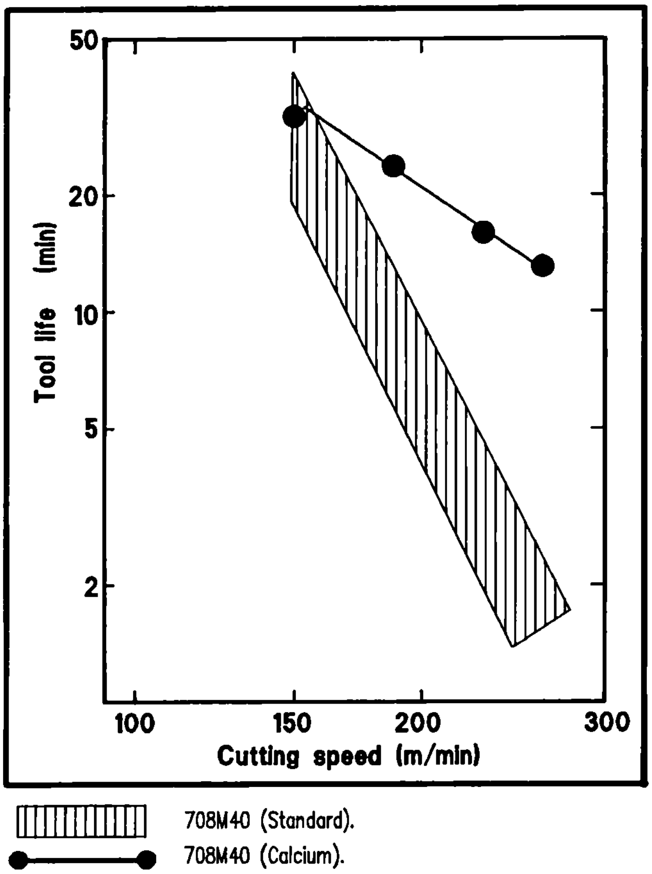
In the second research project (4), Irsid demonstrated correlation between the surface hardness and surface ductility (Figure 5-19). On the basis that cracks arise due to a lack of ductility at the surface of the metal being treated, this provided a simple means of quality control for decreasing the occurrence of defects and in evaluating the effects of technological process parameters (selection of tools, estimation of wear rates, adjustment of machine tools).

5.3.2. Metallurgical factors and properties of steel

The large proportion of the total cost of a mechanical engineering component, which is occupied by machining operations, explains the large amount of research involving the machining of steels. Sulphur content is an important factor involved in machinability, although it must be combined with other characteristics. Efforts have been made to obtain both machinability and appropriate through thickness properties simultaneously.

Three projects, those of British Steel (5), GKN (6) and VDEh (7) have demonstrated the interest of sulphur contents up to 0.1%, in combination with a globularization treatment based on the addition of calcium, for grades of carbon steel (C 35 and C 45) and for micro- or low-alloyed grades (49 Mn VS 3, 41

Figure 5-20
Finite element calculation of a carbide cutting tool



Cr 4, 42 Cr Mo 4, 20 Ni Cr Mo 2). The high level of consistency between the results of these three projects should be emphasized. Not only were the required properties obtained, but there was also a beneficial effect on carbide tool life (Figure 5-20). This subject was also investigated by Deltasider in collaboration with Fiat (8). This research showed that for Mn Cr grades of cementation steel the calcium treatment promoted an optimal combination of properties (formability, surface hardening characteristics, toughness, and fatigue resistance).

Commercial exploitation of resulphurized and calcium-treated steels is current in Germany, France and Italy.

CSM determined to what degree controlling sulphur contents in 304 and 316 austenitic steels improved their suitability to cold-working (9).

Another project, aimed at improved economy, consisted of reappraising the use of quenching and tempering operations to which mechanical engineering steels are sometimes subjected. A priori, such treatment improves fatigue resistance provided that the hypothesis of purely elastic loads is acceptable.

In reality, due to the effects of stress concentration caused by the shape of the component, it may be that cyclic deformations beyond the elastic zone occasionally occur at certain positions of these components. In other words, it cannot be excluded that during the life of a vehicle, certain critical points of the metal are subjected to a certain number of oligocyclic deformations.

Even though experience shows that the frequency of such situations is extremely low, the fact cannot be ignored that quenched and tempered steels tend to soften under the effect of oligocyclic deformations, thus partly losing the advantages of heat treatment. On the contrary, the air-cooled microalloyed steels tend to harden under the effects of oligocyclic fatigue cycling. This has led to the concept of replacing the former grades of steel by the latter for certain vehicle components.

Several CSM projects carried out in collaboration with Fiat [(10) to (12)] examined this problem. They demonstrated that if the effects of local cyclic (and possibly oligocyclic) deformations are taken into account, predictions of fatigue resistance of different mechanical components are, in road tests, within reasonable limits.

In conclusion, a completely different area, that of turbine rotors, is considered. These are components which have to provide sufficient strength at high temperatures (greater than 300°C) in combination with a certain toughness. The grades of steel concerned are of the 1 Cr Mo V type for high pressure turbines and 3.5 Ni Cr Mo V for low pressure rotors.

The Electrical Power Research Institute in the United States has shown the advantages of reducing the content of not only chemical constituents such as phosphorus, silica, and manganese, but also trace elements, in order to increase the performance of these steels. This gives rise to the concept of 'super-clean' steels. Japanese industry has progressed rapidly in the same direction. Funding by the ECSC and research carried out by Creusot-Loire (13), VDEh and CSM [(14) to (16)] and by CSM in collaboration with Terni (17) mean that the European industry is at the forefront in extending service uses as well as working temperatures.

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(2) 7220-MA/813 — British Steel: 'Steels for precision forging'.

(3) EUR 8998 EN 1984 — British Steel: 'Development of steels for the fastener and cold forging markets by testing under fastener production conditions'.

(4) EUR 10748 FR 1987 — Irsid: 'Simplification de la préparation de surface des barres pour le formage à froid'.

(5) EUR 8626 EN 1983 — British Steel: 'Effects of sulphur and sulphide shape on the properties and machinability of alloy steels'.

(6) EUR 9091 EN 1984 — GKN: 'Enhancement of machinability of forging quality steels'.

(7) EUR 9266 DE 1984 — VDEh: 'Beeinflussung der Sulfidform und deren Auswirkung auf die mechanischen Eigenschaften und die Zerspanbarkeit von Edelbaustählen'.

(8) EUR 10732 IT 1987 — Deltasider: 'Sviluppo di acciai ottimizzati per ingranaggi'.

(9) EUR 12504 IT 1990 — CSM: 'Acciai inossidabili a prestazioni migliorata mediante trattamento al calcio'.

(10) EUR 10283 IT 1986 — CSM/FIAT: 'Promozione dell' impiego di acciai negli autoveicoli mediante la valutazione delle loro proprietà per la progettazione a vita definita (1ª fase)'.

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(12) EUR 11509 IT 1988 — CSM: 'Relazione tra microstruttura e comportamento alla fatica elastoplastica di acciai per impieghi automobilistici'.

(13) EUR 10325 FR 1986 — CLI: 'Influence du silicium sur la durabilité des aciers pour turbines'.

(14) EUR 8580 DE 1984 — VDEh: 'Untersuchungen zur Verbesserung der Gebrauchseigenschaften warmfester Stähle für den Turbinenbau'.

(15) EUR 8262 IT 1983 — CSM: 'Miglioramento delle proprietà di impiego degli acciai resistenti a caldo per turbine'.

(16) EUR 11311 DE 1988 — VDEh: 'Untersuchungen zur Verbesserung des Zeitstand- und Zähigkeitsverhaltens warmfester Stähle für den Turbinenbau'.

(17) EUR 11177 IT 1987 — CSM/Terni: 'Studio delle proprietà microstrutturali di acciai per grossi componenti per impieghi energetici in funzione delle variabili operative nei trattamenti termomeccanici'.

5.4. Electrical engineering (magnetic steels)

The ECSC has helped to promote and coordinate industrial research in the field of electrical engineering steels, for over 15 years.

During the last decade, the accent has been placed on non-oriented grain steels (NO steels). The influence of various manufacturing techniques on these steels, their chemical composition, strip-rolling and annealing operations, as well as the design of manufactured components has been examined.

Two investigations, one carried out by Galiléo Ferraris (1), and the other by British Steel (2), have examined magnetic losses. The influence of sheet thickness has been demonstrated for both NO steels and those with oriented grains. An optimal thickness value has to be determined. For transformers it can be shown that losses can be reduced substantially through correct design of joints employing sheet overlap. Theoretical studies, in combination with experimental observations, have led to the development of models which simulate magnetic flux lines and predict losses in transformer cores due to eddy currents.

The constitution and type of oxide films which develop on steels containing up to 3% of silicon and 2% of aluminium during manufacture have been studied by Stahlewerke Bochum (3).

The Ugine Aciers company in Saint-Chély-d'Apcher has developed a Fe, Si, Al alloy (1.8% Si, 1.8% Al) with very low levels of interstitial elements [(4) and (5)]. The project demonstrated that it was possible to obtain Fe, Si, Al sheet with a pseudo-cubic structure. It was also shown that any improvement in the understanding and control of techniques giving rise to an imperfect cubic structure could be the basis of important industrial developments. In the case under consideration, a new product was obtained which was more suited to use in generators and motors than conventional NO sheet, especially for stators in high power rotating machinery. Initially, tests were carried out in the laboratory; they were then continued as industrial experiments in the form of a pilot project (6).

Terni also demonstrated the interest in extensive refining and removal of inclusions from continuous cast NO steels containing 3% of Si and 0.5% of Al. Ladle metallurgy techniques meant that substantial energy savings were achieved for electrical engineering components by reducing sulphur content to 5 ppm (7).

This same research project also developed a surface coating composed of aluminium phosphate in conjunction with a resin which proved to be both more economical and more environmentally acceptable than the hexavalent chrome coating developed in Japan.

The refining techniques and the new coating were immediately adopted by Terni (1984).

Several projects have been based on the theme of the relations between the metallurgical variables, crystallographic texture and anisotropy of magnetic properties in steels with 1.3 and 3% of Si. This was the case for both CSM and British Steel. The latter company has just completed a research project (8) which provided optimal rolling and annealing conditions for this type of steel, in order to combine low energy losses with low magnetic anisotropy.

This also provided a strip with improved magnetic properties.

This very special field of steel strip for electrical engineering clearly demonstrates the efficiency of research carried out with the support of the ECSC; on the one hand it very often provides results which are rapidly adopted by industry, and, on the other hand, through close contact between Community research personnel, it contributes to avoiding redundancy in research effort.

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(2) EUR 8270 EN 1983 — British Steel: 'Basic properties of grain-oriented electrotechnical steels'.

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(6) 7225-MA/301 — UACG: 'Mise au point préindustrielle d'une nouvelle qualité de tôles magnétiques à grains non orientés pour la construction des stators des machines tournantes de fortes puissances'.

(7) EUR 10134 IT 1986 — Terni: 'Miglioramento delle caratteristiche magnetiche e della proprietà di impiego dell'aécciaio a grano non orientato prodotto in colata continua'.

(8) EUR 12968 EN 1990 — British Steel: 'Low anisotropy non-oriented electro-technical steels'.

5.5. Car body industry (bodywork, structural components, lorry chassis)

We shall examine a field which is characterized by the following points:

(i) heavy competition from alternative materials for non-structural components;

(ii) the use of steel sheet for certain components which is both stronger and thinner (weight savings);

(iii) the importance accorded to the surface appearance of the sheet, to reduce certain manufacturing incidents (galling in press tools), to increase the life span of body plates and to provide an impeccable aspect after painting;

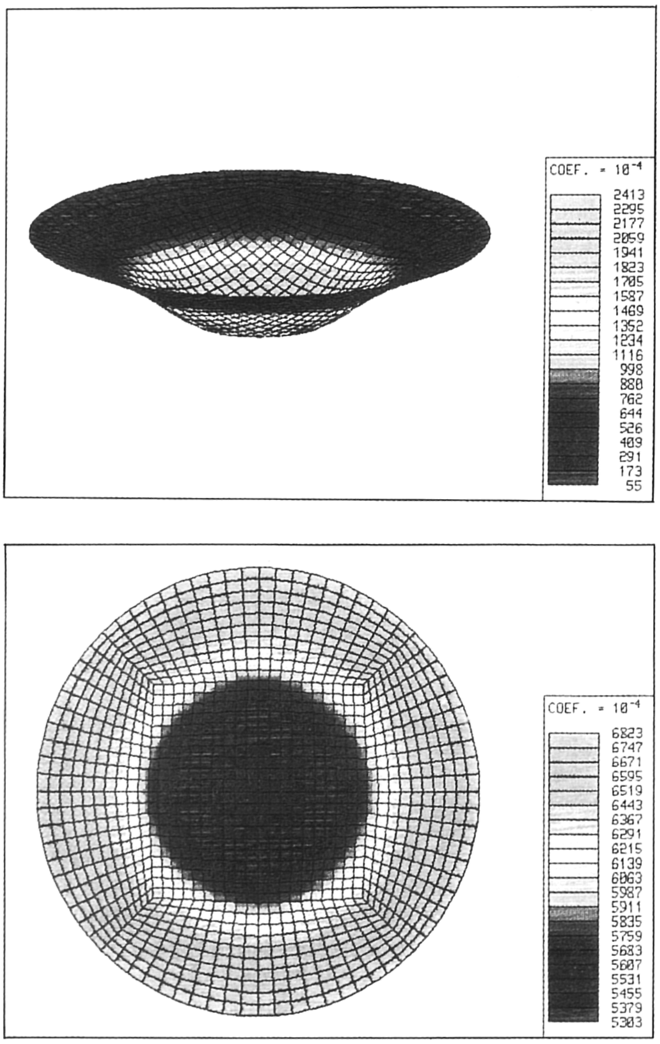
(iv) the need for steel to retain its advantage as an inexpensive raw material.

We shall look at high-strength sheet, then sheet surface qualities, with and without metallic coating.

Before examining these points, a study carried out by Renault, PSA and Sollac (1) (Figure 5-21) into modelling of forming operations is referred to. This is a very topical subject, regardless of the grade of steel sheet concerned. Computer simulation of forming provides major advantages in developing press tooling shapes. Modelling is complicated since it is necessary to calculate large deformations of the sheet in stretching, in drawing, and in plane strain; and the manner in which the metal behaves in the plastic zone is not yet described in a fully satisfactory manner. Models do exist for simulating components with a rotational symmetry. These two-dimensional models have the advantage of being able to describe the complete behaviour on the basis of what happens in a single, cross-sectional element.

The current study consists of developing a three-dimensional finite element programme which can be used for asymmetric components. This model is of the membrane type and thus only constitutes an initial stage.

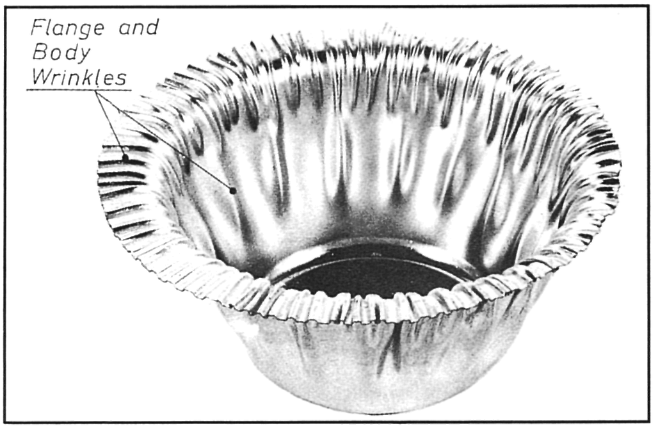
Figure 5-21
Finite element calculation of a cup stamped from a clamped flange; without lubrication (μ = 0.25) (1)

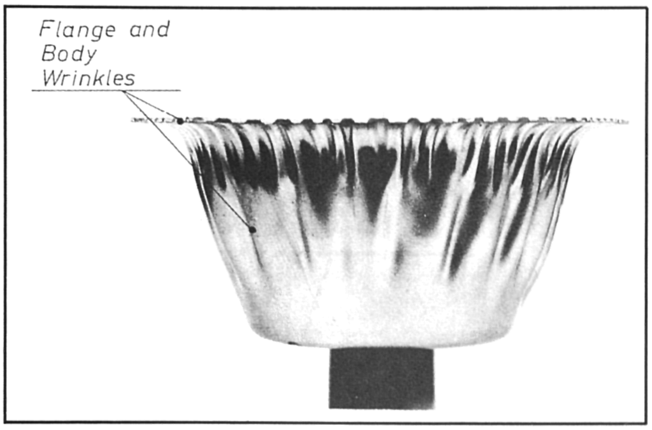


5.5.1. Manufacturing with high-strength steels

Two typical problems encountered during forming operations with high-strength steels are the tendency to form wrinkles, and the spring-back effect.

Figure 5-22
Example of conical cup with wrinkle formation



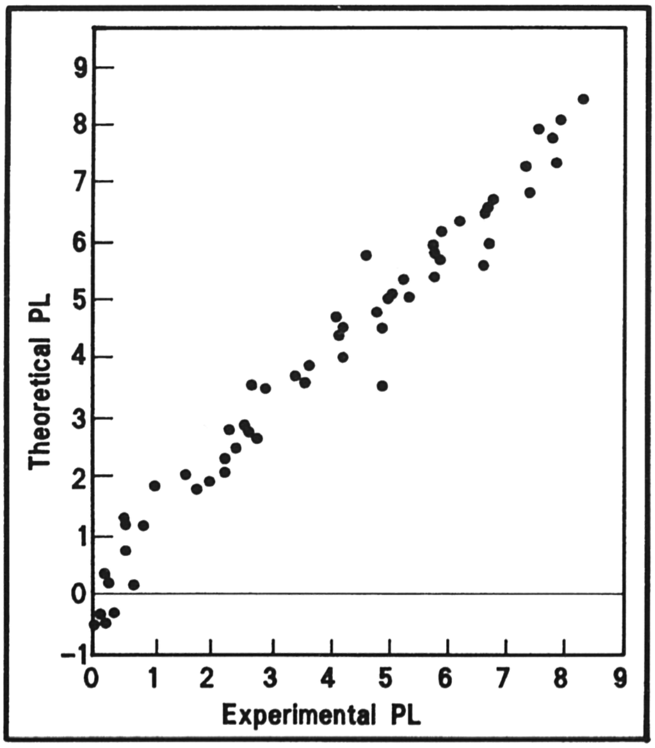


Wrinkles tend to form when compression stresses develop in the plane of the sheet and produce plastic deformation while causing a swelling of the sheet (Figure 5-22).

As British research (2) has demonstrated, this effect is promoted by an increase in the elastic limit of the strip, and a reduction in its thickness, as well as a low value for the coefficient of plastic anisotropy (Figure 5-23).

The spring-back effect can occur during forming. As soon as the contact between the tool and the steel sheet is removed, the elastic recovery of the sheet deforms the angles that have just been formed. This effect can be allowed for and the shape of the tool corrected, but it is vital that the spring-back effect remains constant from one batch of sheet to another. CRM has developed a mathematical model for simulating the spring-back effect (3) in plane strain, which provides a method of quantifying the influence of variations in characteristics such as the elastic limit of the sheet, its thickness as well as wear in the tooling. The importance of wear in the tooling has thus been demonstrated. The model can also allow for a concomitant phenomenon known as 'curling'. The validity of the CRM model has been confirmed by several constructors including DAF trucks.

Figure 5-23
The tendency to form wrinkles may be expressed by a coefficient PL which depends upon the thickness (t) of the sheet, its elastic limit value (Ys), its ultimate yield strength (Ts), the value of its work-hardening coefficient (n) and its plastic anisotropy (v) (2)

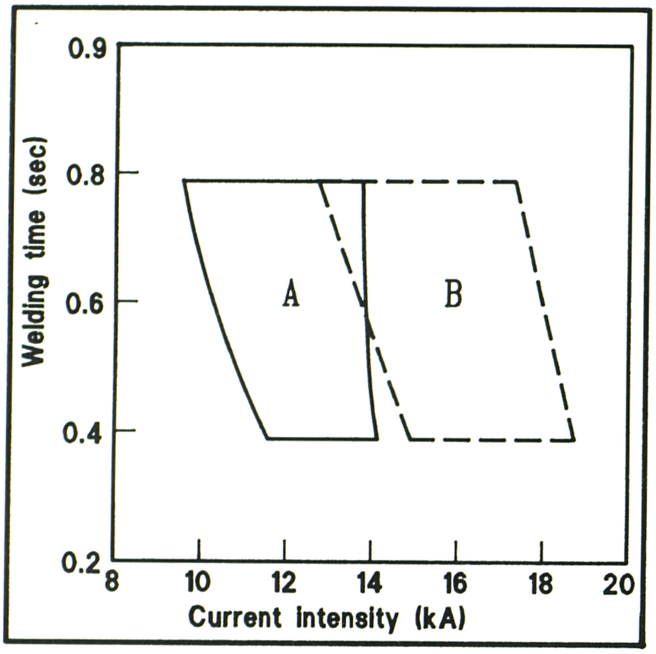


In the research projects carried out over this decade, special attention has been paid to those grades of steel having a relatively low initial elastic limit and which can harden considerably through work hardening during forming operations (strain hardening) and by being heated above 150°C (bake hardening) in baking ovens for automobile bodies after painting. This is particularly true for certain rephosphorized steels and steels with a double-phase structure.

A project to investigate the in-service behaviour of structural components manufactured from hot-rolled 2 to 5 mm-thick sheet of double-phase structured steels, has just been concluded by Irsid (4) in collaboration with Sollac, Renault, and PSA. It was demonstrated that using current manufacturing techniques for components such as suspension arms and shock-absorber housings, deformations in the critical zones and reductions in thickness are more favourably spread in the case of components manufactured from double-phase steels rather than from microalloyed steels. It was also shown that the sensitivity of edges to slitting was not greater than that for mild steels provided that the play in the punch tooling was limited to between 5 and 10%. Finally, a method for estimating damage caused by cutting out and its influence on the fatigue limit was tried out with success.

Spot welding of high-strength, microalloyed, rephosphorized and double-phase steels was investigated by British Steel (5) both for setting up the welding equipment, as well as acceptance criteria for checking com-

Figure 5-24
Comparison of weldability zones for 2.1 mm-thick steels microalloyed with niobium (A) and titanium (B)



pleted spot welds (Figure 5-24). In particular, it was shown that the straightforward transposition of the results of tests developed for mild steels, carried out at shop-floor level, was open to discussion.

The Welding Institute delimited the influence of welding equipment and current generators on evaluating the weldability and the conclusions to be drawn in defining welding schedules (6).

5.5.2. In-service behaviour of high-strength steels

The main theme was the fatigue behaviour of structural components. We have already mentioned above the evaluation of edge damage caused during cutting out and its influence on fatigue limits.

For spot welds, CSM has combined data from published works with its own laboratory test results into a single rule which determines the number of cycles N as a function of the corresponding stress amplitude (s_a), the stress amplitude (s_A) for 2.10^6 cycles and a K coefficient denoting the probability of survival:

$$N = 2.10^6 (s_a/s_A)^{-K}$$

For example: K = 3.5 for a 90% probability of surviving. The influence of the distance between spot welds has also been examined (7).

The use of hot-rolled, high-strength steel strip for manufacturing lorry chassis has been investigated by SSN (8). Special attention was paid to comparing the fatigue resistance of joints made by rivetting with those by welding. Graphs of service life under constant and variable loads were developed for typical configurations.

It should be remembered that one of the reasons for introducing microalloyed steels into automobile mechanical engineering at the expense of quenched and tempered steels was their ability to harden under the effect of small alternating and occasional plastic deformations, as compared to the quenched and tempered steels.

It is not impossible that such deformations occur locally in structural components of the bodywork (Figure 5-25). The behaviour, under such conditions, of different types of high-strength steels was studied by British Steel (9). It was demonstrated that there is no fear of decohesion for steels having a continuous tensile curve without any apparent yield.

CRM terminated a study (10) which proposed evaluating the strength of components where there exists critical points susceptible to occasional oligocyclic deformations, by means of a concept known as 'evolutive tensile curves'. It was on the basis of this work that rephosphorized steels were successfully employed for the floor panels of certain models of car.

Figure 5-25
Example of recording dynamic forces on a critical area of a vehicle component using strain gauges
(Under extreme conditions on a test track, forces exceeding the elastic domain are superimposed on the 'background noise'. That these forces may arise occasionally during the life of a vehicle is a factor that should not be neglected. This factor is taken into account when selecting the characteristics and composition of the steel to be used)

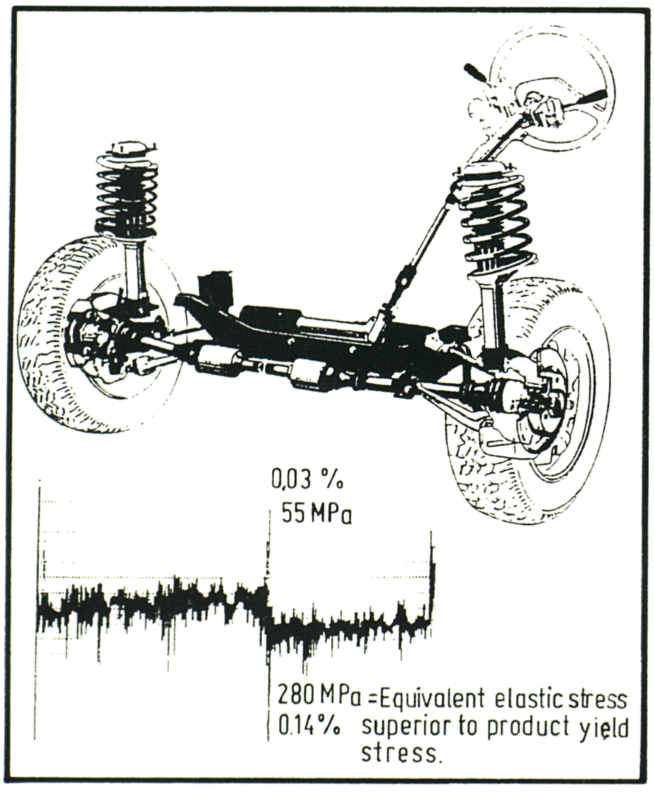


Figure 5-26
Laser roughness

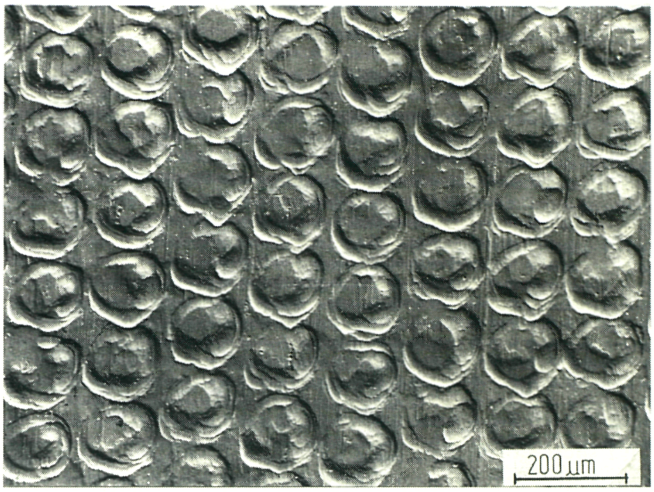
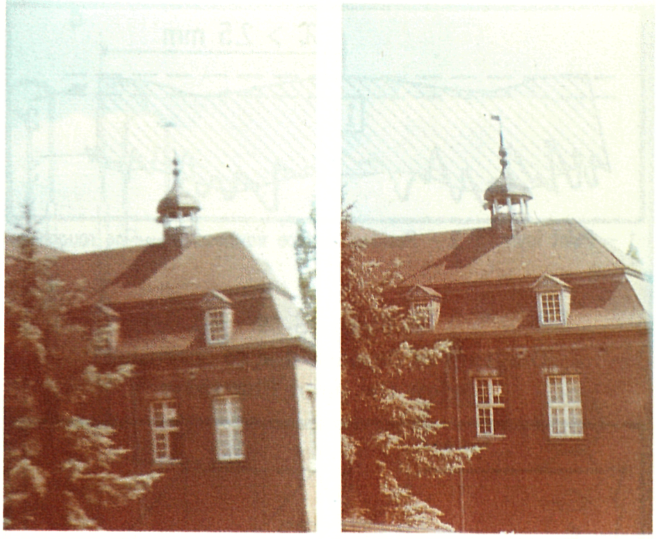


Figure 5-27
The clarity of the image reflected in the painted bodywork is an important factor in its finished appearance [(16) and (17)]



A very large research project was carried out by five German steel manufacturers and the Porsche Development Centre with the objective of determining the basic principles for using cold-rolled microalloyed and rephosphorized steels in the automobile bodywork industry [(11) and (12)]. The manufacturing and in-service behaviour were analysed. The main conclusions were as follows:

(i) forming requires that component design be well suited to the characteristics of high-strength steels. The main problem is that of the spring-back effect;

(ii) welding does not pose any particular problems;

(iii) dynamic indentation tests (doors and sills) show that a stronger steel can be reduced in thickness by 10%;

(iv) crash behaviour also favours high-strength steel; the thickness of structural components can be reduced by 20% by doubling the elastic limit;

(v) noise levels inside the vehicle are the same as for mild steel;

(vi) scrap can be recycled;

(vii) the proportion of high-strength steel that could be introduced into automobile bodywork is estimated to be 15 to 20%.

5.5.3. Sheet surface finish and manufacturing with steel: in-service behaviour of coated steels

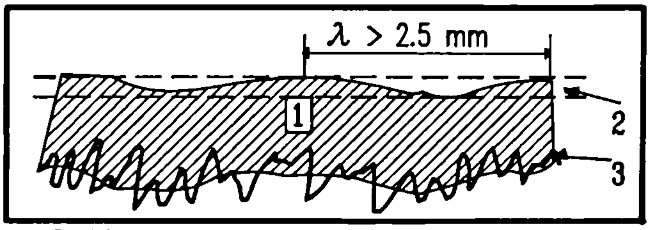
Contact between the steel sheet and the press tools is an important aspect of forming operations. Friction depends upon many factors, which strangely enough had not been systematically studied for the case of forming. This means that the choice of a suitable coefficient of friction to be adopted, for example, in a mathematical model of forming, had previously been purely empirical. CRM attempted to fill in this gap. In a research project (13), the relative importance of the roughness of the tooling, the sheet, the lubrication and the state of deformation, and finally the clamping forces exerted by the blank holders, was determined. The experimental methods adopted for measuring friction under the different situations encountered during a forming operation (in the draw beads, in the die corners, and in the blank holders) were analysed and perfected. In the end, several friction models were developed, each taking into account a limited number of parameters, which were then linked together.

A limit case is produced when, during a long production run forming components, the accumulation on the press tooling of fine metallic particles removed from the sheet produces an instability in the friction parameters which causes galling.

British Steel (14) confirmed the role played by surface roughness of the sheet in this type of incident in preparing rolling mill rolls by gritblasting or electro-erosion. The frequency of galling incidents can be decreased if the depth and the length of the pattern forming the roughness profile respects certain rules.

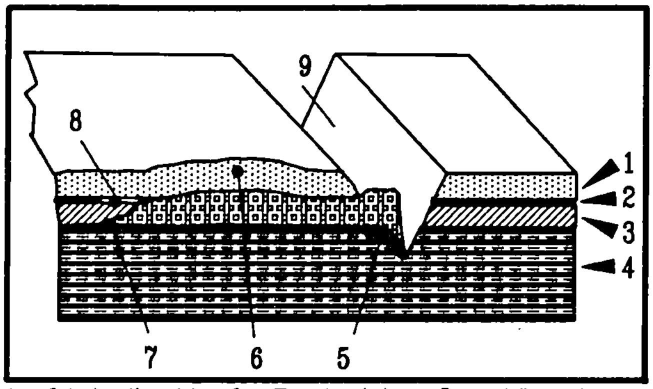
CRM demonstrated the advantages of roughness composed of patterns that are regular in shape and have an optimal dimension such as may be obtained by laser beam roughness engraving of skin-pass rolling mill rolls (15) (Figure 5-26). This type of specified roughness is completely new, and the parameters employed in defining conventional roughness are no longer suitable. CRM has thus proposed new (16), more suitable parameters for defining the ability of these new roughness patterns to diminish the tendency to gall, and to improve appearance after painting.

Figure 5-28
The clarity of the reflected image is mainly influenced by the waviness of the painted surface [(16) and (17)]



1 – Paint layer. 2 – Residual surface waviness. 3 – Fine roughness.

Figure 5-29
Diagram of damage due to corrosion below the paint film (20)



1 – Cataphoretic paint. 2 – Zinc phosphate. 3 – Metallic coating.
4 – Steel. 5 – Corrosion products. 6 – Blistering.
7 – Leading edge of damage area. 8 – Cathodic delamination. 9 – Scratch.

Our understanding of surface roughness has greatly improved over recent years. This is confirmed by a research project (17) in which CSM explained the influence of surface roughness on the final appearance after painting. An attractive finish for bodywork is not due to the gloss, but to the ability of large surface areas (bonnets and door panels) to reflect clear images of the surroundings (Figure 5-27). In fact, a mirror deforms images when its surface is not perfectly flat. If we transform this concept to painted sheet, we can consider that the effect is due not to the fine surface roughness which is buried in the paintwork (Figure 5-28), but to the amplitude of surface waviness with a wavelength greater than 0.25 mm which is not completely hidden by the paint layer. CSM has characterized this surface condition by a new parameter known as LAMM. This research has also shown that forming operations may influence the surface morphology and the appearance after painting. From a practical point of view, it confirms, as does research work (16), the importance of grinding cold-rolling rolls to avoid waviness of the sheet.

Sheet with a zinc-based coating is widely employed in increasing the life of bodywork panels. CRM has studied certain aspects of forming and welding these sheets, as well as their behaviour in the electrophoretic paint baths (18). Irsid has investigated adherence of these products (19) and their behaviour in the phosphating baths (20) (Figure 5-29).

The opportunities offered by bonding thin sheets have been actively investigated by British Steel which has just finished a project (21) in collaboration with Austin Rover in manufacturing formable sandwich panels which can provide weight savings for certain vehicle components.

Studies of coated products have also provided certain conclusions concerning the in-service behaviour of the various types of coating tested (electrolytic zinc, minimized hot-dip galvanized Fe Zn, Fe Ni, Zn Al alloys) and their corrosion resistance classification. CRM has compared accelerated corrosion tests under actual conditions. Actual conditions are taken to mean the exposure of samples beneath urban buses for several years (18). Marked differences have been noted between the classification of product life under actual conditions compared to that obtained from saline mist tests.

5.5.4. Metallurgical factors and in-service properties

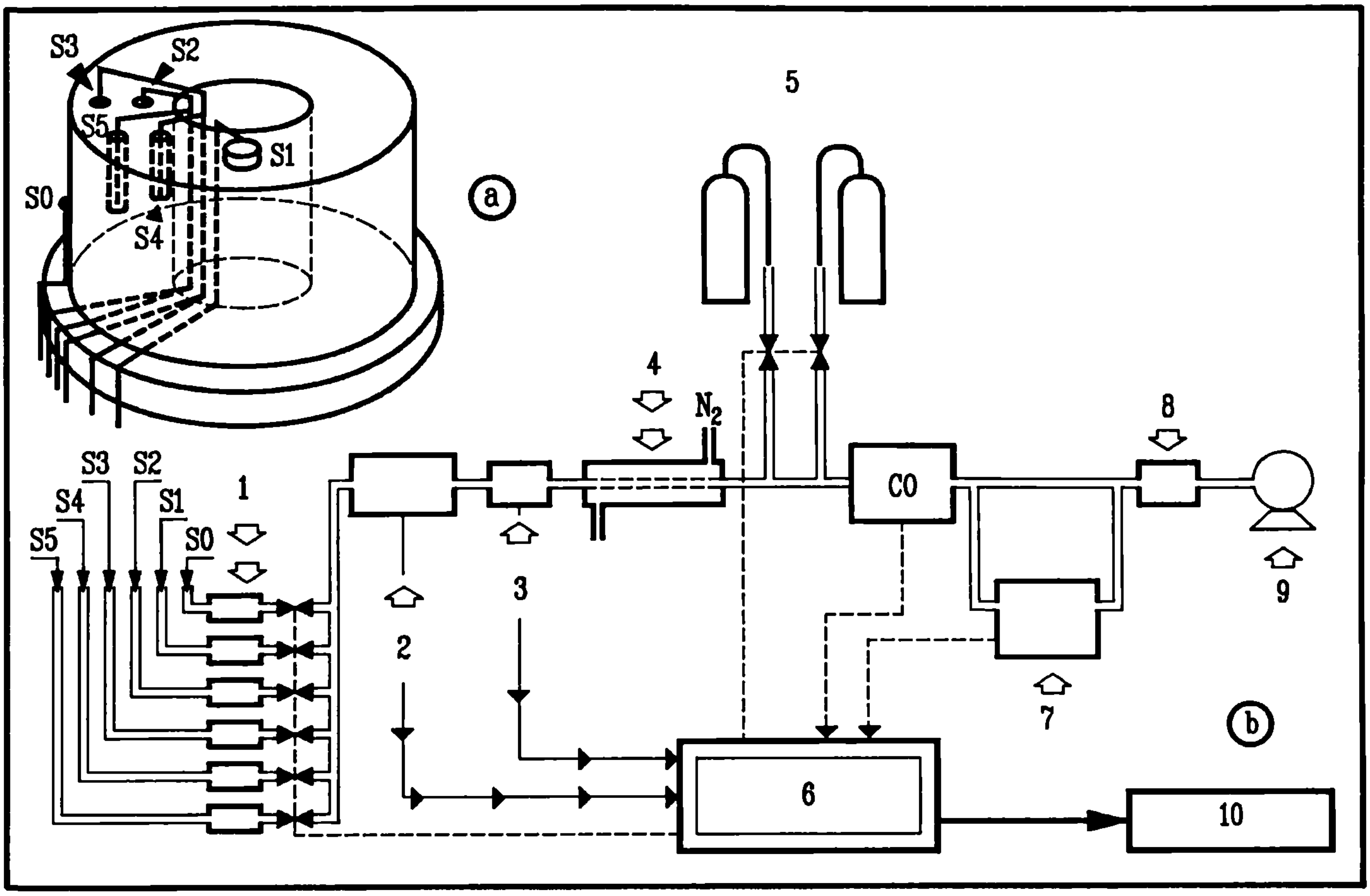
Thin sheet and hot-rolled strip are steel products on which much research has been carried out in relating manufacturing cycles (pickling, rolling, annealing, coating techniques), microstructures and service properties.

The amount of effort made can be explained by the following remarks:

In its attempts to improve corrosion resistance, the automobile bodywork industry requested sheet with a surface suitable for rapid phosphating and which favoured the formation of thick, high-adherence layers, in particular a surface free of difficult-to-remove carbon residues. Sheet with a clean surface was also needed in order to be able to apply metallic coatings using electrolytic techniques.

The steel manufacturers were deciding whether to install continuous annealing plants and which types of installations provided the best thermal cycles. The aim was to provide a wide range of grades and, in particular, high-strength steel sheet for forming and drawing operations (a compromise between the elastic limit and the coefficient of plastic anisotropy), sheet suitable for work hardening in the presses or for ageing in the baking ovens of bodywork paintshops (double-phase steels, pseudo-rimming mild steel sheet). Those grades considered suitable for tinning were also products of interest.

Figure 5-30
Principle of system for analysing gas trapped between the turns of a coil in an annealing oven (27)



1 – Filters. 2 – Dewpoint. 3 – Thermic flowmeter. 4 – Permatube. 5 – Gas for calibration. 6 – Data logger. 7 – Mass spectrometer. 8 – Flowmeter. 9 – Pump. 10 – Results.

For the surface condition of the cold-rolled strip, annealed in bell ovens, it was necessary to comprehend the formation of carbon residues and then to discover the remedies.

CRM followed the evolution of surface chemistry starting from the hot-rolling stage and in particular during pickling [(22) and (23)]. British Steel and Hoesch demonstrated the mechanism of formation of amorphous carbon during annealing by the cracking of ferruginous soaps derived from certain components of the oils and greases used in the cold-rolling mills [(24) to (26)]. Through sophisticated manipulation, CRM was able to analyse the reactions between the gaseous phase and the metallic surface within the layers of the coils inside the industrial bell ovens (27) (Figure 5-30).

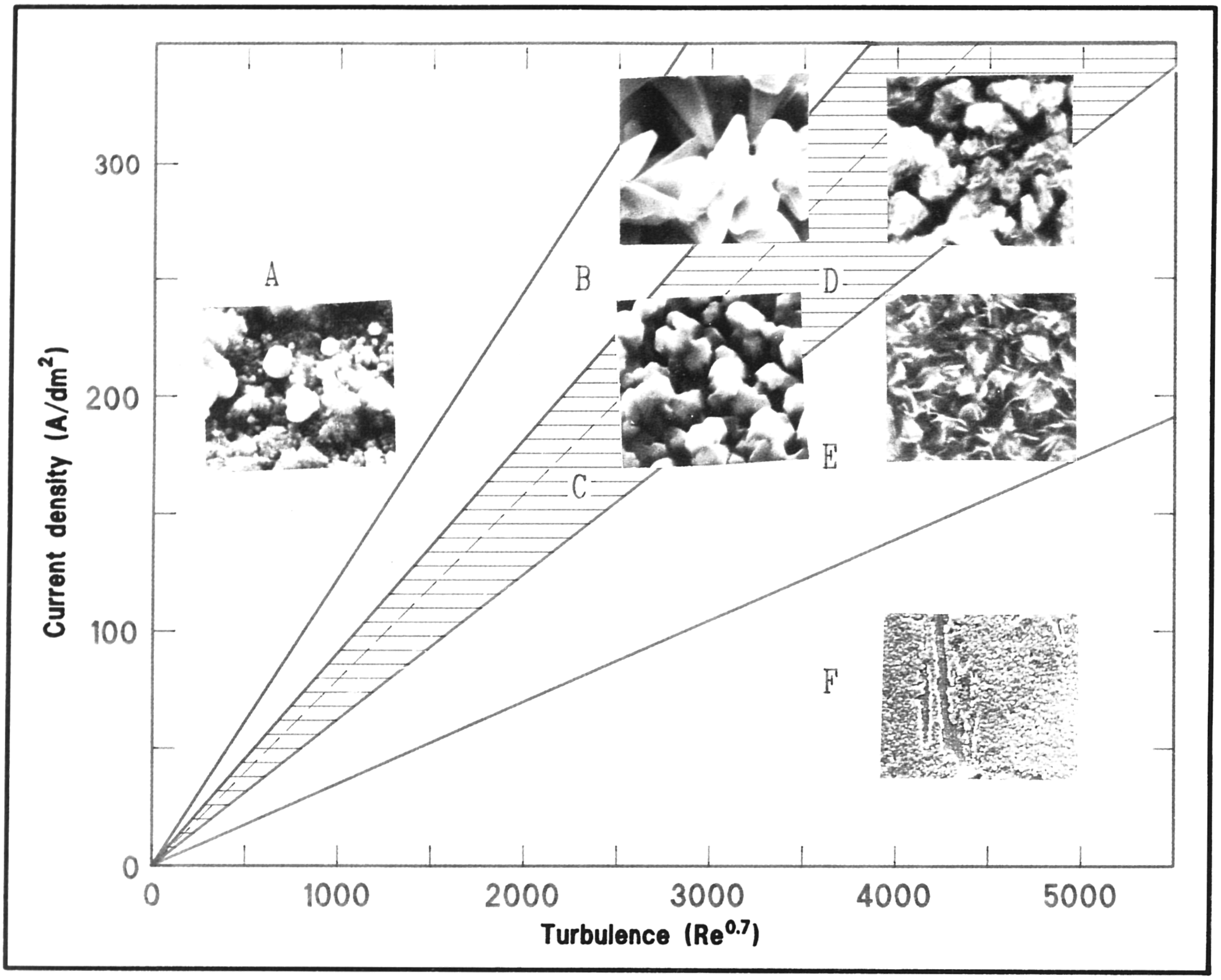
The remedy suggested by this research work consisted of rendering the metal surface slightly oxidizing. CRM proposed injecting water vapour into the oven atmosphere under controlled conditions during a precisely defined period of the thermal cycle (27).

Research was undertaken, in particular by CSM (28), into the suitability for phosphating, and the influence of the surface chemistry and certain segregations between grain boundaries on the nucleation of phosphate crystals.

This institute also distinguished itself in developing a new, electrolytic pickling technique under neutral conditions. Research (29) showed that it was applicable to both hot- and cold-rolled strip.

CSM studied electro-deposition in high current density cells (30). A micrographic examination of the samples demonstrated correlation between coating structure and galvanizing conditions: current density and dynamic behaviour of fluids (Reynolds number). If the fluid speed is increased, for a fixed current density, and all other parameters remain the same, the coating appearance changes systematically, passing successively from a powdery structure, to a compact poly-oriented structure, then to a compact mono-oriented, acicular, and spongy structure. It has been proven that high corrosion resistance is obtained from a mono-oriented coating of zinc. Tests on a pilot scale have allowed the conditions for obtaining this type of deposit to be defined (31) (Figure 5-31).

Figure 5-31
Diagram showing the morphological phases of zinc deposits as a function of applied current density and the turbulence in the electrolytic solution



A – Powder phase (low adherence). B – Dendritic phase (low adherence). C – Mono-orientated phase (good adherence).
D – Compact crystalline phase (good adherence). E – Acicular phase (satisfactory adherence). F – Discontinuous phase (satisfactory adherence).

CSM also developed a coating composed of zinc, chrome and chrome oxides (32). Using an existing pre-coating line at Zincor, consisting of four radial galvanizing cells and a vertical cell for rapid electrolytic deposition of a chrome/chrome oxide layer on top of a zinc layer, this coating demonstrated on a pilot scale that it was possible to obtain a very high-performance multi-layer coating (33).

The corrosion resistance of multizincrox is almost three times higher than that of galvanized steel for the same weight of zinc coating. It also demonstrates excellent painting qualities and good spot weldability. The factor of improvement in life expectancy is of the order of four or five times that of electrozinced phosphated.

Let us examine the subject of continuous annealing and research into the various possibilities of this process.

Irsid, in a research project (34), set a target of manufacturing sheet with so-called 'balanced' properties. This means combining an elastic limit of 350 MPa with a coefficient of plastic anisotropy of 1.4. To achieve this, the hardening effects due to microalloying elements and elements in solid solution (P) have been combined by associating the advantages of continuous annealing.

CSM has concluded that it is possible to obtain three classes of formable steels (elastic limits between 320 and 420 MPa) from the same hot strip microalloyed with niobium, which is cold-rolled, and subjected to different annealing temperatures (35).

CRM was interested in a completely different field — in particular, in establishing how to obtain grades for drawing (DQ and DDQ), with an elastic limit below 190 MPa, low hardening characteristics at ambient temperatures, capable of hardening in the bake ovens of painted bodywork, using low-aluminium steels and produced in combined blowing steelworks or under moderate vacuum. The solution consists of adding suitable amounts of boron and titanium, combined with a specific coiling temperature (36). The results of this research have been applied industrially. The possibilities of continuous annealing for the production of grades suited to tinning have also been investigated by CRM (37), in the case where quenching is achieved with boiling water.

Thin strip with a double-phase structure constitutes another possible application of continuous annealing.

It is also possible to obtain this type of microstructure in hot strip, using a conventional rolling mill. In this case, the problem is in avoiding or limiting steel additives of costly chemical elements such as molybdenum. For the first point, research by CRM (38) and CSM (39) provided comparisons between the respective merits of steels (Mn, Si) and (Mn, Cr) and different thermal cycles in the case of intercritical annealing.

British Steel (40) demonstrated the possibility of obtaining a range of grades with double-phase structures (ultimate stresses ranging from 550 to 350 MPa), with (Cr, Si) steels provided that the hot-rolling and coiling conditions ensured a fine microstructure and that intercritical annealing was performed at a temperature low enough to avoid grain growth.

For hot-rolled strip, CSM (41) and British Steel (40) concluded that it was possible to obtain a double-phase structure with a chemical composition of the type: 1% Mn, 1% Si and 0.2% Mo. The process becomes unstable if the molybdenum is omitted.

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5.6. Packaging

Certain research projects mentioned in the previous chapter are of interest for sheet intended for packaging purposes, as is the case for those projects involving continuous annealing and in particular a project by CRM (1). A limited number of projects are specific to the field of packaging.

British Steel contributed to the development of very thin sheet (2) using double reduction. It was thus possible to define what specifications could be required of a product with a final thickness of 0.1 mm on the basis of the initial chemical analysis, the rolling process and the alternative of final annealing. Processes were tried which differed in the degree of reduction in successive rolling stages and in conditions of any final annealing. Certain solutions require further investigation since their economic viability is not obvious despite the attractive properties of the final product which provides excellent formability and low planar anisotropy which very significantly decrease the size of the earings. It was also considered that the products showed future potential in the form of composites (thin sheet, plastic film), as well as in the development of novel shapes for packaging.

A research project that has been completed by Hoogovens (3) suggests that the cost of tin cans can be reduced using a new method of manufacture. This process consists of manufacturing a long cylindrical can in a single extrusion process, and then dividing this can into two components. The one which already has a base becomes a two-piece can (body + lid) while the other one provides a three-part can (seamless body + two lids). The study has demonstrated the feasibility of the process following manufacturing tests on cans 75 mm in diameter and 58 mm high.

Compared to the conventional manufacturing processes, the economy in materials is estimated to be between 10 and 20% according to the specific case.

The first stages of a pilot industrial production unit are to be set up in the near future.

Rasselstein has studied the influence of materials on high productivity welding of the longitudinal seams of cans for jam with diameters between 52 and 99 mm. High productivity welding is taken to mean high-speed seam welding (50 m per minute). The results obtained illustrate the importance of the ability of the sheet to adopt the rounded shape of the can in the machine (negative influence of the spring-back effect on the fit up). This suitability is thus influenced by the elastic limit of the metal. Concerning operating conditions, it should be remembered that the current intensity must be adjusted according to the thickness of the tin layer. A coating of at least 1 g per m^2 is required. The report also shows the results of corrosion (4).

In the field of uses for tinplate, Rasselstein, in collaboration with British Steel and Hoogovens, has ventured into developing steel drink-can lids and has set up a pilot production line (5) (Figure 5-32).

Figure 5-32
Packaging cans incorporating a new design of steel lid, shown stacked for corrosion testing

As a basis for this development work, the contractors have acquired a licence from Broken Hill Proprietary Company Ltd, Australia, for a twin-opening device: one acts as a vent and one for pouring. Development work has looked at tooling for cutting out and forming, at the type of anti-corrosion coating for the metal and at the organic joints providing sealing of the openings and the assemblies, and finally at details concerning the geometry of the vents. The corrosion-resistance conditions — less than 1 ppm of iron dissolved after six months; and pressure resistance (7 bar) — imposed by the end-users have been met. Engineering work on the production lines capable of producing up to a billion lids per year has been completed.

Launching several million all-steel cans on to the market has made it possible to appreciate the excellent acceptability of this type of lid by consumers, presenting the notable advantages of improved recycling (a single metal), substantial energy savings and an improvement in environmental impact through the use of non-detachable tabs. This represents a potential market opening of 150 000 tonnes per year for the tinplate producers.

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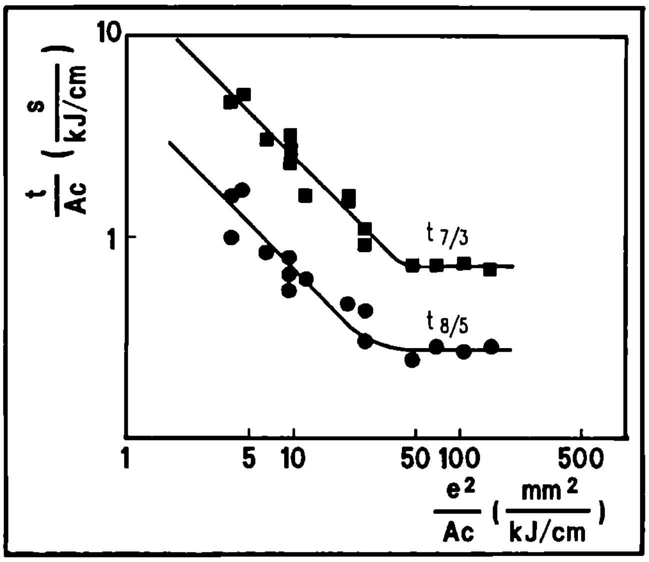
5.7. Basic research

Alongside the applied research which has been discussed so far, a certain number of research projects of a more theoretical nature have also benefited from ECSC support. These research projects are not necessarily oriented towards one or the other specific field of steel utilization, but are intended to develop basic knowledge liable to improve our understanding of the behaviour of metal, to develop new steels, or to progress towards new manufacturing techniques. We shall comment briefly on some of them as examples.

The development, in the field of analytical techniques, of the third generation of image analysers capable of supplying sophisticated information about the microstructure of the metal has meant that the best methods of employing this information in predicting metal properties have had to be revised. Several institutes have worked in parallel. MPI (1) has looked into the evaluation of inclusions and their consequences on the ductile values of the transition curve. CRM (2) adopted the theme of heterogeneity of grain size and its influence on toughness and tensile properties. Irsid (3) has developed algorithms for describing grain shape, their distribution and their dimensions, as well as localizing inclusions with the end goal of fully automated analysis.

Figure 5-33
CO_2 laser welding
The characteristic heat flow parameters, i.e. the cooling time from 800°C to 500°C (t 8/5) and from 700°C to 300°C (t 7/3) can be calculated from diagrammatically presented rules based on energy input (Ac) from the laser beam and the sheet thickness (e). The position of the curves on the graph depends upon the proportion of the energy reflected by the sheets



British Steel has specialized in the description of fracture mechanisms. During the previous decade, a model had already been developed for the quantitative evaluation of fatigue crack growth under varying amplitude loads (4). A second model has been developed more recently for evaluating the behaviour of cracks in the case of fatigue-corrosion. The success of this model lies in its ability to predict the fatigue-corrosion phenomenon in marine environments, taking into account local hydrogen embrittlement and blunting of the crack tip by anodic dissolution. This model is used to describe the effects of cyclic load frequency and shape, as well as those of cathodic polarization.

A third study in which British Steel and CSM [(5) and (6)] collaborated, concerned the analysis of damage to steels in high temperature service. The damage has been correlated with the number of pores which form at the grain boundaries and their growth, and also with the analysis of carbide precipitates. This work represents an important contribution to evaluating the residual service life of metallic components operating at high temperatures.

MPI investigated the development of high-strength, low-carbon steels in which the microstructure is formed of lanceolated martensite. A yield strength of 1 800 MPa was recorded in conjunction with an elongation at failure of 15%. At the current stage of development, toughness remains a weak point (7).

This institute has also envisaged the possibility of forming ultra-thin superficial layers, providing the underlying steel with a temporary protection against corrosion. Such layers could be produced on coils of thin strip during their annealing, using the CVD technique, i.e. forming a layer by chemical reaction between a vapour or gas, and the metal surface. Possibilities exist using gaseous mixtures ($TiCl_4$, N_2, H_2) or (NH_3, H_2) at 700°C (8).

Welding has also been the subject of basic research and we shall mention two research projects which widely differ, although their point in common is joined assemblies without any exterior filler material. The Welding Institute has studied joints made using diffusion techniques at a temperature of 600°C in order to obtain the same characteristics as those of the base metal (9).

Irsid investigated laser beam welding, which offers many possibilities for thin sheet both for the rolling mill operator (joining coils) as well as steel-users.

Working with CO_2 laser beams with power ratings ranging from 1 to 7 kW, the data concerning the welding heat fields and the penetration have been formulated as a function of the power of the beam, the thickness of the sheet and the welding rate (Figure 5-33). Microstructural modifications and the properties of welded joints using current grades of steel have also been studied (10).

Irsid has studied the influence of the microstructure and inclusions on the cold drawing behaviour of typical grades of steel for forming. This work has allowed conditions for a rigorous analysis of the phenomena occurring during the process to be defined. It has opened the way for substantial savings by showing how to avoid too strict requirements, and overestimations of the restrictions to be imposed on steel (11).

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EUR 13782 — Ten years of research and development — 1981-92

J. Ferron

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Over the last decade, the European steel industry has been subject to profound changes, with, on the one hand, the modernization of production plants allowing high levels of productivity with large savings in energy and raw materials requirements to be achieved, and, on the other hand, the development of grades of steel for which the quality, dimensional tolerances and characteristics of use have, for many of them, little in common with previous products.

The R&D efforts undertaken by the European steel industry, despite the crisis which has prevailed for the greater part of this decade, have played a vital role in the success of these changes.

This report, which is illustrated and includes an extensive bibliography, will provide steelmakers as well as planners with greater details of the effort made over these years and will also help in locating the many references included in this document, both for the manufacture of steel as well as its use.

A special chapter is devoted to research work being carried out in parallel under several other ECSC programmes in the field of environmental protection and social research work: health and safety at work, ergonomics, industrial medicine, use of by-products.

It should be noted that the collaborative work that has been set up between Community researchers has also meant that redundancy of effort has been reduced, that much larger and longer-term projects which exceed individual financial capabilities have been able to be undertaken, and that it has also created suitable conditions for the development of a true European spirit, as demonstrated by many Community synergies.

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