

Continuous Casting of Steel

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CONTENTS

SUMMARY	xi
1 INTRODUCTION	1
1.1 Historical background	1
1.2 Description of the Continuous Casting Process and the Evolution of Machine Design	7
1.2.1 Brief Description and Basic Principles of the Continuous Casting Process	7
1.2.2 Evolution of Machine Design	13
1.3 Advantages of Continuous Casting over Ingot Casting	18
1.3.1 Improved Yield	19
1.3.2 Reduced Energy Consumption	20
2 LIQUID STEEL SUPPLY	22
2.1 General details	22
2.2 Compositional Control	22
2.2.1 Carbon Removal for Low Carbon Strip Grades	24
2.2.2 Hydrogen Removal	24
2.2.3 Sulphur Removal and Control	24
2.2.4 Nitrogen Removal and pickup	25
2.2.5 Oxygen Control	26
2.3 Temperature Control in Ladle and Tundish	28
2.4 Tundish Technology	30
2.5 Ladle to Tundish Teeming	32
2.6 Tundish to Mould Teeming	33
3 MACHINE COMPONENTS, HEAT TRANSFER AND STRAND SOLIDIFICATION	37
3.1 Mould Technology	37
3.1.1 Mould Design Details	37
3.1.1.1 Mould length	40
3.1.1.2 Mould Materials	40
3.1.1.3 Mould Oscillation	40
3.1.1.4 Variable Width Moulds	43
3.1.1.5 Moulds for twin and triple casting	44
3.1.2 Mould Heat Transfer	44
3.1.2.1 Affect of Cooling Water Flow Rate	51

3.1.2.2	Affect of Mould Lubrication	51
3.1.2.3	Affect of Carbon Content	52
3.1.2.4	Affect of Casting Speed	54
3.1.2.5	Temperature Distribution in Copper Plates	55
3.1.2.6	Heat Transfer Measurements on a Slab Mould	55
3.2	Strand Support Systems and Secondary Cooling	58
3.2.1	Strand Support System Details for Various Machine Types	58
3.2.1.1	Below Mould Support System for Slabs	59
3.2.1.2	Main Strand Support Systems for Slab Casters	60
3.2.2	Secondary Cooling	62
3.2.2.1	Spray Cooling with Water Only	66
3.2.2.2	Spray Cooling with Water and Air (Air Mist)	67
3.2.3	Roller Design and Performance	68
3.3	Strand Straightening and Strand Withdrawal	72
3.3.1	Strand straightening	72
3.3.1.1	Strand Completely Solidified	73
3.3.1.2	Straightening with a liquid core	73
3.3.1.3	Straightener design	74
3.3.2	Strand Bending	76
3.3.3	Withdrawal Units	78
3.4	Computer Simulation Models	79
3.4.1	The Strand Solidification Model	80
3.4.2	Strand Deformation Model	82
3.4.2.1	Critical Strain Levels	87
3.4.3	Roller Temperature and Deflection Models	87
4	PRODUCT REQUIREMENTS AND FACTORS AFFECTING AS-CAST QUALITY	93
4.1	Categorisation of Final Products and the As-cast Quality Requirements	93
4.2	Affect of Chemical, Process and Engineering Parameters on Surface Defects	95
4.2.1	Categorisation of Surface Defects	95
4.2.2	Compositional Factors	96
4.2.2.1	Peritectic Grades	96
4.2.2.2	Grain Refined Steels	98

4.2.2.3	Affect of Residuals such as sulphur and phosphorus	100
4.2.3	Mould Parameters	103
4.2.3.1	Mould Level Control	105
4.2.3.2	Mould Lubrication	106
4.2.3.3	Mould Oscillation	112
4.2.4	Secondary Cooling	118
4.2.4.1	Below Mould Cooling	118
4.2.4.2	Hard and Soft Cooling for Production of Grain Refined Steels	119
4.2.5	Machine Geometry	120
4.2.5.1	Machine Alignment	120
4.2.5.2	Strand Straightening	120
4.3	Effect of Chemical, Process and Engineering Parameters on Internal Quality	120
4.3.1	Categorisation of Internal Defects	120
4.3.2	Casting Temperature	122
4.3.2.1	Effect on Steel Cleaness	122
4.3.2.2	Effect on Internal Structures	122
4.3.3	Electromagnetic Stirring (EMS)	129
4.3.3.1	EMS on Billet and Blooms	130
4.3.3.2	EMS on Slabs	135
4.3.4	Compositional Factors	138
4.3.5	Machine Geometry	140
4.3.5.1	Affect on Inter Columnar Segregation	141
4.3.5.2	Affect on Centreline Segregation	143
4.3.6	Secondary Cooling	147
4.3.7	Casting Speed	149
4.4	Geometrical Defects	150
5	SPECIAL PROCESSES AND EMERGING TECHNOLOGIES	156
5.1	Horizontal Casting	158
5.2	Beam Blank Casting	162
5.3	Thin Slab Casting	165
5.4	Strip Casting	173
6	PROCESS CONTROL AND ANCILLARY EQUIPMENT	177
6.1	Automatic On-line Process Control Systems	179
6.1.1	Tundish Level Control	179
6.1.2	Automatic Mould Level Control	179
6.1.3	Secondary Cooling Water Control	182

6.1.4	Automatic Start of Casting	185
6.1.5	Automatic Mould Powder Feeding	186
6.2	On-Line Monitoring Systems	186
6.2.1	Detection of Slag from the Ladle	186
6.2.2	Continuous Tundish Temperature Measurement	187
6.2.3	Mould Thermal Monitoring (MTM) and Sticker Breakout Prediction	188
6.2.4	Mould Oscillation Monitoring	195
6.2.5	Spray Water Monitoring	196
6.3	Off-Line Measuring Systems	196
6.3.1	Mould Geometry Measurements	196
6.3.2	Strand Condition and Spray Water Distribution Monitoring	196
6.3.2.1	Measuring head	197
6.3.2.2	Computer Hardware	197
6.3.2.3	Computer Software	197
6.4	Quality Control Systems	197
6.4.1	On-line Hot Surface Inspection	199
6.4.2	On-line Quality Prediction Systems	201

INDEX	205
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1. INTRODUCTION

1.1 Historical Background

For well over a century the traditional method for the conversion of steel from the liquid phase to the solid phase was by the use of ingot moulds. Each mould consists of cast iron forming a thick walled container open at the top and set up before casting on large cast iron 'bottom plates' or 'stools'. Figure 1.1 shows several different designs of ingot moulds.

Each ingot was cast independently, the number of ingots from a single ladle of liquid steel depending on the ladle size and the size of each individual ingot. After the steel within the ingot mould had solidified the ingot moulds were removed using a 'stripping' crane and the ingots were then charged into soaking pits so that they could be reheated for rolling to semi-finished or finished products. Even as early as the nineteenth century the attraction of solidifying steel using a more continuous method was recognised and some of the methods attempted by early workers such as G E Sellars (1840), J Laing (1843) and H Bessemer (1846) were applied to the casting of non-ferrous metals with low melting points but not in the case of steel due to the many technical problems associated with the higher temperatures involved and the low thermal conductivity of steel.

However, the possibility of solidifying liquid steel using a water cooled mould, open at the top and bottom, was pursued by R M Daalen in 1887.¹ He envisaged a process where a stream of liquid steel was poured

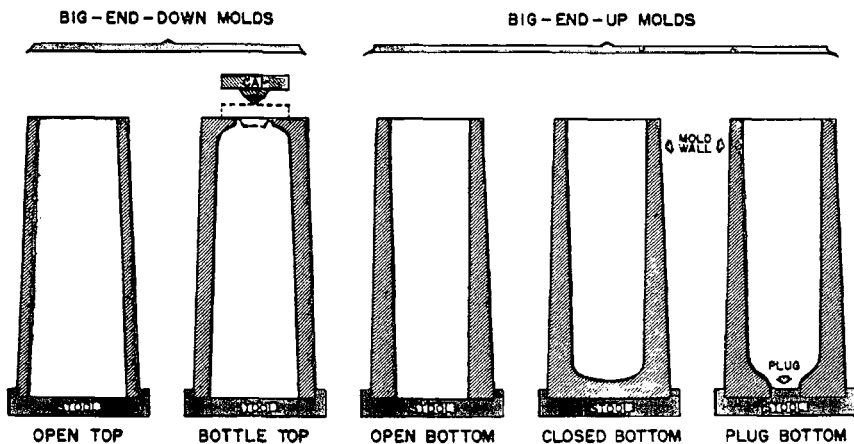


Figure 1.1 Various designs of ingot moulds.

vertically into an open ended mould and then passed into a secondary cooling system and withdrawn by pinch rolls prior to being cut by a torch device. The process would be started by the use of a retractable dummy bar. These features are all integral parts of the modern process for the continuous casting of steel.

Even so, it was recognised that with steel considerable problems occurred due to the sticking of the solidified steel to the water cooled mould wall and relative motion between the metal being cast and the mould wall was therefore required. It was not until 1933 when Siegfried Junghans² developed and patented his mould oscillation system that the foundations were laid for the large scale application of the process for the continuous casting of steel.

It was not until after the Second World War that semi-industrial pilot plants began to emerge for the continuous casting of steel.

Before pursuing the description of specific casting machines it is necessary from the reader's point of view to be familiar with the terminology and the definition of various as-cast sections in steel production. These are:

- *Billets* are defined as small square sections usually up to 150 mm square and up to 150 mm diameter rounds.
- *Blooms* are defined as square or rectangular cross-sections greater than 150 mm square to as large as 800 mm × 400 mm usually with an aspect ratio less than 2. Also rounds with a diameter greater than 150 mm.
- *Slabs* are anything larger than blooms and usually with an aspect ratio greater than 2. The largest slabs currently continuously cast are 2725 mm × 254 mm.

One of the first machines constructed was a vertical caster installed in 1946 for the production of steel billets at Low Moor, Great Britain.³ In 1947 the British Iron and Steel Research Association (BISRA) considered casting with a spring suspended mould whilst in 1948 Babcock and Wilcox commissioned a vertical plant with intermittent strand withdrawal in the U.S.A.³

In 1949, tests began in Austria with a fixed mould. In the same year, S Junghans in Germany and the Allegheny Ludlum Steel Corporation³ in the USA began casting on vertical machines incorporating the Junghans mould oscillation system.

From 1950 onwards the development of the technology for the continuous casting of steel on a large scale accelerated rapidly.

A production plant went into operation at Mannesmann AG in Duisburg-Huckingham, West Germany in 1950 and in 1951 it was decided that a continuous casting plant be installed at Barrow Steel, Great Britain⁴ to develop the casting of billets ranging from 50 mm to 100 mm square and small slabs 150 mm × 50 mm. The General Manager of the Barrow Steel

Works, GNF Wingate met up with Irving Rossi who had acquired a share in the patent rights held by Siegfried Junghans on the principle of the reciprocating mould. Irving Rossi later founded CONCAST AG with the then United Steel Companies Ltd of the U.K. being a major shareholder.

The design and construction of the Barrow plant was carried out in conjunction with Irving Rossi. The machine itself, based on the Junghans/Rossi principle of casting with a reciprocating mould, had facilities for twin strand casting and was initially fed from a 5 tonne electric arc furnace and later fed from a 40-tonne open hearth furnace. However, early work was concentrated on a single strand until casting practices were established on a reliable basis at suitable casting rates. On 2 December 1952 this machine made its first cast and within five months of start up was casting 50 mm² billets at a speed of 5 m/min for short periods.

Initially the billets were cast vertically with the length of the vertical cast billets being cut off by a traversing torch. An important early development of this machine was to bend the as-cast billet by a pneumatically powered tilting frame enabling the billet to be discharged horizontally prior to torch cutting. This of course enabled higher productivity with less machine height and is an integral feature of modern continuous casting machines.

Table 1.1⁵ lists some 16 of the more important pilot and production machines built between 1945 and 1955. All of these were initially vertical casters the majority producing billets, but including two USSR casters capable of producing small slabs up to 200mm × 600 mm in dimensions.

In 1954 a major breakthrough in the continuous casting of steel was achieved at Barrow with the use of 'negative strip'. This involved accelerating the mould on the downward stroke of its cycle so that the speed of the mould exceeds that of the exit velocity of the product for part of the oscillation cycle. This development, which is a feature of all modern steel casting machines, resulted in a dramatic reduction in breakout frequency and made possible further substantial increases in casting speed.

The number of machines for the continuous casting of steel continued to increase steadily for the next twenty years with the following, reproduced from the second study of continuous casting by the International Iron and Steel Institute,³ representing important installations and developments during the period 1956 to 1975.

- 1956 A vertical billet strand is bent below the pinch rolls into the horizontal plane at Barrow Steel, Great Britain (Concast/Halliday).
- 1958 Slab of 1,000 mm width is cast at Böhler, Austria (Mannesmann-Demag-Böhler).
- 1959 An eight strand billet plant with stopper operated ladle and stopper operated tundish in Terni, Italy (Mannesmann-Demag-Böhler).

Table 1.1 Vertical steel continuous casters, 1945 to 1955

Company	Year commissioned	No. of strands	Strand sizes (mm)	Remarks
Babcock & Wilcox Tube, Beaver Falls, PA, USA	1948	1	150 round	Strand withdrawn intermittently
Gebr. Böhler u. Co., Kapfenberg, Austria	1949	2	120 square 150 × 200	Fixed mould
Mannesmann Hüttenwerke, Duisburg FRG	1950	1	135 round 140 × 180	Oscillating mould
Krassny Oktjabr, USSR	1951	2	180 × 600	Withdrawal caster
Barrow Steelworks, Great Britain	1952	2	50 square 90 square	With strand bending
CAFL, J. Holtzer, Unieux, France	1953	2	Oval 80/105	—
Eisenwerke Breitenfeld, Austria	1953	2	110 square 130 square	—
Novotulsk, USSR	1953	1	200 × 600	—
Fives Lille Cail Denain, France	1954	4	240 square	—
Atlas Steel, Canada	1954	1	140 × 545	—
Mannesmann Hüttenwerke Duisburg, FRG	1954	4	200 × 240 330 square	—
Nyby Bruk A/B, Norway	1954	1	50 square 185 square	Stainless
Sumitomo Metal Ind., Osaka, Japan	1955	1	50 square 130 square	—
Forges d'Allevard Isere, France	1955	1	75 square 87 × 138	—
Krassnoye, Sormovo, USSR	1955	1	174 × 420	—
Freital, GDR	1955	3		Withdrawal caster

- 1961 Vertical slab caster with bending and straightening into the horizontal in Dillingen, F.R. Germany (Concast).
- 1962 Introduction of casting powder at SAFE, France, and Mannesmann, Germany.
The ladle turret is patented (Concast).
Multi purpose plant for casting either 4 slabs up to 1,500 mm width or 8 blooms or 8 square or round billets at Mannesmann, Germany.
- 1963 Curved caster with curved mould 200 mm × 200 mm at Mannesmann, Germany.
Curved caster for billets at von Moos Stahl, Switzerland (Concast).
Centrifugal continuous casting for solid rounds at Société Métallurgique d'Imphy, France (SCEC-Vallourec).
- 1964 Curved caster for wide slabs at Dillingen, Germany (Concast).
Curved caster with progressive straightening for wide slabs up to 2,100 mm at Mannesmann, Germany (Mannesmann-Demag). The first super low head machine (overall height 4.0 m) of segment construction with segmented rolls.
Continuous casting of hollow rounds on a production scale at Mannesmann, Germany.
Automatic tundish stopper control system at Barrow Steel, Great Britain (Concast).
World's first 100% continuously cast production at Shelton Iron and Steel, Great Britain (Concast).
- 1965 Curved caster for round strands at Eschweiler Bergwerksverein, F. R. Germany (Mannesmann-Demag).
Submerged nozzle casting at SAFE, France, and Mannesmann, Germany.
Progressive bending and straightening produced by Olson in USA.
- 1966 Application of ladle stream shrouding at Mannesmann, F. R. Germany.
Multi roll drive for withdrawal machine in slab caster at Mannesmann, Germany.
Tests employing the 'compression casting' process at Mannesmann, Germany.
Cooling plates used below the mould instead of rolls (Concast).
- 1967 Strand guide section quick change unit (oscillating table plus first segment) at Mannesmann, Germany.
Twin casting operation employing a common mould in a slab caster at Mannesmann, Germany.
Greenfield steel plant in the Western hemisphere with 100% continuously cast production: Rautaruukki Oy, Finland (USSR technology).

- 1968 Production scale casting of 'beam blanks' at Algoma, Canada (BISRA/Concast technology).
 Ladle turret on a continuous caster (Voest, Austria).
 Hot charging of continuously cast slabs into induction furnace at McLouth Steel, USA.
 Semi -industrial horizontal casters installed by General Motors, U.S.A, and Davy-Loewy, Great Britain.
- 1969 Tests with 120°C wide angle spray water nozzles at Mannesmann, Germany, (Mannesmann-Demag-Lechler).
 'Permanent' dummy bar head (Concast)
- 1971 Application of the 'compression casting' process at US Steel Gary Works, USA.
 Cooling grids below the mould instead of rolls at Oxelösund, Sweden (Concast).
 Horizontal casters installed on a production scale by General Motors, Lansing, USA, and Davy-Loewy, Jarrow, Great Britain.
- 1972 Stepwise slab mould width adjustment during casting introduced at NSC, Hirohata, Japan.
 'Walking beams' below the mould instead of rolls employed at Kobe Steel, Kakogawa, Japan.
 Ladle turret with lifting system at Peine-Salzgitter, Germany (Mannesmann-Demag).
 'Top fed' dummy bar system for reduction of set up time introduced at Peine-Salzgitter, Germany (Mannesmann-Demag).
- 1974 Air mist spray nozzles employed at Mannesmann, F.R.Germany (Mannesmann-Lechler).
 Production scale application of EMS below the mould at SAFE, France (SAFE-IRSID-CEM).
- 1975 Production use of the pressure box to prevent reoxidation of the ladle pouring steam at Mannesmann, Germany.

In 1970 the world continuous casting ratio (the amount of steel continuously cast as a percentage of liquid steel produced) was 5%. In the 10 years from 1974 it grew fourfold from 11.4% in 1974 to 47% in 1984⁶ and in the Western countries it had increased to 63.3% by that year. Figure 1.2(a) shows the continuous casting ratios for Western Europe and the World,⁷ from 1960 to 1989 while Figure 1.2(b) shows the application of continuous casting in different parts of the world in 1989. In 1991 the continuous casting ratio for the Western world, the EEC and the U.K. had reached 83%, 90% and 85.5% respectively⁸.

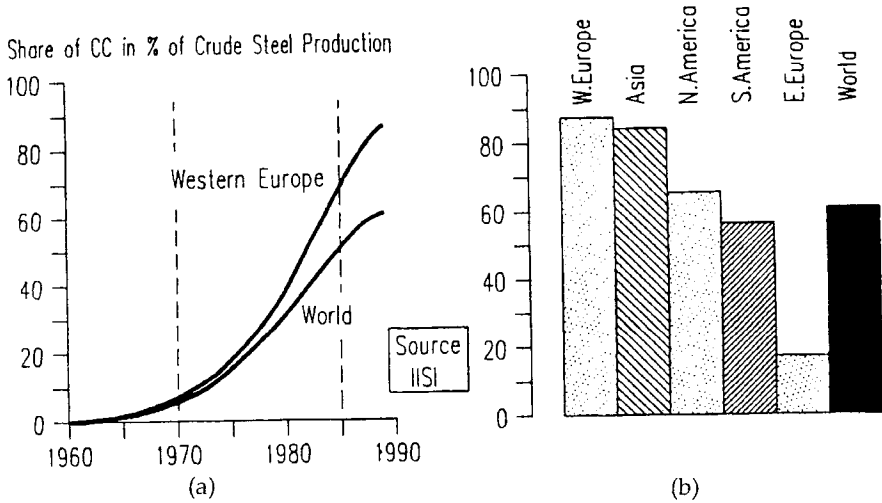


Figure 1.2 Continuous casting ratios for (a) Western Europe and the World from 1960 to 1990 and (b) application of continuous casting in different parts of the World (1989).⁷

1.2 Description of the Continuous Casting Process and the Evolution of Machine Design

1.2.1 Brief Description and Basic Principles of the Continuous Casting Process

The basic principle of the continuous casting process for steel is based on teeming liquid steel vertically into a water cooled copper mould which is open at the bottom. Figure 1. 3 illustrates this principle.

Heat transfer to the water cooled copper immediately solidifies the liquid steel and a solid skin is formed which increases in thickness down the length of the copper mould. Two very fundamental principles are required to avoid sticking of the solidifying skin to the copper mould. These are:

1. The mould is reciprocated sinusoidally at a frequency which provides negative strip i.e. the mould moves downward faster than the solidifying skin for a percentage of the oscillating cycle.
2. A lubricant has to be provided as an interface between the solidifying skin and the copper plate. Prior to around 1965 rape seed oil had been used almost exclusively as the lubricant and is still used for smaller billet sizes where a refractory submerged entry nozzle cannot be used. On most other machines a synthetic casting powder is used on the top of the metal in the mould. The powder in contact with the liquid steel

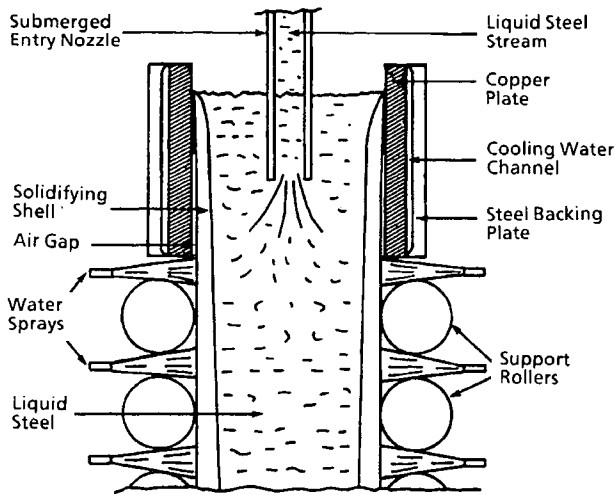


Figure 1.3 Basic principle of continuous casting.

melts to form a slag which infiltrates into the gap between steel and copper at the meniscus to provide lubrication. This important and fundamental technology will be discussed more fully in Chapters 3 and 4.

As soon as the solidified skin is sufficiently thick to contain the liquid steel the strand leaves the mould and is further cooled by water sprays. The reason why the copper mould is not continued for further solidification is that, due to the skin cooling and contracting, the mould becomes less efficient in heat transfer due to the 'air' gap forming between the copper wall and the outer side of the solidified skin. It is therefore, more efficient to use direct water spraying from high pressure nozzles. However, the hot solidified skin cannot withstand the pressure arising from the liquid steel within the solidified skin and, if unconstrained, would bulge outwards. Therefore it is necessary to support the continuously solidifying shell by rollers or some other mechanical systems. The design and diameter of the rollers will be discussed in section 3.2.3. since these are determined by the ferrostatic forces and product quality requirements.

In the steady state the solidifying shell is withdrawn from the mould at constant speed by withdrawal rolls further down the machine.

A brief description of a modern continuous casting machine at this stage will help the reader to appreciate the various aspects of the process. Figure 1. 4 shows a general layout of a modern continuous slab casting machine, showing the ladles in the ladle turret. This turret revolves so that a full ladle of steel can be brought to the casting position quickly to enable continuity of casting.

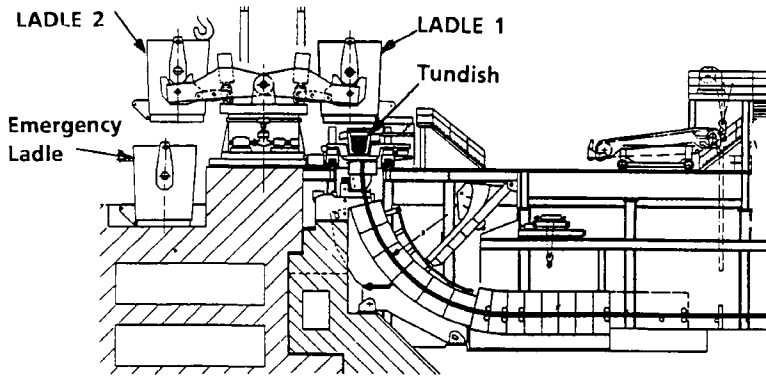


Figure 1.4 General layout of a modern continuous casting plant.

Figure 1.5 shows a schematic diagram of a slab caster indicating the main components. Both these figures describe the curved mould machine which currently is the most common type. Other designs are included in the later discussions of how machine designs have evolved.

The liquid steel is initially teemed from the steelmaking vessel into the ladle and following any appropriate secondary steelmaking processing the ladle is lifted by crane onto the continuous casting machine and supported by either a ladle car or ladle turret. The liquid steel is then poured from the ladle into a tundish by way of a sliding gate valve mechanism and the stream is protected by a refractory tube to avoid any reoxidation from the atmosphere (see section 2.5). Since it is common to have more than one continuously casting strand operating in parallel the steel is poured into a tundish the main functions of which are to distribute the steel over the number of casting strands and to provide a more constant

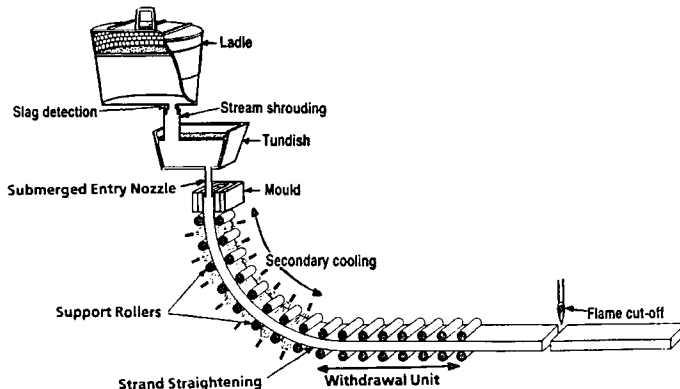


Figure 1.5 Schematic diagram of a modern slab casting machine showing the main components.

head to help in the control of pouring the liquid steel into the continuous casting mould. The tundish design and configuration depends on the number of strands and the distance apart of the strands. In slab casting the number of strands rarely exceed two and some machines only have a single strand. Nevertheless a tundish is still used in this event since other functions are served by the tundish (See section 2.4). For bloom casting the number of strands can be from 2 to 8 depending on ladle size, bloom size and required casting rate. When 8 strands are used then it is usual to use 2 tundishes. For billet casting the number of strands can range from 3 to 8. When eight strands are used for billet casting only 1 tundish may be required because of the reduced centre line separation of the strands when compared to the casting of larger blooms

The various configurations are shown in Figure 1.6.

To achieve a high utilisation of the machine several ladles are often cast in sequence (termed the sequence factor or the sequence ratio) i.e. the process continues whilst the empty ladle is replaced by the next full one and quick ladle changing is achieved by the use of the ladle turret or by having two ladle cars. As a further effort to extend the sequence length the tundish is often replaced 'on the fly' since the tundish and, in particular, the submerged nozzle or stopper rod can limit the number of heats.

Apart from the smallest section sizes (billets below about 130 mm square) the liquid stream between tundish and mould is again protected

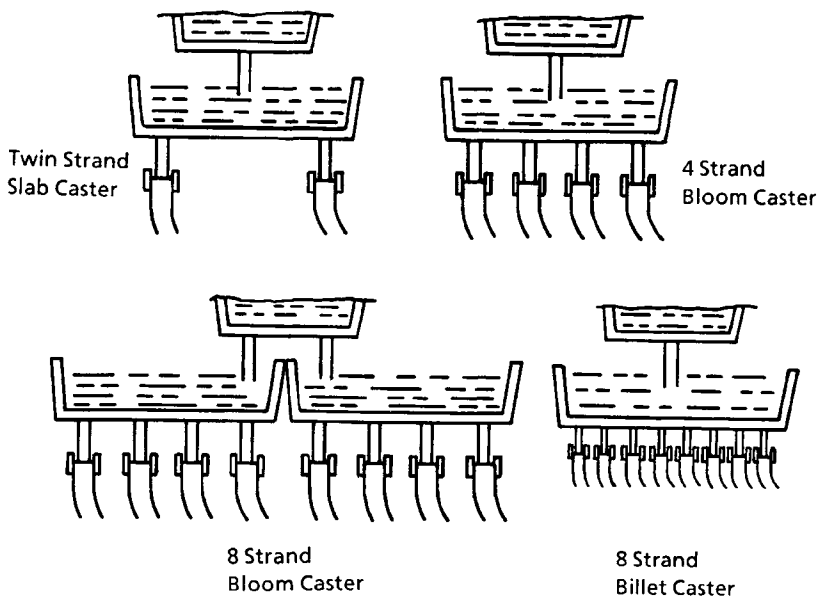


Figure 1.6 Typical tundish strand configurations.

from the atmosphere by a refractory tube. For the smaller billets open pouring is used but the stream is protected by gas shrouding.

Further details of tundish design and the tundish technology is discussed in Section 2.4.

The strand becomes completely solid after passing several metres down the machine the position depending on the casting speed, cooling conditions and the product thickness.

To enable the fully solidified slab to be withdrawn in a horizontal position the slab is cast on a curvature the radius of which depends on several factors concerned with product dimensions and quality requirements and which are described later.

The strand is straightened by the use of rollers at the position where it becomes horizontal and is withdrawn from the machine by power-driven pinch rolls. In billet casting this may only consist of one or two pairs of driven rolls but in slab casters the withdrawal unit may consist of many driven rolls and sometimes arranged in segments. In this case the withdrawal unit is after the strand straightening and invariably extends to the end of the machine (Figure 1.5). After the slab exits the machine a torch unit travelling at the same speed as the strand cuts the slab transversely and on the completion of the cut reverses to its original position. The cut slab is then accelerated down a roller table for further processing.

The start-up of the process requires that a dummy bar head which is marginally smaller in cross-section than the mould is driven in to the bottom of the mould by steering it up from the bottom of the machine using a series of linked units known as the dummy bar chain. The dummy bar chain is driven up by the 'withdrawal' rolls and the head is placed in position which extends slightly into the bottom of the mould. Packing is then inserted into the small gaps between the copper wall and the dummy bar head. The dummy bar head is shaped in a claw like fashion so that when liquid steel enters the mould it solidified around the 'claw' and when the mould is filled withdrawal is started and the dummy bar commences to withdraw the partly solidified steel from the mould. When the dummy bar head and the leading end of the strand exit the machine the head is disconnected and the dummy bar chain withdrawn separately and parked in ambush. Figure 1.7 shows the operational and ambush positions of a bottom fed dummy bar chain.

In more recent years the use of the top fed dummy bar has been employed with the aim of reducing re-stranding time between sequences. This enables the dummy bar chain to be guided into the strand through the mould while the previously solidified strand is still being run out. Figure 1.8 shows the arrangement of a circulating top fed dummy bar.

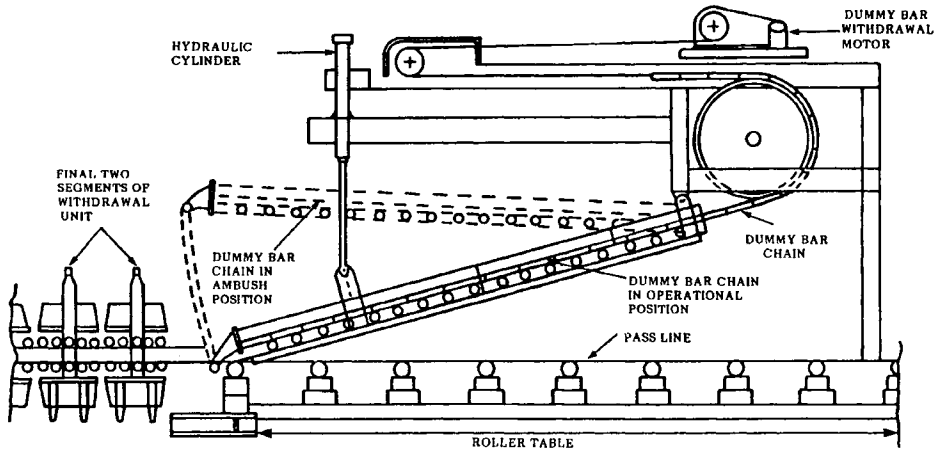
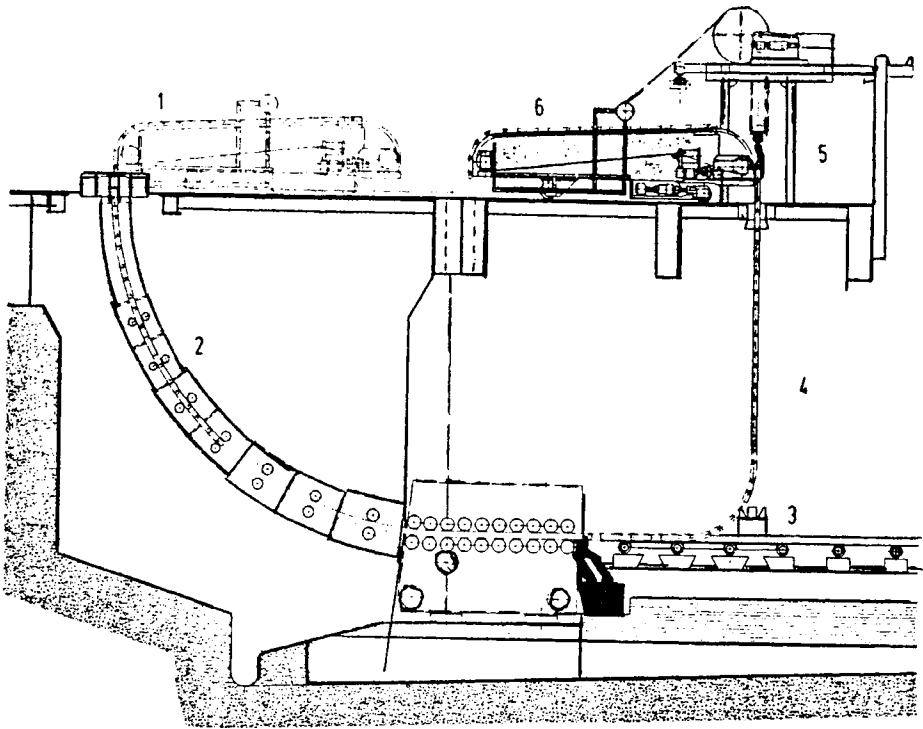


Figure 1.7 Operational and ambush positions of bottom fed dummy bar.



- | | |
|---------------------------------------|---|
| 1. Car in dummy bar lowering position | 4. Dummy bar after disconnection |
| 2. Roller apron | 5. Dummy bar lift |
| 3. Runout roller table | 6. Dummy bar transfer and alignment car |

Figure 1.8 Circulating top fed dummy bar system.⁵

Detailed descriptions and functions of all the components of continuous casting machines will be described in Chapter 3.

It should be appreciated that the solidifying shell as it leaves the mould is relatively weak and any undue friction in the mould or any reductions in the skin thickness due to uneven cooling can lead to a breakout. Breakouts are very undesirable and expensive in that they can lead to an interruption to the sequence and casting time is lost whilst the machine is recovered from the results of the spilled molten steel often requiring changing the mould and top zone. Breakouts can also occur during the start of the process due to rupture of the initially solidifying steel around the claw of the dummy bar head. Much work has been carried out to avoid breakouts and, when they do occur, to ensure machine design allows for a rapid recovery time.

1.2.2 Evolution of Machine Design

It is interesting to note at this stage how the design of casters has evolved over the years.

Early casters were totally vertical but such casters required considerable height to achieve reasonable production rates per strand and with the rapid development of the Basic Oxygen Steelmaking (BOS) process which can produce in excess of 400 tonnes/hour the need to match the casting machine rate with the steelmaking furnace would require more strands. Figure 1.9 shows the different designs of machine which have evolved over the last 30 years, these ranging from the totally vertical machine (Caster 1) to the 'low head' machine (Caster 5)

It is appropriate to state the designation of each type of machine which will be maintained throughout this publication. These are shown in Table 1.2.

Table 1.2

Caster no.	Description	Designation
Caster 1	Vertical machines (straight mould) with cut off in vertical position	V
Caster 2	Vertical machines (straight mould) with single point bending and straightening. Full solidification in vertical section	VB
Caster 3	Vertical machines (straight mould) with progressive bending and straightening	VPB
Caster 4	Circular arc (bow type) machines with curved mould and single point straightening	CS
Caster 5	Circular arc (bow type) machines with curved mould and progressive straightening	CPS

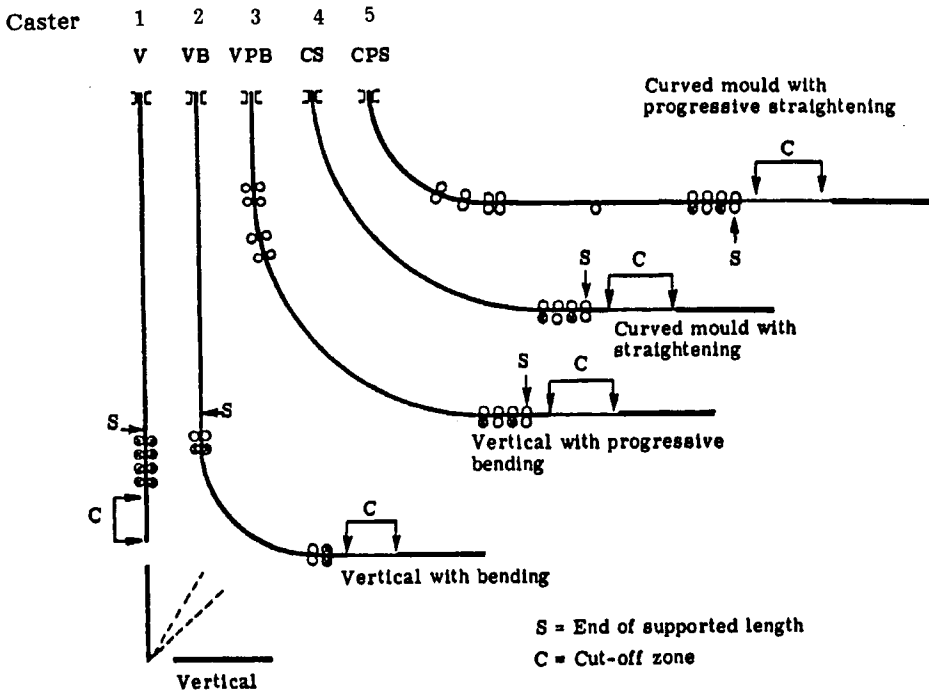


Figure 1.9 Principal types of continuous casting machines.⁹

In 1965, the continuous casting machines were very simple. 80% of the casters, for slabs, blooms and billets, were vertical machines. Curved machines then took over and in 1975 80% of the slab casters and 70% of the bloom and billet casters were of the curved type. This trend continued to progress but towards more complex geometry, with the application of progressive bending and straightening which in 1984 was used in 30% of the slab casters and in 20% of the bloom and billet casters. Figure 1.10 shows the evolution of machine design.

The main disadvantages of the vertical casters were:

1. The excessive height to achieve higher production rates.
2. The extra costs in buildings and crane height.
3. The mechanism for turning the slab to a horizontal position after cutting was complex and expensive. To reduce building and crane heights the bottom end of vertical casters were often built with deep pits which required subsequent slab lifting after cutting and turning. To simplify and reduce the cost of the turning and lifting mechanism several machines in the early 1960's included bending and straightening pinch rolls after solidification and hence the cast strand was travelling in the horizontal direction prior to cut off. This however did not significantly

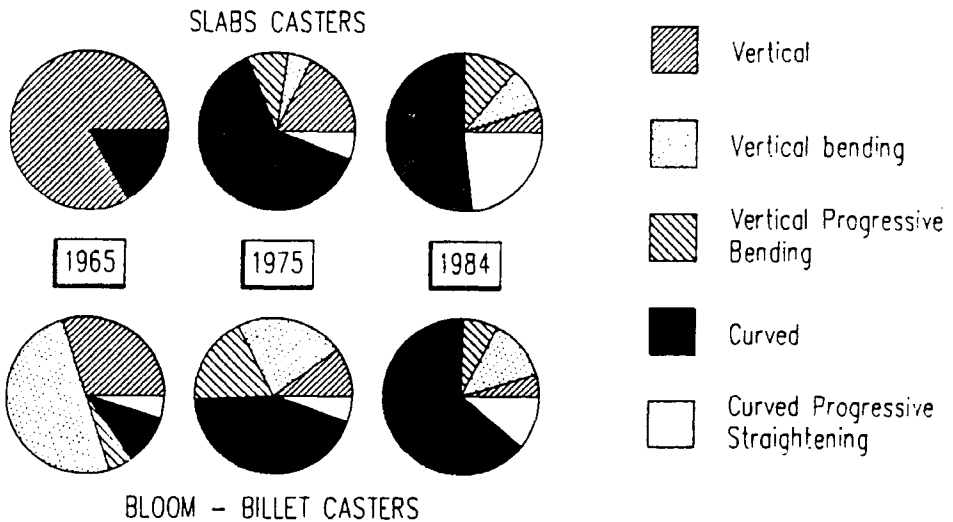


Figure 1.10 Evolution of machine design.

reduce the overall height of the machine although some limited benefit was obtained (see Figure 1.9, Caster 2).

4. The other main disadvantage of Caster 1 and Caster 2 was the duty on the roller support system due to the greater ferrostatic forces caused by the machine heights. Consequently this would increase maintenance involved to ensure the roller gap geometries and roller alignments remained within the tight tolerances required.

In recent years the curved mould machine (Caster 4) has been widely used. This enables the radius of such a machine to be typically 8 to 12 metres depending on product size and thickness. This in turn reduces the ferrostatic forces whilst achieving the throughput requirements and, in many machines, the solidification position can be 30 to 40 metres from the meniscus without increasing the ferrostatic force beyond the machine radius. Multi radius machines (Figure 1.9, Caster 5) are now also in use which enables a further reduction in ferrostatic forces but other considerations relating to quality and mould teeming difficulties limit the minimum height. In fact, in the limit the strand could become totally horizontal but considerable difficulties occur with the liquid steel feed arrangement. However, considerable work has been carried out over the years to further develop total horizontal casting and several machines now exist but these are limited mainly to billet casters. Such developments will be discussed further in Chapter 5.

This evolution clearly reflects the need for higher casting speeds with the trend towards longer machines but without increasing the machine height. With the circular arc machines it is possible to increase the supported length

(S in Figure 1.9) without further increasing machine height and for slab machines the strand needs full support until after complete solidification.

The production rate per strand (T) for slab, bloom and billet casters and the solidification lengths (L_s) are given by the following equations.

$$T = b \times w \times \rho \times v \times 10^{-6} \text{ t/min}$$

and
$$L_s = \frac{b^2 v}{4 K^2} \text{ m}$$

where b = strand thickness (mm)

w = strand width (mm)

ρ = steel density = 7.6 t/m³

v = casting speed (m/min)

K = solidification constant (mm/min^{1/2})

The solidification constant is determined by using the solidification model described in Section 3.4.1 and a value of 25 mm/min^{1/2} is typical for slab casting. The value of K is in the region of 29 for square billets or blooms due to the increased affect of two dimensional heat flow.

Figure 1.11 represents the relation between casting speed, casting rate/strand and the solidification length for a 250 mm slab thickness and varying widths.

The tap-to-tap times for a BOS vessel can be typically 35 to 50 mins. The casting times for 1200 mm and 1800 mm slab widths, when casting with two strands at 1.0 m/min, are shown to be about 55 and 36 minutes respectively. This demonstrates that for narrower widths the casting times become much longer than the tap-to-tap times and therefore faster casting speeds are required to match the production rate of the steelmaking vessel.

As a further illustration of the relationship between production rate, slab width and slab thickness Figure 1.12 shows the effect of slab width for various slab thicknesses and casting speeds and relates these production rates to various BOS steel vessel sizes with a 48 minute cycle time.

Slabs for strip and plate used to be produced in a wide range of widths. The width varies according to the type of final product such as tin plate, strip for deep drawing, hot rolled strip, heavy plates or tubes. Typically the required slab width can range from 800 mm to greater than 2000 mm in increments of 50 mm. Until about a decade ago slab width changes on the caster were only possible during non casting time which limited the sequence length and productivity. Many machines still only have this capability.

Various methods have been developed to deal with the requirement of a large number of widths and which reduces the range of production rates. These can be listed as follows:

Variable Width Moulds Systems have been developed for changing width during casting. This technology will be described in more detail in Section

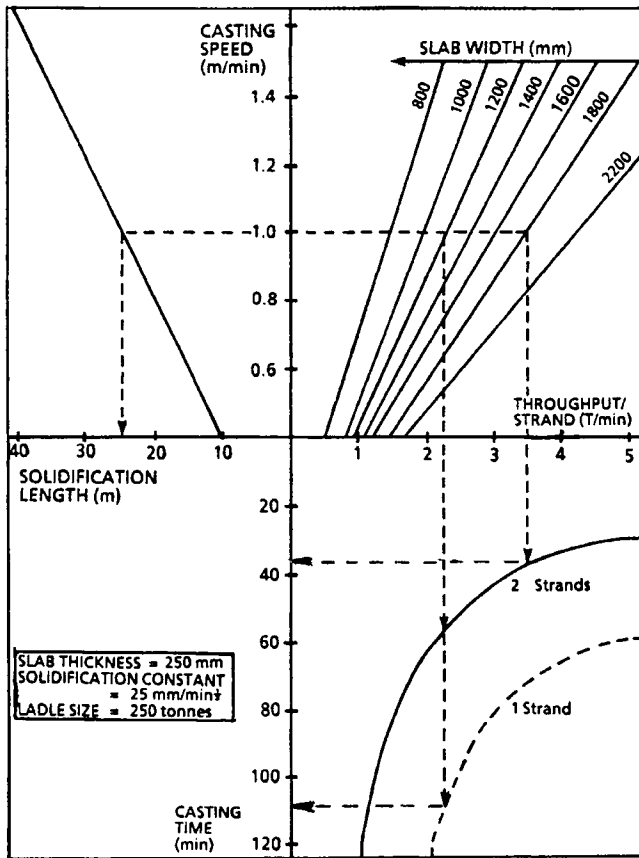


Figure 1.11 Relation between casting rate/strand, casting speed, and solidification length for a 250 mm thick slab.

3.1.1.4. This can significantly increase sequence length and hence overall productivity but cannot achieve the sufficiently short casting times when casting the narrow widths unless combined with twin casting as described below.

Twin and Triple Casting This development enables two or three narrow sizes to be cast on one strand of a slab machine. This is achieved by replacing the single wide slab mould by 2 or 3 small moulds. Twin casting can be done by the use of two separate moulds or by a water cooled copper divider in the slab mould. In the latter case each of the two narrow slabs can be varied in width by the use of the variable width technology as described above. Twin and triple casting is described in more detail in Section 3.1.1.5

Edge Reduction in the Rolling Mill In a hot strip mill some limited width reduction can be achieved by the use of an edger mill ahead of the roughing mill.

Slab Longitudinal Slitting This provides considerable flexibility in

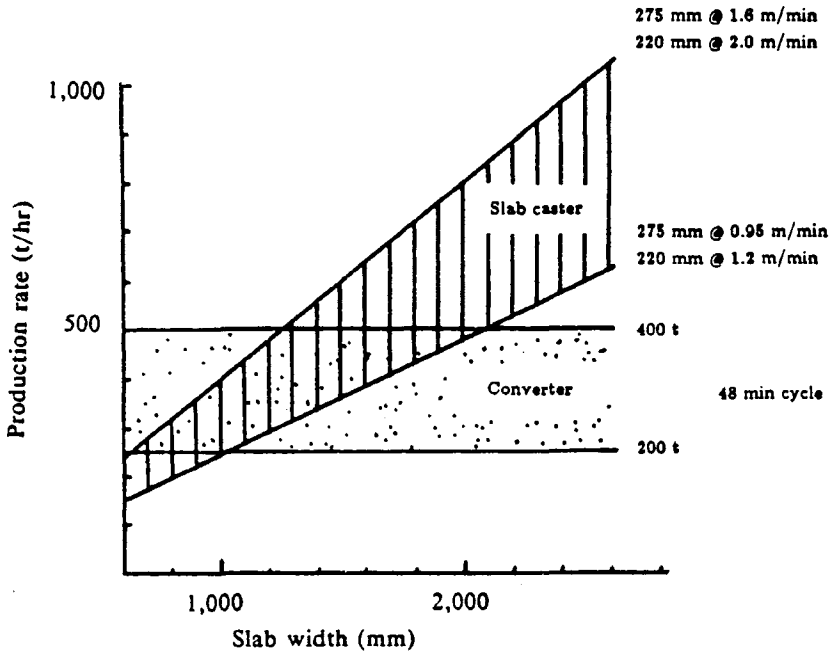


Figure 1.12 Effect of slab width on continuous casting production rate.

achieving a wide range of widths for only a limited range of cast widths without detriment to overall production rate of the steel plant and caster. However a significant yield penalty occurs due to the torch cutting.

1.3 Advantages of Continuous Casting Over Ingot Casting

The continuous casting of steel gives considerable advantages when compared with ingot casting. Figure 1.13 shows the two process routes.

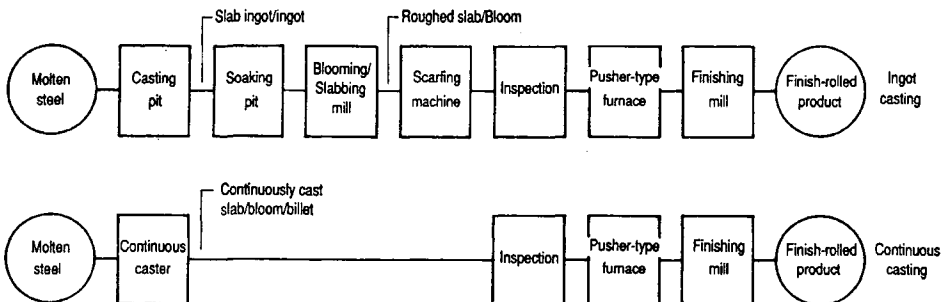


Figure 1.13 Ingot and continuous casting process routes.⁵

Ingot casting involves more processes with at least one extra heating and rolling process to produce similar semi products which are produced directly from the continuous casting process these being either billets, blooms or slabs. The definition of billets, blooms and slabs is given in Section 1.1.

The main advantages of the continuous casting process over the ingot casting route are listed as follows:

- improved yield
- reduced energy consumption
- savings in manpower
- improved product quality and consistency of quality
- lower emissions harmful to the environment and plant operators
- reduced stock levels and shorter delivery times
- reduction in capital costs for new steel plants

The two important items of yield and energy will be discussed in more detail.

1.3.1 Improved Yield

The yield improvements from liquid steel to various semi-finished products for both the ingot and continuous casting routes have been estimated in the IISI report of 1977⁹ and are given in Table 1.3:

The yield figures given in Table 1.3 were based on data from a percentage of the Western World production plants and represents 195 million tonnes/year consisting of 142 million tonnes of semis rolled through the ingot route and 53 million tonnes of continuously cast semis. However these data compiled in 1975 included semi-finished products after rectification and since that time there has been a very significant reduction in the amount of continuously cast semis which are scarfed thus further increasing the liquid steel to semi-finished products yields for the continuous casting route.

Table 1.3

Semi-finished product	Ingot route	CC route	Increase
Billet	81.29	95.57	14.28
Bloom	82.93	95.87	12.94
Slab	84.28	94.74	10.46
Total semis	83.45	95.01	11.56

1.3.2 Reduced Energy Consumption

Reduction in energy consumption when comparing the continuously cast route to the ingot route arises due to the following:

- (a) The elimination of a reheating stage
- (b) The energy saving due to the increased yield because of the inherent energy contained in the liquid steel.

The ingot process route requires that the stock needs to be heated both in the ingot form and after the rolling to a semi product i.e. slab, bloom or billet. In the continuous casting route the first reheating is eliminated with the as-cast semi product being reheated for rolling.

A comparison between conventional ingot rolling and continuous casting, even in the most unfavourable circumstances, shows that the continuous casting route uses approximately 25% of the energy of the ingot route in processing from the liquid steel stage to the reheated semi.⁹ The actual savings vary from case to case and depend on the percentage of hot charging of ingots and the degree of the hot charging of as-cast semis in the case of continuous casting. A comparison from liquid steel to as-cast semis shows that the savings in favour of the continuous casting route range between 0.7 and 1.54 GJ/t for 90% hot charged ingot and 100% cold charged ingot respectively.

These figures are for semis which are allowed to cool to ambient temperatures prior to further processing. During the course of the last decade, there has been a considerable drive to further conserve energy by direct transfer of the as-cast semi to the reheating facilities with as little loss of heat as possible. In some cases slab casting has been linked directly with the hot strip mill with very minimal reheating. The energy savings which can be achieved by hot connecting to the reheating furnaces are typically 0.4 and 0.6 GJ/t semi for bulk mean temperatures of 600°C and 800°C respectively. With direct rolling the savings can be of the order of 1.0 GJ/t semi.¹⁰

In the case of the overall energy consumption in the stages from iron ore to semi product, and which includes the yield benefit due to the inherent energy in the liquid steel, the reduction in energy can amount to around 2 GJ/t of semi in going from 100% ingot production to 100% continuous cast production.¹¹ This does not include any hot charging or direct rolling of the as-cast semis and with a high percentage of hot charging and/or direct rolling savings approaching 3.0 GJ/t are possible.

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2. LIQUID STEEL SUPPLY

2.1 General Details

To ensure a good return on capital expenditure continuous casting machines for steel semi production (slabs, blooms and billets) require to operate at high production rates whilst achieving high surface and internal quality standards of the as-cast semis. To achieve high production rates it is necessary to obtain high utilisation of the casting machines. It is therefore necessary to cast a large number of ladles in sequence. It is quite common to cast many ladles in sequence without stopping the casting process. The sequence ratio can vary between a small number of ladles to more than one hundred depending on the circumstances which are influenced by product size and quality mix and several other factors.

When the product grade and size mix allows a sequence ratio of, say, greater than 10 ladles the tundish can become the limiting factor in achieving the sequence level. The tundish life is usually limited by erosion or blockage of the submerged entry nozzle (SEN) to the mould or alternatively the stopper rod life if stoppers are used. A particular method to overcome limited SEN life has been to carry out SEN tube changing during casting; an alternative method to maintain the sequence is to carry out tundish changes 'on the fly'. Both methods can involve a disturbance to normal casting with tundish changing involving a strand stoppage of around 5 minutes.

To achieve the required high production levels and the required product quality it is essential that ladles of steel are supplied to the casting machine with tight limits on temperature, of the required composition and at the correct time. It is normal practice to ensure that the casting conditions are selected to obtain a ladle drain time (which is the time to cast a ladle) which equates to the tap-to-tap time of the steelmaking furnace.

2.2 Compositional Control

To meet the very tight compositional control demanded of the present day product requirements there are often several secondary steelmaking processes between the steelmaking vessel and the caster. There is also often requirements to reduce certain elements to very low values e.g. sulphur, phosphorus and also to minimise the levels of gases such as oxygen, nitrogen and hydrogen.

Table 2.1 Typical analysis levels achievable by the conventional BOS/CC route

Element	Maximum product levels currently achievable (ppm)
Carbon	20
Manganese	500
Silicon	100
Sulphur	10
Phosphorus	50
Nitrogen	30
Hydrogen	1
Total oxygen	10

Table 2.1 shows the levels to which the various elements can currently be reduced although very rarely are all of these required in the same steel grade.

Figure 2.1¹ shows how complex the process route can be for a plant producing a range of demanding steel grades.

A few examples of how various secondary steel process routes are used to achieve certain compositions will now be given.

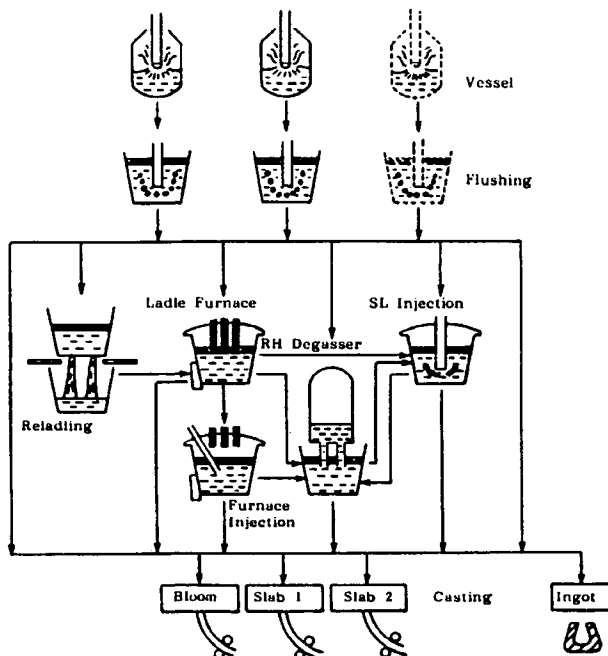


Figure 2.1 Secondary steelmaking process route options.

2.2.1 Carbon Removal for Low Carbon Strip Grades

Carbon values in the range 0.02–0.03% can now be consistently achieved from basic oxygen furnaces (BOF) and electric arc furnaces (EAF) and the carbon level determines the oxygen activity and therefore affects the consumption of deoxidants such as silicon and aluminium. To achieve lower levels of oxygen steel degassing has to be used, the most prominent degassers used for bulk steelmaking being the RH and DH methods. When a reduction to extremely low carbon concentrations is required, the amount of argon injection to induce the decarburising reaction in the RH or DH vessel is of the utmost importance: recently 5–15 ppm carbon has been achieved by this method.

2.2.2 Hydrogen Removal

Many steel products are very sensitive to hydrogen. On the other hand, basic slags, secondary heating in the ladle furnace, and newly lined tundishes, particularly those with a cold board lining, promote hydrogen pickup.

To eliminate the risk of hydrogen cracking in the final product many steels require degassing in the liquid state and/or dehydrogenisation in the solid state. For liquid steel degassing both tank and ladle (DH and RH) degassing processes are used. Again, it is mainly the amount of inert gas injected, as well as the vessel pressure, that determines the amount of hydrogen removal obtained with melts which have already been deoxidised. Hydrogen levels less than 1 ppm are often achieved.

2.2.3 Sulphur Removal and Control

Until recently high sulphur contents restricted the amenability of steels to continuous casting. Thanks to engineering advances, the beneficial use of electromagnetic induction stirring coils, and casting speeds tailored to the sulphur content, it is now possible to continuously cast even free cutting steels in blooms and billets.

Ultra low sulphur contents are now often required by the product particularly for plates and enhance amenability to casting. At the same time calcium treatment (See Section 2.2.5) for sulphide type and shape control can considerably improve mechanical properties such as transverse toughness. With the aid of synthetic slags and intense inert gas stirring as well as by injection it is now easily possible to obtain sulphur contents of <20 ppm in basic ladles. In individual cases, values of <5 ppm have been reported. The widely employed practice of intermediate ladle furnace treatment further promotes desulphurisation², as illustrated by Figure 2.2.

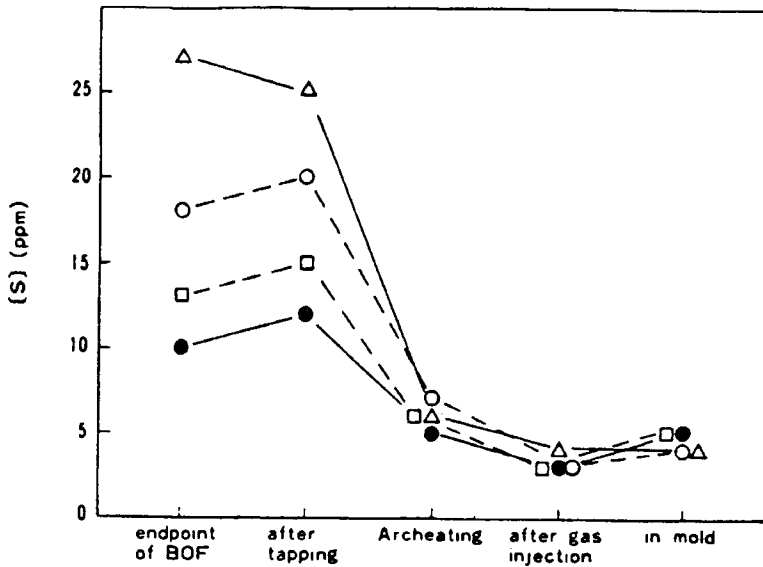


Figure 2.2 Sulphur content during desulphurisation.

For the continuous casting process, the sulphur level, whether it be high or low, does not present any problems, and no special measures are necessary during casting. Ultra low sulphur levels are entirely dictated by product demands to obtain the necessary mechanical properties.

2.2.4 Nitrogen Removal and Pickup

Nitrogen removal is largely affected in the melting unit itself, i.e. the basic oxygen or electric arc furnace. During tapping the steel may pick up some nitrogen depending on the degree of deoxidation. Normally degassing does not result in appreciable nitrogen removal. When very low sulphur levels have been achieved, however, care must be taken to ensure that the steel comes into as little contact as possible with the atmosphere since ultra low sulphur steels can very rapidly pick up nitrogen. Treatment under vacuum or in an inert gas atmosphere is thus the obvious move.

In continuous casting nitrogen pickup is prevented to the extent that the steel is successfully protected from exposure to air. Since avoidance of reoxidation is a vitally important factor, nitrogen pickup by the steel on its way from the ladle to the mould is often used as a measure of how effectively the molten metal is shielded from the air. As already indicated, nitrogen pickup is more difficult to avoid with very low sulphur steels (<50 ppm) since, as Figure 2.3 shows, they absorb the gas more readily.^{3,4}

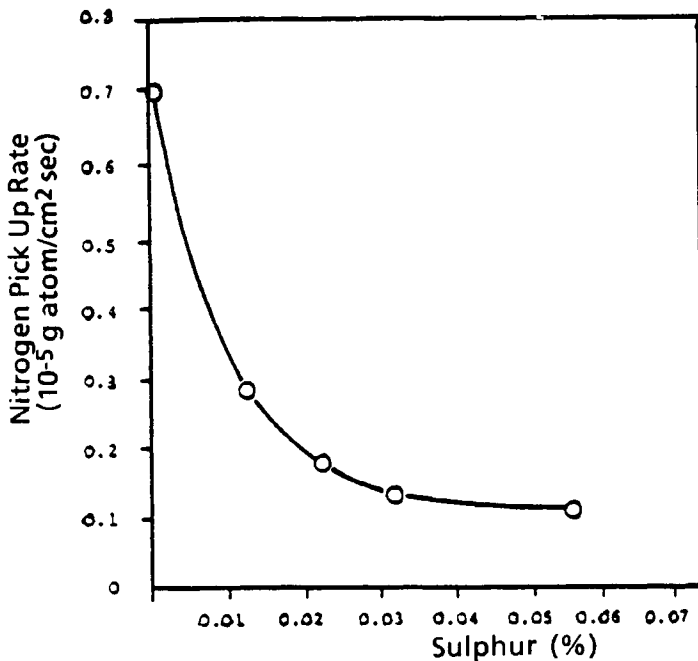


Figure 2.3 Effect of sulphur on the rate of nitrogen pickup.

2.2.5 Oxygen Control

While the steel is being prepared for continuous casting, the cleanness is controlled by many factors. Oxygen removal, the type of deoxidation products, their separation and the prevention of reoxidation during casting all have a decisive bearing on the ease of casting and on product quality in terms of cleanness. The importance of slag free tapping and the choice of refractories for the ladle lining is also important. The removal of oxygen from the steel and the prevention of reoxidation will be fully discussed.

For the adjustment of the steel for continuous casting the total oxygen content, not just the dissolved oxygen, is of importance as a measure of the inclusions still suspended in the melt. Their separation requires physical aids such as argon gas stirring and vacuum treatment and in special cases modification of the inclusions. It is important that the synthetic slag is capable of catching and holding the deoxidation products which float up as a result of stirring. Injection of calcium silicide and/or lime powder can also appreciably reduce the total oxygen content.

Calcium treatment improves the mechanical properties of the steel, particularly its toughness characteristics such as elongation, reduction in area

and impact strength through the improvement in oxide content and the globular shape of the Ca-Al-S-O particles (See Figure 2.4). This also reduces the likelihood of casting disruptions occurring as a result of clogging of the submerged entry nozzles which can frequently occur in non calcium treated aluminium killed steels. Owing to the high oxidation capacity of calcium, its low solubility in steel and its high vapour pressure, the efficiency of the calcium treatment is greatly dependent of certain process prerequisites such as slag-free tapping, the use of a basic ladle refractory lining, the stirring and injection conditions and the efficiency of the shrouding system to avoid re-oxidation. Due to the high vapour pressure it is essential to ensure that the calcium is injected deep into the ladle. Figure 2.4 shows the typical changes brought about by calcium treatment on the sulphide and oxide inclusions in plate specimens.⁵

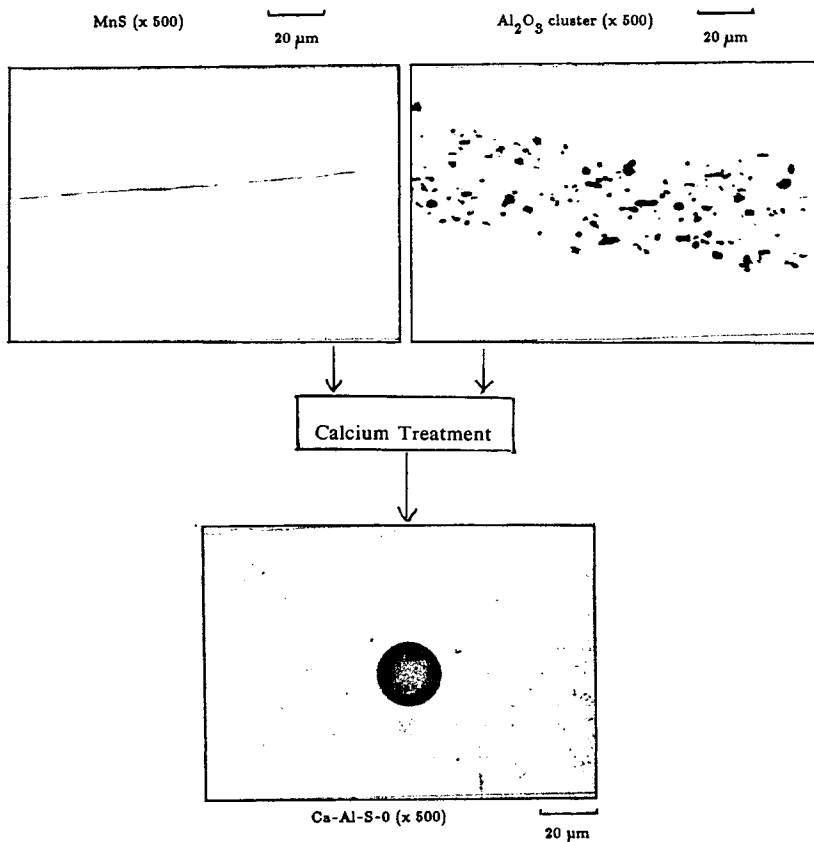


Figure 2.4 Example of inclusion shape control by calcium treatment for plates.

The addition of calcium, however, has to be carefully adjusted with higher sulphur contents ($>0.030\%$). With the very low oxygen activity from aluminium deoxidation the sulphur activity may cause the preferential formation of calcium sulphides, which are solid at liquid steel temperatures and lead to severe clogging problems. In the case of sulphur contents below about 0.010% an appropriate calcium addition converts existing sulphides into a spherical shape. Spherical oxide inclusions, however, only form if a specific calcium to aluminium ratio is obtained. The liquid calcium aluminates separate more easily and prevent clogging of the submerged entry nozzles with solid deoxidation products which can occur with normal aluminium deoxidation. Nozzle clogging, of course, can lead to severe operational problems.

Calcium addition can also be made to the tundish but this method is not regularly used because of severe splashing and the inability to always obtain uniform treatment.

Generally speaking, the removal of inclusions in the ladle by argon bubbling and vacuum treatment is essentially determined by the intensity and duration of treatment.⁶ Bottom stirring with porous plugs is preferred to lance stirring by some works for the production of clean steel since it is easier to control turbulence and hence reoxidation.

The inclusion of a ladle arc furnace as one of the secondary steelmaking vessels allows the input of heat to enable better control of temperature.

2.3 Temperature Control in Ladle and Tundish

For both operational and product quality reasons it is essential to be able to control the range of steel temperature as it enters the continuous casting mould for the whole of the casting time for each ladle. There are many ways in which heat losses or gains can occur from the liquid steel in the ladle. In deciding the tapping temperature in the steelmaking vessel and the temperature as the ladle leaves the ladle arc furnace there is a requirement to make allowances for each of the potential heat losses (or gains).

The extent of the heat losses/gains depends on several factors which are listed below:

1. Radiation losses from the tapping stream.
2. Alloy additions to the ladle.
3. Heat losses to ladle and tundish refractories (can be controlled by preheating).
4. Radiation losses from steel surfaces in ladle and tundish (can be limited by use of slag cover and lids).

5. Heat losses by radiation during gas stirring (can be minimised by using optimum gas flow rates).
6. Heat losses during degassing.
7. Heat input at the ladle arc furnace.
8. Radiation losses from the ladle to tundish teeming stream/refractory shroud.
9. Radiation losses from the casting stream/submerged entry nozzle.
10. Heat losses can also be accelerated by adding scrap as a coolant.

A mathematical model has been developed^{7, 8} to take account of all these factors, including the transient effects of heat conduction to the refractories and the heat losses through the slag. This calculates the average bulk steel temperature in the ladle as a function of time from the final turn-down temperature in the BOS vessel. In practice gas stirring is carried out to reduce temperature non-uniformity and stirring is also carried out during the input of heat at the ladle arc furnace.

The liquid steel temperature in the ladle continues to fall during casting but the rate of heat losses through the ladle and tundish walls also decrease due to the transient nature of conduction to the brickwork. A heat balance is carried out on the tundish (allowing for the conduction to the bricks and radiation losses) and therefore the casting temperature can continuously be calculated.

The heat fluxes to both ladle and tundish bricks are functions of time and can be calculated using a thermal diffusion model. These heat losses are dependent on preheating conditions.

The temperature in the tundish has been assumed uniform where in practice temperature gradients will be established. Much work,⁹ assisted by water modelling, has been carried out on tundish design to increase mixing, to obtain satisfactory flow patterns and to define and minimise the periods of indeterminate composition for each strand when changing ladles with different steel grades during sequence casting. This work has significantly reduced differences in temperature of the steel from the various tundish nozzles.

The complexity of the secondary steelmaking process routes often means that the liquid steel is in the ladle for up to 3 hours from tapping to finish casting and the need to predict and allow for heat losses and gains is essential and has led to sophisticated on-line predictive computer systems^{1,10} giving steel temperature profiles of the liquid steel both in the ladle and also the tundish right up to the end of casting that particular ladle. This can be re-calculated each time a ladle temperature is taken in the course of processing. The advent of the use of the ladle arc furnace in recent years has given scope for more accurate temperature control as well as for improved compositional control.

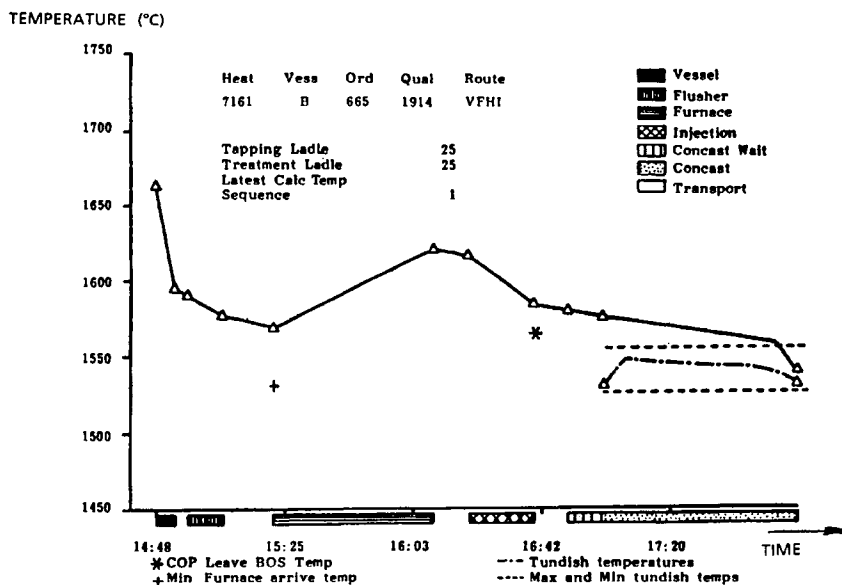


Figure 2.5 Forward prediction of liquid steel temperatures in the ladle and tundish.

Figure 2.5 shows a typical forward prediction of liquid steel temperatures for an on-line computer system.

2.4 Tundish Technology

One of the main functions of the tundish (as described in Section 1.2.1) is to distribute the liquid steel over the appropriate number of continuous casting strands. Other important functions are:

- To help further remove inclusions from the steel.
- To act as a reservoir during ladle changing whilst enabling the continuation of casting under the required conditions.

One of the requirements to achieve the above is to ensure an adequate tundish volume and operating depth. Additionally the shape and internal arrangement of such things as weirs and dams are used to facilitate inclusion removal and increase the residence time of steel in the tundish.

Physical and mathematical models have been developed⁹ to determine the flow patterns and temperature differentials at the exits for each strand. These have been used extensively to design or redesign tundishes to ensure optimum performance. A cover powder is used on top of the steel in

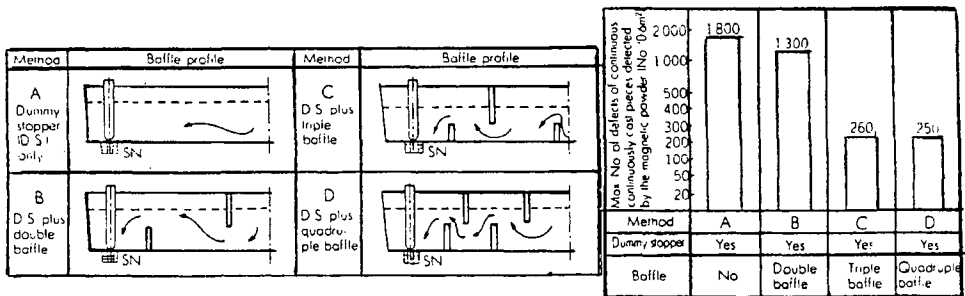


Figure 2.6 The effect of baffles on defects determined magnetically.

the tundish to act as an insulation to reduce radiative heat losses and also to absorb the inclusions which float out of the steel. Refractory lined lids are also used on both ladles and tundishes to further reduce heat losses. The optimum design of tundish is invariably achieved by the selected use of weirs and dams. Figure 2.6 shows in addition to the damless design three variants which, in ascending order, are claimed to enhance the degree of cleanliness.¹¹

Figure 2.7 shows a typical tundish for a twin strand slab caster.

The tundish life often determines the number of ladles which are cast in sequence. Refractory problems especially with the stoppers and nozzles

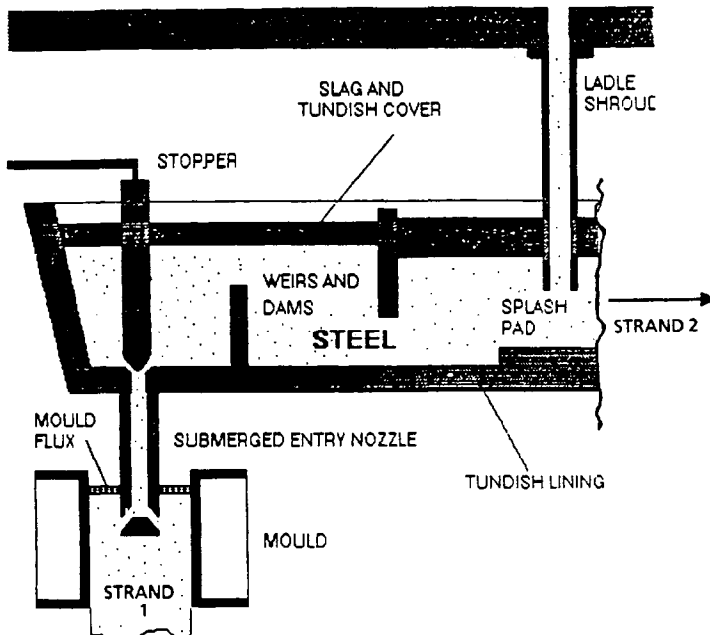


Figure 2.7 Typical tundish design for a twin strand slab caster.

are one of the limiting factors. Although high alumina brick or magnesia brick are generally used as tundish refractories, inner linings of monolithic refractory, such as castables, are also used. In some cases magnesia heat insulating boards or tiles are used inside the lining bricks which require little or no drying and preheating. However, some preheating is often necessary due to hydrogen being picked up by the steel from the bonding material in the tiles, particularly during the first slab/blooms cast at the start of the sequence. This is undesirable in many steel grades.

2.5 Ladle to Tundish Teeming

The flow of liquid steel from the ladle to the tundish is controlled by the use of a sliding gate valve. This valve consists of three refractory plates, two fixed and one free which can be moved horizontally by means of an hydraulic ram. Figure 2.8 shows the arrangement.

By continuously weighing the tundish or by other means such as eddy current coils behind the tundish refractories the level of steel in the tundish can be automatically controlled by continuous adjustment to the sliding gate to control the flow rate from the ladle. This control system will be discussed more fully in Section 6.1.1.

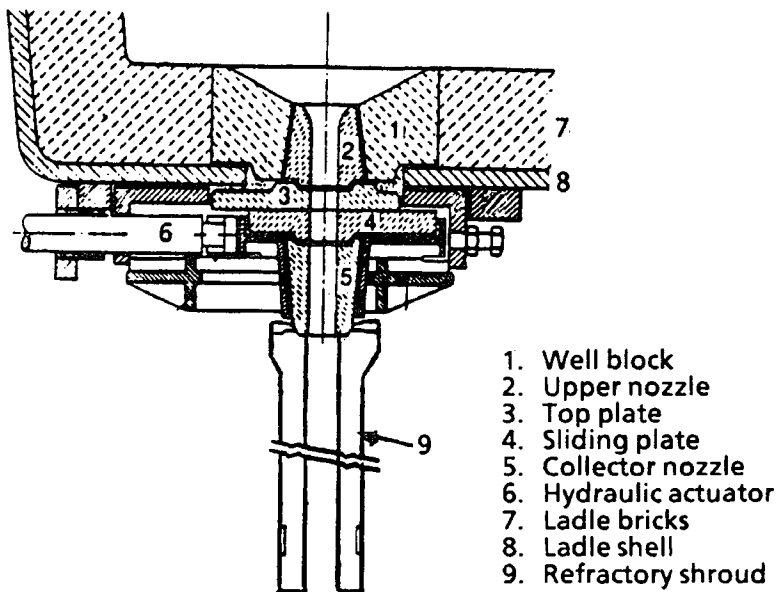


Figure 2.8 Details of ladle sliding gate valve and refractory shrouding tube.

For a long time, protection from oxidation of the teeming stream between the ladle and tundish was neglected or its importance underestimated. However, during the mid 1970s it was realised that the key to maintaining clean products depended on efficient ladle stream shrouding.

Modern secondary steelmaking methods ensure that the liquid steel in the ladle is of high quality with much reduced deoxidation products and vastly cleaner than 15–20 years ago. In addition calcium treatment is often used to purposely modify certain inclusions to enhance final product properties and performance. Many steel specifications now require very low sulphur and nitrogen levels and such steels, if exposed to the atmosphere, very rapidly pick up nitrogen. Therefore efficient shrouding is paramount to:

- Reduce oxidation of aluminium since steels containing aluminium are very sensitive to reoxidation.
- To prevent nitrogen pick up on low sulphur steel.

Due to the low pressure generated in the sliding gate nozzle and the refractory tube by the venturi effect there is a great risk of sucking in air between the sliding gate plates and the joint between the lower nozzle on the plate and refractory tube. Various systems are used whereby inert gas (usually argon) is used to 'gas shroud' those areas.

In addition to the reoxidation protection of the pouring stream the preventing of slag flow from ladle to tundish on emptying the ladle is of great importance, in particular when sequence casting.

Systems for the detection of slag during casting or for monitoring steel level in the ladle are now used (See Section 6.2.1). These systems should make it possible to close the ladle gate as soon as slag appears and thus ensure ladle slag does not build up in the tundish.

2.6 Tundish to Mould Teeming

The flow of steel from the tundish to the mould is controlled either by a sliding gate mechanism (similar but smaller than that on the ladle) or by a stopper rod device which is mounted in the inside of the tundish (Figure 2.9). Metering nozzles are used to control steel flow in most billet casters.

Figure 2.9 also shows the submerged entry nozzle (SEN) between tundish and mould and which is used for all but small billet sizes (less than about 130 mm square). Other methods such as gas shrouding need to be used for these small billets due to the mould size constraints.

For casting reoxidation sensitive steel grades, mainly aluminium killed grades, submerged tubes between tundish and mould are the only

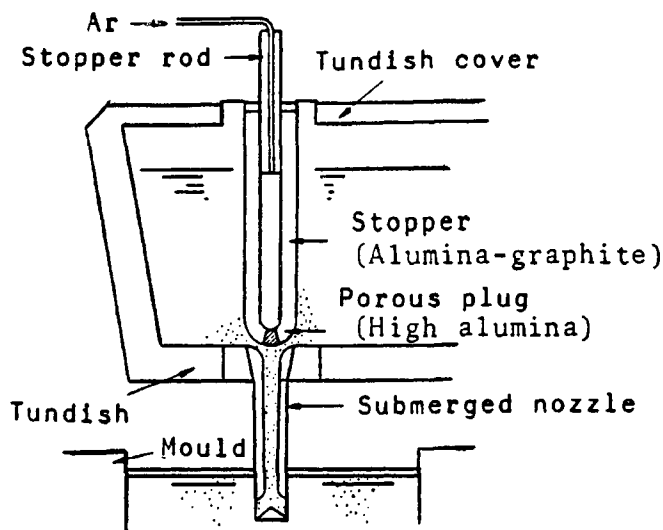


Figure 2.9 Schematic diagram of stopper rod and submerged entry nozzle (SEN) between tundish and mould.

successful solution. It is essential that the connection between the submerged tube and the tundish is gas and air tight. For that reason, a single piece nozzle is common in units when a stopper rod is used. With a slide gate the system may have to be flooded with inert gas in order to prevent any ingress of air.

It is important to choose suitable materials for the submerged entry nozzles. In order to ensure good steel cleanliness and to show sufficient life for long sequences they have to withstand the chemical attack of steel alloying elements such as aluminium, sulphur, manganese and the attack from mould casting powder slags.

In many cases alumina graphite nozzles seem to be adequate but for even higher requirements zirconia sleeved nozzles are used in the mould meniscus region for higher wear resistance against attack from the mould slag.

When casting aluminium-killed steels, nozzle clogging can occur due to alumina adhering to the submerged entry nozzle material. To reduce the occurrence of nozzle clogging, argon gas is injected down the stopper rod (see Figure 2.9).

Other factors, which may have considerable influence on the cleanliness of the cast products, is the immersion depth, the shape and outlet configuration of the submerged entry tubes, i.e. the diameter, number and angle of the outlet ports.

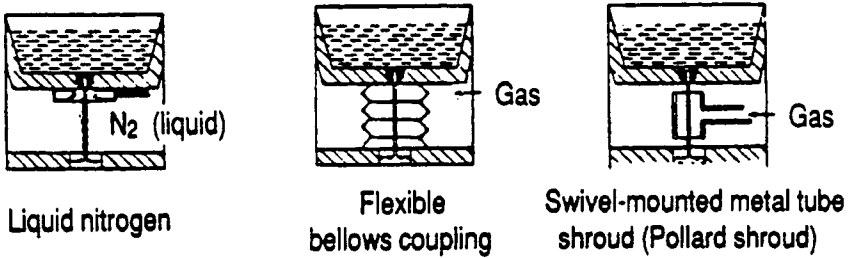


Figure 2.10 Several systems for shielding the tundish to mould teeming stream during billet casting.

Many billet casters for common steel grades do not use this system but apply other methods,¹² shown in Figure 2.10. If reoxidation and other contamination is successfully prevented, steel of good quality can be delivered into the mould.

For many quality-control reasons it is important to maintain the variations of the level of liquid steel in the mould within tight control and therefore sophisticated mould level control systems are used for this purpose. This usually involves the use of a radioactive source within the mould wall to measure the absorption of gamma rays due to the presence of liquid steel. Another popular method is to employ an eddy current sensor above the mould to detect the metal level. The mould level signals are then fed into a control system which moves the tundish stopper or sliding gate valve to adjust the teeming rate. Metering nozzles are used in billet casters (see Figure 2.10). This means that the flowrate of the steel is controlled by the nozzle diameter and the head of steel in the tundish. In this case the mould level signal is used to continually control the withdrawal speed to maintain mould level control. Further details of these control systems and their impact on product quality will be discussed in Sections 4.2.3.1 and 6.1.2.

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3. MACHINE COMPONENTS, HEAT TRANSFER AND STRAND SOLIDIFICATION

This chapter gives details of the main components of the casting machine and includes the mould, the strand support systems, the secondary cooling arrangements, strand straightening and strand withdrawal. In each case consideration is given to design principles and, in particular, the quantification of heat transfer in various parts of the machine and which is fundamental to the control of strand solidification. Additionally, methods will be described which have provided heat transfer data which can be used in various computer simulation models and to enable the design of systems and methods to control the solidification process. The computer simulation models dealing with mould technology, strand solidification and strand geometry will also be described in some detail.

The effects of these parameters, along with factors such as steel chemistry, on the presence of defects in the as-cast semis will be described in Chapter 4. This applies to both internal and surface defects.

3.1 Mould Technology

3.1.1 Mould Design Details

The mould is the only mechanical part of a caster that is exposed to molten steel. It is probably the most important part of the machine and has to operate under severe conditions. It needs to create a homogeneous shell by efficient uniform heat transfer. The mould also needs to be long lasting, be capable of rapid change of section sizes, and require the minimum of maintenance effort.

Continuous casting moulds are all cooled by high quality water, often demineralised, supplied from a recirculating system. The design and fail safe systems are usually arranged to provide a minimum water flow velocity in the cooling channels of 8 m/sec. Moulds are invariably tapered internally to accommodate contraction of the steel but the amount of taper depends on the section sizes and casting speeds involved.

Figure 3.1 shows the basic construction of a billet (a), bloom (b) and slab mould (c) respectively. The copper moulds are contained by steel backing

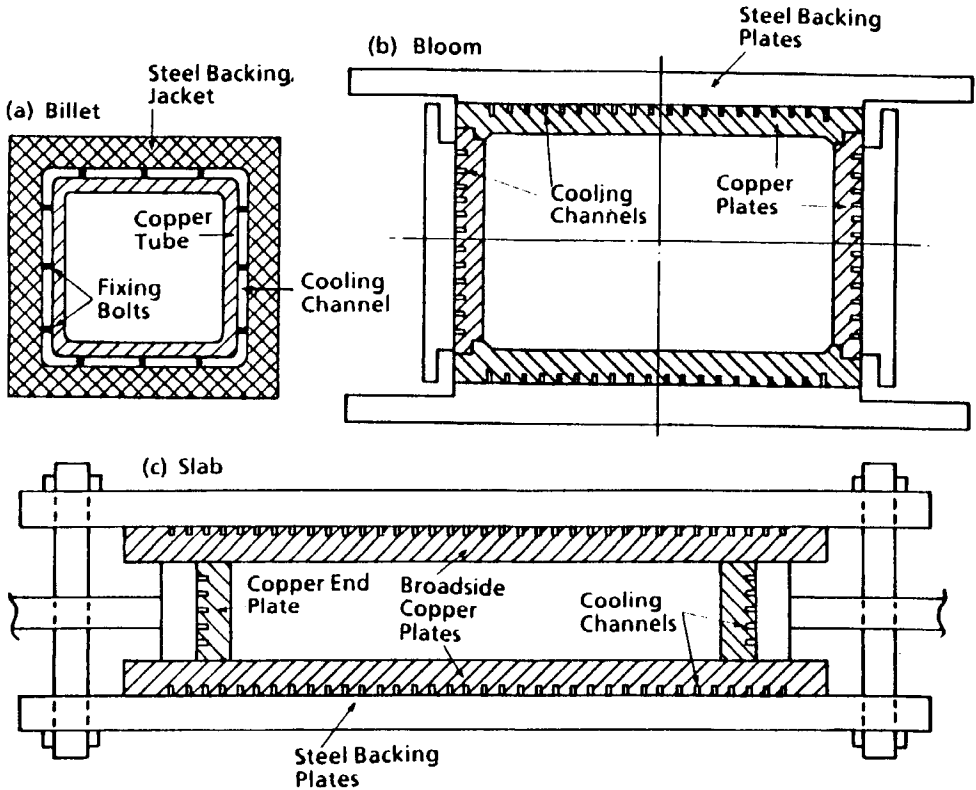


Figure 3.1 Mould constructions for billet, bloom and slab casters.

plates with water inlet and outlet manifolds at the bottom and top of the mould respectively.

The water cooling grooves are machined in the back of the copper plates from top to bottom in slab and bloom moulds the dimensions of these being about 15 mm deep and 5 mm wide. In billet moulds the water channel is usually a parallel gap between the tubular copper mould and the backing plate.

To ensure a thin boundary layer at the copper surface and hence no nucleate boiling, a high Reynolds number is required in these water cooling grooves which results in a need for the water velocities being greater than 8 m/sec.

The following are the two main mould types. These are:

Tubular Moulds. These are frequently used for casting small sections such as billets. The copper tube is surrounded by the water cooling jacket and, although easily deformed, the tube can be quickly exchanged or straightened. The maximum practical size is about 230 mm square, or 430 mm diameter for rounds castings but they are normally less than 200 mm

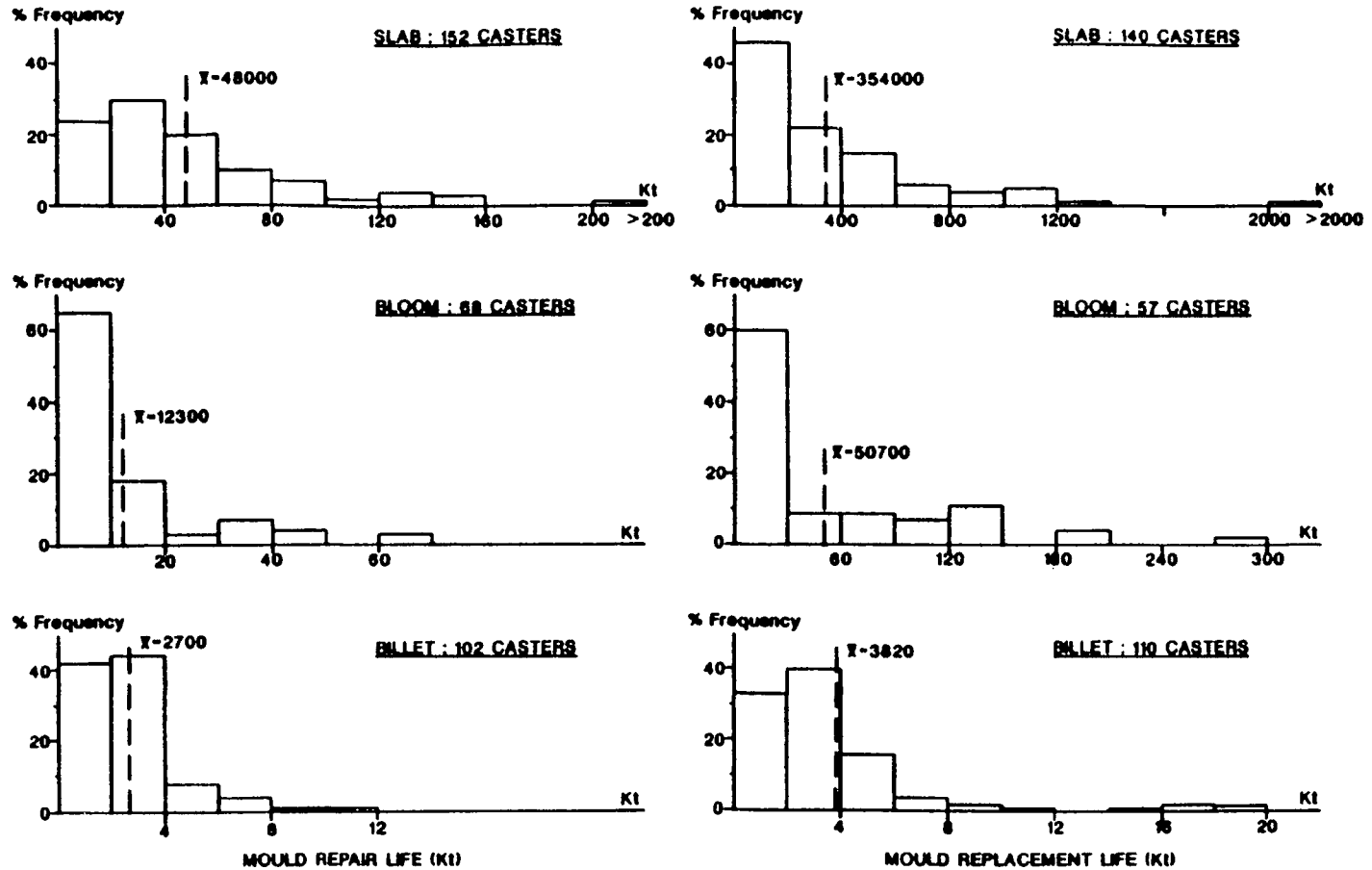


Figure 3.2 Mould lives for billet, bloom and slab casters.

across. The larger sizes have greater wall thicknesses of about 20 mm and on small sizes

Plate Moulds. These are assembled from four copper plates of 40 to 60 mm thick. The cold faces are grooved and covered with a steel backing plate. The cooling water passes through these grooves or, in an alternative design, through circular cooling channels machined in the copper. These moulds usually enable the narrow faces to be adjusted for different widths and these mechanisms can in some cases now be operated during casting (Section 3.1.1.4).

The copper plates in bloom and slab moulds are usually between 50 and 60 mm thick when new and about 40 mm thick at the end of their lives. Usually several machinings of the face are carried out during the plate life. Figure 3.2 shows the distribution of heats cast between machinings and for the total lives of slab, bloom and billet moulds respectively.¹

3.1.1.1 Mould Length

The normal mould length was, until recently, 700 mm, but the range extends from 500 to 1,200 mm. The most recent trend has been towards 900 mm moulds to provide an increased solidified thickness at the mould outlet when casting at higher speeds.

3.1.1.2 Mould Materials

The mould material must rapidly transmit the heat from the solidified steel to the cooling water and hence good thermal conductivity is essential. Copper and copper alloys are invariably used but it is necessary to minimise distortion from thermal stress. Silver, chromium and zirconium alloying additions are used because of their improved high temperature properties;² Table 3.1 and Figure 3.3 give details. In some cases, the working face of the mould is plated to minimise wear. This is claimed to reduce star cracks formed when copper adheres to the solidified shell but many plants, particularly in Europe, operate successfully without plating.

Various methods of plating the copper with nickel and chromium have been developed. One technique uses a thick layer so the mould can be re-used after surface dressing. Other techniques taper the coating or use a two stage plating method, the intention being to minimise wear at the lower part of the mould. Another technique uses nickel iron plating and the increased hardness doubles the wear resistance. Mould plating is most common in Japan and finds only limited application elsewhere.

3.1.1.3 Mould Oscillation

The original idea of a reciprocating motion to prevent sticking between the shell and the mould is attributed to Junghans, see Section 1.1. With a few

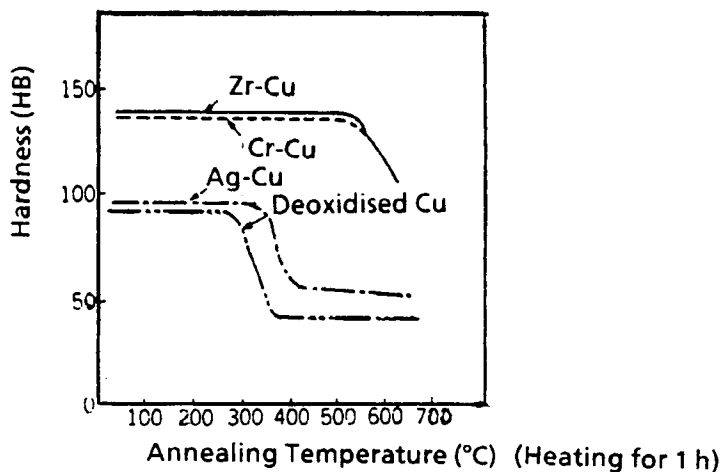


Figure 3.3 Softening resistance of copper alloys.

Table 3.1 Copper specifications

Chemical composition		Mechanical properties (minimum)				Electrical conductivity
Cu	Others	Tensile strength	0.2% proof strength	Elongation	Hardness	%IACS
(%)	(%)	(N/mm ²)	(N/mm ²)	(%)	(HB)	(20°C)
99.9		200	40	40	45	98
(Cu + Ag) 99.9	Ag 0.07–0.12	250	200	10	80	98
(Cu + Ag) 99.9	P 0.004–0.915 Ag 0.07–0.12	250	200	15	80	85
98.0	Cr 0.5–1.5	350	280	10	110	80
98.0	Cr 0.5–1.5 Zr 0.08–0.30	350	280	10	110	70
98.0	Cr 0.5–1.5 Zr 0.08–0.30	300	240	15	100	70

exceptions, the mould oscillation cycle is sinusoidal but in every case the downward velocity exceeds the casting speed for part of the cycle. During this time, (termed the negative strip time or heal time), sticking between the mould and the shell is overcome.

Mould oscillation is essential for the elimination of breakouts and under carefully controlled conditions the breakout rate can be virtually zero. The movement for mould oscillation is derived from a motor driven cam but

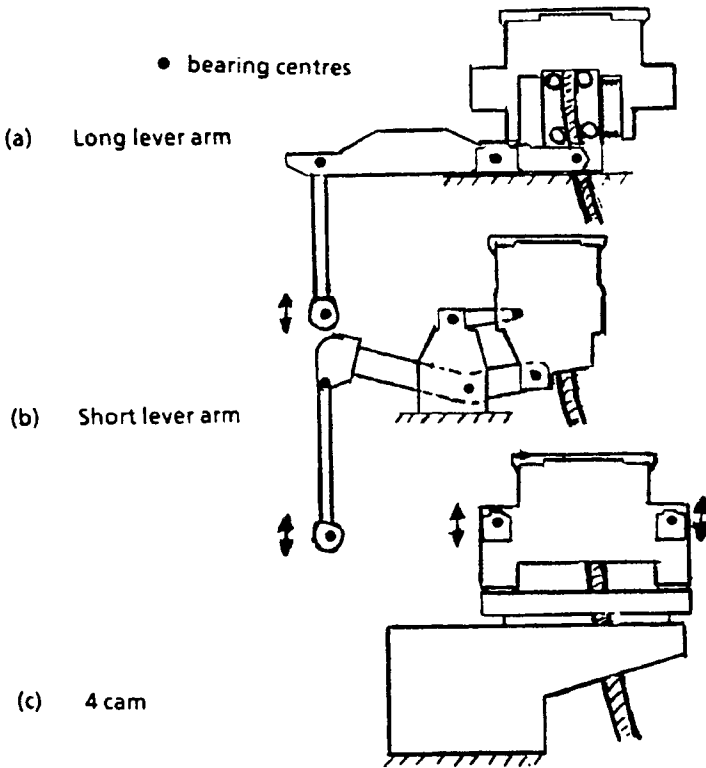


Figure 3.4 Mould oscillation mechanisms.

hydraulic devices have been developed. The design of the structure, bearings and lever arms is critical since the stroke length must remain equal at different points on the mould and only very small horizontal or radial movements of less than 0.2 mm can be tolerated. There are several design principles used such as direct cam drive, short or long lever arm or, more recently, hydraulic movement and some of them¹ are illustrated in Figure 3.4.

For best results the mounting points of the oscillation system should be separated from the casting floor and machine frame. Defective oscillation will result in increased breakout rate and surface defects on the strand.

Recent work has shown that there can be significant improvements to surface quality by operating with small heel times. This is usually achieved with small stroke lengths, down to 4 mm on slab machines³ and down to 8 mm on billet machines and oscillation frequencies of 200 cycles/minute (cpm) or greater compared to the more usual 100 or 120 cpm. These higher frequencies and small stroke lengths, have shown benefits on some stainless steel casters and are becoming more common

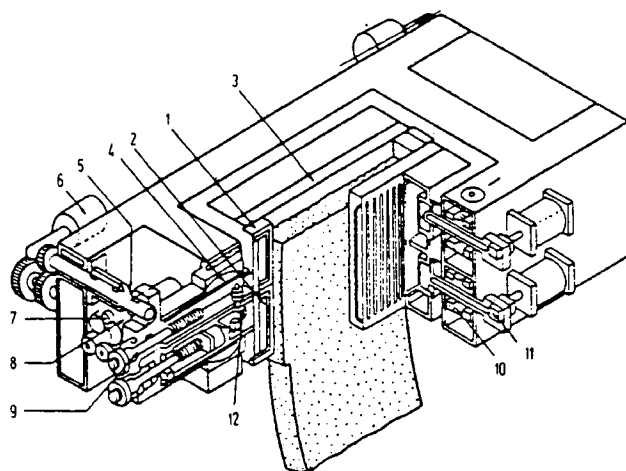
elsewhere, and place a greater demand on the design and upon the engineering standards for trouble free operation. More details of how the oscillation conditions affect as-cast quality will be given in Section 4.2.3.3

3.1.1.4 Variable Width Moulds

Over the last decade mould width changing during casting on slab machines has been established in a response to the demand for different slab widths without interruption of a sequence cast. The technique is applied in many current slab casters. A maximum width changing speed of 200 mm/min has been achieved by using a carefully chosen sequence of moving the narrow plates.⁴

The variable width is achieved by careful movement of the narrow faces which are power adjusted inwards or outwards during the casting process. The adjustment is made over a period of time and results in a tapered slab which may need special attention during reheating. Figure 3.5 shows the main components required for such adjustments.⁵

It is critical during the width change that the taper of the end plate is accurately controlled, the taper varying as the width is changed.



Mould construction:

- 1 - Top narrow faces
- 2 - Bottom narrow faces
- 3 - Broad faces

Taper adjustment system:

- 4 - Cage with rotary segment
- 5 - Cam
- 6 - Drive

Width adjustment and measuring system:

- 7 - Position indicator (pulse generator)
- 8 - Positioning motor
- 9 - Spindle

Mould clamping system:

- 10 - Release mechanism for width change
- 11 - Mould clamping device for casting
- 12 - Narrow face locking mechanism

Figure 3.5 Width adjustable mould with horizontally split narrow faces.

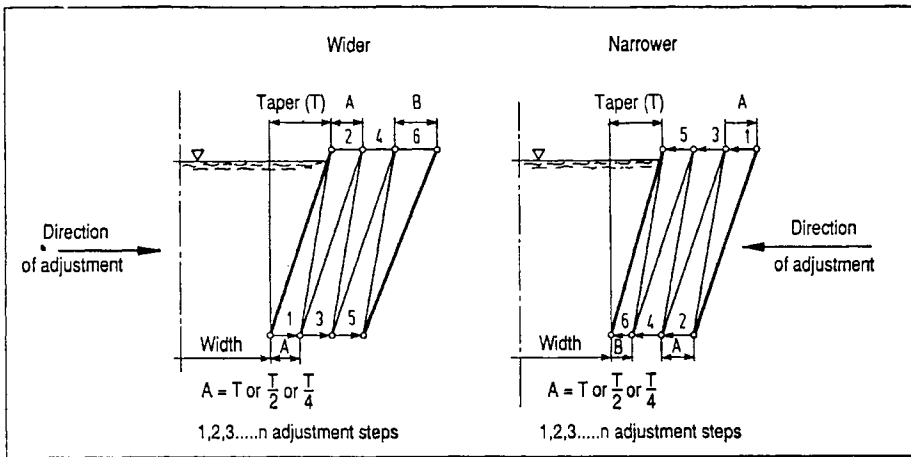


Figure 3.6 Stages in a width adjustment operation.⁶

It is necessary to have inclinometers installed to measure the taper continuously and Figure 3.6 shows the sequence of events for both changing to a wider or narrower slab width.

It is reported⁶ that width adjustment during casting can result in an increase in production of 30–50%, a reduction in refractory costs by 30–50%, an increase in yield of 0.3–0.5% and significant savings in energy. The energy savings are realised by the fact that width changing increases the ability to hot charge and/or direct roll since it is then possible to match the rolling schedule.

3.1.1.5 Moulds for Twin and Triple Casting

In discussing machine productivity in Section 1.2 the twin or triple casting of narrow slabs or blooms was briefly mentioned. Wide slab slitting is another method of achieving narrow slabs or blooms from a slab machine. The mould and top zone for twin or triple casting on a slab machine is basically two (or three) separate moulds and top zones, with two (three) SENS for the one 'slab' strand on the tundish. The remainder of the strand remains the same so that the two (or three) blooms have a common withdrawal system. In some cases the wide slab mould with a central water cooled copper divider is used rather than two separate bloom moulds. For a very large slab mould two slabs can be cast with widths up to around 1000 mm. Figure 3.7 shows a sectional view of a twin mould slab caster.

3.1.2 Mould Heat Transfer

The heat transfer details, mechanisms and the solidification behaviour in the water cooled copper mould are among the most important processes

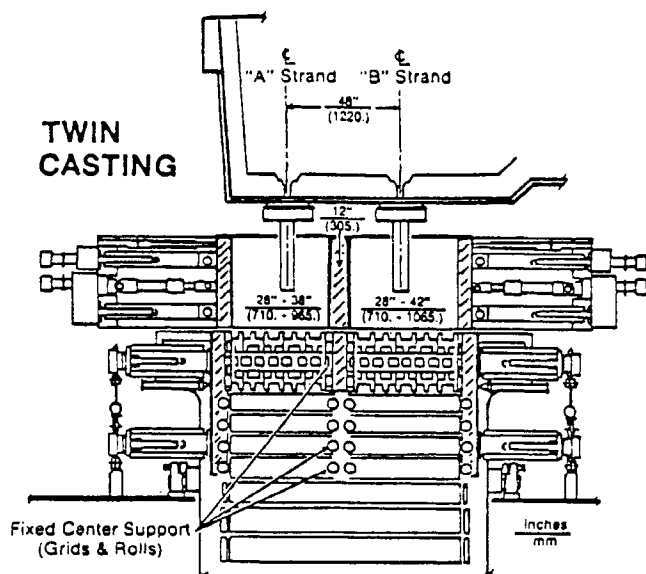


Figure 3.7 Sectional view of twin mould slab casting.

taking place during the continuous casting of steel. It is fundamental that the mould extracts heat from the steel in as uniform a manner as possible with some degree of control. The surface quality of the cast semi is very dependent on mould parameters since this is where the surface is formed and can, therefore, be the source of many surface defects. Uniform heat transfer also helps to avoid breakouts.

Further details of the defects and how they can be related to certain mould parameters are given in Chapter 4. Figure 3.8 shows the temperature distribution between the solidifying steel and the cooling water.⁷

The heat flux Q is given by:

$$Q = h_{ss} (T_{ss} - T_{hf}) = \frac{K}{D} (T_{hf} - T_{cf}) = h_{cf} (T_{cf} - T_{bw}) \text{ Kw/m}^2$$

where:

h_{ss} = heat transfer coefficient from the face of the solidifying steel (kW/m² K)

T_{ss} = temperature of the outer face of the solidifying steel (°C)

T_{hf} = copper 'hot face' temperature (°C)

T_{cf} = copper 'cold face' temperature (°C)

K = thermal conductivity of copper (kW/m K)

h_{cf} = heat transfer coefficient of the 'cold' copper face (kW/m² K)

T_{bw} = bulk temperature of the cooling water (°C)

D = thickness of copper (m)

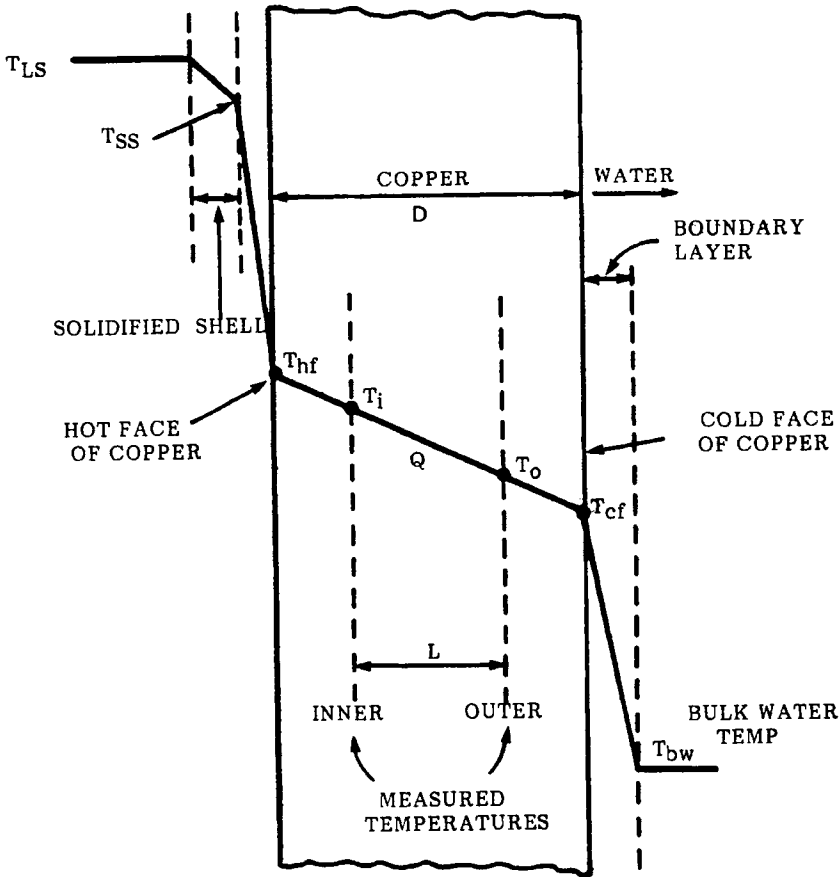


Figure 3.8 Temperature distribution between steel and cooling water.

From the liquid steel temperature in the mould, there is a temperature drop across the solidifying skin which will be discussed more fully in Section 3.4.1. The interface between the steel shell and the hot face of the mould wall incorporates the film of lubricant and any gaps which form and this component of the heat transfer represents a major factor governing the heat flux from the steel to the cooling water in the mould. The high conductivity of the mould wall material ensures a small temperature drop across the copper. The 'cold' face of the mould wall can be significantly higher than the bulk cooling water temperature due to the boundary layer which is present in any water cooling channel. This boundary layer, however, can be affected by the cooling water flow conditions in the cooling channel and the temperature drop across the boundary layer can be fairly confidently predicted from well proven heat transfer theory. It is

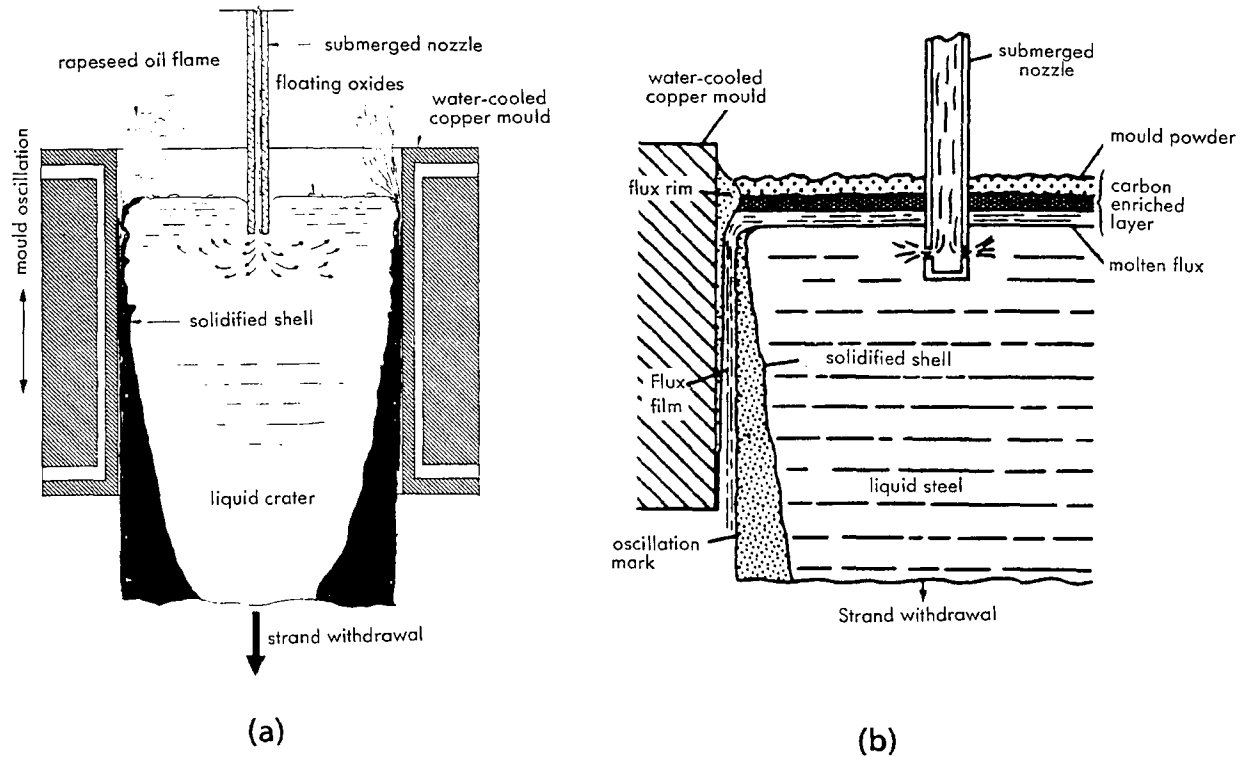


Figure 3.9 Teeming and mould details for lubrication using (a) rape seed oil and (b) mould powder to provide a slag.

necessary to maintain the cooling water velocities sufficiently high (8 m/s) to avoid nucleate boiling.

The interface between steel and copper, the major component to the thermal impedance, is a complex area and needs discussing in more detail. This is very much affected by the type of lubricant used.

In billet casting squares <~130 mm and rounds <~130 mm diameter it is difficult to use a refractory submerged entry nozzle. In these cases 'open' teeming using a metering nozzle is practised but invariably using an inert gas shroud around the open teeming stream (see Figure 2.10). Rape seed oil, fed from small holes in the copper face above the meniscus, is used as a lubricant in this case. Figure 3.9 (a) shows the details in the mould when using rape seed oil as the lubricant.

In slab and bloom casting a submerged entry nozzle (SEN) is used together with a synthetic mould powder which forms a fluid slag between the powder and the steel in the mould. Figure 3.9(b) shows the details in the mould and the interface with the copper when using a submerged entry nozzle and synthetic powder.

The main advantages of using mould powder over rape seed oil are:

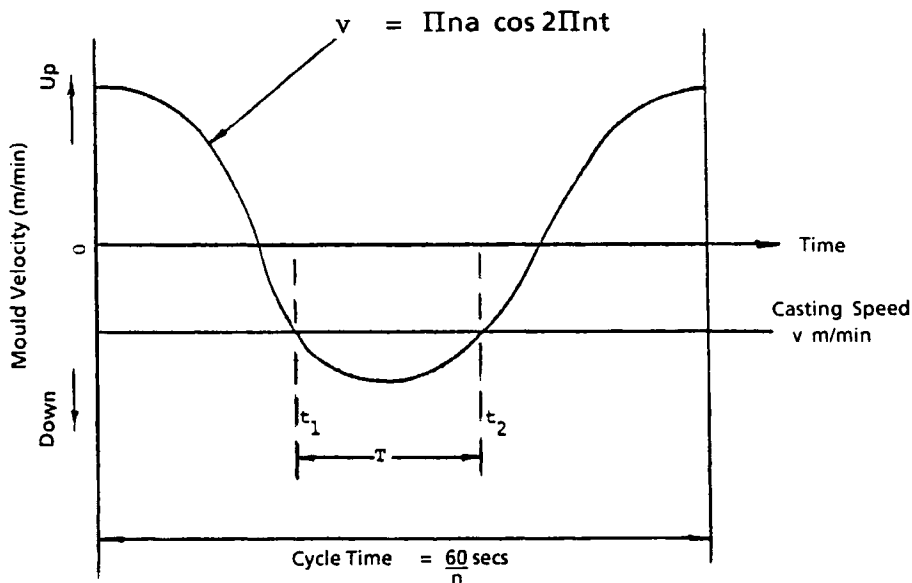
- A submerged entry nozzle (SEN) is used with mould powder which is a more efficient method of stream shrouding.
- It prevents radiative heat losses from the metal surface in the mould and prevents solidification on the surface which can lead to 'plating' defects.
- The slag formed from the powder absorbs non-metallic inclusions (e.g. Al_2O_3) which float out of the metal pool in the mould.
- The slag allows more uniform heat transfer to the copper wall.

The mould powder composition and properties needs to be such that the heat from the liquid steel produces a continuous fluid slag layer of adequate thickness and with a viscosity which enables a continuous flow of slag into the meniscus at the copper wall.

A further fundamental requirement is that the mould is oscillated sinusoidally in such a manner that for a certain percentage of the cycle the mould would be travelling in a downward direction faster than the solidifying shell.

Figure 3.10 shows the oscillation cycle and that part of the cycle where the mould travels downwards faster than the strand. This is called the negative strip time, or heal time, and is chosen as a compromise between lubrication (and hence friction) and the maintenance of uniform heat transfer. This will be discussed in much more detail in Section 4.2.3.3.

The interactions between the mould oscillation, mould slag feeding and variations in mould metal levels are quite complex and several computer



T = Heal Time (secs)

a = Stroke Length (mm)

Figure 3.10 Oscillation cycle showing negative strip time.¹

models have been developed⁸ to determine the mould powder consumption rate and the solidification characteristics at the meniscus as a function of mould oscillation, mould level and powder slag properties. This will be discussed further in Section 4.2.3.2.

All these factors determine the slag film thickness which in turn determines the thermal impedance of the interface. Additionally, the gap between the solidifying steel and the copper wall is affected by the surface temperature and shell contraction, which can cause 'air' gaps to form which may depend on section size and shape. Figure 3.11 shows for various strand cross-sections the formation of an 'air' gap between the strand shell and the mould wall such as occurs below the meniscus level.

These gaps can also vary down the length of the mould usually increasing from below meniscus level. This is counteracted by a three-dimensional taper for billet and bloom cross-sections. In the case of slab moulds only the narrow faces follow the shrinkage in the cross-section and only the end plates are consequently tapered. Due to bulging no gaps form along the broad faces for slabs and the broad faces are set parallel to each other.

Much work has been carried out⁷ using thermocouples embedded in the mould copper plates to measure the heat flux through the mould

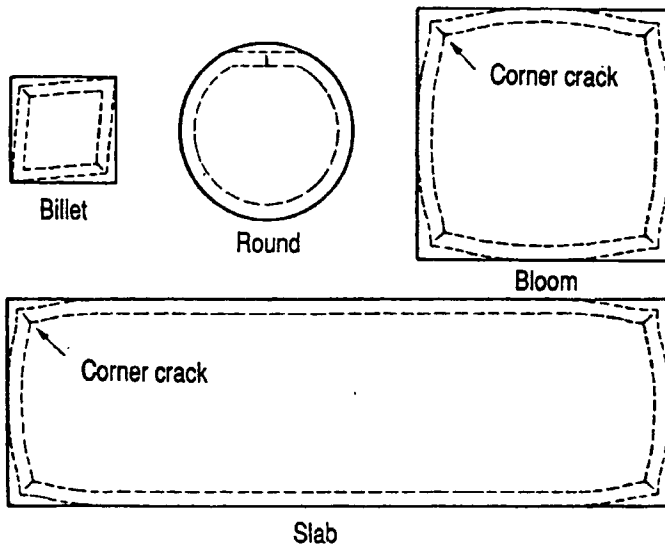


Figure 3.11 Gap formation and change in cross-section resulting from shrinkage in the mould.⁶

plates. This work has generally concentrated on the inter-relation of the heat flux, heat flux distribution, mould wall temperatures, type of mould lubricants used, steel compositional factors and operating practice. The implications of some of these factors on as-cast steel quality will be discussed in Chapter 4.

The general temperature distribution from the solidifying steel to the cooling water is shown in Figure 3.8. Figure 3.12 shows the location of thermocouples inserted in the copper end plate of a 330 mm × 254 mm bloom mould.

Thermocouples were arranged in pairs mid way between the water cooling channels. The thermocouples in each of these pairs were situated 7 mm and 18 mm respectively from the 'hot' face of the copper mould. 7 pairs were installed down the length of the mould as shown in Figure 3.12. This thermocouple arrangement enabled heat fluxes to be measured and the 'hot' face temperature of the copper plate to be calculated.

Both mould wall temperatures and heat flux distributions down the length of the mould were investigated. These investigations included the effect of:

1. The flow-rate and hence the velocities of the cooling water.
2. Type of mould lubricant used.
3. Carbon content of the steel being cast.
4. Casting speed

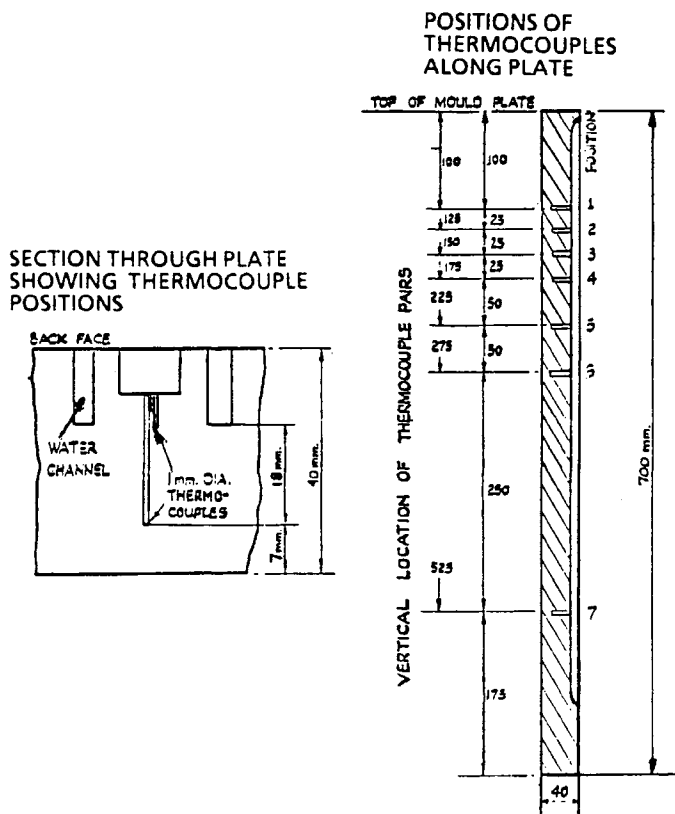


Figure 3.12 Location of thermocouples in a 254 mm end plate.

3.1.2.1 Effect of Cooling Water flow-rate

The cooling water flow-rate was varied over a wide range and Figure 3.13 shows the effect of the cooling water flow-rate on heat flux and 'hot' face copper temperature.

It can be seen that the heat flux is fairly constant for this wide variation in the cooling water flow-rate which confirms the point made that the over-riding controlling factor on heat extraction from the solidifying steel is the interface boundary between the steel and the hot face of the copper mould. The effect of the boundary layer can be seen to have driven the copper temperatures higher for a lower water flow rate.

3.1.2.2 Affect of Mould Lubricants

Figure 3.14 shows the effect of various mould lubricants on the heat flux distribution down the mould and on 'hot' face copper temperatures. These distributions are shown for two mould casting powders and for rape seed

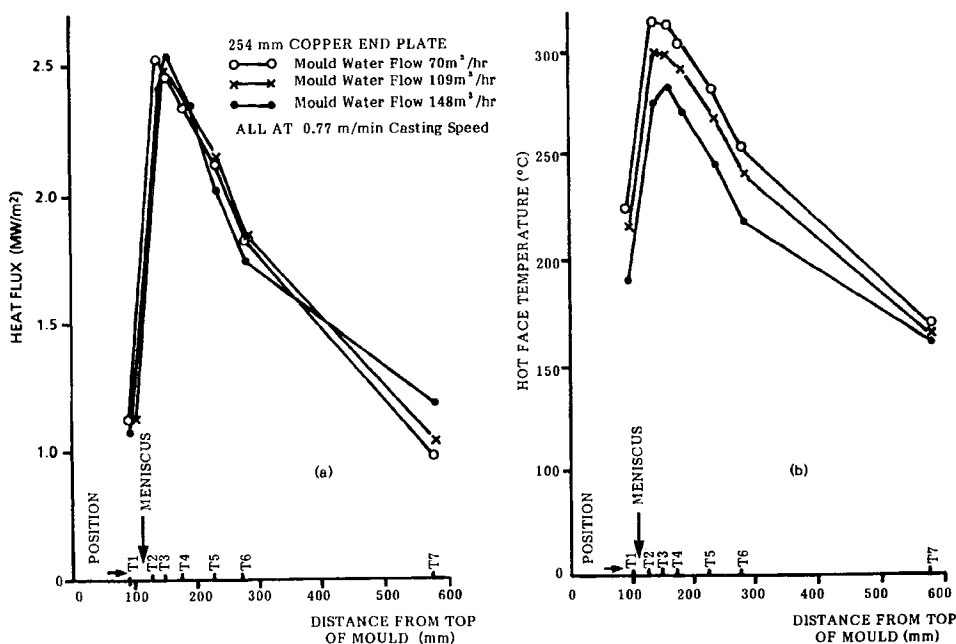


Figure 3.13 Effect of cooling water flowrate on (a) heat flux and (b) hot face temperature.

oil. As can be seen from these results, the heat fluxes are considerably higher for rape seed oil and it is worth noting in particular the very increased heat flux in the meniscus region.

3.1.2.3 Effect of Carbon Content

The effect of steel composition and particularly carbon content on the overall mould heat transfer has been reported from several sources.^{7,9} Figure 3.15 shows the measured average heat flux in the mould over the carbon range of 0.02% to 1.6%. The effect of carbon content on heat transfer leads to some quality problems being more acute within the carbon range 0.06 to 0.14% (the peritectic range).

Irregular shell thicknesses down the length of the mould have been observed^{10,11} for 0.1% carbon steels. It was proposed that this irregularity in shell thickness and in non-uniform heat transfer is caused by the γ to δ phase transformation and associated volume changes and shrinkages which occur at this particular carbon level. Figure 3.16 shows the temperatures as measured by a thermocouple near the front face for two levels of carbon and, as can be seen from these recordings, the temperature fluctuations are lower at the higher carbon level (0.55%) while marked fluctuations occur during casting steel with 0.15% carbon. The lower heat fluxes

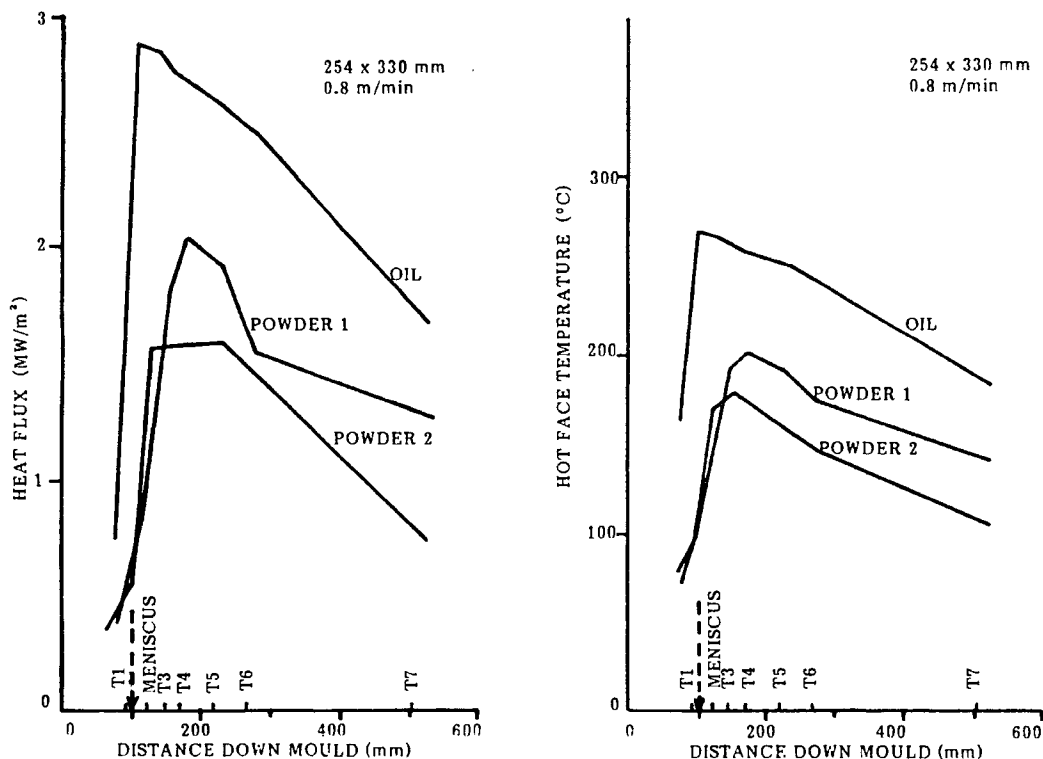


Figure 3.14 Affect of lubricant type on (a) heat fluxes and (b) hot face temperature.

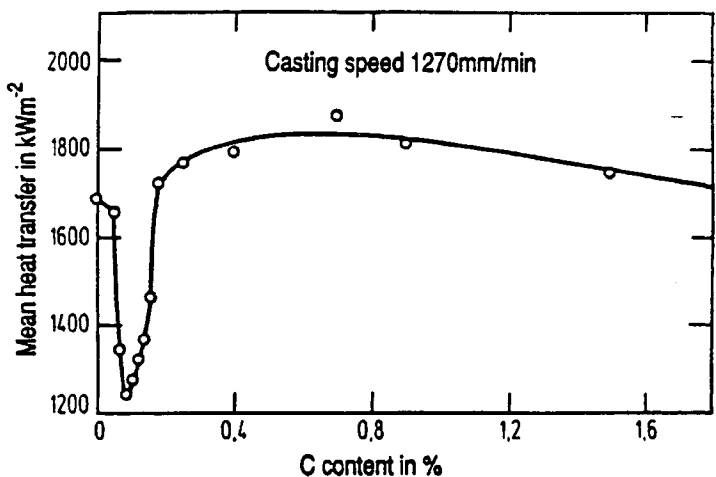


Figure 3.15 Affect of carbon content on mould heat flux.⁹

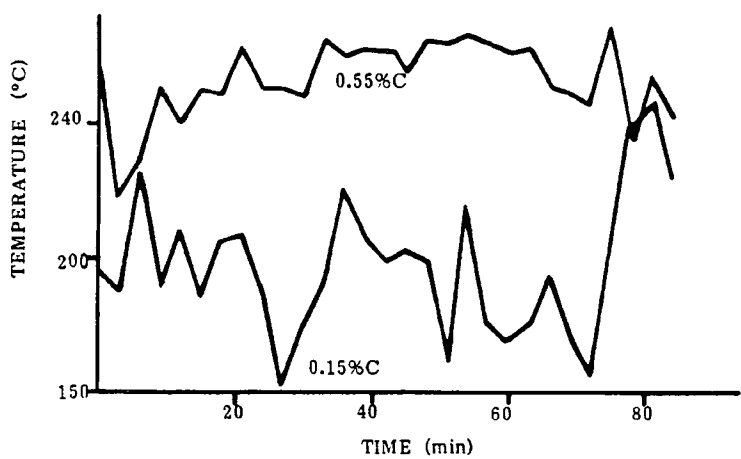


Figure 3.16 Thermocouple temperature for 0.55% and 0.15% C.

at around 0.1% carbon level lead to specific defects arising at these carbon levels and these will be discussed further in Section 4.2.2.1.

3.1.2.4 Effect of Casting Speed

Casting speed also has a marked effect on the distribution and mean heat flux in the mould. Figure 3.17 shows the mean heat flux as a function of the distance down the mould at different casting speeds ranging from 0.8 m/min to 1.3 m/min.

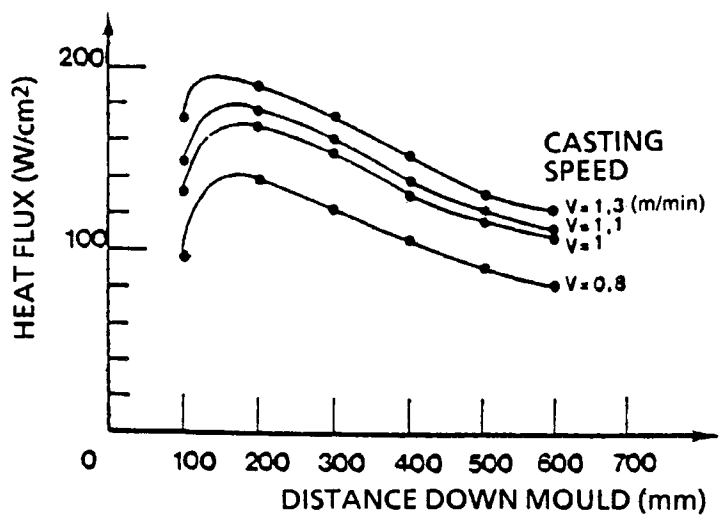


Figure 3.17 Heat flux down the length of the mould for various casting speeds.¹

3.1.2.5 Copper Temperature Distribution

A computer model, which has been calibrated with the above experimental data, enables the complete temperature field within the mould walls to be calculated. ⁷ Figure 3.18 shows the vertical temperature field in the mould wall material along with measured data. The data which have been acquired by these many extensive plant measurements are used as the boundary conditions in the mould when running the strand solidification and temperature distribution mathematical model which is described in Section 3.4.1.

3.1.2.6 Heat Transfer Measurements on a Slab Mould

A more comprehensive number of thermocouples were inserted into a slab mould copper plate and Figure 3.19 shows the arrangements for these thermocouple pairs.

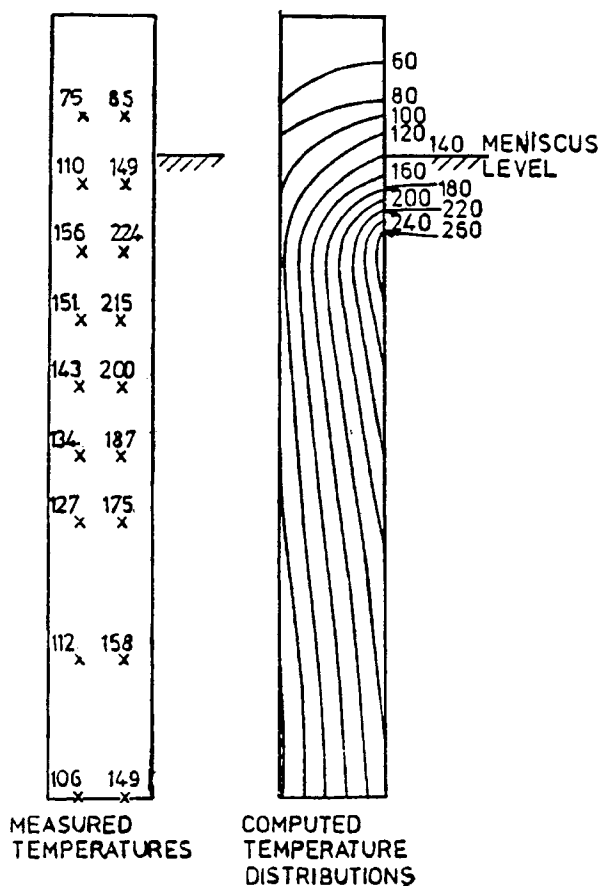


Figure 3.18 Computed and measured temperatures in the vertical section of the 254 mm copper end plate.

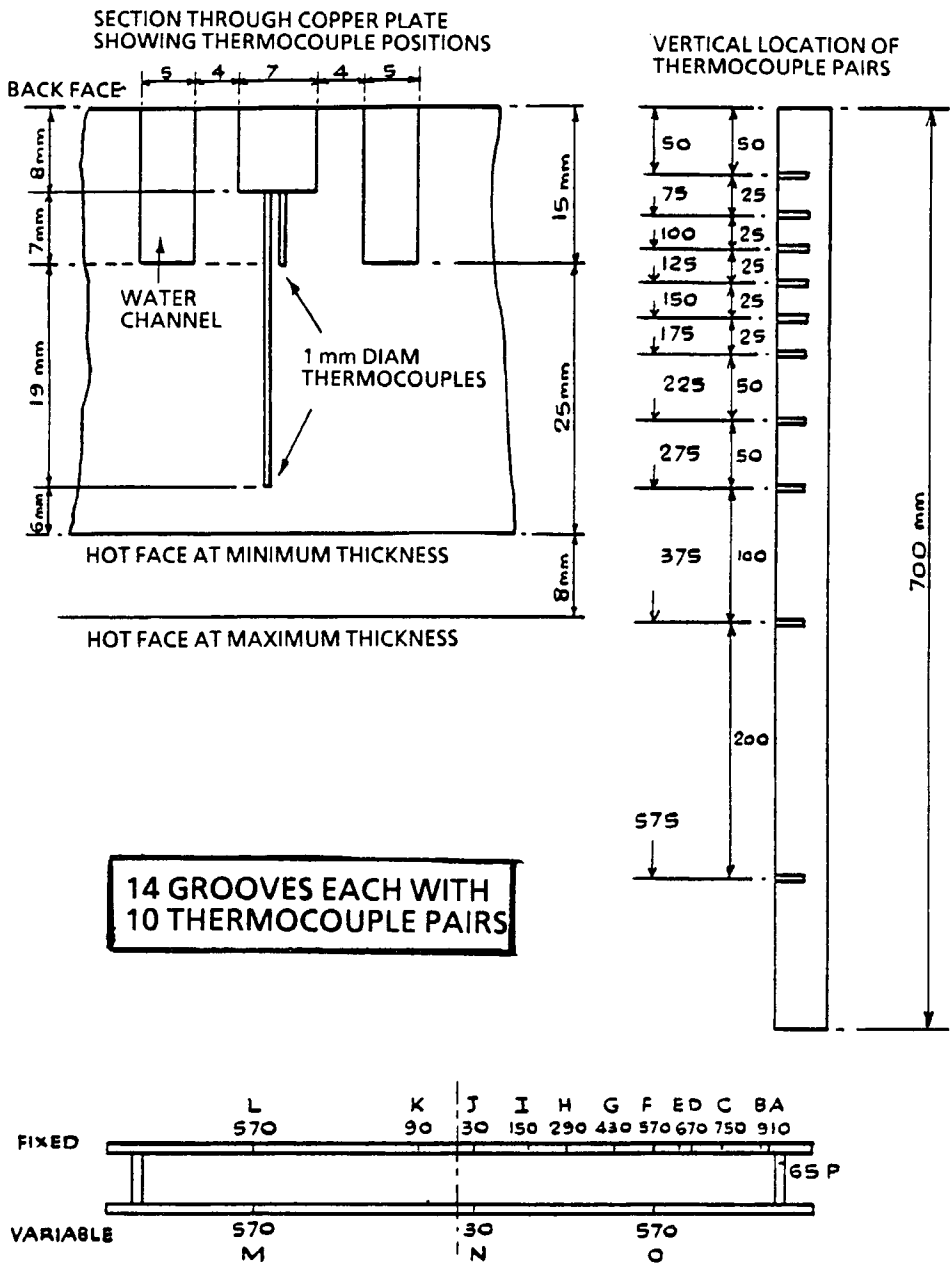


Figure 3.19 Arrangement of thermocouple pairs in a slab mould broad face copper plate.

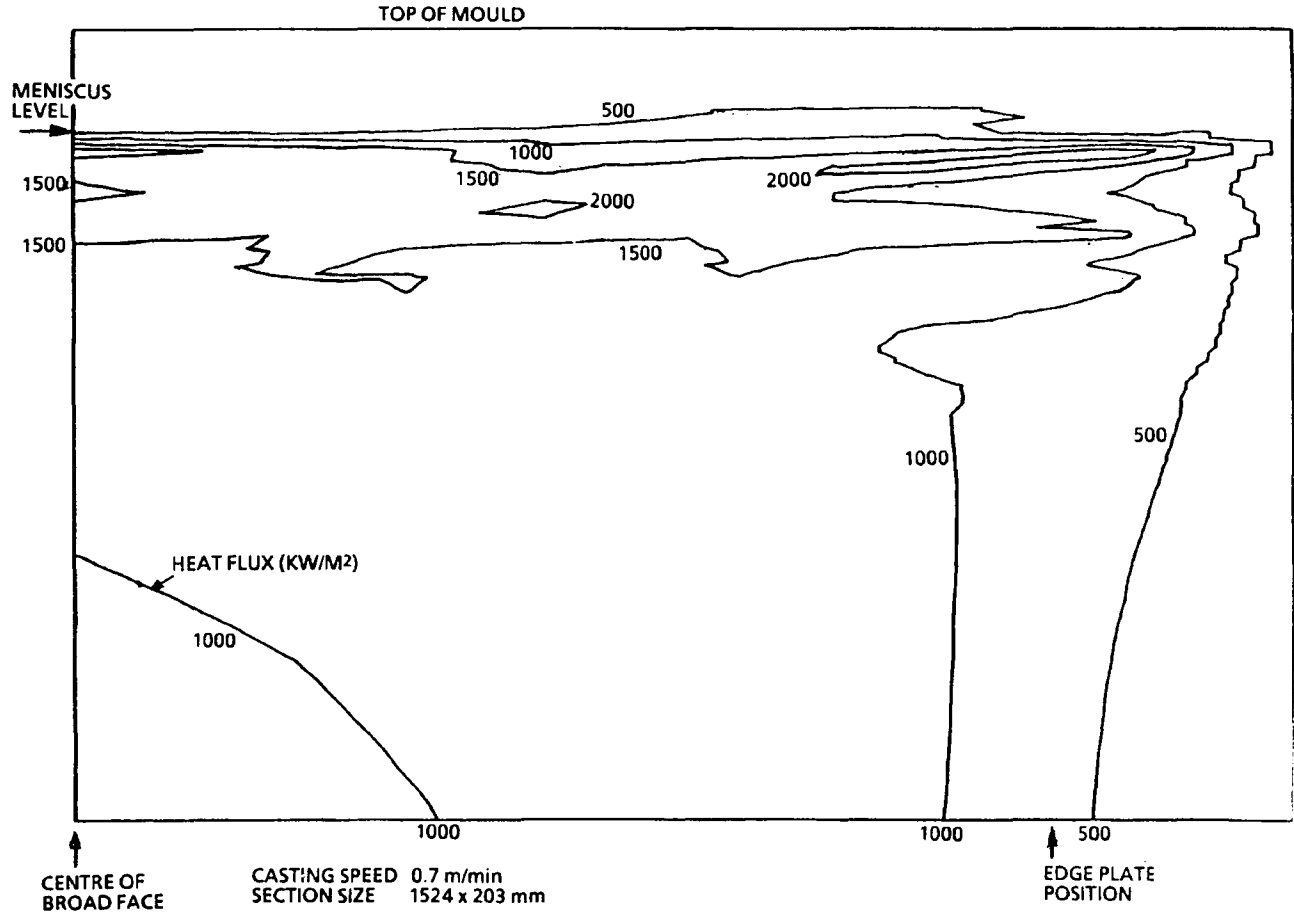


Figure 3.20 Heat flux contours for one half of a slab caster broad face copper plate.

The heat flux contours of one half of the broad face copper plate are shown plotted in Figure 3.20.

3.2 Strand Support Systems and Secondary Cooling

The partly solidified shell as it emerges from the mould is in the region of 10–25 mm thick (depending on casting speed) with a surface temperature of around 1000°C increasing to the solidus temperature (~1500°C) at the solid/liquid interface. It is subject to the ferrostatic pressure of the liquid steel and would consequently quickly bulge outwards without constraint.

This thin shell, as it emerges from the mould, requires both continual cooling and mechanical support. Secondary cooling sprays are used to control the cooling but the strand support structure, being water-cooled for protection, also extracts heat from the strand. Radiation also contributes to the total heat transfer. The design and operation of the secondary cooling system is dependent on the type and design of the strand support system which in turn depends on the section size and shape being cast. The details of the support equipment for various machines will first be described.

3.2.1 Strand Support Systems for Various Machine Types

The strand support systems vary considerably between those required for billet, bloom and slab casters. For small square sections such as billets the restraining influence of the billet corners are sufficient to prevent shell bulging apart from the region just below the mould. In this case the mould foot rollers combined with support rollers on each side for the first metre or so may be adequate support. This gives more scope further down the strand for more uniform cooling from sprays. However, some billet casters, operating at lower casting speeds and producing section sizes less than about ~130 mm square or rounds with diameters less than ~150 mm have no containment support other than the foot rolls attached to the mould. Any rolls in such machines are usually just to guide the strand and to re-thread the dummy bar. For higher casting speeds for billet casting more support rollers may be required. In any such event the alignment of these rolls with each other and the mould exit is quite important.

The mould length is usually between 700 and 900 mm long (see Section 3.1) but for some billet machines casting at higher speeds a mould extension device is sometimes used. This consists of four spring loaded plates with cooling being provided through orifices in the plates. This mould together with the extension is termed the 'Multi Stage (MS) Mould'.

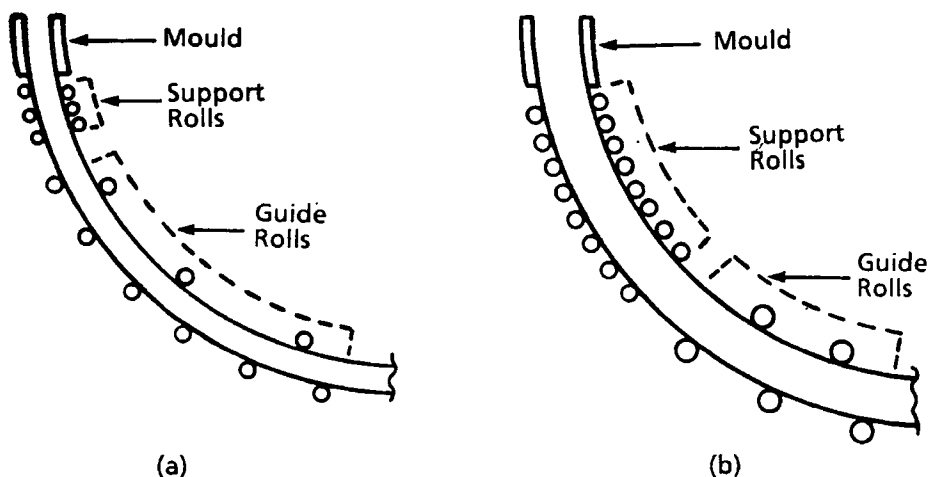


Figure 3.21 Extent of support rollers for typical billet and bloom casters.

For larger billet casters and bloom casting there is an increased propensity for bulging when the shell is still hot and thin and consequently support rolls have to extend further down the strand. Typical support systems for a billet machine and a bloom machine are given in Figure 3.21.

For slab machines the bulging of the broad faces extend to the point where solidification is complete and invariably strand support of the wide faces extends the full length of the machines. The latter part of the machine requires rollers for strand withdrawal. Since slab machines are the most complex by both the extent of the support, and the bulging forces involved, the detailed description of the design and operation of strand support systems will concentrate on slab machine requirements. It should be noted that the strand support system contributes significantly to the cooling of the strand and these cooling affects will be included in Section 3.2.2. on 'Secondary Cooling'.

3.2.1.1 Below Mould Support for Slab Casters

A variety of strand support and cooling systems just below the moulds in slab machines have or are currently being used. These are:

- Rollers
- Grids
- Cooling plates
- Walking beams

Walking beams proved to be mechanically too complex whilst cooling plates generated too much friction.

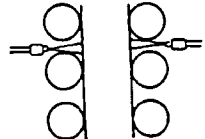
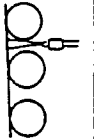
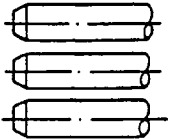
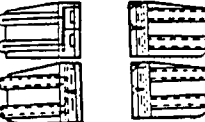
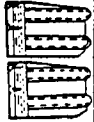
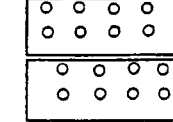
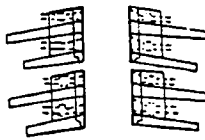
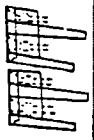
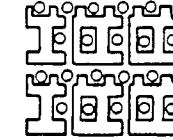
	Schematic diagram			Secondary cooling water covering ratio	Slab supporting ratio	Withdrawal resistance	Remarks
Roll				13.7%	3.0%	Low	Direct cooling system (flat spray)
Cooling plate				3.7%	89.3%	High	Indirect cooling and direct cooling system
Cooling grid				25.6%	56.3%	Medium	Direct cooling system (full cone spray)

Figure 3.22 Characteristics of below mould support systems for slab casters.¹²

The aim is to obtain uniform cooling with minimum friction whilst maintaining accurate support geometry. Today rollers and grids are in most common use with rollers providing the system with least friction between strand and support system.

Figure 3.22 gives details of the characteristics of rollers, cooling plates and grids.

The secondary cooling arrangement just below the mould very much depends on the strand support system used. For example, with rollers flat sprays are used because of the small gap between the rollers. For grids, however, full cone sprays are used and aligned to direct the cooling water into the rectangular apertures in the grid. With cooling plates the water is directed through a matrix of small holes and the resulting water film between the plate and the strand provides the cooling.

3.2.1.2 Main Strand Support Systems for Slab Machines

In a continuous slab caster the main support systems are generally composed of segments containing between three to six pairs of rolls with the ability to rapidly exchange the whole segment. The segment frames are clamped together by hydraulic cylinders and the roll gaps are preset using chocks and shims. Figure 3.23 shows the details of a typical slab machine segment (a) with single piece rolls, (b) with 'divided' or 'split' rolls and (c) the end view.

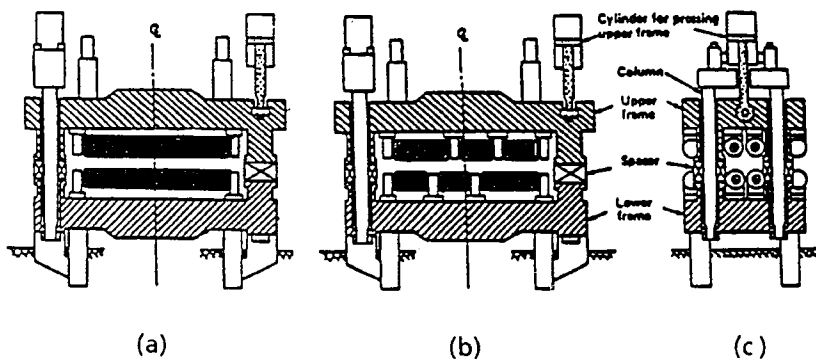


Figure 3.23 Details of typical roller support segments (a) with single piece rolls, (b) with divided rolls and (c) end view.

The secondary water sprays are aligned on headers so that the solidifying strand is cooled in the gaps between the rolls.

The segment as a whole is fixed rigidly to the frame of the casting machine and the inner radius rolls can be adjusted by the hydraulic cylinders to enable a change of casting thickness (by selection of thicker chocks) or for fully opening which is required in the case of an over cooled slab in the machine which has to be removed by cutting or for scheduled maintenance of the segments *in situ*.

It is necessary to have the facility to rapidly exchange the segments and Figure 3.24 shows a schematic diagram of how each segment can be withdrawn from the machine by way of guide rails along which a crane lifts the segments from the machine.¹² In some machines the segments are removed horizontally sideways prior to lifting them out by use of a special crane.

Complex finite element models have been developed to predict the degree of bulging of the solidifying shell both between adjacent roll contacts and when a roll is misaligned with respect to the adjacent rolls. These will be described in para 3.4.2. Such models are used to design the optimum diameter and pitch of the support rolls. The pitch has to be such that there is insignificant bulging between the roller contacts and the rolls need to be of such a diameter that minimises the degree of roll bending due to the ferrostatic force generated by the liquid core and the thermal stresses due to non symmetrical heating of the rolls.

Up to about 1980 most slab machines used single piece rolls but over the last decade there has been a significant increase in the application of 'divided' or 'split' rolls. Single piece rolls extend to over the full width of the strand and are supported by bearings at each end of the roll (see Figure 3.23). With the advent of improved bearing technology (cooling

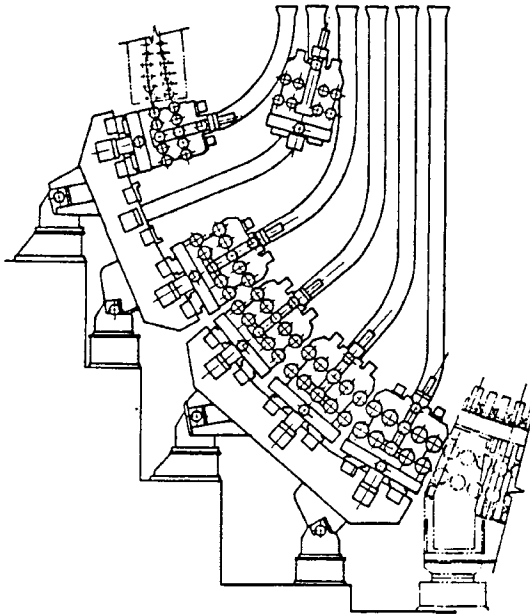


Figure 3.24 Removal of segments via vertical guide rails.

and lubrication in a hot environment) most new wide slab casters and many which have been rebuilt now contain divided rollers. Divided rollers consist of shorter lengths of roller barrels supported part way across the strand by 'central' bearings. This allows greater scope to reduce roll diameters and pitches whilst maintaining rigidity and hence roll gap geometry.

The effect of roller design and performance on slab quality will be discussed fully in Section 4.2.5 (surface quality) and Section 4.3.5 (internal quality). Much work has been done to evaluate the performance of various roller designs and details of their behaviour as a function of design and other operating parameters are more fully discussed in Section 3.2.3. Details of mathematical models to support this work are described in Section 3.4.3

3.2.2 Secondary Cooling

The total 'secondary cooling' is a combination of several components which are:

- Cooling due to radiation
- Cooling due to the water sprays both by the evaporation of the spray water droplets on the slab surface and by the deflected water which accumulates in the entry nip between the rolls.

- Cooling by conduction to the rolls (see para 3.2.3).

In this section details will concentrate on the water sprays themselves but the design and operation of these sprays are very much dictated by the strand support design and as such the individual effects of the sprays on strand solidification cannot always readily be separated.

As described earlier high intensity water sprays are used between the support rollers to further accelerate the solidification process and to assist in controlling of, and reducing fluctuations in, the strand surface temperatures.

The secondary spray cooling achieves the following:

- The main purpose is to extract heat from the solidifying strand.
- The spray nozzles can be designed, arranged and the water flow-rates controlled to give an optimum surface temperature which is necessary to achieve the required surface quality.
- The spray water contributes to the cooling of the strand support rollers although these are all internally cooled (see Section 3.2.3).

In the earlier days of continuous casting of steel water only nozzles were used for secondary cooling but during the late 1970s and early 1980s air-mist sprays were introduced on a wide scale. These consist of both a water and air supply to a nozzle at high pressure resulting in a much finer water particle size whilst also having a wide angle. This enables a much more uniform application of water and the smaller particle size has the advantage of increasing the heat transfer coefficients. Figure 3.25 shows the two systems.

To obtain the basic heat transfer coefficients for both water and air-mist sprays much work has been done in various laboratories. The water flux

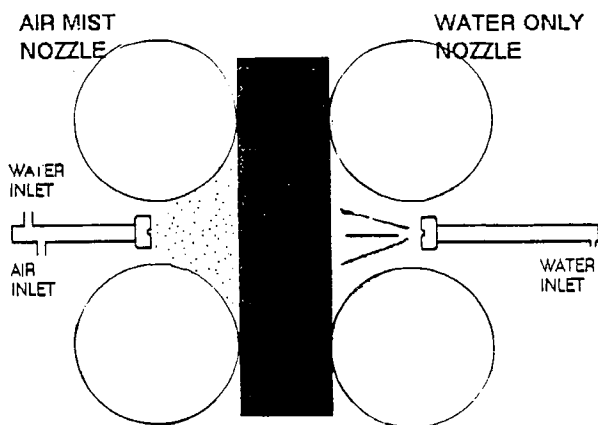


Figure 3.25 Arrangement of water only and air mist spray systems.

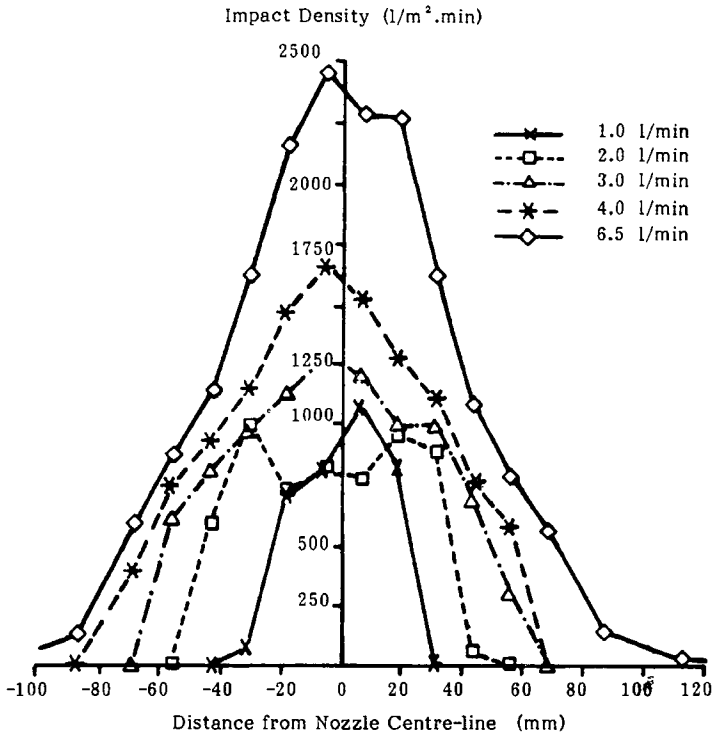


Figure 3.26 Transverse impact density distribution.

distributions and the heat transfer distributions have also been acquired during such measurements. Figure 3.26 shows the transverse impact density distributions for various flow-rates for a particular nozzle. The impact density is defined as the flow-rate per unit area ($L/m^2 \cdot min$).

Figure 3.27 presents a correlation of heat transfer of water spray cooling data after the subtraction of the radiation component. The correlation is based upon the measured data from a number of studies.^{13, 14, 15, 16}

The data have been rationalised into two equations, these being:

$$q = 16 V_s^{0.75} \text{ W cm}^2 \text{ (at 2.5 bar)}$$

$$\text{and } q = 22 V_s^{0.75} \text{ W cm}^2 \text{ (at 8.4 bar)}$$

where q = heat flux (W/cm^2)

V_s = Water impact density ($L/m^2 \cdot s$)

The difference of 38% for the heat flux at these two pressures is attributed to the discharge velocity.¹³

The heat transfer arrangements and required surface temperature profiles are different for machines casting billets, blooms or slabs but in each

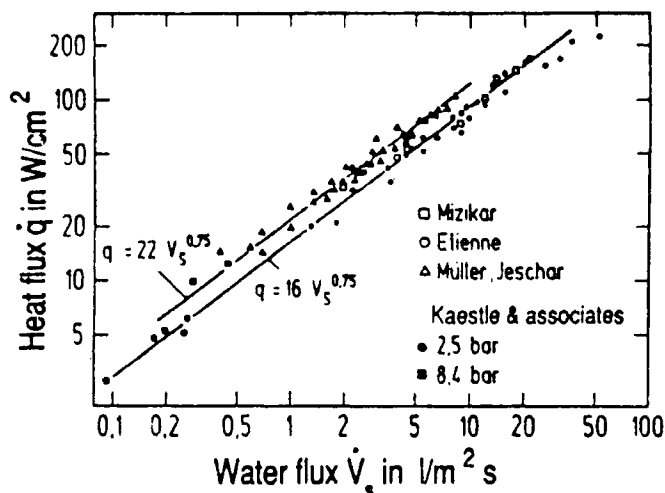


Figure 3.27 Correlation of heat transfer of water sprays after the elimination of the radiative component.

case the cooling is controlled to optimise surface quality. The criteria for the surface temperature profiles invariably depends on the high temperature properties of steel (see Section 4.2.2.2.) and are influenced to some extent by internal quality requirements. There are, however, many fundamental similarities in the secondary cooling of all section sizes and the same theoretical and practical principles can be applied.

The water spray pattern impinging on the strand surface should cover as wide an area as possible but this is often made difficult by the presence of the strand support system. Full cone nozzles are able to cover a large round or square impact area whilst flat spray nozzles can cover a wide impact area across the strand but only a small distance in the direction of casting when used to direct water between adjacent rolls. In billet casters, full cone nozzles are predominately used mounted on header pipes which are installed vertically along each face of the billet strand. The location of support rolls in the upper part of bloom casters and for the whole length of slab casters invariably means that flat spray nozzles have to be used. The length of the entire spray section varies between 0.5 and 6.0 m in the case of billet and small bloom casters and can extend up to 20 metres in high speed slab casters. The secondary cooling system is divided into a number of independently controllable zones down the length of the machines. The spray water supply systems are quite independent of both the mould cooling water and the 'closed' water system to cool the rolls and bearings and other machine elements.

Where air mist cooling is employed, atomisation is by high pressure compressed air acting as the carrier gas. The steam generated is extracted from the spray chamber by large fans. The non vaporised water which may contain scale and grease is returned down a flume beneath the caster to the water cooling and cleaning plant.

3.2.2.1 Spray Cooling with Water Only

In secondary cooling with water alone, the atomisation of the water occurs at the nozzle by virtue of the water supply alone, without additional assistance from other media. In slab casters, the number of horizontal trajectory nozzles located between the rolls determines the system nomenclature. A single-nozzle system denotes the arrangement of one nozzle (occasionally two) which produces a wide-angle spray (up to 120°) at each inter-roll space (spray zone); the multi-nozzle system involves the grouping of many nozzles with a small spray angle at each spray zone. Figure 3.28 shows these alternate nozzle system arrangements.

The single-nozzle system is currently well suited to the majority of the usual slab grades and sizes produced. It began to replace the multi-nozzle system around the mid 1960s because the small nozzle orifices of the latter tended to become clogged very easily. In the meantime, the multi-nozzle system has been revived for certain casters for sheet and sensitive grades, with high spray water flux in conjunction with high casting speeds. The water employed in such systems must have only a minimal content of suspended particles.

The advantages of the single-nozzle system are obvious: fewer nozzles, simpler supply system and easier to maintain. As the single nozzle is installed further away from the strand, it is better protected. Another important benefit in wide-angle single nozzles lies in their relatively high flow capacity (same volume of water with fewer nozzles = greater throughput

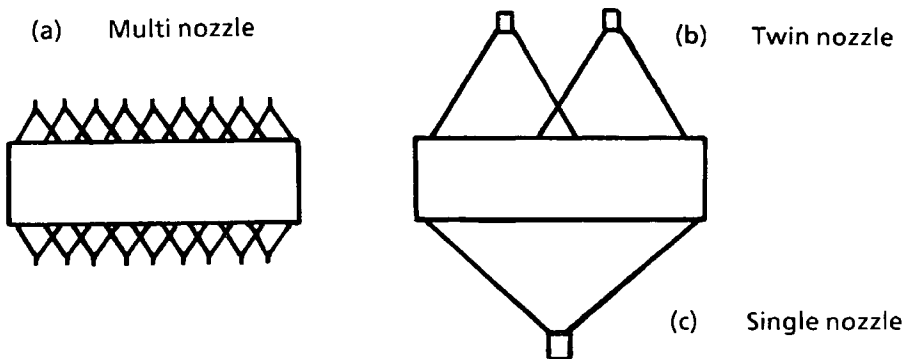


Figure 3.28 Alternative nozzle sytem arrangements.

per nozzle) and hence a larger outlet bore. The outlet bore determines the capacity range of a nozzle, and the flow-rate is controlled within this range by the water pressure. However, large changes in pressure also alter the spray angle, and if the pressure becomes too low, the spray angle collapses and the water flows out of the nozzle orifice without the desired spray effect. The lower pressure limit is generally considered to be 0.5–1.0 bar.

A disadvantage common to all spray nozzles in water-only systems is their comparatively narrow volume flow control range which, given the usual operating pressure encountered in continuous casting plant of 1.0–8.0 bar (at the nozzle tip), is only 1 : 3.5 on average.

In continuous casters in which slabs of various steel grades have to be cast over a very wide range of casting speeds, this limited control range of the nozzles in water only cooling systems may render the installation of two separate spray systems necessary in order to produce the necessary range in water flux. Such systems feature two nozzles of different ratings arranged side-by-side at each cooling zone, and depending on the required water flux, either the smaller, the larger or both nozzles together are employed. Dual systems of this kind are, of course, more expensive and complex.

3.2.2.2 Spray Cooling with Water and Air (Air Mist)

In water-air mist spray cooling systems, the cooling water is mixed with compressed air in a mixing chamber ahead of the nozzle, and the mixture emerges from the nozzle as a finely atomised, high-impulse, wide-angled spray. This type of spray cooling is particularly suitable for high-grade steels which are susceptible to cracking. Its more important advantages include a particularly uniform cooling pattern and a very wide volume flow control range.

A combined air and water cooling system can easily offer a volume flow control range of 1 : 12 and more. The most important benefits of this system are:

- Large flow-rates from nozzle orifices, therefore little danger of nozzle clogging.
- Large volume flow control range, therefore only one nozzle type required for all steel grades and casting speeds
- Uniform water flux over a wide slab surface area (from roll line to roll line), therefore reduced danger of local over-cooling of the strand surface for a given overall rate of heat extraction.
- Formation of extremely fine water droplets for optimum cooling effect.
- Efficient vaporisation of the fine droplets results in less water accumulation ahead of the roll nip.

3.2.3 Roller Design and Performance

The design of the support rollers in continuous casting machines for slab production is a compromise of several factors. As indicated in Section 3.2.1.2 for slab casting machines installed before 1980 the majority of the support rollers were a single roll with support bearing at each end. In the early 1980s with the advent of the development of bearing technology to resist the adverse environmental conditions in the machine, two or three piece rollers were used. Figure 3.29 shows the change in roller pitches for new machines supplied prior to and after around 1980.

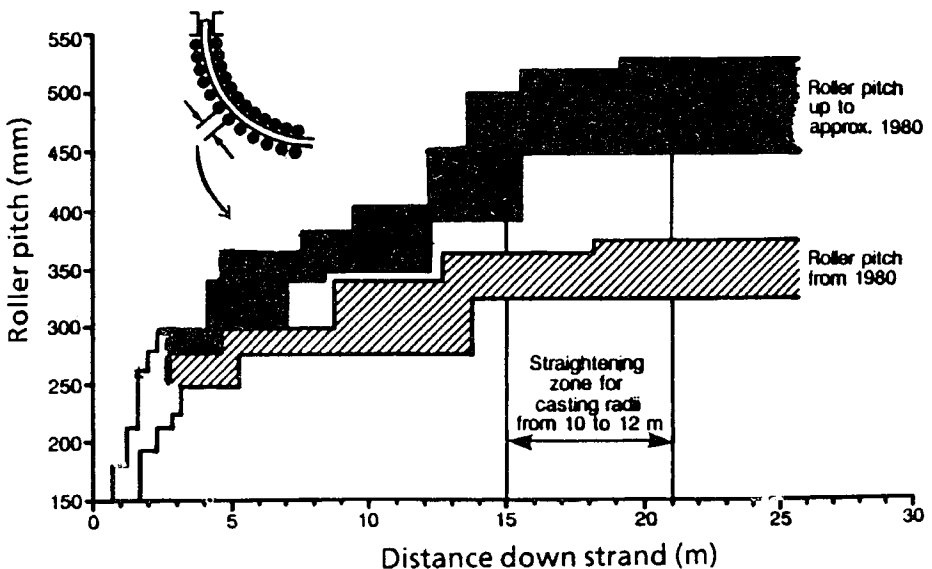


Figure 3.29 Comparison of roller pitches prior to and after 1980 for new slab machines.

All rollers and bearings need to be water cooled and apart from some of the smaller rolls in the upper part of the machines (where high secondary water flow-rates are used) all rollers are internally cooled. However, there are several different designs of rollers and the internal cooling efficiency can vary from one design to another. The main requirements of support rolls are:

1. The diameters and pitches should be such that the inter-roll bulging of the strand should be minimised. This in turn depends on the degree of secondary cooling (i.e. the strand temperature), the casting speed (primarily determines shell thickness), the distance down the strand, and the grade of steel. The creep properties of steel can vary significantly

depending on steel grade. On a 12 m radius machine the ferrostatic pressure at the tangent point is 86 t/m^2 so the force on the solidifying skin is quite large. The degree of bulging is also time dependent and therefore the time taken for a particular element of the solidifying shell to pass from one roll to the next is related to casting speed.

2. Geometrically the rolls should remain stable. If the rolls were too small in diameter and maybe 2 metres long (a typical slab single roll length) then the rolls would bend due to:
 - (a) the ferrostatic force
 - (b) the thermal stresses since the rolls have an asymmetrical temperature distribution during operation.
 - (c) during a strand stoppage the asymmetric temperature is magnified considerably.

The water cooled support rolls themselves can extract a significant amount of heat from the solidifying strand and the amount of heat extracted depends on the roll design. The various types of roll designs and roll cooling methods are illustrated in Figure 3.30 which shows the main roll design and cooling methods.¹⁷ Examples are for single piece rolls but many of the principles also apply to divided rolls.

Because the cooling channels of the peripheral-bore design and the scrolled design are near the surface the roll surface is kept colder.

These are commonly called 'cold' roll designs whilst the centrally bored cooling is termed a 'hot' roll design. The 'cold' roll designs extract significantly more heat from the strand than does the 'hot' roll design. However, the cold roll designs are more stable and much less prone to permanent bending when the strand stops and the roll bends due to grossly asymmetric temperature distribution leading to severe thermal stresses. If a roll

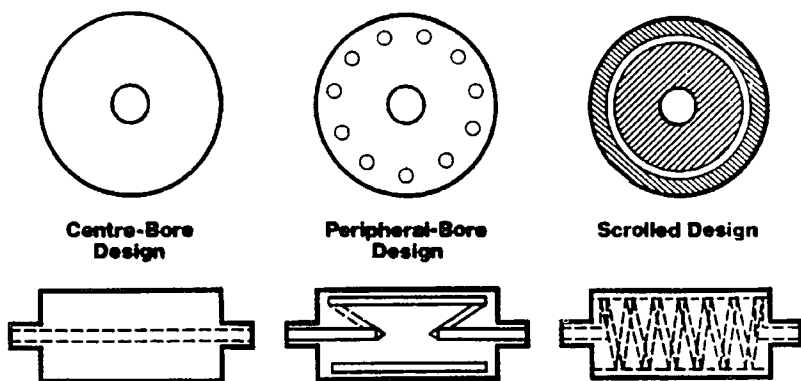


Figure 3.30 The different types of internal roll cooling.

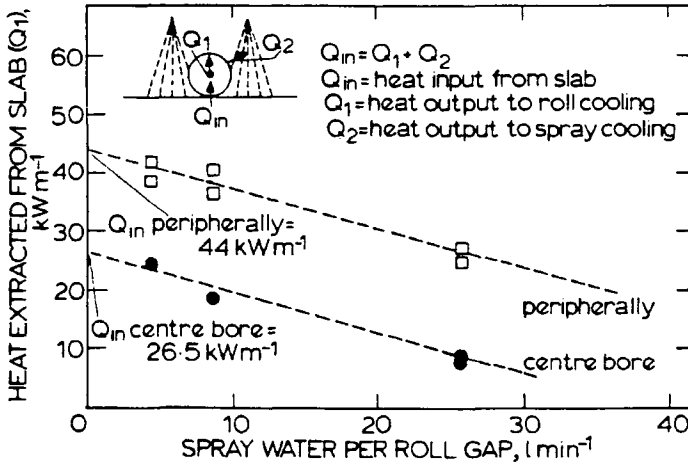


Figure 3.31 Heat extraction from the slab by the roll.

becomes permanently bent to a degree of greater than $\sim 1 \text{ mm}$ at the centre this can lead to poor internal quality. The mechanisms of this poor quality are explained in Section 4.3.5

Much work has been done on evaluating roll performance both in terms of geometrical stability and heat extraction capability.¹⁸ It is interesting to note that the amount of spray water used affects the heat extracted by the roll. Figure 3.31 shows the amount of heat extracted from both a peripheral bore roll and a centre bore roll for various amounts of spray cooling water entering the roll gap. With no spray water entering the roll gap the heat extraction is 44 kW/m and 26.5 kW/m respectively. (These values are the kW per metre length of roll).

Data have also been obtained on the geometrical stability of the various types of roll design.¹⁸ Bulgometers have been used to measure both roll behaviour and the bulging of the strand. These bulgometers consisted of linear displacement transducers (LDT) on the end of units which were rigidly fixed in the machine with the LDTs resting on the back of the rolls or the strand surface as appropriate.

Three such bulgometers at any single location in the strand are used, two on adjacent rolls and one on the strand between the two rolls. These instruments can be left in the strand over long periods and the behaviour of the rolls and strand have been investigated for many events such as strand stoppages or slow downs and for various secondary cooling conditions in casting different steel grades. Figure 3.32 shows such behaviour for 2 roll pairs at different positions down the strand both for a reduction in casting speed and when there has been a strand stoppage.

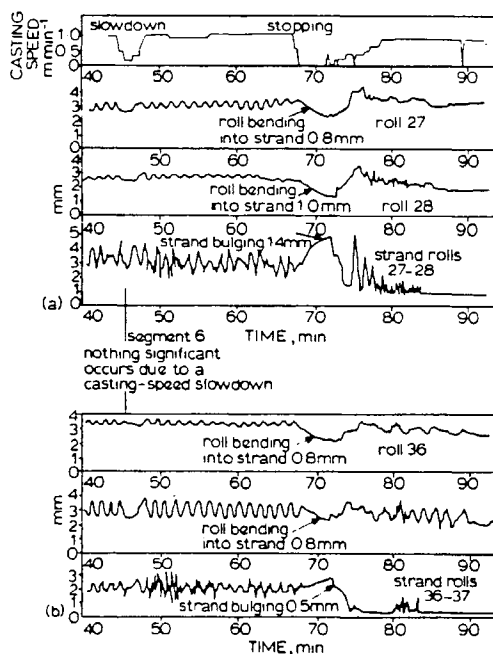


Figure 3.32 Roll bending and slab bulging during a slow down and strand stoppage at positions (a) 11 m and (b) 14.3 m from the meniscus.

Such deviations of roll geometry need to be avoided since these lead to unacceptable surface and internal quality. This is described in greater detail in Chapter 4.

All the work just described was carried out on single piece rolls which have to compromise between a sufficiently small diameter (and roll pitch) to prevent inter-roll bulging of the strand and a sufficiently large diameter to avoid bending under the mechanical and thermal loads to maintain good roll gap geometry. Over the last decade there has been a very significant increase in the application of split rolls as described previously (Figure 3.23). Most new wide slab casters and many which have been rebuilt now contain split rolls. This means that the individual roll barrel length is much reduced which reduces the bending of the roll significantly and thus allowing smaller diameters and roll pitches.

The roll gap geometry can also be affected by roll wear. The roll material is therefore also very important and a combination of roll material and efficient cooling can reduce roll wear as a serious cause of loss of roll gap geometry. The roll material needs also to be resistant to fire cracking and stress corrosion cracking and to meet these requirements the rolls are 'hard faced' with a layer of metal comprising 12 wt% Cr and 88 wt% Fe.

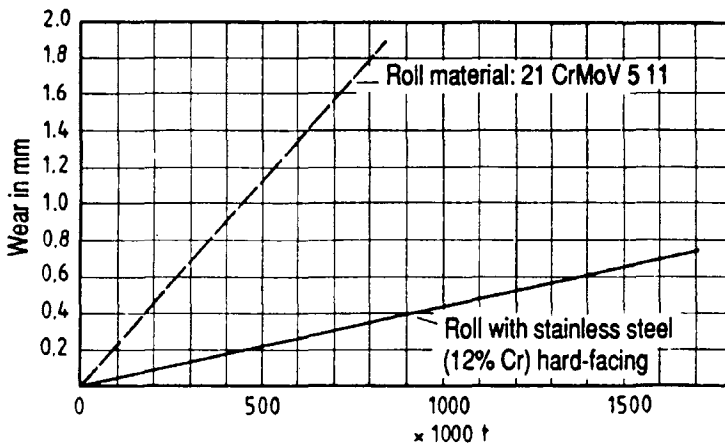


Figure 3.33 Roll wear as a function of material and tonnage produced.⁶

Figure 3.33 shows the effect of this surface on roll wear for 360 mm diameter rollers.

3.3 Strand Straightening and Strand Withdrawal

For casting machines, where the strand is either cast in a curved mould or is bent into a curved position below the mould, the strand requires to be straightened before it can be discharged horizontally. The design of the straightener (or the bending zone where the strand is curved after being cast in a vertical mould) is dependent on machine radius, section size, steel grades to be cast and other casting parameters. Details will be described in Section 3.3.1 below.

Additionally, sufficient power and traction need to be imparted to the strand to enable withdrawal to be reliable and consistent. Details are given in Section 3.3.2.

3.3.1 Strand Straightening

As indicated previously, the curved strand needs to be straightened to achieve horizontal discharge. The design of the straightening unit depends on several factors and it is important to ensure that any stresses caused by the strains imposed due to straightening are smaller than the inherent strength of the material.

The strain distortion across the fully or partially solidified strand can be determined from standard beam bending theory but due to the tempera-

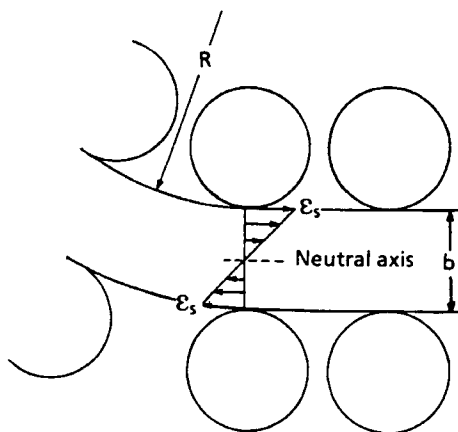


Figure 3.34 Strain distribution across the solidified strand during single point straightening.

tures involved creep occurs and hence to design for the overall strains required to straighten the strand the strain rate is also an important consideration. The strain distribution across the strand also depends on whether the strand is completely solid or whether a liquid core still exists. In modern machines requiring higher throughput a liquid core usually exists during straightening. The two situations will be dealt with separately.

3.3.1.1 Strand Completely Solidified

The strain distribution in this case depends entirely on the initial curvature and strand thickness and is shown in Figure 3.34.

The the surface strain is

$$\epsilon_s = \frac{b}{2R} \times 100\%$$

this being a tensile strain on the top surface and a compressive strain on the bottom surface. The strain rates can be reduced by applying the required strain over more than one unbending point or even continuously straightening over a given length of strand. These systems will be described later.

3.3.1.2 Straightening with a Liquid Core

In this case both the upper and lower solidified shell is considered as separate beams but the calculated strains can depend on the constraining influences of the solidified edges. These can be significant at low aspect ratios, when the solidified shell has reached a significant thickness and the shape of the shell has been influenced by the two dimensional heat

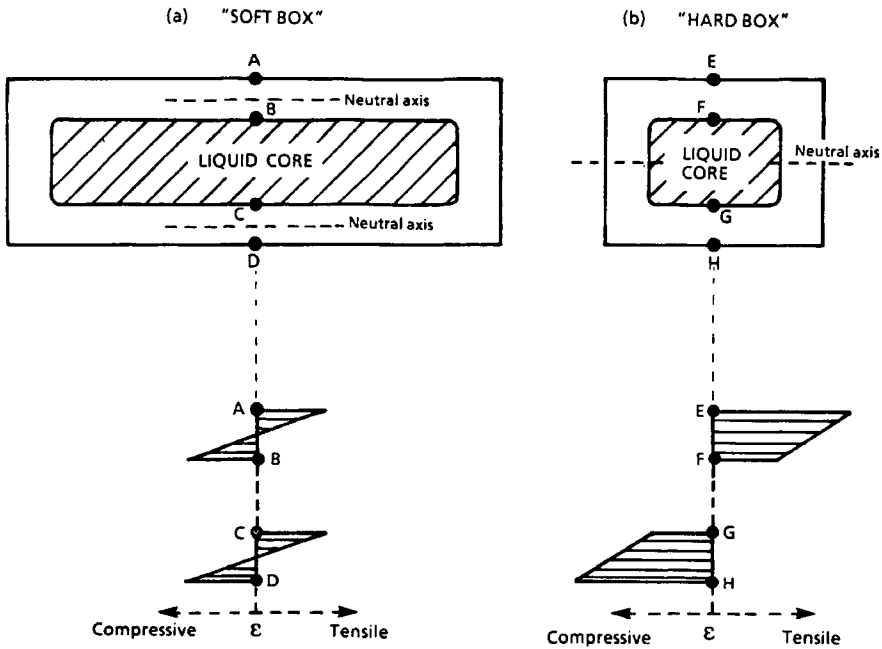


Figure 3.35 Strain distribution in solidifying shell using (a) the 'soft box' approach and (b) the 'hard' box approach.

transfer. Two approaches are therefore adopted. These are termed the 'Soft Box' and 'Hard Box' approach respectively(19).

- *'Soft Box' Approach.* The strand is considered to be a 'soft box' when the upper and lower solidified shells deform independently of each other i.e. there is no restraining influence of the solid edges. This is the situation in the case of a slab where the aspect ratio is high and the shell thickness small compared to the slab width. Figure 3.35 shows the strain distribution occurring in the solidifying shell due to straightening at the tangent point.

The neutral axis is assumed to be along the centreline of both the upper and lower shell although this is not strictly true because of the temperature gradient. It has been shown by using finite element analysis that the true neutral axis is nearer the cold surface.²⁰ There are tensile strains both at top outer surface and at the solid/liquid interface of the lower shell. These strains are a function of strand radius and shell thickness at the point of straightening.

The surface strains in this case are given by

$$\epsilon_s = \epsilon_i = \frac{t}{2R} \times 100\%$$

where ϵ_s = outer surface strains; (tensile at A: compressive at D)
 ϵ_i = solid/liquid interface strains (tensile at C: compressive at B)
 t = shell thickness (m)
 R = machine radius (m)

● *'Hard Box' Approach.* In this case the bending is primarily influenced by the stiffness of the solidified edges and the neutral axis in this case is assumed to be along the section mid thickness and the surface strains are similar to the situation where the strand is totally solid i.e.

$$\epsilon_s = \frac{b}{2R} \times 100\%$$

The solid/liquid interface strains in this case are given by

$$\epsilon_i = \frac{b - 2t}{2R} \times 100\%$$

It has been demonstrated²⁰ that the 'soft box' approach is appropriate for slabs or large blooms with a high aspect ratio. The 'hard box' approach is only applicable to billet and small bloom sections.

As indicated earlier the strain rate often determines whether a crack defect (either internal or on the surface) will occur. The inherent strength of the steel particularly at the solid/liquid interface is very low at the temperatures involved (see Figure 4.3) but at these temperatures creep rapidly reduces stresses resulting from the strains imposed. Therefore by reducing the strain rate the stresses can be maintained at low values and total high strains can be achieved by spreading the straightening over a length of the machine. This is done by the use of multi point straightening.

Figure 3.36 shows such a design using 3 point straightening

At point A the radius changes from R_1 to R_2 and then at point B to R_3 . Finally at point C an infinite radius is achieved so that the strand can emerge horizontally. Figure 3.37 compares the strains and strain rates for this case and that when the same initial radius strand is straightened at a single point.

In the limit continuous straightening⁽²⁰⁾ is used on some machines over a length L of the machine. In this case the strain rate is given as:

$$\dot{\epsilon}_s = \frac{(\epsilon_s)v}{L} \text{ per min}$$

where v = casting speed in m/min
 L = length of continuous straightening unit (m)

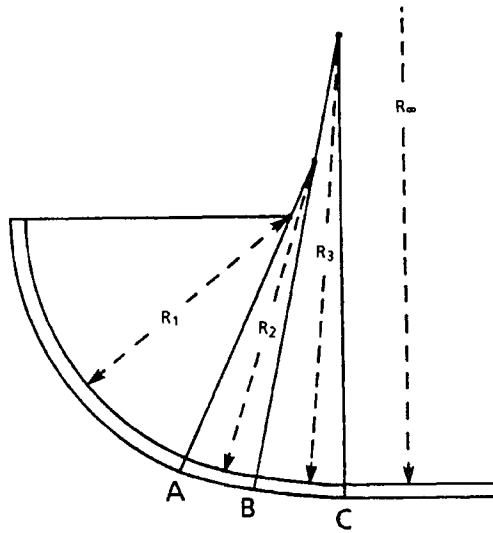


Figure 3.36 Strand showing three-point straightening.

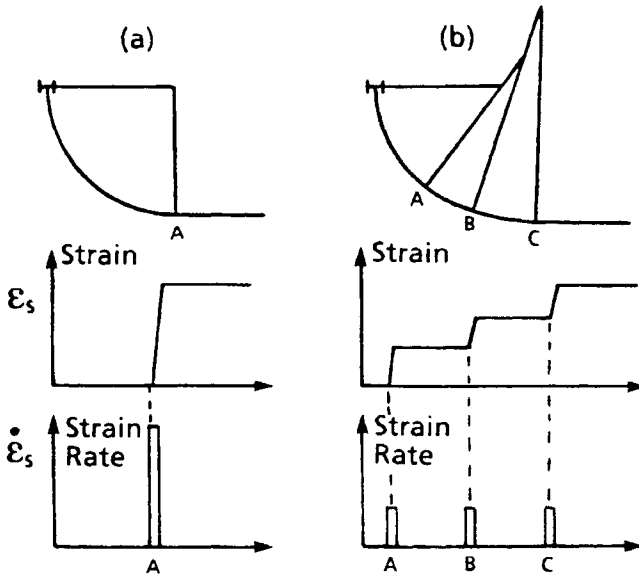


Figure 3.37 Surface strains (ϵ_s) and strain rates ($\dot{\epsilon}_s$) for (a) single and (b) multi-point straightening.

3.3.2 Strand Bending

In the situation where a vertical straight mould is used the strand is bent to the appropriate radius below the mould. In this case the solidified shell is

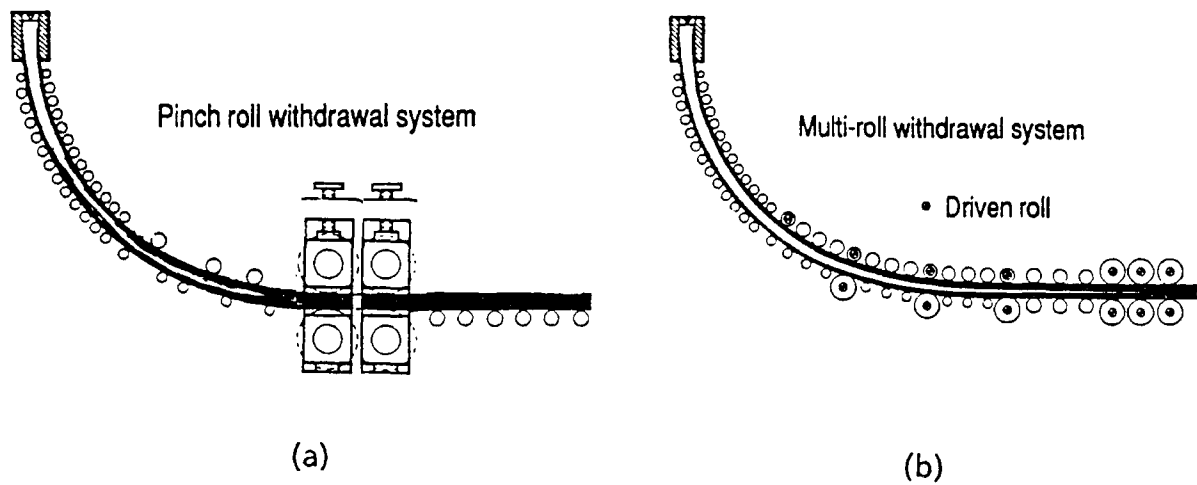


Figure 3.38 Strand withdrawal unit for (a) a bloom machine and (b) a slab machine.

still relatively thin and therefore the strains are usually not as high as when straightening with a liquid core. However, the same principles apply and many casters with straight moulds use multi point bending to achieve the required radius whilst reducing the strain rates to avoid internal defects. In such cases misalignment of the bending rolls again requires to be minimised to reduce misalignment strains (see para 3.4.2)

3.3.3 Withdrawal Units

The strand needs to be withdrawn from the machine under constant and controlled conditions and sufficient power and traction needs to be applied to achieve this. The withdrawal force has to be sufficient to overcome the frictional forces acting on the strand. These can arise due to:

- strand friction in the mould,
- friction of the support rolls in their bearings resulting from their operating loads,
- rolling friction owing to strand bulging between the rolls.

It should also be noted that the dead weight of the strand itself acts in favour of reducing the required withdrawal force.

Figure 3.38 shows examples of withdrawal units for a bloom machine and a slab machine.

Modern withdrawal units for slab machines are multi roll withdrawal systems, the traction and power being distributed over several roll pairs. The drive roll pairs achieve the correct amount of traction by the use of hydraulic forces slightly in excess of the ferrostatic force at that position. The withdrawal forces occurring in slab machines can only be overcome by the multi roll withdrawal system. Such a system successfully reduces the strand withdrawal force at an early stage, reducing it to a low level as the strand progresses through to caster. In Figure 3.39, Curve (a) represents the tensile force pattern calculated for a slab measuring $2000 \text{ mm} \times 205 \text{ mm}$ cast at a speed of 0.8 m/min .⁶

The tensile force just below the mould shows a slight initial decrease owing to the dead weight of this strand. It remains at the relatively low value until the strand reaches the straightening section where it abruptly increases in magnitude. Following complete solidification the rate of increase eases due to the elimination of ferrostatic forces. Curve (b) represents the sum of the tensile forces measured at the individual drives. The difference between the calculated and the measured force at the ends of the two curves, which indicate the total tensile force, constitutes the error between the calculated and measured values. This error amounts to about 10% and is due to the many assumptions made. Curve (c) represents the

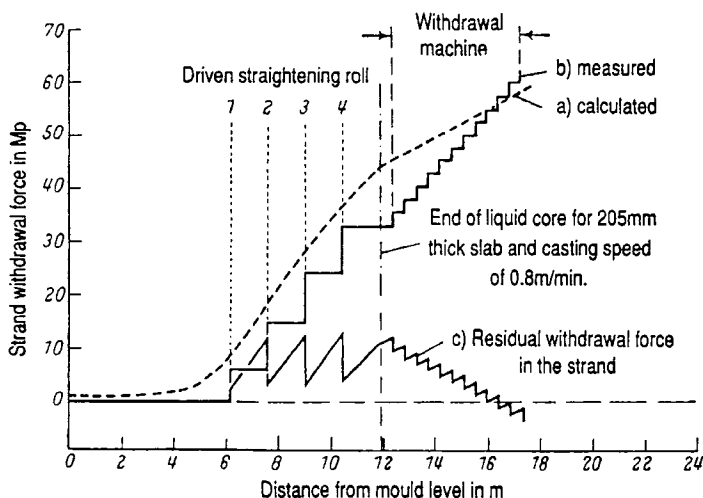


Figure 3.39 Measured and calculated strand withdrawal forces in a bow-type caster with four straightening points.

tensile forces remaining in the strand after application of the withdrawal forces and, as such, indicates the loading to which the strand is subjected during the withdrawal process. This curve was determined from the difference between the values represented by curves (a) and (b). The negative withdrawal force value indicates that the strand is being pushed and thus no longer subjected to tensile forces.

3.4 Computer Simulation Models

There are many computer models which have been developed for various aspects of the continuous casting process. These include:

- Liquid steel temperature model in the ladle and tundish (described briefly in Section 2.3)
- Fluid flow models of tundish and mould
- Powder feed model (see Section 3.1.2)
- Temperature distribution in the mould copper plates (see Section 3.1.2.5)
- Strand Solidification Model.
- Strand Bulging Models
- Roll temperature Distribution and Deflection Models

This chapter will only deal with the solidification model, the strand deformation models and the roller temperature and deflection models all of

which depend entirely on the data which have been acquired and described in Sections 3.1, 3.2 and 3.3.

3.4.1 The Strand Solidification Model

The strand solidification model²¹ developed over many years in British Steel tracks a rectangular section normal to the axis of the strand and solves numerically by the finite difference method the Fourier equation for heat diffusion subject to the time dependent boundary conditions encountered by the section as it passes down the strand. The Fourier equation is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c}{K} \frac{\partial T}{\partial t}$$

where x, y and z are the cartesian co-ordinates
 T is the temperature in °C at the point x, y, z
 ρ = density (Kg/m³)
 c = specific heat (J/Kg K)
 K = thermal conductivity (W/mK)
 t = time (s)

The data for ρ , c and K are all included in the model as functions of temperature. It has been shown²² that the high lateral heat fluxes produced by the mould, spray, rollers and radiative cooling (i.e. in the x and y directions) allow a two dimensional treatment to be valid since conduction along the strand axis (z direction) is negligible. Therefore the $\partial^2 T / \partial z^2$ can be eliminated.

For all practical purposes the cooling is symmetrical about the mid vertical planes of the wide and narrow faces. Therefore only one quarter of the strand section is considered. This results in the saving of time for each simulation run.

Details of the early developments of this model were first published in 1975²¹ and therefore considerable further developments have occurred over the intervening time. More importantly however, is the accumulation of the vast amount of measured data (as described in Sections 3.1, 3.2 and 3.3) which enables relative and accurate boundary conditions to be used in the solution of the basic Fourier equation. This means that at each position as the section travels down the strand heat fluxes can be applied and which can vary around the periphery of the section. At the solidification front the latent heat (L) liberated on solidification is dealt with by essentially multiplying the calculated temperature differential by the ratio $c/(c+L)$ in the solidus/liquidus region for the appropriate mesh points in the finite difference calculation procedure. The mixing in the liquid steel is

accounted for by the use of an increased thermal conductivity in this region.

The running of this model enables temperature distributions within the tracked section to be computed at each position down the strand. Printouts, therefore, of temperature profiles down the strand can be obtained at any position around the periphery. The shell thickness as a function of distance from the meniscus (of the liquid metal in the mould) can be readily obtained. This represents the solidus isotherm. Figure 3.40 shows an example of shell thickness (solidus isotherm) for a 240 mm slab soft cooled and cast at 0.8 m/min. Also included is a plot of the liquidus isotherm.¹⁹

The region between the liquidus and solidus isotherm is partly liquid and partly solid and is termed the 'mushy' zone. The 40% and 70% solid fraction positions are also shown.

Figure 3.41 shows the temperature profile down the mid broad face of a 1830 mm $\times$ 230 mm C/Mn slab cast at a speed of 0.8 m/min. The secondary cooling sprays for this simulation extended to 17.5 metres down the strand on the broad face and the specific water consumption was 0.35 L/Kg.

It should be noted that the surface temperature during the contact of each roll drops by about 100°C whilst, in this case, spray water effect is much less ('soft cooling').

The solidification model has been used extensively to design the secondary spray cooling systems on many casters to enable the conditions to

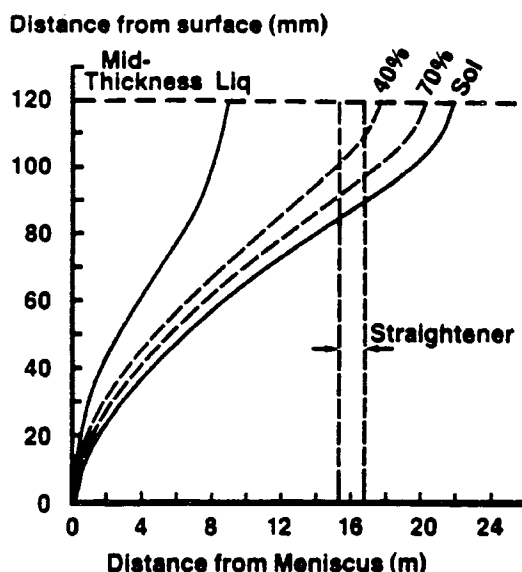


Figure 3.40 Solidus and liquidus isotherms for a 1100 $\times$ 225 mm slab.

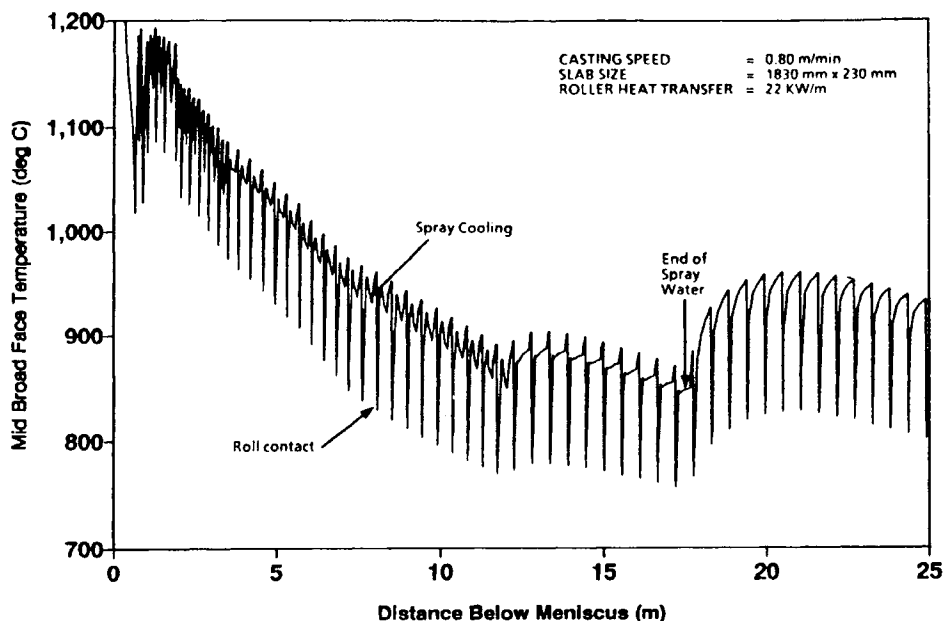


Figure 3.41 Surface temperature profile down the mid broad face for a 1830 mm $\times$ 230 mm slab.

be changed and controlled for various steel grades, with different steel grades requiring particular surface temperature patterns. This will be discussed more fully in Section 4.2.

3.4.2 Strand Deformation Model

During bloom and slab casting the ferrostatic pressure of liquid steel causes the strand to bulge between the guide rolls, resulting in strains at the solid/liquid interface, which can cause cracks to form, and which are penetrated with solute enriched liquid. The strength and ductility of steel decreases rapidly at the solid/liquid interface such that strains in the range 0.3–1.5% are sufficient to cause cracking. In addition to inter-roll bulging, strains arise in the solidifying shell as a result of roll misalignment, roll bending and strand straightening. Increasing the roll pitch results in an increase in bulging and an increase in bulging strain. However, strains due to the same roll misalignment decrease with increasing roll pitch. There is therefore an optimum roll spacing which minimises the combined bulging and misalignment strains.

To enable the solid/liquid interface strains to be calculated there is a need to be able to calculate the amount of inter-roll bulging and the curvature of the outer surface of the strand in the casting direction.

The temperature distribution within the solidified shell is calculated using the solidification model described above for the appropriate casting speed and cooling conditions.

Finite element models²³ have been developed to calculate the inter-roll bulging, bulging strain and misalignment strains. These models use the output from the solidification model to define the temperatures together with measured creep properties for the particular steel grade.

The following gives a brief description of the principles used in the bulging and strain calculation models.

Slab movement is simulated in the model by a mechanism of shifting columns of elements, with their associated viscoplastic strains and displacements, in the casting direction such that a column of elements leaving one roll position will effectively travel a complete roll pitch to the next roll. This is achieved by arranging columns of elements of equal width in the model such that the time to travel one element length t_e is given by

$$t_e = L/VN$$

where L = roll pitch

N = number of columns of element

V = casting speed

The slab shell is allowed to creep in increments Δt for a total time t_e after which the viscoplastic strains and displacements for each column i are transferred into columns $i + 1$ and a column of elastic elements are substituted into column 1 (see Figure 3.42). The column of elements moving into the N th column, however, will have displacements which result in the surface of the slab moving inside the roll. This displacement into the roll is

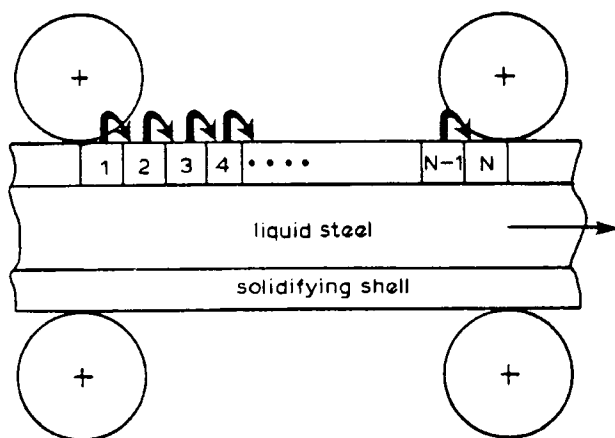


Figure 3.42 Simulation of slab movement.

Table 3.2 Comparison of calculated and measured inter-roll bulging

Roll pitch (mm)	Measured bulge (mm)	Calculated bulge (mm)
430	0.4– 1.6	0.36
860	5.0– 4.0	6.9
1290	35.6–42.0	46.2

gradually reduced to zero, during the next time period t_e in proportion to the time increments Δt (incremental displacement techniques), such that at the end of the time period t_e the boundary conditions are satisfied and the slab comes into perfect contact with the roll.

Slab bulging calculations using the incremental displacement method, and measured creep material properties for 0.185% C steel,²⁴ have been compared with measurements of slab bulging.²⁵

Measurements of slab bulging were made for three roll pitches by first removing one then two adjacent rolls to give roller spacings of 430, 860 and 1290 mm. Calculations of slab bulging for each of these roll spacings have been used as a check on the validity of the model calculations. The results given in Table 3.2 show good agreement between calculations and measurements.

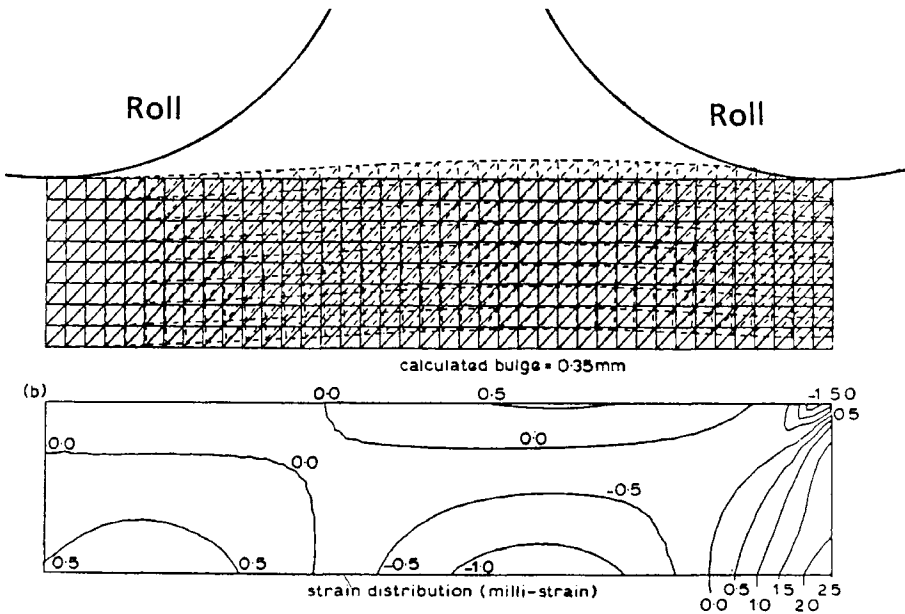


Figure 3.43 (a) Calculated slab bulging and (b) shell strain distribution 7 m from the meniscus: roll pitch 363 mm, shell thickness 77 mm and casting speed 0.8 m/min.

Model results used to analyse slab bulging and bulging strains for slabs cast on a 12.5 m radius machine with well designed roll pitches show that during normal operation slab bulging, and strains at the solid/liquid interface are small. A typical result is shown in Figure 3.43 where slab bulging at a distance of 7 m from the liquid metal level is calculated to be 0.35 mm and the resulting strain at the solid/liquid interface beneath the roll is calculated to be 0.25%.

However, strains at the solid/liquid interface can also be induced by misalignment of adjacent rolls or by one of the rolls becoming permanently bent. Normally the tolerance for the deviation of roll gaps is 0.5 mm for machines casting segregation sensitive grades.

In a particular machine the roll diameters and pitches vary down the machine. Figure 3.44 shows the calculated inter-roll bulging and consequent bulging strains for a typical slab casting machine using single piece rolls. The calculations have been carried out for

- a casting speed of 0.8 m/min with secondary cooling of 0.1 L/Kg
- a casting speed of 0.9 m/min with secondary cooling of 0.7 L/Kg

Whilst smaller roll pitches will reduce the strains due to inter-roll bulging they increase strains due to roll misalignment. Roll bending as described earlier, is only one reason for rolls deviating from the true pass line. Deviation can occur for the following reasons.

- roll eccentricity
- roll misalignment due to bearing wear or even failure
- roll wear
- segments not properly aligned with each other
- distortion of the segment frame due to mechanical and thermal loads.

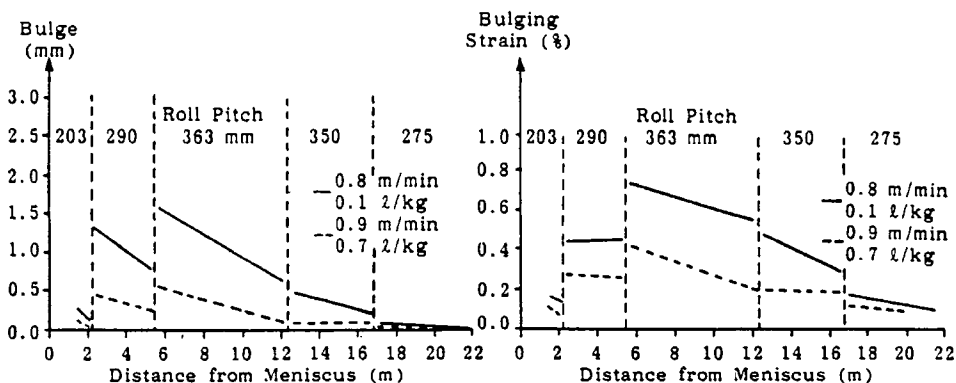


Figure 3.44 Calculated inter-roll bulging and bulging strains.¹⁹

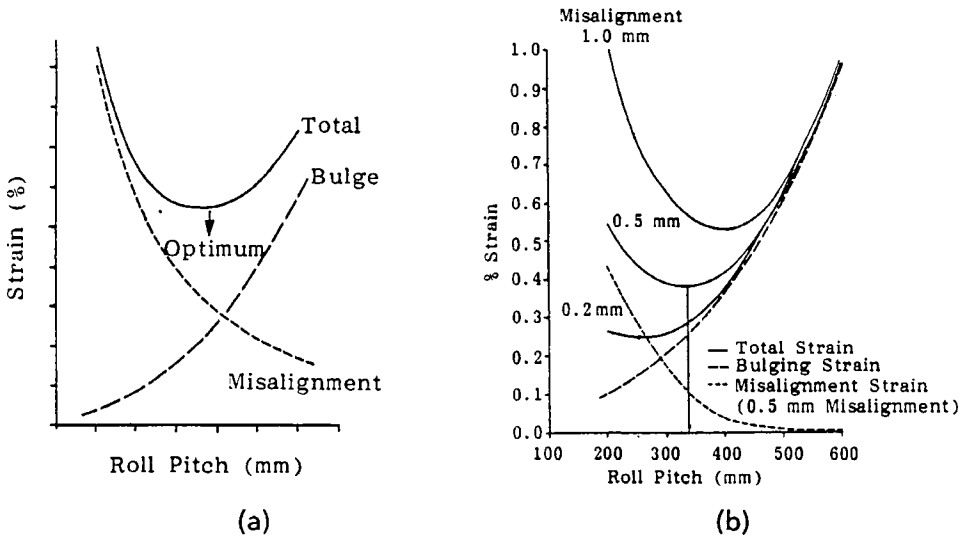


Figure 3.45 Calculation of inter-roll bulging and misalignment stresses showing (a) general principal of strain summation and (b) specific calculations for various misalignments.

Superimposed on the bulging strains, (shown in Figure 3.44) are strains caused by roll misalignment. Misalignment strains (for a given misalignment) are reduced by increasing the roll pitch and therefore an optimum roll pitch can be found which minimises the total strain resulting from bulging and misalignment as shown in Figure 3.45 (a). The influence of different assumed values of total roll misalignment on strains can be assessed as shown in Figure 3.45 (b) for each position down the caster.

The *total* strain at the solid/liquid interface is the critical issue in segment design. These can also be calculated using the models for particular roll misalignments. Additional strains are also induced when the strand is straightened.

Figure 3.46 gives an example of the calculations of the various strains at the straightener for a 240 mm thick slab cast at 0.9 m/min. This shows the bulging and misalignment strains as shown in Figure 3.45(b) but with the straightening strains at both the outer surface and the solid/liquidus interface included.

3.4.2.1 Critical Strain Levels

Critical strain levels (above which cracking occurs) depend on the products e.g. more strain is acceptable for most strip grades than for many plate grades for which the internal quality is more sensitive to different types of segregation. Therefore it may not always be necessary to incur the

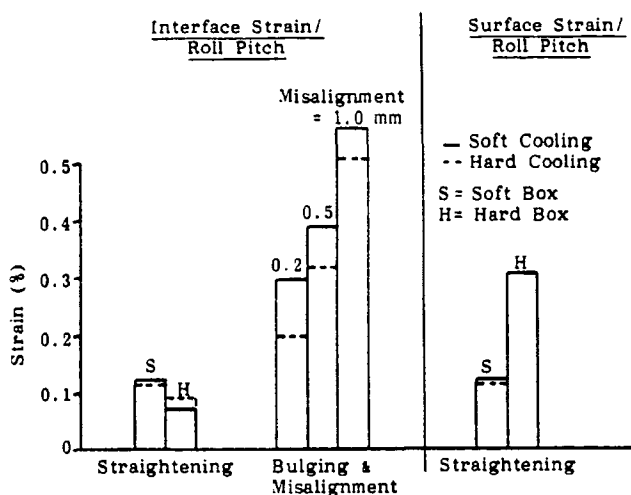


Figure 3.46 Calculated total strains during strand straightening.

expense of employing all possible means of reducing strains (e.g. split roll installation and maintenance costs). Critical strain levels are also affected by the rate of strain, since higher strain levels can be tolerated where the rate of strain is lower. Consequently, there is no simple answer to what is a tolerable strain level; indeed laboratory testing of slab samples would at first suggest higher strain levels could be tolerated than the levels which in practice give problems on casters; it is concluded that in casting there is a cumulative effect of strains at successive rolls.

3.4.3 Roller Temperature and Deflection Models

Finite element models have been developed²⁶ to calculate the temperature distribution and the amount of deflection which occurs due to mechanical and thermal forces and for various roller designs. Two main models were used. The first model is used to calculate the temperature distributions within the roller both during normal operation and during strand stoppages. This temperature information is then input into the second model which determines the amount of bending due to both the thermal loadings and that due to the mechanical loadings which are applied to the rollers by the strand ferrostatic pressure. Symmetry is assumed both for the rollers and the strand and Figure 3.47 shows the finite element mesh arrangement for the temperature modelling of the three types of rolls shown in Figure 3.30 i.e. centre bore, peripherally drilled and scrolled rolls respectively.

In this case all the rollers were single piece rollers with no centre support and were 310 mm in diameter. Figure 3.48 shows the finite element

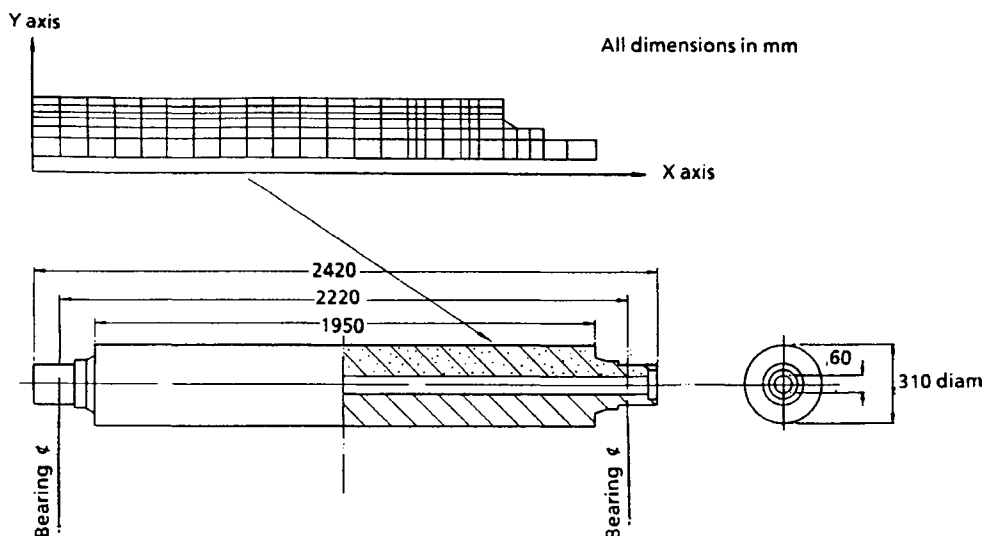


Figure 3.47 Finite element meshes used to determine temperature with various roller designs.

mesh arrangement used to determine roller bending from the thermal and mechanical loadings.

As outlined in Section 3.2.3 the stability of the roller geometry is an essential requirement to achieve good internal and surface quality and one of the most arduous situations for the rollers is when a strand stoppage occurs usually at ladle changeover or as a result of a breakout. In this case the thermal loading is increased very significantly due to the increased temperature gradient across the roll diameter. In these extreme cases the roller can become permanently bent and hence detrimental to maintaining a constant roll gap geometry. The roller models have been used extensively to support the experimental work described in Section 3.2.3 and Figure 3.49 shows how the models indicate the bending which occurs during a prolonged strand stoppage for the three different roller designs discussed earlier.

It should be pointed out that stoppages of this duration are very infrequent and the long duration of 40 minutes is mainly hypothetical in the course of the deformation studies. Any strand stoppages which do occur are usually less than 5 minutes and often result during ladle or tundish changing.

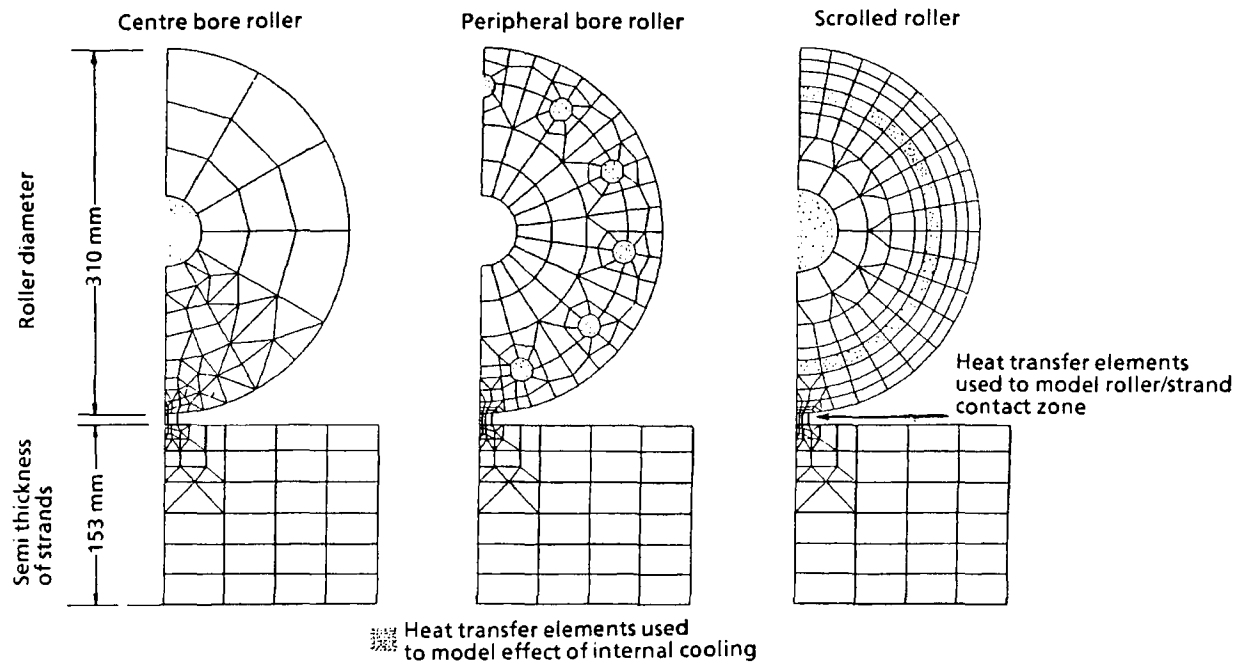


Figure 3.48 Axisymmetric finite element mesh used to determine roller bending due to thermal and mechanical loadings.

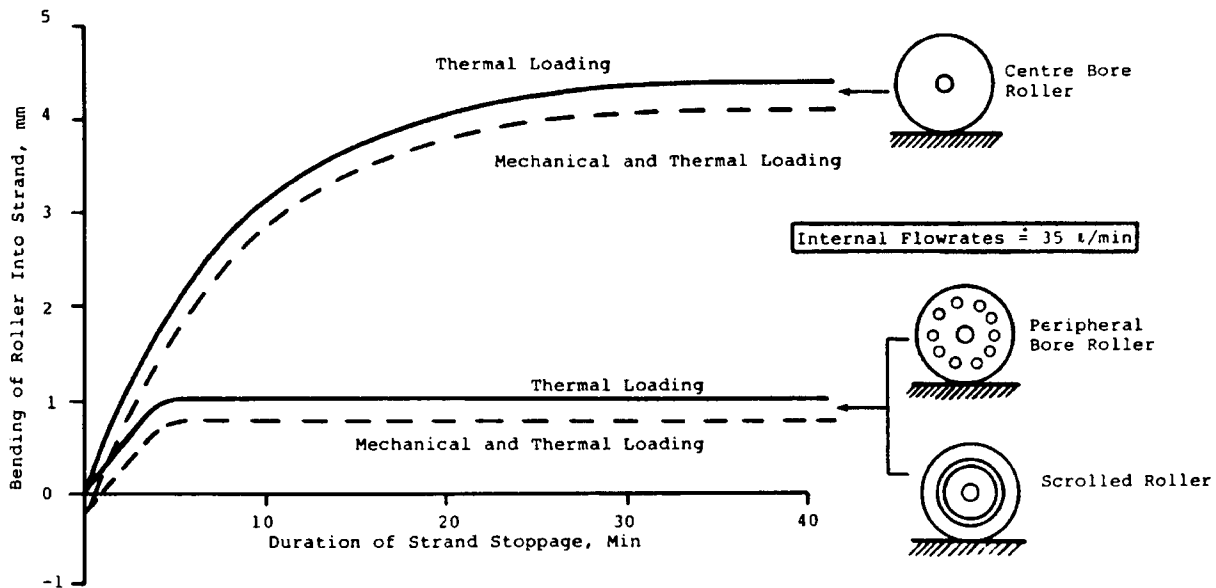


Figure 3.49 Comparison of predicted bending of different roller designs during a 40-minute stoppage.

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4. PRODUCT REQUIREMENTS AND FACTORS AFFECTING AS-CAST QUALITY

Prior to dealing with the extensive subject of how the as-cast quality is affected by the steel chemistry, the process parameters and the machine design aspects it would be useful to briefly describe and categorise the types of finished products, the performance and duty of which determine the size, chemistry, shape and quality requirements of the as-cast semi.

4.1 Categorisation of Final Products

The following categorises the typical range of final products.

Strip Products generally produced from slabs which are hot rolled and then further cold rolled to thicknesses ranging from 0.1 mm to around 5 mm and sold to customers for further processing in either sheet or coil form.

The various applications are:

- automobiles e.g. car bodies, bumpers etc.
- domestic appliances e.g. cookers, fridges, washing machines etc.
- tin plate products such as beverage and food cans
- for coated products such as galvanised and coated steels
- barrels, drums etc.
- construction industry e.g. cladding, window frames and radiators
- longitudinally welded tubes

Most of the strip products are mild steels with low carbon but many strip products are also made from stainless steel.

Plate Products are again produced from slab semis but are rolled on reversing mills to a thicker range than strip products. Their range is from around 10 mm to 150 mm thick. The slabs are also partly cross rolled for wider plates.

The various applications are:

- shipbuilding

- boilers
- fabrication of off-shore structures
- large diameter pipes

Section Products. A wide range of simple to complex cross-sections are produced from various sizes of semis. These are usually produced from rectangular billets or blooms but some of the larger wide flange beams are produced from slab semis. Examples of these products are:

- joists
- universal beams
- universal columns
- channels
- equal and unequal angles
- rails
- sleepers
- base plates
- bulb flats
- fish plates
- sections for tracked vehicles

Bar and Rod Products. A wide range of both high and low carbon bar and rod products are produced from cast bloom and billets depending on final product properties and application. The less demanding grades can be produced from as-cast billets thus reducing the costs whilst some of the more demanding applications require to be produced from as-cast blooms.

The following lists typical products in this category:

- automobile engineering steels, e.g. gears, crank shafts, rocker arms etc.
- wire rope products, such as tyre cord wire, meshing for fencing, wire ropes, bailing wire etc.
- small sections such as angles

As-Cast Semi Quality Requirements of Final Products.. The final product applications define the quality requirements of the as-cast semis. These quality aspects are categorised into (a) Surface Quality and (b) Internal Quality.

The International Iron and Steel Institute (IISI) has previously defined the various types of defects in as-cast semis for slabs, blooms and billets and these will be described under the two categories in (a) and (b) above.

4.2 Effect of Chemical, Process and Engineering Parameters on Surface Defects

4.2.1 Categorisation of Surface Defects

The IISI in their most recent survey¹ have categorised the types of surface defects which can be found on continuously cast semis. Figure 4.1 shows the various types of surface defects which can occur on the as-cast semis for both slabs and blooms/billets.

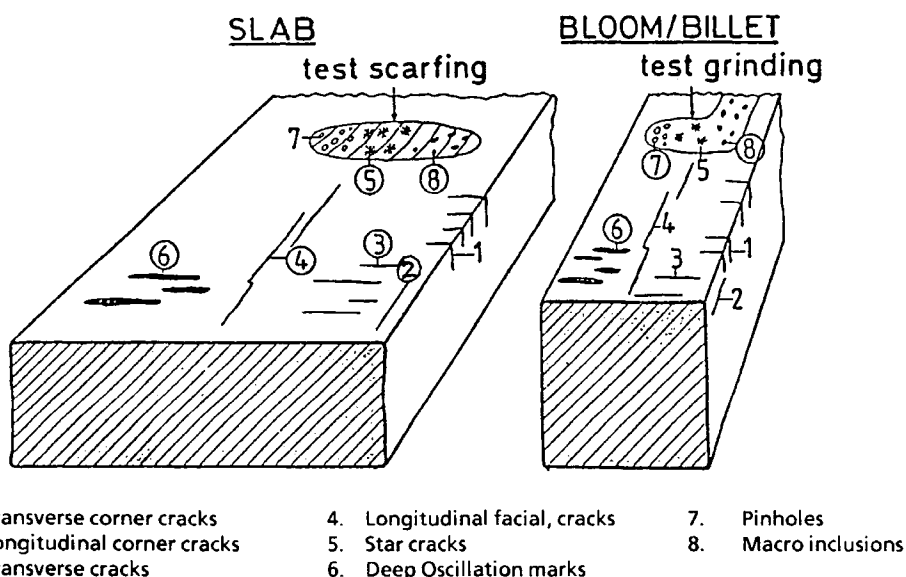


Figure 4.1 Surface defects on continuously cast semis.

Following extensive studies by many operators over recent years the cause of each type of defect has been established and the following lists the chemical, process and engineering factors which influence each type of defect:

1. Longitudinal Facial Cracks

- chemical composition e.g. a carbon level of between 0.08% and 0.14% (the peritectic range) causes non uniform heat transfer
- mould powder slag layer not uniform
- poor mould level control
- high mould wear and poor mould surface
- uneven oscillation movement
- insufficient strand support below mould, including misalignment
- non uniform cooling often related to mould powder and mould oscillation

2. *For Transverse Cracks*

- mould powder
- a sensitive chemical composition
- mould taper too large
- poor oscillation conditions
- a low surface temperature at straightening
- non uniform cooling
- abrupt speed changes

3. *Surface or Sub-Surface Macro Inclusions*

- dirty steel
- inadequate mould powder slag thickness
- large fluctuations in mould level
- very low casting temperature
- clogging of submerged nozzle
- low steel level in tundish
- poor mould and tundish level control

4. *Star Cracks*

- copper from mould plates
- uneven cooling of surface

Sticking marks and deep oscillation marks can also be considered as surface defects.

The effect of some steel compositional, process and machine design factors on surface quality can be demonstrated further by the following examples:

4.2.2 Compositional Factors

There are certain chemical compositions of steel which are prone to specific surface defects and can be categorised as follows:

- (a) Peritectic grades
- (b) Grain refined steels

4.2.2.1 *Peritectic Grades*

At carbon levels between 0.08% and 0.14% the newly formed shell undergoes a γ to δ transformation with an associated additional linear shrinkage^{2,3} which in turn often leads to cracking at the surface during the initial stages of solidification. Figure 4.2(a) shows² the effect of the carbon content on longitudinal cracking which is caused by non-uniform heat extraction. It can be seen that there is a sharp rise in this defect at 0.08% C

with a peak at around 0.10% C: the two curves for 180 mm thickness showing the effect of different casting powders which can also cause variability in heat transfer in the mould. Figure 4.2 (b) shows the effect of carbon content on heat transfer⁴ which was discussed in Section 3.1.2. It can be observed that there is a direct correlation between the low heat transfer and longitudinal cracking.

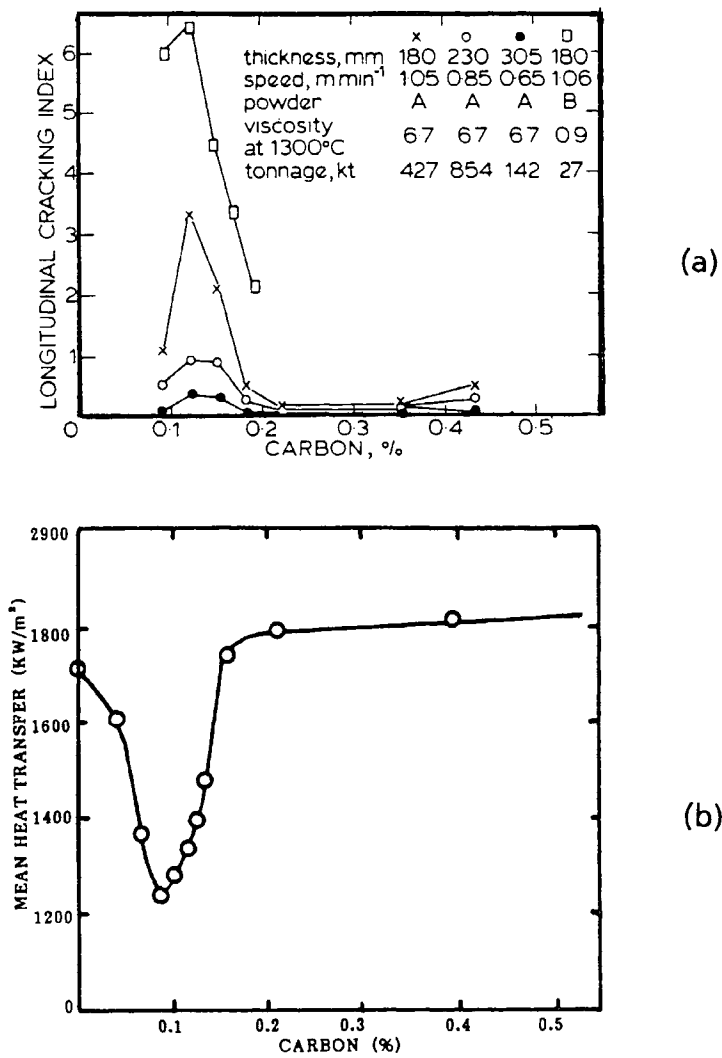


Figure 4.2 Effect of carbon on (a) longitudinal cracking and (b) mould heat transfer.

4.2.2.2 Grain Refined Steels

Many steel grades have additional elements added during steelmaking to enable second phase particles to be precipitated during hot rolling to give the steel improved strength and toughness properties. Examples of the elements which may be added for this purpose are niobium, vanadium, nickel and copper. Niobium is amongst the most common element used for this purpose and during hot rolling niobium carbides and carbonitrides precipitate to the grain boundaries thus preventing grain growth during transformation. These second phase carbides and nitrides also precipitate out during the casting process and as a result the steel ductility in

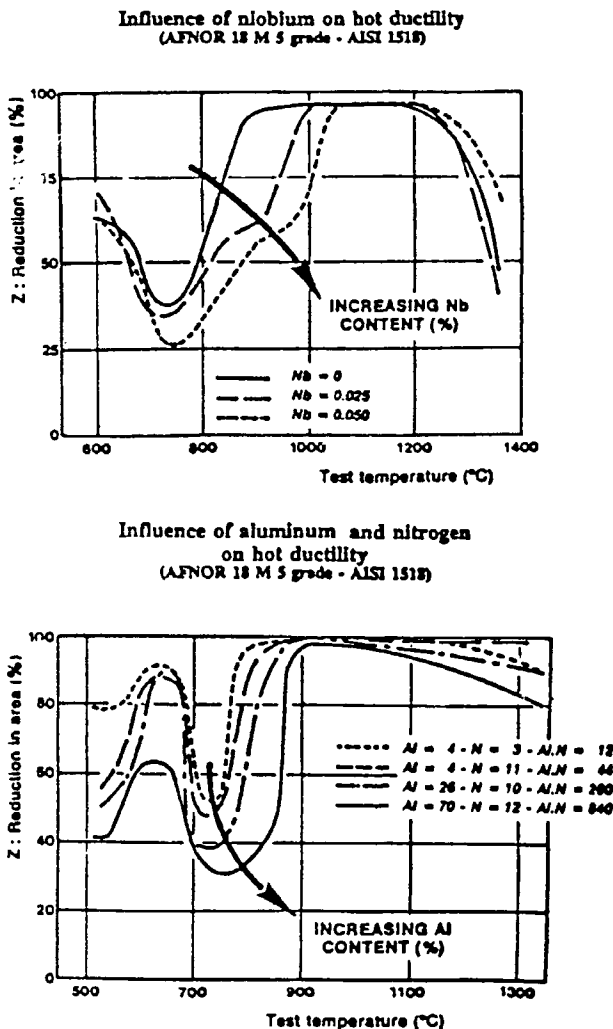


Figure 4.3 Effect of niobium, aluminium and nitrogen on hot ductility.

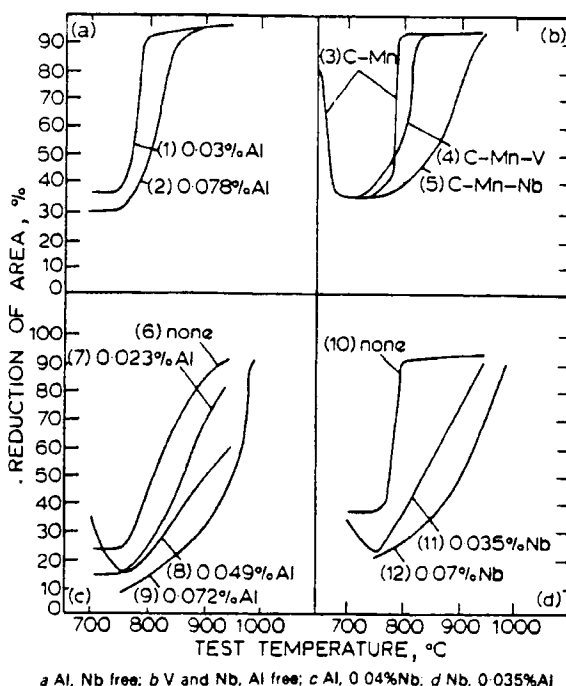


Figure 4.4 Effect on hot ductility of varying Al, Nb and V content for C-Mn steels.

certain temperature ranges is poor and this can lead to surface transverse cracking due to the incipient strength of the steel being less than the total stress occurring during solidification. The total stresses occurring are a summation of thermal, mechanical, transformation and straightening stresses. The latter stresses due to straightening of the strand commonly leads to transverse facial and transverse corner cracking (See Figure 4.1) when the surface temperature during straightening is in a region of low ductility.

Figures 4.3¹ and 4.4² show the unfavourable effect of elements such as niobium, vanadium, aluminium, and nitrogen which can cause poor ductility regions between 700°C and 1000°C. It should be noted from Figure 4.3 that the ductility above 1300°C up to the solidus temperature also deteriorates markedly and this affects the propensity for internal cracks as described in Section 4.3.4.

Other elements such as titanium, copper, and nickel show similar ductility troughs. Precipitation of aluminium and nitrogen forming aluminium nitride in austenite commences at around 1000°C during cooling.

All these elements are also known to increase the sensitivity of steels to surface cracks, particularly the effect of straightening on transverse

cracks.^{2,5} Increasing the straightening temperature above a critical level (about 900°C) can reduce the frequency of transverse cracks by up to four times.

There are two approaches to avoiding these ductility troughs. The first is soft cooling which aims to control the surface temperature at the straightening point to greater than 900°C; the second is hard cooling with the target straightening temperature of less than 700°C, the objective being to avoid the poor ductility trough which extends between 700°C and 900°C depending upon the steel composition. Figure 4.5 shows the computed surface temperatures down the length of the mid broad face for hard and soft cooling respectively.⁶

The second strategy, hard cooling, needs greater care in the distribution and uniformity of the larger quantity of cooling water. Given this careful attention, this approach can be successful and has therefore advantages of improved internal quality, (see Sections 4.3.5 and 4.3.6) because of reduced bulging tendencies.

4.2.2.3 Effects of Residuals such as Sulphur and Phosphorus

The sulphur and phosphorus levels both have deleterious effects on the propensity to cracking due to low temperature melting point second phase materials, such as ferro sulphides and phosphides. The safe levels of these residuals can be affected by other factors such as basic machine

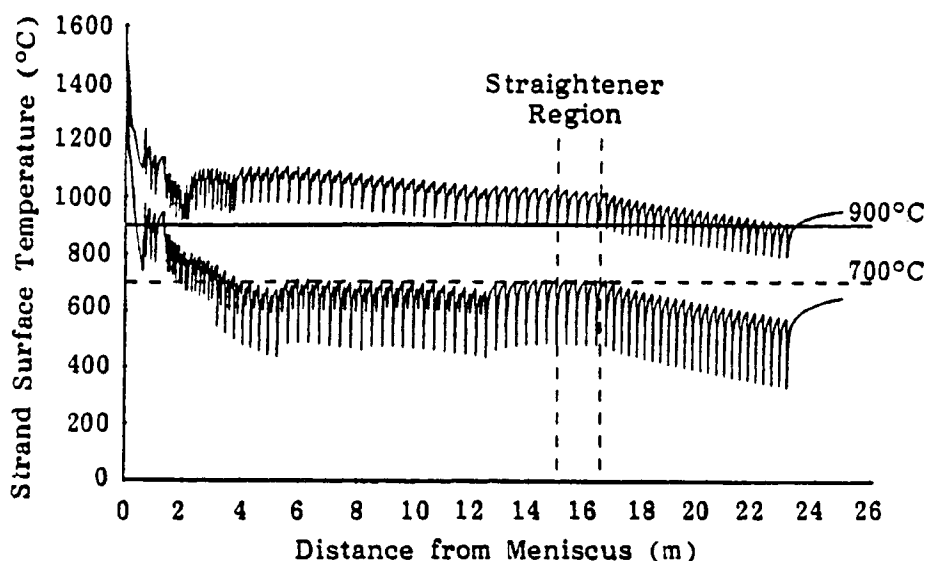


Figure 4.5 Calculated mid broad face surface temperatures for 'soft' and 'hard' cooling respectively.

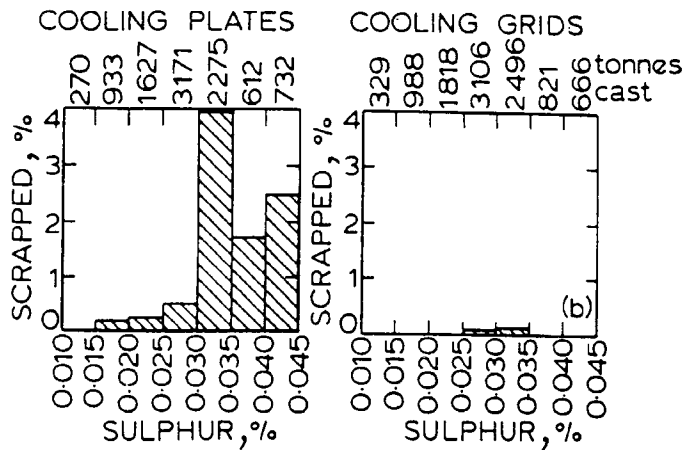
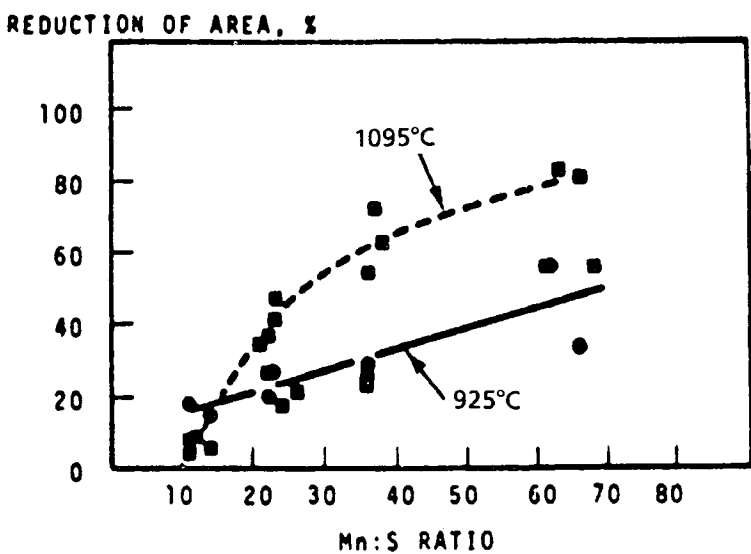


Figure 4.6 Effect of top zone cooling and support systems on mid face longitudinal cracking in slabs.

design when casting slabs or large blooms. This is readily demonstrated in Figure 4.6.⁷ In this case the effect of sulphur levels on longitudinal facial cracks in two strands of a slab caster one fitted with cooling plates below the mould the other fitted with cooling grids (see Figure 3.22).

Many residual elements such as sulphur, phosphorus and copper have an influence on billet casting.¹



Effect of Mn/S on ductility of steel after melting, casting, cooling at 14° C/s to 1425°C, then cooling at 5° C/s to test temperature of 1095°C or 925°C

Figure 4.7 Influence of manganese to sulphur ratio on hot ductility.

Table 4.1 Effectiveness of tundish to mould gas shrouding on billet casting¹

<i>Operating conditions</i>						
Steel grade	0.17% C 0.79% Mn 0.26% Si		0.05% C 0.62% Mn 0.17% Si		0.06% C 0.58% Mn 0.11% Si	
Use of blast pipe	no		yes		yes	
Use of jacket	no		yes		no	
Use of gas shroud	Without <i>n</i> = 12	With <i>n</i> = 15	Without <i>n</i> = 6	With <i>n</i> = 12	Without <i>n</i> = 6	With <i>n</i> = 12
<i>Size fraction (μm)</i>						
50–100	69.0	11.6	90.8	15.8	86.8	29.6
100–150	32.7	2.0	23.3	3.2	24.3	8.6
150–200	14.2	0.7	10.0	1.2	10.3	3.0
200–250	5.9	0.3	2.7	0.5	4.2	0.8
250–300	2.5	<0.1	0.8	0.2	2.7	0.2
300–400	2.0	0	1.3	<0.1	2.8	0.3
400–500	0.2	0	0.7	0	0.5	0
>500	<0.1	0	0	0	0	0
Total	126.6	14.7	131.6	21.0	132.1	42.5
%	100	11.6	100	15.9	100	32.2
Improvement	near 90%		near 85%		near 70%	

The bulk of the billet casting uses the electric arc furnace for steel production and consequently the residual levels of these elements are higher than in basic oxygen steelmaking due to the high residual elements in the scrap resulting from the 100% scrap usage.

Deformation studies between 1000°C and 1300°C show that ductility decreases strongly when the Mn:S ratio decreases. Figure 4.7¹ shows the reduction of area during tensile testing related to the manganese to sulphur ratio. As the manganese increases the quantity of low melting point iron sulphides decreases and less segregation occurs at the grain boundaries.

The effect of phosphorus, arsenic and sulphur contents on longitudinal cracks in billets¹ are shown in Figure 4.8.

Reoxidation of the tundish to mould stream is a particular problem in billet casting. As indicated in Section 2.6 it becomes practically difficult to use refractory shrouds between tundish and mould for the casting of billets less than about 130 mm square. Different methods to shroud the stream to avoid reoxidation in billet casting were shown in Figure 2.10 (Section 2.6) Several other methods have also been used. A typical comparison of internal cleanliness levels and surface pinhole frequency for open poured and gas shrouding practices is summarised in Table 4.1.

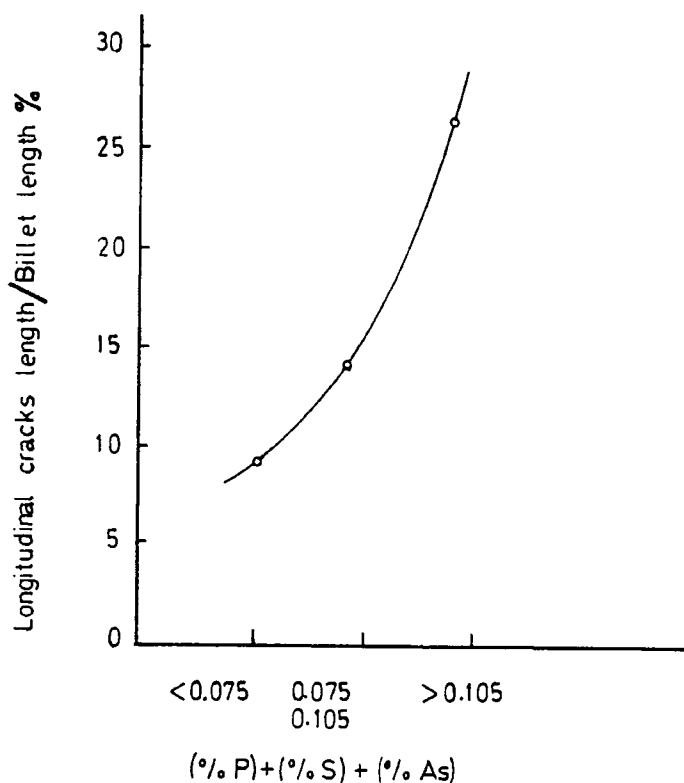


Figure 4.8 Effect of phosphorus, arsenic and sulphur on longitudinal cracks in billets.

Metal in the tundish having 40 to 60 ppm oxygen, close to the equilibrium value for silicon killed steel, is relatively free of inclusions. During open pouring of these steels the oxygen content of the metal in the mould is more variable and appreciably higher than equilibrium.⁸ The excess oxygen over equilibrium is a measure of the amount of reoxidation during teeming in air and is in the form of reoxidation products and inclusions.

4.2.3 Mould Parameters

The surface of the solidifying strand is formed in the mould and consequently the bulk of the surface defects are related to mould technology. The complexity of the heat transfer in the mould was described in some detail in Section 3.1.2 and emphasised the interaction between several parameters.

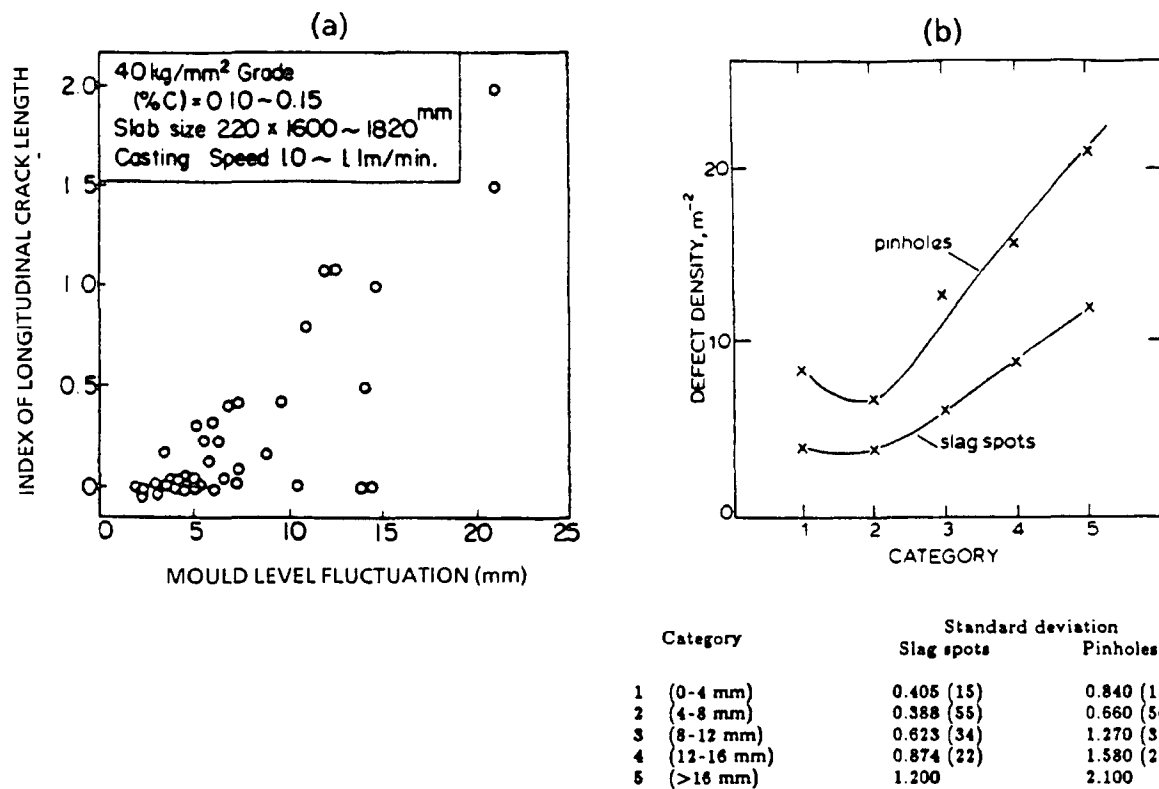


Figure 4.9 Effect of mould level fluctuations on (a) longitudinal cracks and (b) surface slag spots and pinholes.

4.2.3.1 Mould Level Control

Variation of the meniscus level in the mould can have a significant affect on the quality of the strand surface as it is formed. The teeming system from tundish to mould was briefly described in Section 2.6 and, apart from small billet casting, the tundish stopper rod or sliding gate is used to control the steel flow to maintain a constant level in the mould. There have been many examples published of how mould level variations affect surface quality. Figure 4.9 (a)⁹ shows how the incidence of longitudinal cracks in plate slabs can be affected by fluctuations in mould level and Figure 4.9(b) shows the effect of mould level on the number of slag spots (usually entrapped mould powder) and pinholes in the surface or subsurface of plate slabs.^{2,10}

The adverse affect of poor mould level control on the incidence of transverse cracks has also been well demonstrated² and is shown in Figure 4.10.

These results were obtained on the same study as those in Figure 4.9 (b). During this investigation metal level was deliberately varied during the evaluation of level control detectors. Crack assessment was based on the worse of the upper and lower slab surfaces. Severity of cracking is not taken into account in the above results but there was a correlation between severity and incidence. These results were further substantiated when the analysis omitted first and last slabs of a sequence and slabs cast during ladle changeover.

In billet casting higher casting speeds are used and cross-sectional areas are much smaller than for slab casting. This generally requires an extremely fast response control system to avoid high fluctuations in metal

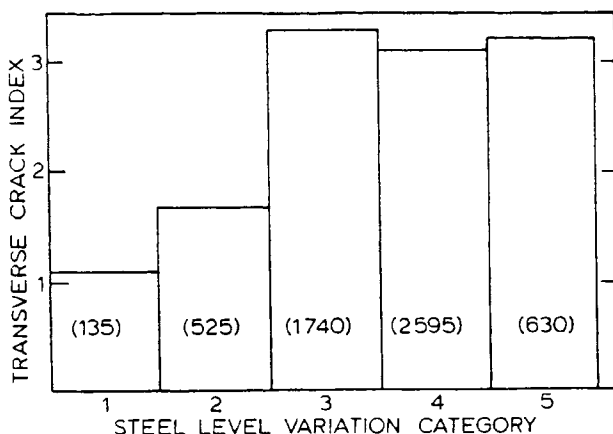


Figure 4.10 Effect of mould level variations on transverse crack index. Numbers in parentheses are slab tonnages assessed.

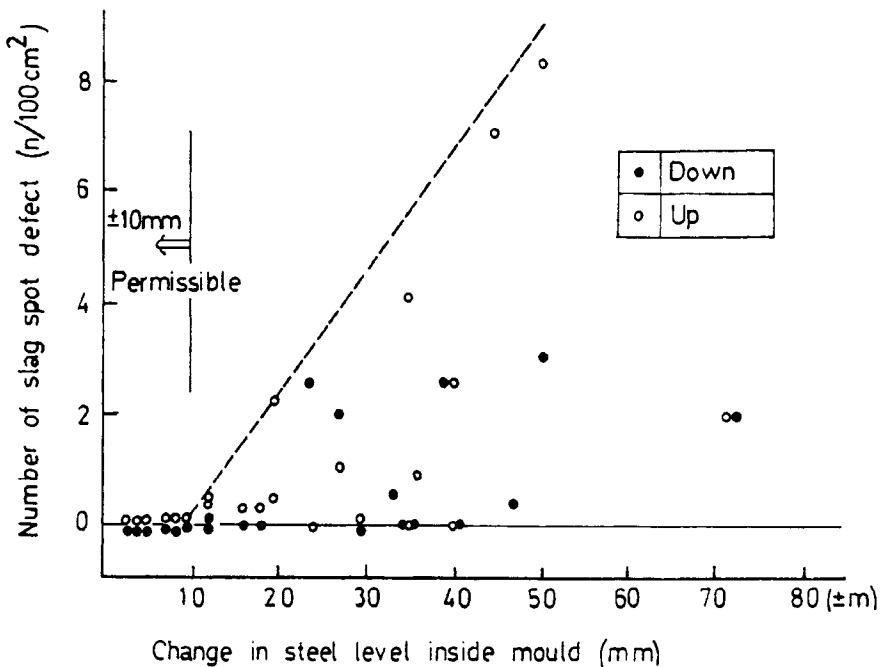
level control. However standard deviations of less than 10 mm can be readily achieved. Automatic start-up is also a regular feature in billet casting (See Section 6.1.4)

Figure 4.11 shows how the number of surface slag spot defects increase with steel level fluctuations in billet casting and Figure 4.12 shows the difference in the incidence of surface pinholes for automatic and manual level control respectively.

4.2.3.2 Mould Lubrication

It has already been emphasised that the lubrication within the mould coupled with the mould oscillation as described in the following paragraph is fundamental to the casting of steel and can markedly affect surface quality. The lubrication method is also the predominant factor in determining heat transfer (see Section 3.1.2) It is, therefore, worthwhile describing the lubrication methods in further detail. There are two main methods which were described in Figure 3.9 and para 3.1.2. These are:

1. Lubrication by oil as used in small billets and rounds
2. Lubrication by the use of synthetic mould powder



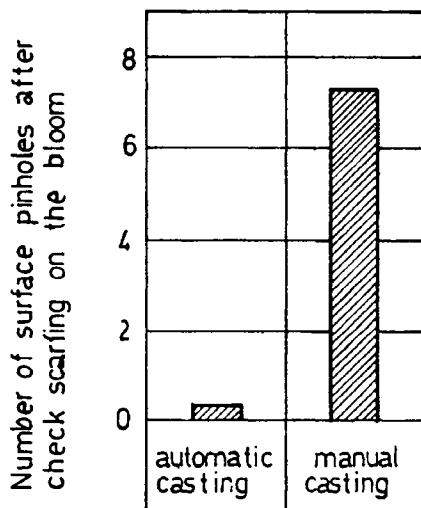


Figure 4.12 The effect of mould level control on pinholes.¹

Lubrication by Oil. In billet casting the normal practise is to use oil lubrication. This is for practical reasons as powder lubrication using pouring tubes is difficult when casting small section sizes, especially with sequence casting. The main problem areas are the thin wall and short life of pouring tube materials and the melting speed of powders. In billet casting the effective meniscus area for powder melting is small and the specific powder consumption is high because the casting speed is high and the specific surface is large.

The mechanism of oil lubrication is different from that of powder lubrication. In oil lubrication a thin oil film is distributed onto the mould wall above the meniscus level (the cold zone). Near the meniscus the oil decomposes (pyrolysis) to form a 'gas cushion' which prevents the strand shell sticking to the mould walls.

Average mould heat transfer is about 15–20% higher with oil^{1,12,13} (see Figure 3.14) than with powder lubrication because the thermal conductivity of the gap composed of gases formed with oil lubrication is higher than that of the molten slag layer when powder is used.

The oil lubrication should fulfil the following functions:¹

- (a) Ample distribution of oil in the upper part of the mould tube which requires suitable:
 - kinematic viscosity (30–35 cSt at 50°C, 400–600 cSt at 0°C)
 - pour point (-20 to -30°C)
 - sedimentation of oil at low temperatures
 - addition techniques

- (b) Optimum thermal stability of lubricant to ensure good lubrication behaviour. This leads to an optimum consumption (0.1–0.6 L/m.min or 50–200 ppm). Optimum decomposition during pyrolysis prevents sticking of the strand and minimises pinhole formation.
- (c) Safe working conditions and good clear view of meniscus. Factors to be considered:
 - formation of a small quantity of non toxic fumes
 - no excess sparking or splashing
 - no excess flame formation (flash point 220 to 250°C, combustion flash point 50 to 100°C)
- (d) The oil does not create dirt on the mould walls
- (e) Proper lubrication behaviour required when using gas shrouding of streams (partially inert atmosphere).

Conventional rape seed oil was the traditional lubricant used but both mineral and synthetic lubricants have now been developed which can produce better lubrication behaviour than rape seed oil. One investigation tested some 20 different lubricants.^{1,14}

Lubrication by Casting Powder. The mould powder is expected to fulfil the following functions:

- protection of the liquid steel surface in the mould from oxidation by air
- thermal insulation of the liquid steel surface
- absorption of oxide inclusions which float to the surface
- to encourage uniform heat transfer between the strand and the mould
- to form a lubricating film between the fragile steel shell and mould

These functions can be controlled by choosing the proper combination of physical and chemical properties of mould powder and resulting molten slag. Essential properties are:

- melting range and melting rate
- viscosity
- crystallisation and glass forming temperature

Table 4.2 gives the analysis of some typical commercial casting powders.¹⁵

The melting range of the casting powder should be large so that the slag close to the strand remains liquid down the whole length of the mould to provide good lubrication.

Lubrication efficiency of the mould strand gap is dependent on the slag viscosity. As long as the slag remains an homogeneous liquid, slag flow

Table 4.2 Analysis of typical commercial casting powders

Application	Slabs			Blooms		Billets, rounds
	(%)			(%)		(%)
CaO	38.7	37.5	32.3	31.6	21.6	26.0
SiO ₂	29.2	33.0	25.5	31.6	25.8	30.5
Al ₂ O ₃	4.2	6.5	7.8	7.6	11.8	5.6
TiO ₂	0.2		0.2	0.2	0.5	0.2
MgO	0.2	0.5	0.7	0.6	—	3.1
Na ₂ O	6.2	7.5	10.7	4.4	4.1	3.4
K ₂ O	0.6	0.5	0.8	0.6	2.0	0.4
Fe ₂ O ₃	2.5	1.0	2.4	2.3	4.4	1.0
MnO	0.1	—	6.4	0.7	—	0.04
F	6.0	7.0	6.0	4.7	4.9	4.3
C	3.5	4.0	5.4	8.5	20.0	22.7
	°C	°C	°C	°C	°C	°C
Softening temp.	1100	1120	1045	1110	1170	1200
Melting temp.	1175	1140	1120	1135	1245	1250
Flow temp.	1185	1170	1135	1165	1265	1255
Viscosity in Pa s	0.159	0.36	0.12	0.4	1.5	0.7
at 1300°C basicity	1.32	1.15	1.27	1.0	0.84	0.85

properties are completely characterised by the viscosity temperature curve.^{16,17} The slag basicity has to be as high as possible for good inclusion absorbing capability^{17,18} (Figure 4.13), and the slag viscosity is also strongly affected by alumina content.

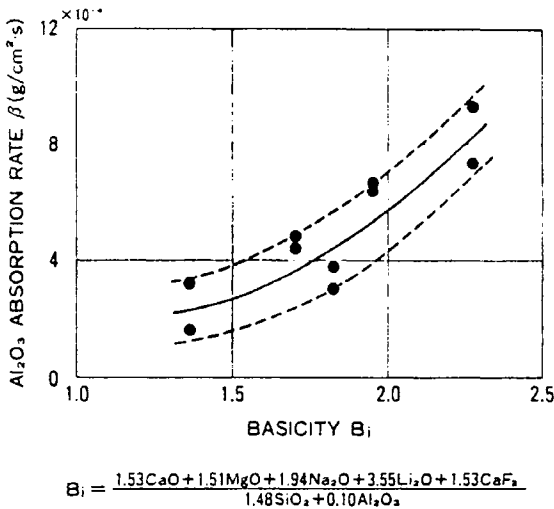


Figure 4.13 Effect of basicity of casting powder on the rate of alumina dissolution.¹⁸

Many of the powder fluxes exhibit viscosity/temperature relationships with a 'break-point' where viscosity increases abruptly with decreasing temperature. This behaviour is attributed to initial crystallisation during cooling of the slag which appears to be related to its basicity.¹⁶

Very viscous or low basicity fluxes (i.e. silica-rich slags) form glasses. On the other hand, with low viscosity or high basicity fluxes (lime rich, basicity 2.0) crystal formation occurs more readily. The addition of alumina to a flux suppresses crystalline precipitation and serves as a glassifier. In a study of the causes of sticker breakouts¹⁹ it was determined that the properties and analysis of the mould powder slag can cause carbonaceous agglomerates which prevent the flow of molten flux into the mould/strand gap at the meniscus.

For successful casting the melting rate of the powder has to equal the powder consumption. At the same time, for efficient thermal insulation, a complete powder cover has to be maintained on the molten slag.

The fusion rate of a powder flux can be controlled by blending materials with sufficiently high fusion temperature (skeleton materials). For this purpose powdered coke and graphite are most commonly used. The melting rate depends very much on the type, quantity and grain size of these skeleton materials.¹⁷

Under ideal conditions the powder on the molten steel surface forms a thin layer of molten slag and the fine carbon particles floating upward result in an intermediate layer consisting of molten slag droplets surrounded with carbonaceous particles. The powder layer maintains a complete covering on the molten steel surface.

Under these conditions oxidation is prevented, thermal insulation is assured and the molten slag feeds the mould/strand gap. Under steady casting operations a uniform slag thickness provides good lubrication, uniform heat transfer and hence a uniform shell growth. This type of the powder fusion process called 'non sinter type', can be achieved even with low free carbon contents of 1.0 to 2.0% by selecting and controlling the size and type of the carbonaceous particles.

The effect of the main casting parameters on the mould powder behaviour has been illustrated by many plant trials.²⁰ Figure 4.14 shows that increased casting speed and increased slag viscosity both reduce the specific mould powder consumption.

There are many attempts to explain experimental results with mathematical models, based on the hydrodynamic lubrication theory.^{21,22,23,24,25} At a specific casting speed the powder consumption should be equal to the melting rate. Only at this casting speed would the slag film have the maximum thickness and provide optimum lubrication.

Many operational parameters and requirements such as mould level

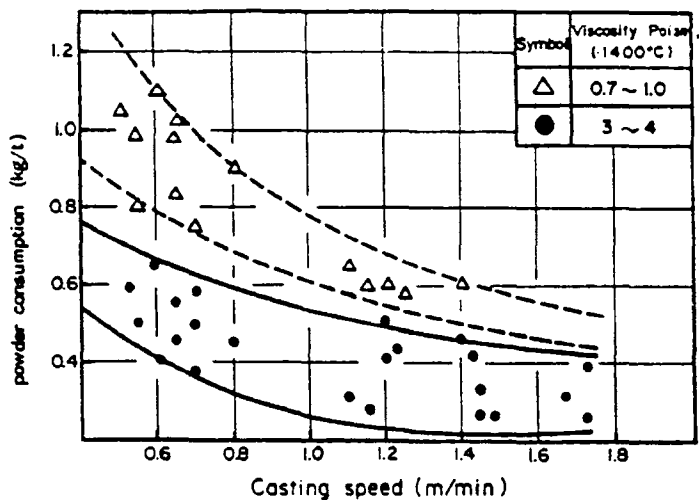


Figure 4.14 Effect of casting speed and slag viscosity on powder consumption.²¹

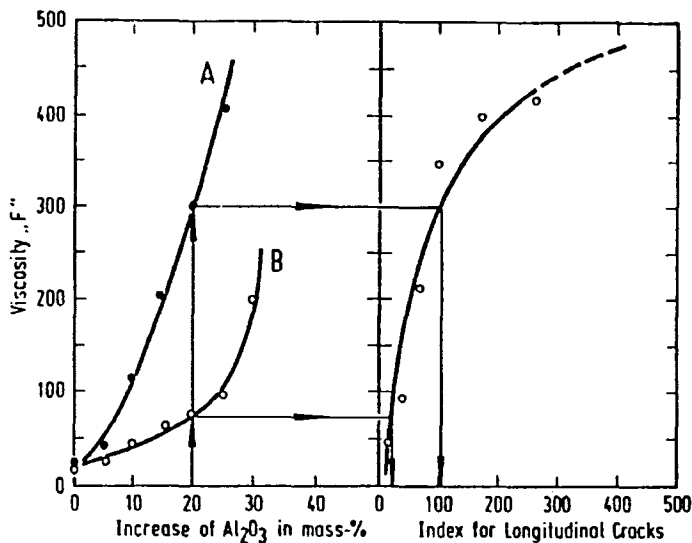


Figure 4.15 The effect of alumina on casting powder slag viscosity for two powders and on longitudinal cracking index.¹

stability, alumina content, powder feeding practice, low mould friction, uniform heat flux and steel cleanliness contribute to mould powder selection. For specific purposes such as ultra low carbon strip steels and stainless steel casting, casting powders with very low carbon levels have been developed.

In aluminium killed steels the alumina which is absorbed by the slag can significantly increase the viscosity which in turn can increase the incidence

of longitudinal cracks due to more erratic heat transfer. Figure 4.15 shows the effect of alumina on casting powder slag viscosity and longitudinal cracking.

4.2.3.3 Mould Oscillation

The main methods of mould oscillation were described in Section 3.1.1.3. Oscillation is predominately sinusoidal and the principal of negative strip time (or heal time) is fundamental to the successful continuous casting of steel. This is defined as the time within the oscillation cycle that the mould wall is moving downward at a higher velocity than strand withdrawal. Figure 4.16 shows a diagram of a cycle of the mould displacement and the velocity related to the casting speed.¹

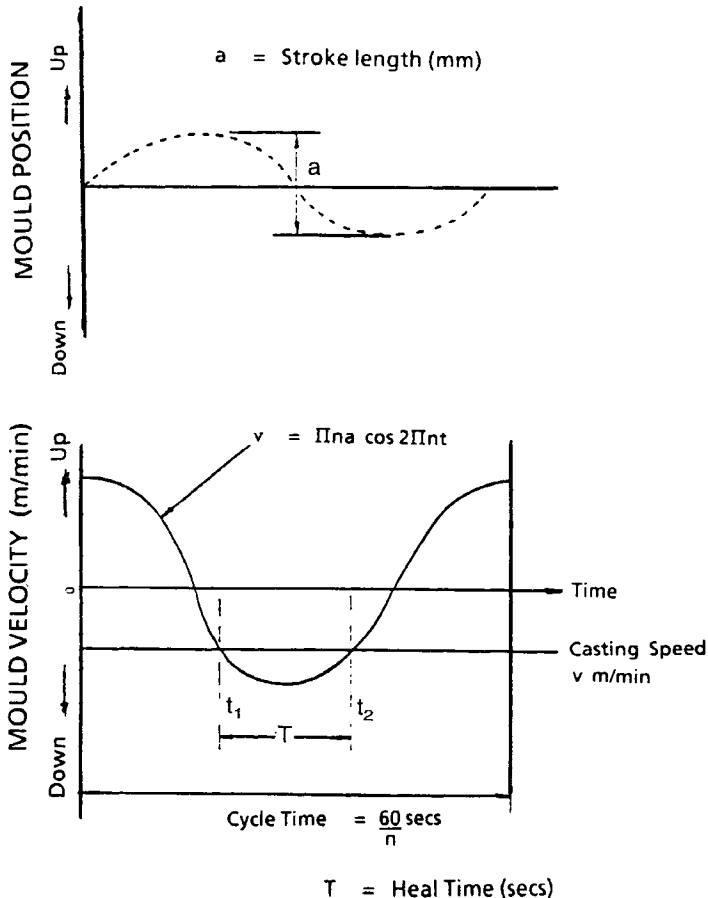


Figure 4.16 Diagram of (a) sinusoidal mould displacements and (b) velocities related to strand withdrawal speed.

The heal time or negative strip time ($t_2 - t_1$) can be expressed in seconds and is given by

$$T = \frac{60}{\Pi n} \cos^{-1} \frac{(V)}{a\Pi n} \quad \text{s}$$

the calculations being in radians.

For any given amplitude a the heal time reaches a maximum at a particular frequency. Figure 4.17 shows a plot of heal time against mould oscillation frequency for various amplitudes and at a casting speed of 0.8 m/min.

The typical range of heal times used in practice is between 0.2 and 0.3 s. If values less than 0.2 are used there is a lack of lubrication from the mould

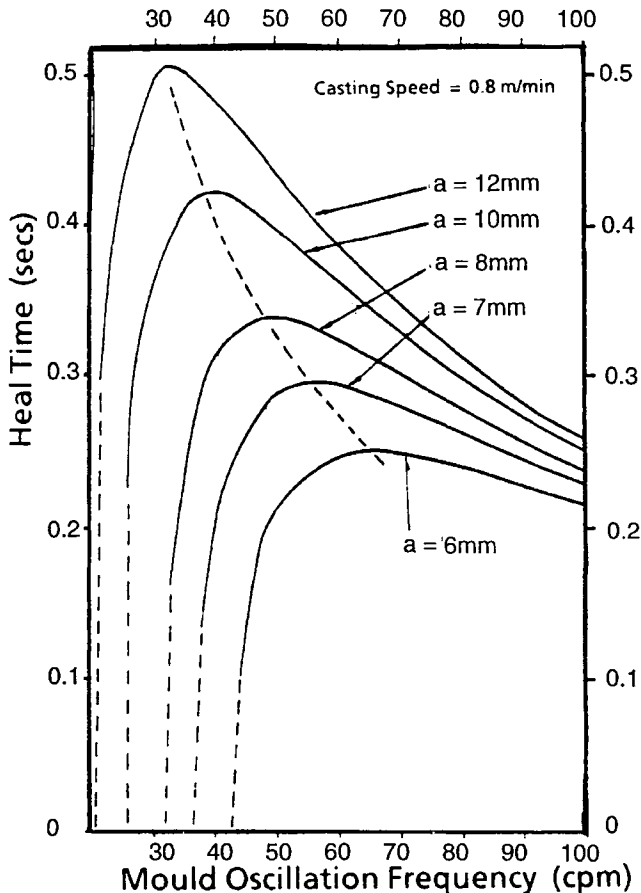


Figure 4.17 The effect of oscillation frequency on heal times at various amplitudes.¹

slag and the risk of sticker breakouts occur. If the values are in excess of 0.3 s, then severe reciprocation or oscillation marks occur giving stress raisers in the cast surface and increasing the probability of transverse cracking in crack sensitive steel grades.

The formation of oscillation marks involves a complex interaction of mould reciprocation, mould powder slag properties, heat transfer and mould level variations at the meniscus.

Oscillation marks appear as equally spaced horizontal ripples on the surface of as-cast semis. Figure 4.18 shows a macroscopic view of typical oscillation marks on an as-cast bloom.

The solidification of the meniscus can be evidenced by a metallographic examination of the structure and Figure 4.19 shows an example from a 250 mm 300 mm bloom.²⁶ The specimen was longitudinally cut in the middle of the wide face.

The formation of these oscillation marks has been explained by several workers.^{16,17,26,27,28} A theoretical approach to the phenomena in the meniscus zone, considering heat transfer and lubrication theory, predicts relations between oscillation marks and casting parameters such as heal time, mould flux viscosity and meniscus level variation.

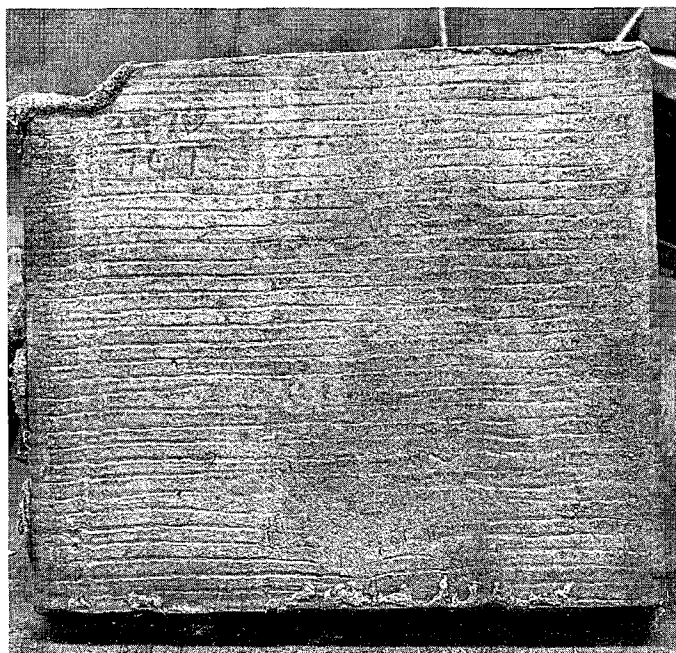


Figure 4.18 Typical oscillation marks on as-cast slab.

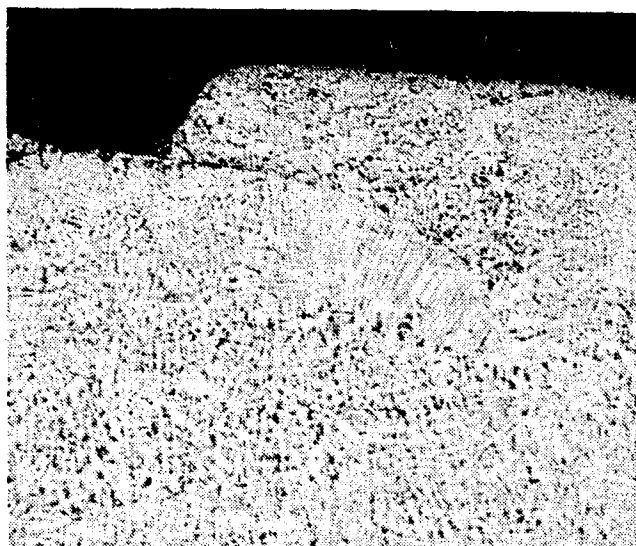


Figure 4.19 Longitudinal section of a 250 mm $\times$ 300 mm bloom showing metallographic details of an oscillation mark.

Metallographic examinations of oscillation marks^{16,17} suggest that the top of the shell is pushed into the molten steel by liquid slag pressure during negative strip, the heal time, as shown in Figure 4.20.

The mould flux is pumped into the gap between the strand and the

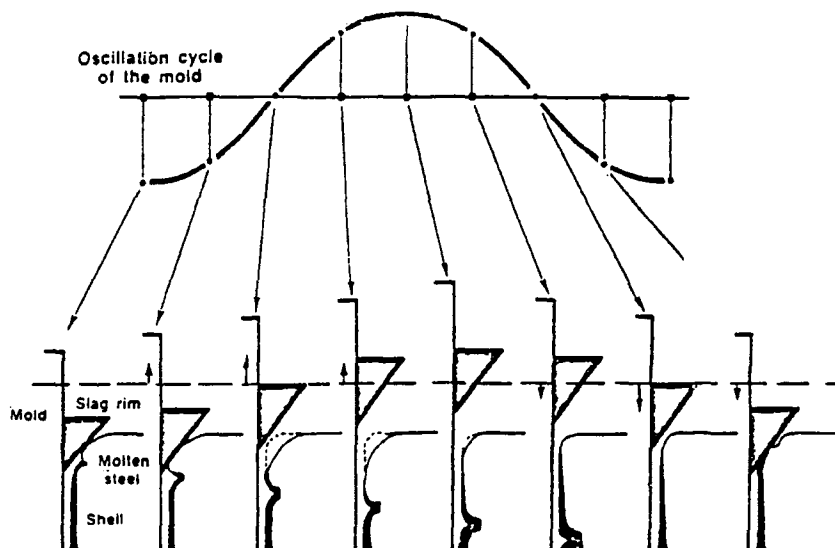


Figure 4.20 The behaviour of the slag rim during mould oscillation.

mould wall by the frozen slag rim attached to the mould wall and the flux pressure generated by mould oscillation. At the end of the negative strip period, when the mould and strand are moving downwards with the same velocity, the flux pressure is released and ferrostatic pressure either causes molten steel to overflow the partially solidified meniscus to form a 'hook', or the meniscus is pushed back towards the mould wall and a 'hook' is not created.

This mechanism of oscillation mark formation is based upon:

- the generation of pressure between the strand and mould wall
- the presence of a rigid or semi rigid skin at the meniscus

If the skin is rigid, overflow at the beginning of positive strip causes a sub surface 'hook' to form which may or may not remelt, whereas if the skin deforms, it moves with the meniscus, overflow does not occur and 'hooks' do not form. Figure 4.21 illustrates the proposed mechanisms.¹⁷

The mechanisms are all based upon the solidification, against the mould, of the curved part of the meniscus. This results in a solidified 'hook', the length and the shape of which are dependent upon the cooling efficiency of the mould, the mould oscillation pattern and the interfacial properties of the steel.

Figure 4.22 indicates the strong correlation between the heal time and the depth of the oscillation mark.²

In addition to the above factors the carbon content of the steel also has a large effect on oscillation mark depth as shown in Figure 4.23.

Oscillation marks need not strictly be a defect and in fact does not cause any problems in the further processing of many grades. However, deep oscillation marks act as stress raisers in the surface and for grain refined grades or any steels which have low ductility at the straightening tempera-

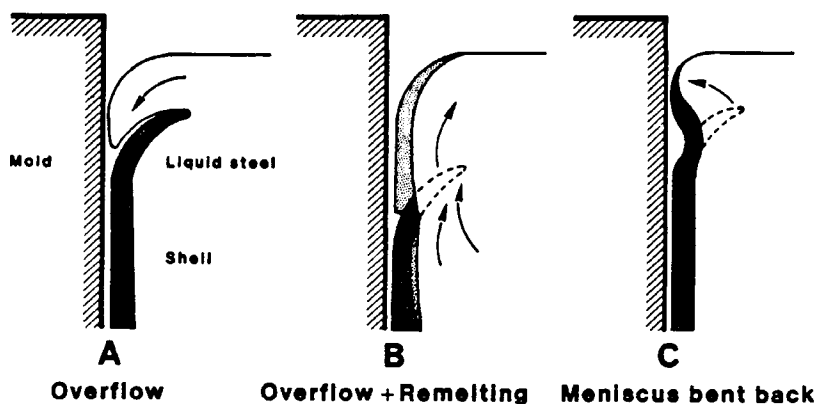


Figure 4.21 Three main mechanisms for the formation of oscillation marks.

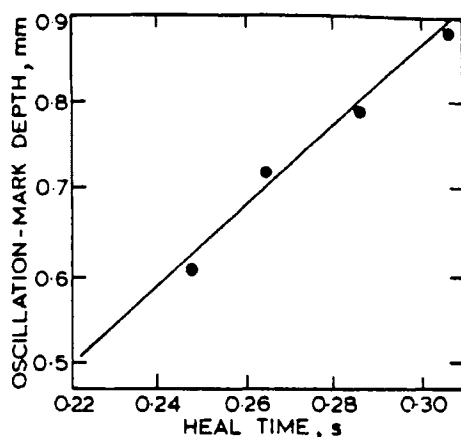


Figure 4.22 Effect of heal time on oscillation mark depth.

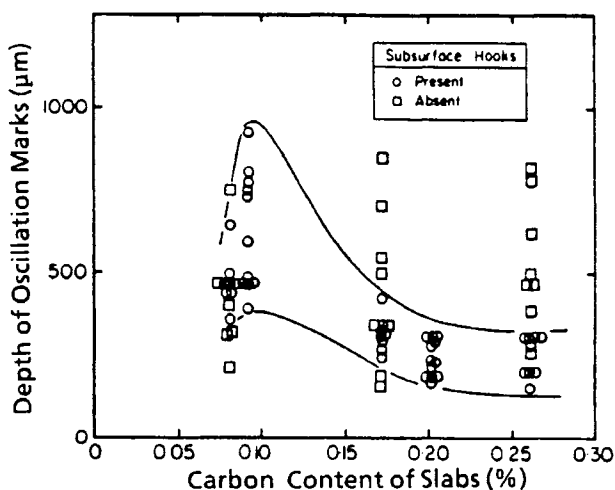


Figure 4.23 Influence of carbon content on the depth of oscillation marks.²⁷

tures transverse cracks can occur. Figure 4.24 shows the strong correlation of the position of transverse cracks after scarfing with the position of the oscillation mark.

In this case it was found that the irregular deep oscillation marks occurred when rapid changes in mould metal level were recorded and in some cases when surface waves in the mould were present caused by a combination of partial blockage of the SEN (due to alumina build-up) or by incorrect argon flow down the stopper rod.

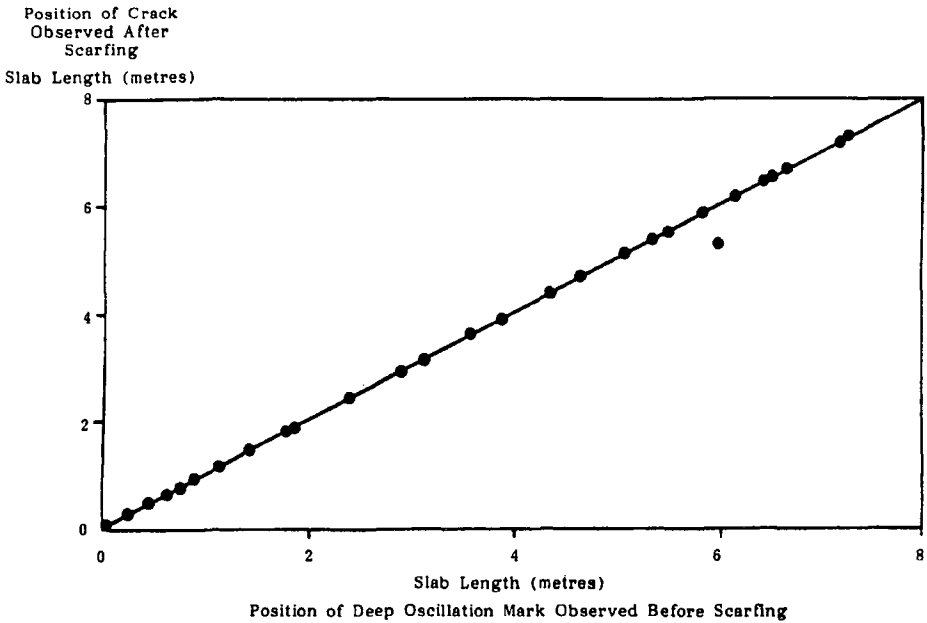


Figure 4.24 Correlation between deep oscillation marks and transverse cracking.

4.2.4 Secondary Cooling

The general details and related heat transfer data for secondary cooling was discussed extensively in para 3.2.2. In explaining the effect of 'secondary cooling' (which includes cooling by the support rollers etc.) reference will be made to Section 3.2.2 and also to Section 4.2.2.2 where secondary cooling conditions are fundamental to the casting of grain refined steels where the steel ductility is very low in certain temperature regimes.

4.2.4.1 Below Mould Cooling

Although it is generally accepted that longitudinal cracking is initiated in the continuous casting mould the degree of cracking can be severely aggravated by the secondary cooling conditions just below the mould. Controlled trials on a slab caster which was equipped with roller support below the mould were carried out and Figure 4.25 illustrates the effect of the amount of secondary cooling water in Zones 1 and 2 of the caster.

On this caster Zone 1 (Z1) consists of two rows of 16 fan jet nozzles on each broad face, one row above and one row below the first support roll. Zone 2 (Z2) consists of nine rows of 6 or 7 nozzles alternately on each broad face. Over a six month period the overall intensity of cooling in Z1 and Z2 was progressively reduced in six controlled stages (Trials I–VI) for

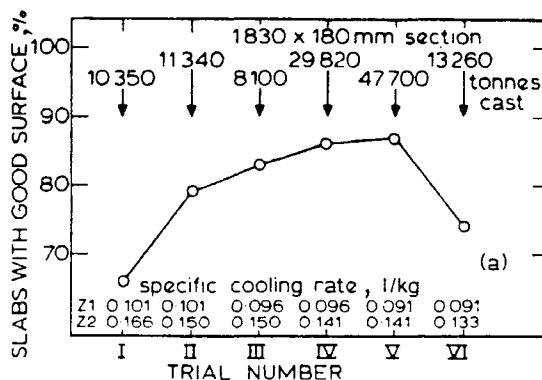


Figure 4.25 Effect of top zone cooling on surface quality (longitudinal cracking).⁶

a total (Z1 + Z2) 0.267 to 0.224 L/kg. Progressive improvement was achieved as shown in Figure 4.25 up to Trial V. Subsequent further reductions in Z2 flow-rate had an adverse effect on surface quality. Each trial was restricted to 1830mm × 180 mm slab section and covered at least 8000 tonnes of production. Total tonnage during the series of trials was over 120 000 tonnes. During the trial the same casting speed was used exclusively and the target casting speed was fixed at 1.0 m/min. Actual variations in carbon content, Mn:S ratio and casting speed are given in Table 4.3.

Table 4.3 Variations in carbon content, Mn/S ratio and casting speed for top zone cooling trials

Factor	Mean	Range
Carbon (%)	0.126	0.11–0.134
Mn/S ratio	43	41–44
Casting speed (m/min)	0.97	0.93–0.99

The cooling below the mould contributes significantly to the total secondary cooling water applied and can significantly reduce the surface temperature to within the low ductility regime when casting grain refined steels and will be discussed in Section 4.2.4.2 below.

4.2.4.2 Hard versus Soft Cooling for the Production of Grain Refined Steels

The poor ductility of many steel grades containing grain refining elements such as niobium and vanadium coupled with various levels of aluminium and nitrogen have been described in Section 4.2.2.2. To reduce the incidence of transverse facial and corner cracks, two approaches to secondary cooling have been used. The first approach termed 'soft' cooling is to

5. SPECIAL PROCESSES AND EMERGING TECHNOLOGIES

Steel companies are under continuous pressure to reduce operating costs and maintain or improve their competitive position. One response to this pressure has been the development of new processes which reduce the number of intermediate production steps or combine them in a continuous line, thus reducing material losses, energy consumption and the required manpower.

So far the casting of billets, blooms and slabs has been discussed in detail using casters of different design but with vertical steel pouring into the mould (termed conventional continuous casting). These casters ranged from totally vertical to the low head design as outlined in Section 1.2.2 and Figure 1.9 in particular. This chapter will describe developments in the following areas:

1. Horizontal casting
2. Beam blank casting
3. Thin slab casting
4. Strip casting

Item 1 is concerned with reducing the machine height to the limit, the potential benefits being low building heights and a very low ferrostatic pressure thus simplifying the strand support requirements. Items 2 to 4, on the other hand, are concerned with attempting to produce cast material which is nearer to the dimensions of the final product and such technologies have become known as 'near net shape casting'.

The wide adoption of conventional continuous casting has significantly decreased production costs and further benefits can be expected from the trend towards direct rolling and hot charging. Widespread application of direct rolling or in-line rolling of flat products are inhibited because the throughput of a caster is much lower than the corresponding hot rolling mill. Better matching of continuous casting and hot rolling requires casting speeds to be roughly doubled but rapid casting of normal sections leads to very long and expensive machines. This can be avoided by casting thinner sections but in order to maintain the present metal throughput it involves a substantial increase in speed. It is then possible to avoid some subsequent rolling operations. These arguments are illustrated in Table 5.1.

Table 5.1 Relationship between slab thickness, casting speed and machine length with conventional cooling¹

As cast slab thickness (mm)	Casting speed (m/min)	Metallurgical length (m)	Comment
220	1.9	30	High productivity slab caster
220	3.8	60	A theoretical possibility for a slab caster
22	38.0	6	Hypothetical thin slab development

Casting thinner sections closer to the final product dimensions has many attractive potential benefits. Casting strip, 1–6 mm thick, to be cold rolled without any hot rolling offers an enormous potential saving by eliminating the hot strip mill and reheating furnace. Casting thin slabs, 10–50 mm thick, which still require hot rolling is also of interest. This can be attractive to integrated steel plants who wish to expand their present hot rolling capacity or rebuild outdated equipment despite the need for hot rolling in a conventional strip mill or in a new type of compact mill. Furthermore, minimills which wish to enter the flat product market feel that this low investment requirement of a thin slab or strip caster may allow them to profitably manufacture standard grades of narrow strip.

Casting thin sections at 10 to 100 times the present casting speeds calls for the development of new casting technology without any relative motion between the metal and mould, that is to say the absence of friction. This precludes an oscillating mould and leads to a moving mould system, with the substrate and the solidifying metal travelling at the same speed, techniques that have been applied commercially to non ferrous metals casting for some years.

Numerous research projects are under way throughout the world to develop new casting methods for steel. The idea is not new; it first appeared in Bessemer's publications which described two rolls for the continuous casting of steel.² In the late 1950's Bethlehem Steel, US Steel and the NRIM in Japan used twin belt Hazelett casters in unsuccessful attempts to produce thin slabs for high quality applications.³ Another early approach to strip casting was the development work by Jones & Laughlin Steel on a ring and drum caster.⁴ Removing a wide strip from within the confines of the ring required a rotating motion of a hot strand that could lead to cracking and tearing and the project was discontinued in the early 1970s.

Developments of these new techniques where every element of the design has to be determined and where high product quality has to be achieved will obviously require long and sustained research effort. In both strip and thin slab casting technology the problems to be solved are the metal feed into the mould, the mould configuration, its lubrication, cast product handling and the rolling technology to meet final product requirements. Excellent surface quality is a prerequisite when casting thin slabs for exposed sheet applications as surface conditioning yield losses would be very large.

The various technologies will be discussed individually.

5.1 Horizontal Casting

Conventional continuous casting has progressed from the totally vertical caster to the low head/multi point straightening design (See Figure 1.9) with the major advantage in reducing overall caster height and ferrostatic pressure. The ferrostatic pressure for the vertical casters impose a severe duty on the support rollers and segments. Much development time has been concentrated on achieving virtually zero ferrostatic pressure by casting entirely horizontally. However, this involves going from a vertical feed into the mould to a device which allows a horizontal feed into the mould. This requires a horizontal tundish/mould joint and special conditions to reduce mould friction since the mould is rigidly fixed to the tundish by this feeding joint.

The mould/tundish link is made by a piece of refractory material which is called the break ring. The arrangement of tundish, nozzle, break ring and mould varies slightly depending on the machine builder. The break ring is made from a special refractory such as boron nitride or silicon nitride (Si_3N_4) which must be resistant to thermal shock, erosion and not be wetted by steel. Moreover this part has to be machined to very accurate dimensions. Figure 5.1 shows a cross-section diagram of a horizontal caster with the tundish and mould rigidly fixed.

The horizontal casting process has the following advantages:

- a very low head machine which can be installed in normal, existing buildings.
- the machine design gives full protection against atmospheric contamination particularly for small sections providing the capability of casting aluminium killed steels in small sections
- the strand undergoes no deformation, which suits special grades such as tool steels and high alloy steels.

This is by no means a new process, the first experimental plants for steel

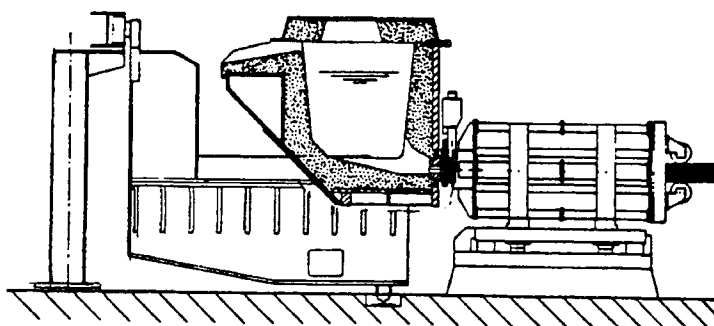


Figure 5.1 Horizontal caster with stationary mould and movable tundish in casting position.⁵

casting date back to 1966-1967 (Davy-Loewy⁶ in Great Britain, General Motors in the USA) but it has raised a lot of revised interest in recent years and much research and development work has been carried out to try to bring the process towards industrial application. There are approximately 30 plants which have been built since 1975; most of them remain pilot plants operated by the various machine builders but a few machines have reached the industrial production level, for example, NKK Fukuyama (1978)⁶ Boschgotthardshütte 1980, Armco 1984⁷ and British Steel (1988).⁸

Horizontal machines can be separated into two types according to their extraction mechanism:

1. the mould tundish assembly is stationary and an intermittent extraction pattern is used.⁵ Figure 5.2 shows (a) the tundish mould arrangement, (b) the typical withdrawal cycle and (c) the formation of the strand shell. This is the most commonly applied design^{6,9,10,11,12} and Technica Guss and Nippon Kokan/Davy Loewy have probably supplied most machines to date.
2. the mould tundish assembly is oscillating and a continuous extraction is used. This technique has been adopted in the USSR and by Krupp.¹³

Two original developments should also be quoted: the Watts process¹⁴ which seems to have now been abandoned and a Russian development (VN II Metmach) where one mould feeds two horizontally opposed strands simultaneously.

The sizes cast using horizontal casting are:

- Wires 3–12 mm dia. on a 12 strand machine could produce 25,000 tpa.
- Rounds up to 330 mm diameter.
- Billets and blooms 50 mm square to 250 mm square, 130mm × 170 mm.

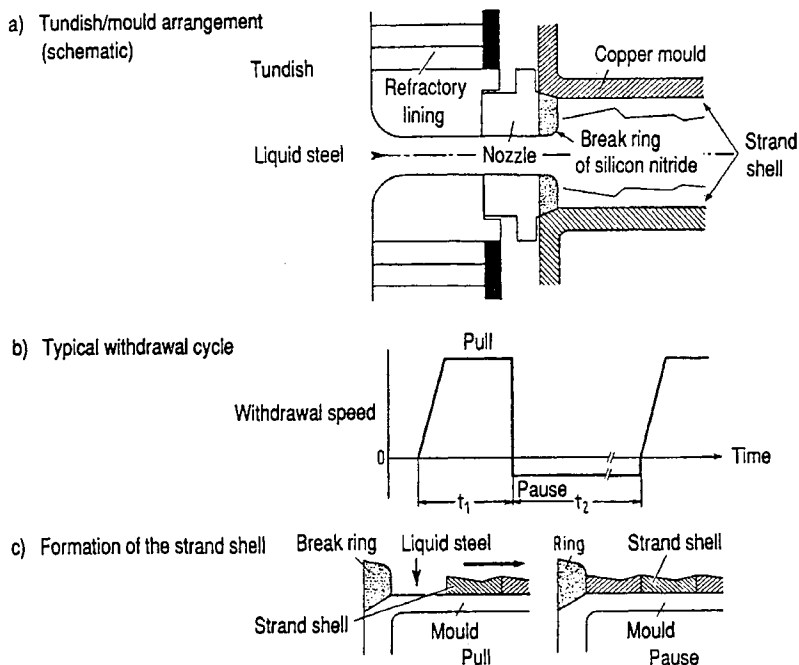


Figure 5.2 Horizontal casting showing (a) the tundish/mould arrangement, (b) typical withdrawal cycle and (c) the formation of the strand shell.

Limitations with the break ring technique have so far not permitted slab casting nor big bloom casting.

Casting speeds are similar to those achieved on a conventional machine but speeds are likely to increase with intensive development. The mould is not lubricated during casting and is made of copper alloy with high erosion and thermal distortion resistance. There is often a graphite section at the exit of the mould.

The main problems met with these processes are:

- the life and cost of the break ring which limits the casting time to a few hours, generally
- the surface quality which must be free of transverse cracks associated with solidification marks, (also termed cold shuts or witness marks) which may require surface conditioning. It is difficult to supply lubricant into the mould to reduce high friction.
- it is not applicable to large section sizes with steel even though similar processes for non ferrous casting are fairly well developed.

The formation of the solidification marks results from the strand formation process at the break ring in the mould as shown in Figure 5.2 (c). Tech-

nological developments such as mould EMS, break ring shape, runner brick shape, oscillation or pulse frequency and an improved knowledge of the process (superheat, mould taper related to steel grade) has improved the surface quality as shown by Figures 5.3 and 5.4. For optimum surface quality it is necessary to adjust the oscillation cycle for different steel grades.

The internal quality, in terms of central segregation and porosity, is similar to conventionally cast products but on large section sizes the struc-

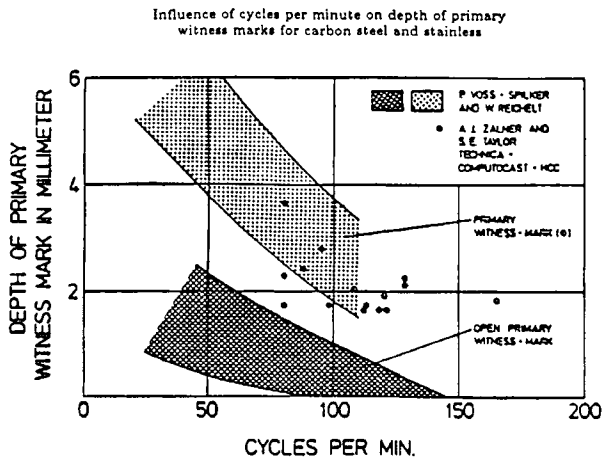


Figure 5.3 Horizontal casting: improvement of surface quality.¹⁵

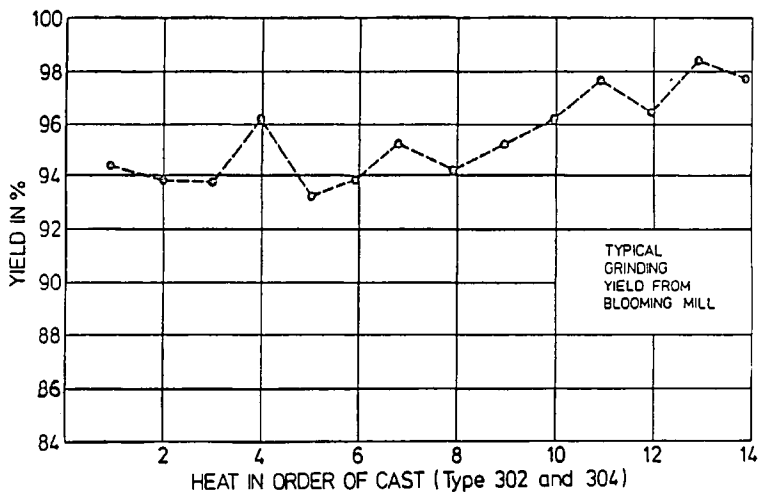


Figure 5.4 Horizontal casting (Technica Güss): grinding yield on stainless steel.¹⁵

ture presents some asymmetry. Electromagnetic stirring in the secondary cooling zone is another development to improve the internal quality which also eliminates the asymmetrical structure.

Initial application of the process has mainly been for special steels where the yield advantage compared to the ingot route is substantial but the tonnage requirements and capital costs moderate. For wider application break ring developments are crucial and the cost and service life of the break ring is probably the main limitation. This limits machine productivity and dominates the economics of the process. Whilst high quality refractory materials are developing rapidly considerable progress is still needed in refractory technology before the process becomes more widely accepted.

5.2 Beam Blank Casting

Prior to discussing the casting of beam blanks it would be useful to briefly describe the process routes for the production of beams and columns. Wide flange beams cover a wide range of sizes with beam heights ranging from 200 mm to 1000 mm and with flange heights up to 500 mm. The weight per unit length of the same sized beams can also vary widely. Universal rolling is used to produce the final beam from a beam blank. Normally these beam blanks are produced from ingots, blooms or slabs by the use of a breakdown mill with specially profiled rolls. Figure 5.6 shows the various stages of producing a wide flange beam from a continuously cast slab when the slab is first shaped to a beam blank in the breakdown mill.¹⁶

Grooves 1 and 2 in Figure 5.5 are the edging grooves or kniving passes where grooves 3 and 4 are the flange spreading grooves. No.5 is the final shape groove to obtain the final beam blank shape for further rolling in the

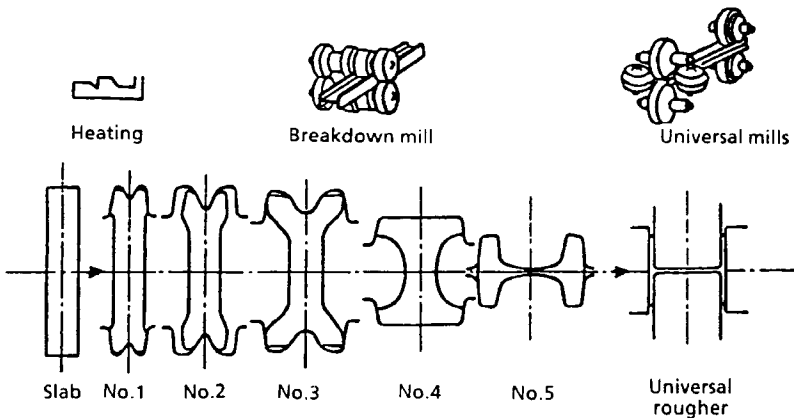


Figure 5.5 Various stages in rolling a slab to a wide flange beam.

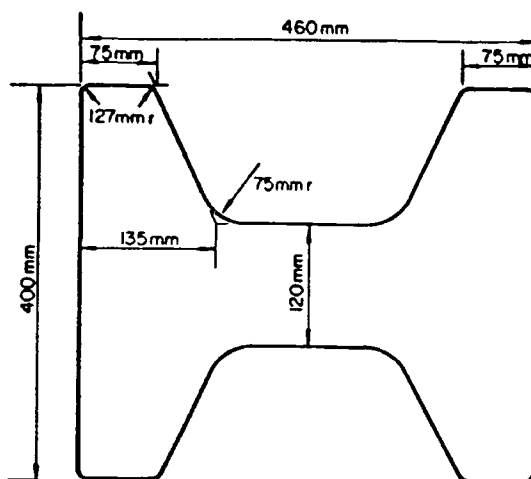


Figure 5.6 Profile of cast beam blank.²⁰

Universal mill. With this rolling method a limited number of beam blank sizes can be produced from a single slab size and hence a particular range of finished wide flange beam sizes. For smaller finished sizes as-cast blooms can be used but these do not require the initial edging grooves. In some plants a limited number of beam blanks are continuously cast, this technology being first developed by the British Iron and Steel Research Association¹⁷ in conjunction with Algoma Steel Co. in Canada¹⁸ where a plant was commissioned in 1968. Much of the earlier work was carried out on the pilot plant at Sheffield (U.K.). A licence for the process was obtained by Concast AG. There are still only a limited number of plants which currently cast beam blanks. Table 5.2 lists the various beam blank casters which have been commissioned.¹⁹

The conventional cast beam blank is shown in Figure 5.6 and it is usual for each plant to cast a limited number of beam blanks often with a maximum of two sizes.

Each cast beam blank is then rolled in the breakdown mill to a specific number of rolled beam blanks as required for the universal mill to roll to a specific size range of finished beams. Figure 5.7 shows this process route.



Figure 5.7 Process route for the rolling of *cast* beam blanks.

Table 5.2 Beam blank continuous casting facilities¹⁹

Plant	Start-up	Strands	Ladle cap (tonnes)	Size (mm)
1. Algoma Steel Corp., Ontario, Canada	1968	2	105	BB 405 × 305 × 100 to 775 × 356 × 102
2. Kawasaki Steel Corp., Mizushima Works	1973	4	200	BB 460 × 400 × 120 BB 460 × 287 × 120 BL 240 × 400 BL 400 × 560
3. Tokyo Steel Mfg., Kochi Works	(1970) 1979	1	25	BB 445 × 250 × 110 (Closed Nov. 87)
4. Yamato Kogyo KK, Himeji Works	1980	1	55	BB 460 × 370 × 140 BL 250 × 300 to 320 × 470
5. N.K.K., Fukuyama Works	1981	4	300	BB 480 × 400 × 120
6. Toa Steel (Toshin), Himeji Works	1982	4	150 50	BB 320 × 440 × 110 BL 200 × 300 to 250 × 355 and 150 sq
7. Tokyo Steel Mfg., Kyushu Works	1984	3	63	BB 400 × 420 × 120 BL 200 × 300 to 230 × 600 SL 230 × 600 to 1050
8. Nucor Yamato Steel Co., Blytheville, Ark.	1988	3	110	BB 400 × 510 × 140 BL 370 × 460 × 140 BL 200 × 280, 350, 400
9. Northwestern Steel & Wire, Sterling Il.	(1982) 1989	6	363	BB 241 × 330 × 201 BB 305 × 406 × 89
10. Northwestern Steel & Wire, Stirling, Il.	1990	3	360	BB 438 × 381 × 121 BB 603 × 502 × 179
11. Chaparral Steel Co., Midlothian, Texas	(1981) 1989	5	135	BB 150 × 255 × 100 BL 127 × 127 to 178 × 254
12. Chaparral Steel Co., Midlothian, Texas	1991	2	135	BB 686 × 305 × 50 BB 533 × 305 × 50 BB 533 × 229 × 50 BB 432 × 305 × 50

BB = Beam Banks; BL = Blooms; SL = Slabs

The method has limited advantages since a breakdown mill is still required. However, in the situation where the breakdown mill is a bottleneck in the process route then the use of cast beam blanks can increase the tonnage capability of the breakdown mill.

In 1991 Chaparral Steel Co In Texas commissioned a beam blank caster²¹ which produces cast sections with web and flange being only 50 mm in thickness, these being much more 'near net shape' than the conventional beam blanks.

The major advantages of casting near net shape are:

1. The breakdown mill can be eliminated
2. The solidification is complete in a very short time giving a fine and uniform structure

However only a limited number of finished sizes can be produced from each cast shape and Chaparral currently cast 4 sizes, these being

$533 \times 305 \times 50$ mm

$533 \times 229 \times 50$ mm

$686 \times 305 \times 50$ mm

$432 \times 305 \times 50$ mm

This enables finished product sizes ranging from

200–610 mm in height

140–260 mm in flange height

39–115 kg/m in weight/unit length

This 'near net shape' caster for wide flange beams is currently two strands with a production capacity of 545 kt per annum and is capable of being expanded to three strands.

Figure 5.8 shows schematically this simplified process route.

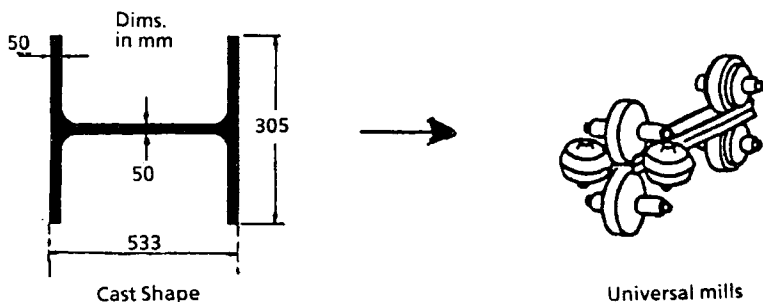


Figure 5.8 Comparison of (a) the thin cast slab process route with (b) the conventional thick cast slab route for hot strip production.

5.3 Thin Slab Casting

Thin slabs will be defined as cast thicknesses ranging from 20 to 80 mm. In the rolling of conventional slabs (say 200–270 mm in thickness) to strip

Table 5.3 Thin slab casting facilities indicating size range and scale of operation²²

Country	Process	Company	Thickness (mm)	Width (mm)	Scale	Furnace (kg or tonne)	Status
China	Twin roll	Shanghai Metal R.I.	50	—	Hot modal	—	—
Germany	Hazelett twin belt	Krupp	20–40	400	Hot model	3000 kg	—
Germany	Horizontal CC	Boschgottaradshutte	40–120	450	Industrial	—	—
Germany	Oscillating mould	Mannesmann-Demag	55	1600	Pilot	220 t	—
Germany	Oscillating mould	SMS	60–40	1000	Pilot	—	—
Germany	Osc. mould + rolls	Thyssen/SMS/U + S	40–10	1000	Pilot	110 t	Started 1989
Italy	Oscillating mould	Danieli	40	1600	Pilot	30 t	—
Japan	Twin belt vert.	NSC	50	600	Prototype	1000 kg	—
Japan	Caterpillar	Kobe Steel	30–40	70–80	Hot model	—	—
Japan	Caterpillar	NKK	50	150	Hot model	500 kg	—
Japan	Hazelett twin belt	Sumitomo Metals	—	—	Hot model	—	Stopped
Japan	Hazelett twin belt	Sumitomo Metals	40	600	Prototype	50 t	Stopped
Japan	Hazelett twin belt	Sumitomo Metals	30–40	1320	Pilot	50 t	—
Japan	Horizontal CC	KSC	20	200	Hot model	—	—
Japan	Twin belt horiz.	KSC	54	100	Hot model	200 kg	Phase 1 stopped
Japan	Twin belt vert.	KSC	30	1200	Prototype	500 kg	Phase 2 stopped
Japan	Twin belt vert.	KSC	30	1200	Pilot	35 t	—
Sweden	Oscillating mould	Avesta	80	—	Industrial	—	Started 1990
Switzerland	Twin roll	CONCAST Service	30–40	—	Design	—	—
Taiwan	Oscillating mould	Feng Lund Steel	75	1220	Industrial	—	cf Danieli
UK	Horizontal train	British Steel	30–75	500	Prototype	500 kg	Reoriented
USA	Hazelett twin belt	Bethlehem	25	—	Pilot	1000 kg	Stopped 1988
USA	Hazelett twin belt	NUCOR	38	1300	Pilot	32 kg	Stopped 1988
USA	Hazelett twin belt	USX	25	430	Pilot	15 kg	Stopped 1988
USA	Oscillating mould	NUCOR	50	1370	Industrial	100 t	Starts 1989
USSR	Twin belt vert.	ZNIITM	60–70	—	Prototype	—	—

products the slabs are reheated to rolling temperatures ($\sim 1250^{\circ}\text{C}$) and then rolled down to an intermediate thickness of around 20-40 mm by a series of 'roughing' passes which can be by two or three continuous rolling mill stands or by a single reversing roughing stand. The intermediate thickness then progresses in-line with the finishing train which may consist of six or seven rolling stands in tandem. The casting of thicknesses below approximately 50 mm gives the potential for eliminating the 'roughing' operation and the as-cast thin slab can be fed directly to a finishing train of mill stands after any appropriate reheating which may be only limited in a continuous operation. Table 5.3 lists the various thin slab casting facilities in the western world but it should be noted that work on several of these has been stopped.

Three installations in particular in Table 5.3 show industrial applications with heat sizes in excess of 100 tonnes. These are Nucor (USA),

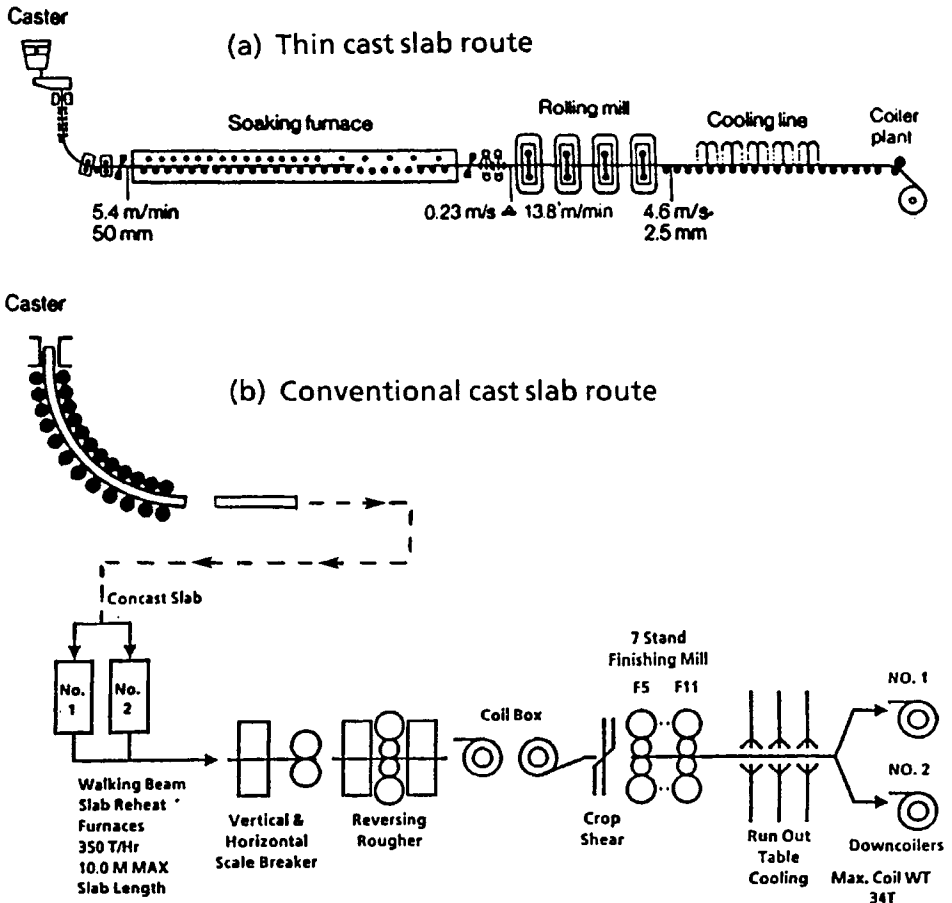


Figure 5.9 The process route at Nucor (Crawfordsville) compared to a conventional hot strip process route.

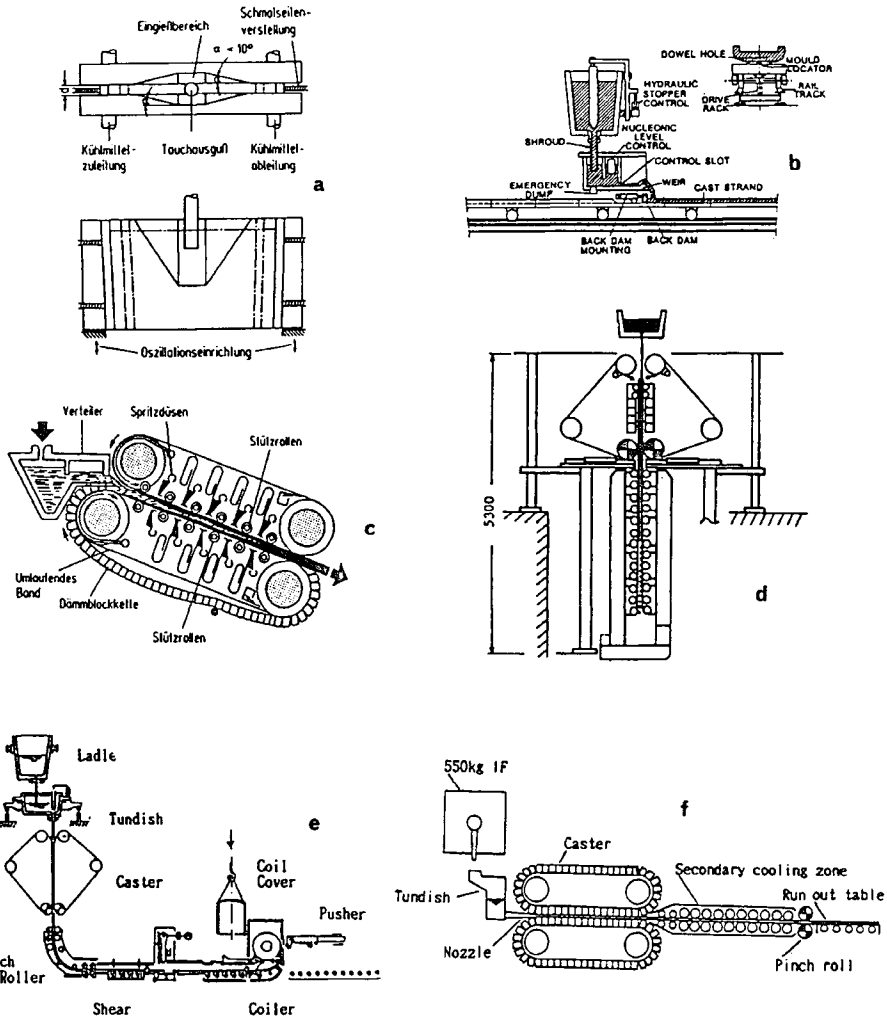


Figure 5.10 Schematic diagrams of some types of thin slab casters (a) SMS oscillating mould type; (b) BS horizontal caster; (c) Hazeltett caster; (d) NSC belt caster; (e) Kawasaki-Hitachi pilot plant; (f) NKK block caster.²²

Mannesmann (Germany) and Thyssen (Germany). The Nucor plant at Crawfordville in the USA was the first greenfield site, the facilities for steelmaking, casting and rolling all being commissioned in 1989.²³ Figure 5.9 compares the thin cast slab process route with a conventional 'thick' cast slab route for hot strip production.

Figure 5.10 shows schematic diagrams of some of the systems listed in Table 5.3.

Figure 5.10(a) shows the mould system used for the Nucor plant where

a normal vertical reciprocating mould was used with the central portion at the top of the mould being larger than the required slab thickness but which is reduced in size down the length of the mould until the lower region of the mould has a rectangular cross-section matching the required cast size in this case 1370 mm 50 mm. This allows extra width at the top of the mould for the specially designed submerged entry nozzle.

One of the major operational difficulties in thin slab casting arises due to the higher casting speeds required to achieve a reasonable production rate. Figure 5.11 shows the relationship between slab thickness and casting speed to achieve 0.25, 1.0 and 2.0 Mt/annum respectively for a 1300 mm wide slab.²²

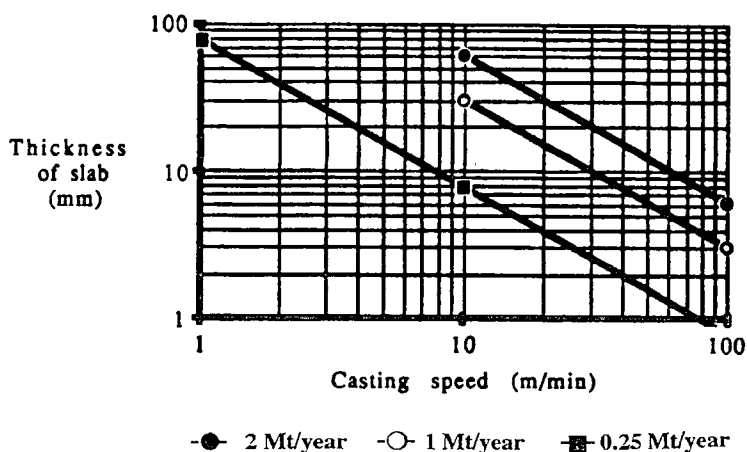


Figure 5.11 Relationship between thickness, casting speed and annual output of thin slab casters (assuming 5500 operating hours/year and a slab width of 1300 mm).

5.4 Strip Casting

There is currently a major research activity in the development of strip casting since this would have the potential for complete elimination of the hot strip mill and the as-cast strip could be fed directly to a cold rolling mill for further processing. The majority of methods involve casting between twin rolls or on a single roll system. Twin roll casting is a concept introduced in 1857 by Sir Henry Bessemer² but only recently has it been revived on a large scale in the iron and steel industry although it has been used more widely in the aluminium industry. Table 5.4 shows details of the various installations around the world for directly casting strip and which range in thicknesses from 0.1 mm to 25 mm.

Table 5.4 Details of steel strip casting installations²²

Country	Process	Company	Thickness (mm)	Width (mm)	Scale	Furnace (kg or tonne)	Status
Australia	Twin roll	BHP	1–3	–	Hot model	–	Started 1988
Austria	Single roll	Vöest-Alpine	1	250	Hot model	–	–
Austria	Twin roll	Vöest-Alpine	0.5–8	250	Hot model	–	–
Brazil	Belt and roll	MSA-DMH	5–10	900	Pilot	–	Started 1989
Canada	Twin roll	IKMRI	2	100	Hot model	25 kg	Started 1988
China	Oscillating mould	CISI, Beijing	2	–	Hot model	–	–
Korea (Sth)	Twin roll	POSCO	–	–	Hot model	–	–
France	Single roll	IRSID	0.5–1.2	200	Hot model	300–8000 kg	–
France	Twin roll	CLECIM	12–16	200	Hot model	300 kg	Stopped 1975
France	Twin roll	IRSID	10–2	200	Hot model	300–8000 kg	–
France	Twin roll	IRSID-CLECIM	1.5–5	800	Prototype	8–90 t	Started 1990
Germany	Belt and roll	Claustal University	5–15	150	Hot model	500 kg	Std. 1989 cfM-D
Germany	Roll and roll	Krupp	2	600	Prototype	3000 kg	Started 1989
Germany	Single roll	Krupp	2	–	Hot model	–	Started 1989
Germany	Twin roll	Thyssen IBH	5	150	Hot model	–	–
Italy	Twin roll	CSM	5–25	150	Hot model	300 kg	–
Italy	Twin roll	CSM	5–25	400–700	Prototype	4–20 t	Started 1989
Japan	Roll and roll	Nippon Metal	2	300	Hot model	300 kg	–
Japan	Roll and roll	Nippon Metal	1.5–2	Prototype	1500 kg	cf. Krupp	–

Table 5.4 (cont.)

Japan	Twin roll	Hitachi	2.3	600	Prototype	-	-
Japan	Twin roll	Hitachi Zosen	6	200	Hot model	350 kg	-
Japan	Twin roll	IHI	3	200	Hot model	100 kg	-
Japan	Twin roll	Kobe Steel	1.5	300	Hot model	100 kg	-
Japan	Twin roll	LSC	0.2-0.6	350-500	Hot model	500 kg	-
Japan	Twin roll	Nippon Yakin	1	600	Prototype	1500 kg	-
Japan	Twin roll	Nisshin Steel	1.5-2	300	Hot model	120 kg	-
Japan	Twin roll	Nisshin Steel	1.5-2	600	Prototype	-	Confidential
Japan	Twin roll	NKK	3.5	400	Hot model	250 kg	-
Japan	Twin roll	NSC	0.1-1.8	100	Hot model	5-8 kg	-
Japan	Twin roll	NSC	0.1-1.8	Prototype	1000 kg	Confidential	-
Japan	Twin roll	Waseda University	1-1.5	100	Hot model	20 kg	Started 1967
Japan	Twin roll	Waseda University	1-1.5	300	Hot model	20 kg	cf. Nippon Yakin
UK	Twin roll + slurry	British Steel	2	76	Hot model	250 kg	-
UK	Twin roll + slurry	British Steel	3	400	Prototype	4000 kg	-
USA	Inside-the-ring	LTV	5-6	153-380	Hot model	-	Stopped 1975
USA	Single roll	Allegheny Ludlum	0.75-1.25	350	Hot model	250 kg	1st step 1984
USA	Single roll	Allegheny Ludlum	0.75-1.25	560	Prototype	3000 kg	-
USA	Single roll	ARMCO/Westinghouse	0.5-0.8	75	Hot model	500 kg	-
USA	Single roll	National/Battelle	1.25-1.75	0.025-125	Hot model	-	-
USA	Twin roll	BS/ARMCO/INLAND/ WEIRTON	2	-	Hot model	-	Started 1984

Figure 5.12 shows some of the twin roll casting systems under development in the iron and steel industries.

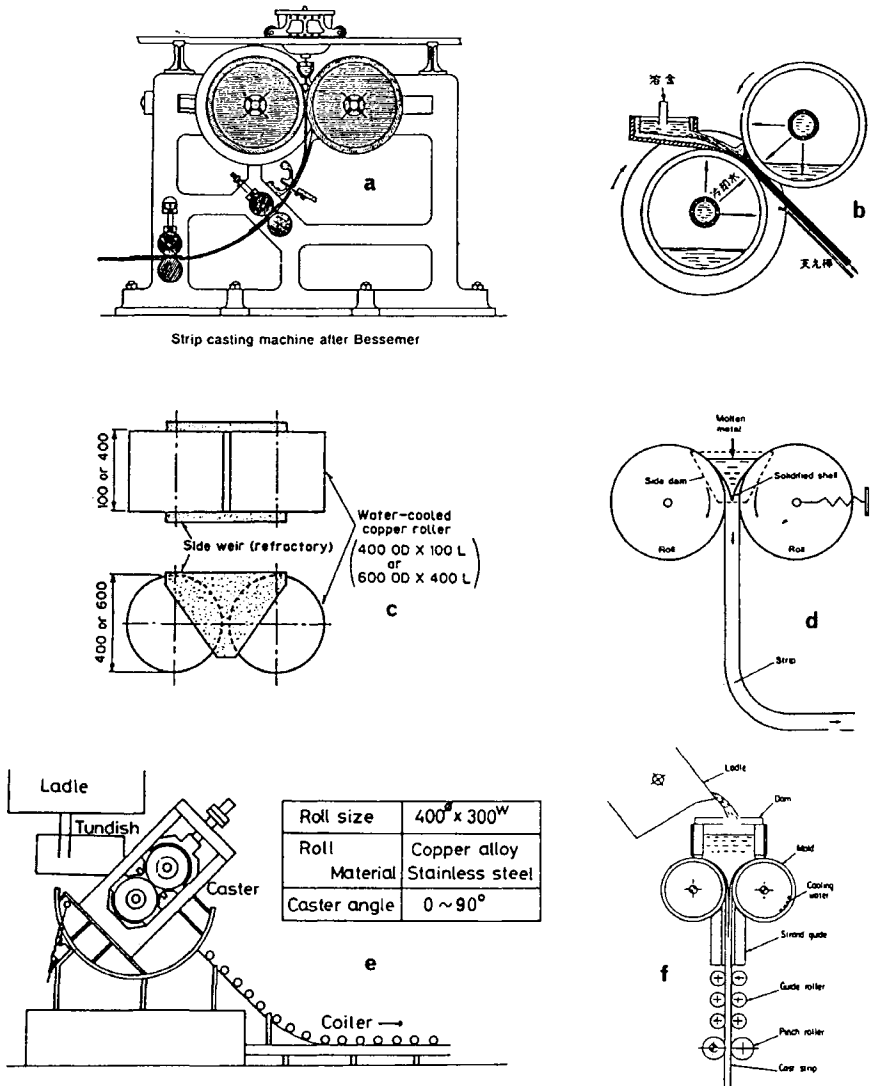


Figure 5.12 (above and opposite) Various twin roll strip casters under development (a) Bessemer's initial design; (b) Professor Kusakawa; (c) NKK; (d) NSC; (e) Kobe Steel; (f) Hitachi Zosen; (g) Kawasaki; (h) Nippon Metals; (i) CSM; (j) IRSD.²²

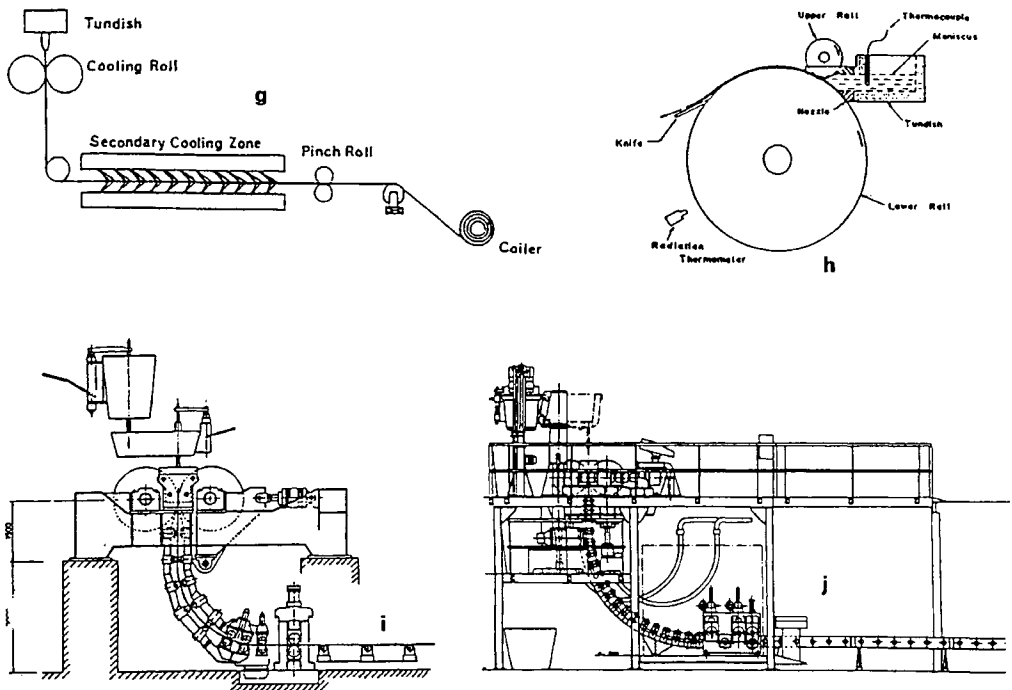


Figure 5.12 (cont.)

They differ in the respective diameters of the two rolls, their organisation in space, the feeding system of liquid steel, the technology used for liquid containment at the ends of the rolls etc. Most twin roll steel strip casters are still in the pilot plant range operating from small capacity furnaces and under rather narrow widths. A wide range of steel grades are included in the research work. However, many workers have targeted on stainless steel strip casting, Nisshin Steel²⁴ Nippon Metals²² and Nippon Steel Corporation²⁵ being typical examples.

In twin roll steel strip casting it is essential to adjust the roll speed and roll gap to allow the final solidification to occur at the 'kissing point' of the rolls. Figure 5.13 shows the effect of the solidification point on the roll separating force.

Two further technical problems which are inherent in strip casters using rollers are:

- (a) the edge containment of liquid steel, and
- (b) the ability to achieve uniform heat transfer to the rolls.

Variations in heat transfer lead to gauge variations on the cast strip and to surface defects. Since it is impractical to condition the surface of thin strip

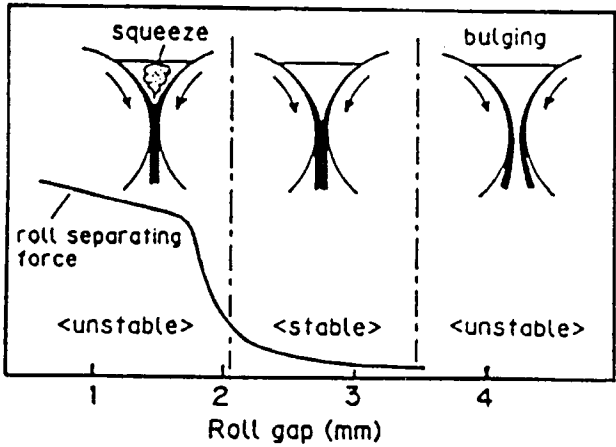


Figure 5.13 Operating conditions of twin roll strip casters.²²

it is essential to obtain a good cast surface free from defects. Further rolling is limited so there is little scope for rolling out surface imperfections.

Again the casting speeds required for strip casting are high and Figure 5.14 shows the relationship between cast strip thickness and casting speed for various annual production rates using twin roll casting.

Practical production rates/strand extend up to about 0.5 Mt/annum

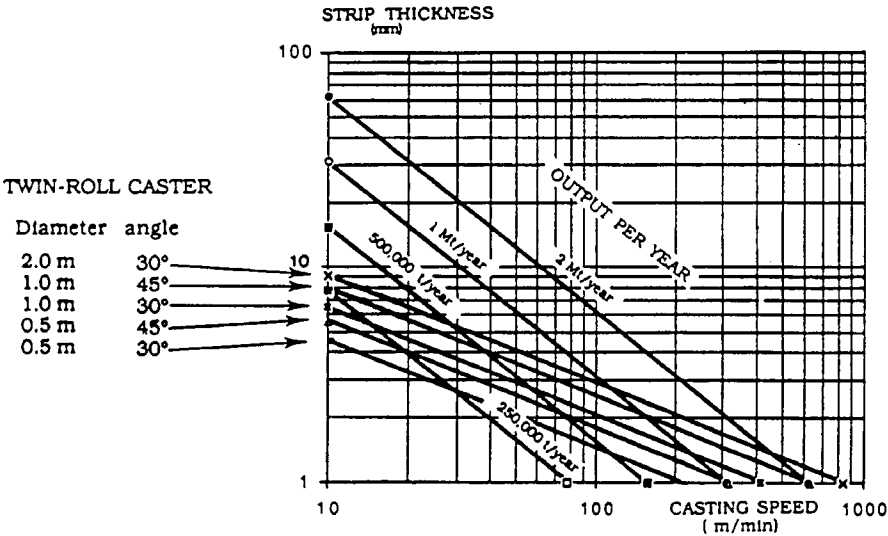


Figure 5.14 Twin roll casters: relationship between thickness, casting speed and productivity as a function of roll geometry.²²

and this is the typical production rates required for many stainless steel production sites and hence the interest in strip casting by stainless producers.

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6. PROCESS CONTROL AND ANCILLARY EQUIPEMENT

It has been emphasised in previous chapters and in particular in Chapter 4 that deviations of many parameters can cause unreliable operation and inferior product quality. These parameters include several important operational factors such as teeming, mould level variations, mould fluxing, surface temperature, casting speed etc and also some important engineering factors such as mould geometry, mould oscillation, strand support design and maintained geometry, straightener design etc. On modern continuous casting machines several parameters are controlled by automatic on-line systems. Additionally process monitoring and special measuring systems have been developed and are used on most plants. Several of these are continuous and on-line during casting whilst others are used during non casting (maintenance) periods.

The various systems can be categorised as follows:

1. Automatic on-line Process Control Systems
 - Tundish level control
 - Mould metal level control
 - Secondary spray water
 - Automatic start of casting
 - Automatic mould powder feeding
2. Continuous on-line Measuring and Monitoring Systems
 - Continuous tundish temperature measurement
 - Mould oscillation monitoring
 - Mould thermal monitoring
 - Spray water monitoring (pressure and flow rate for each header)
 - Hydraulic monitoring system
3. Off-line Measuring and Monitoring Systems
 - Mould geometry measurements
 - Strand condition monitoring
 - Spray distribution monitoring
4. Quality Control Systems
 - Continuous Surface Inspection
 - Quality Prediction Systems.

Each of these categories will be discussed separately.

It should be recognised that the above list only represents the more sophisticated control and monitoring systems. Many more features are

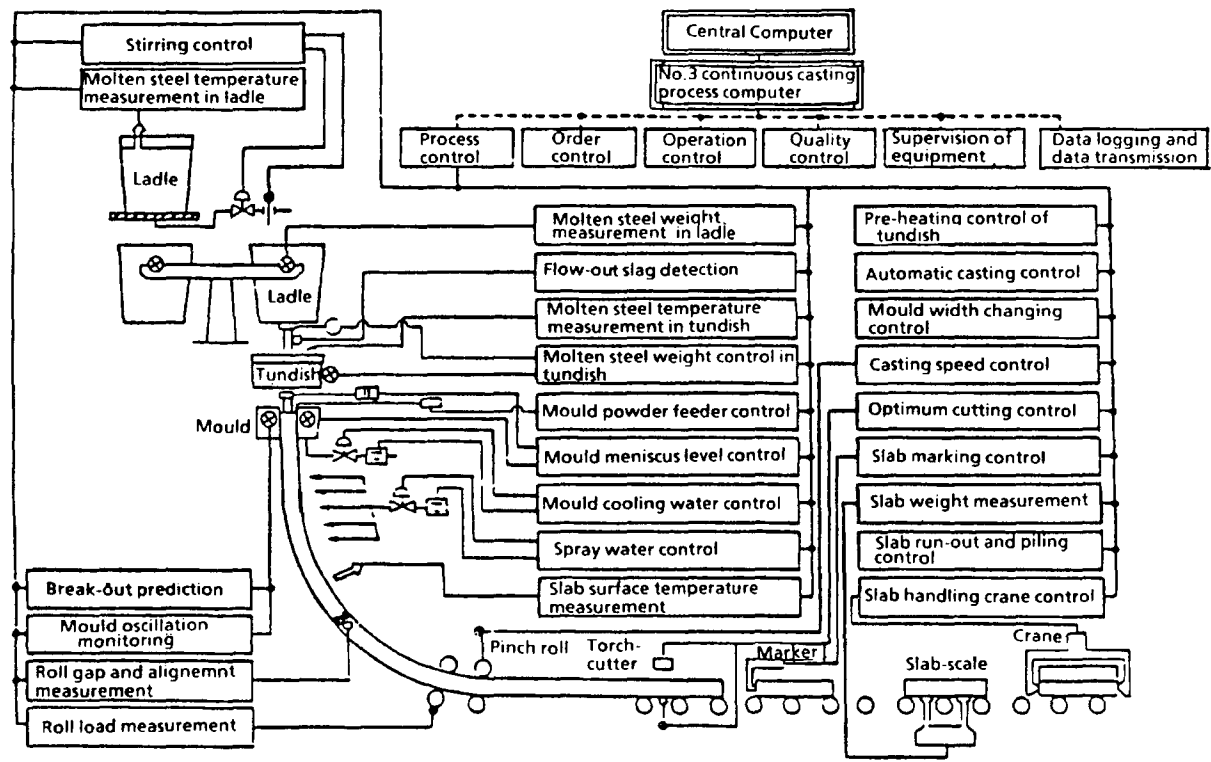


Figure 6.1 Continuous casting computer control system.

controlled automatically such as roller drive control, casting speed control, torch cutting, length measuring etc. Figure 6.1 shows a modern comprehensive continuous casting control system.¹

The more modern installations use distributed microprocessor control under the command of a supervisory control computer which may in turn be communicating with business and management systems.

It should be recognised that for automatic on-line closed loop control three main elements are required. These are a measuring sensor, a controller and a manipulator to exercise the control actions required to achieve the set point of the controlled parameters.

6.1 Automatic On-line Process Control Systems

6.1.1 Tundish Level Control

The steel level in the tundish requires to be maintained to specific limits for quality reasons and to enhance mould metal level control. Often the tundish is covered by refractory lined lids and visibility of the steel level is impaired. As a consequence the teeming by way of the sliding gate valve on the ladle is controlled automatically. This automatic control along with other automatic process control systems can lead to reduced manning requirements. The tundish level is invariably measured by the use of load cells on the tundish car which enables total tundish weight to be continuously measured. This however, does not make an allowance for slag build up in the tundish which can accumulate during the sequence until the tundish is changed or casting stops. Slag carry over from the ladle is often controlled by slag detection equipment in the ladle nozzle well block by the use of electromagnetic coils (see Section 6.2.1). An alternate method of measuring the level of steel in the tundish is by the use of electromagnetic coils installed behind the tundish lining. This method has the advantage that the interface between the steel and slag can be detected thus enabling the true steel depth to be measured. Figure 6.2 shows a schematic diagram of the control system for metal level control in the tundish using load cells.

Flow is controlled by the hydraulic actuator adjusting the slide gate valve on the ladle. Usually an accuracy of 1 tonne is adequate for tundish level control.

6.1.2 Automatic Mould Level Control

The control of variation in the metal level in the mould is fundamental to eliminating many surface and sub surface defects (See Section 4.2.3). For

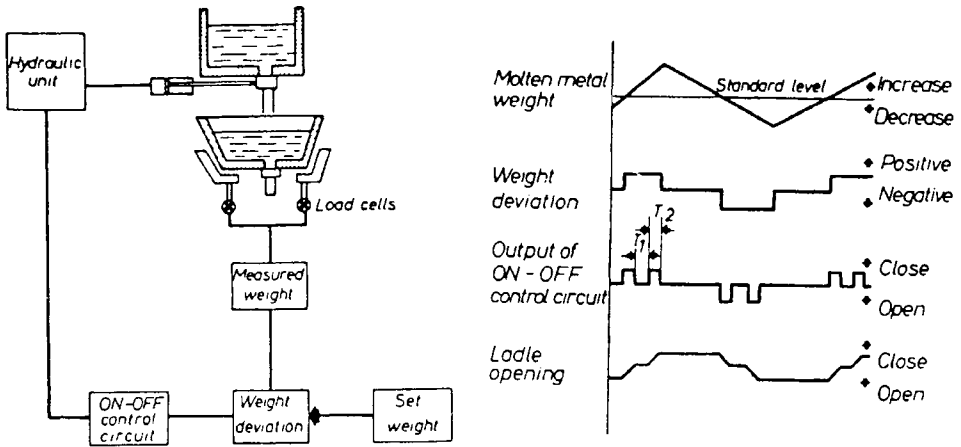


Figure 6.2 Automatic system for metal level control in the tundish.²

Table 6.1 Mould metal level detection systems¹

Methods	Detection	System	Comment
Optical			
Infrared emission from steel	Photodiode	Poncet CEDA	More amenable to open pouring without powder
Reflection of laser beam	Photodiode (time of flight)	Ladar	Requires some reflection from the casting powder
Radioactive			
Radioactive source Cs ₁₃₇ , Co ₆₀	Scintillation counter	Many	Some interference from powder cover
Thermal			
Thermocouple in mould wall	Position of temperature maximum	NSC USEC	Slow response time
Eddy Current			
Pairs of emitters and detector coils	Sophisticated electronic detection. Often special compensation coils used	NKK Conem Alcem	Not affected by powder Rapid response Some systems require careful set up to eliminate drift etc.
Mechanical			
Refractory float	Displacement	—	Limited life. Used at Outokumpu and USINOR

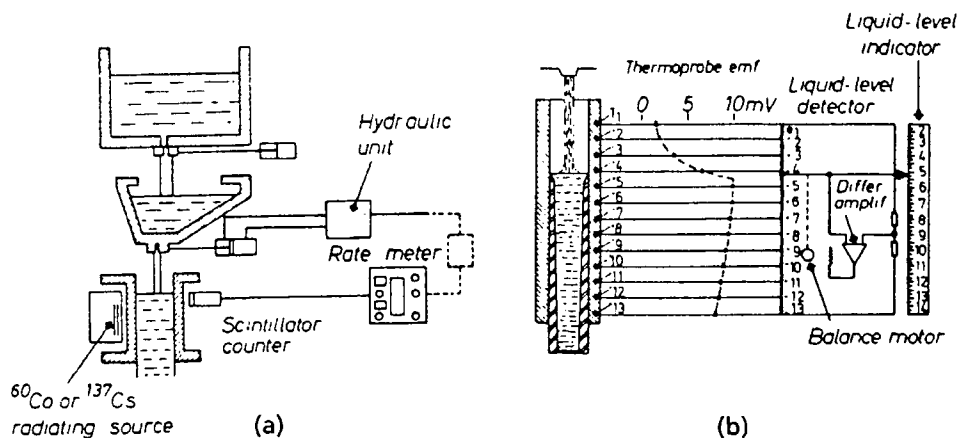


Figure 6.3 Schematic diagram showing mould metal level control systems using (a) the radioactive absorption method and (b) an array of thermocouples.

slab and bloom casting the aim is to maintain variations to less than 5 mm. For billet casting where the casting speed is usually higher and the cross-sectional area much less it is difficult to achieve 5 mm and level variations of twice that figure are not unusual.

A prerequisite for automatic mould level control is a reliable low maintenance system to detect the steel level in the mould. Table 6.1 lists the main systems used.

The systems most commonly used are the radioactive method, the eddy current system and the system using an array of thermocouples. The principles of these three systems will be more fully described.

Radioactive System. The Cs_{137} or the Co_{60} radiation source is built into one side of the mould jacket and a scintillation counter is mounted on the other side of the mould. Figure 6.3 (a) shows this arrangement.²

The γ rays transmitted by the source are absorbed by the steel and hence the scintillation counter and rate meter output are affected by the metal level. However, if there is also mould powder and slag on top of the liquid steel these also absorb, to some degree, the γ rays and errors in the true metal level can occur.

Eddy Current System. This method uses an eddy current generating unit placed above the mould powder in the mould. The output from such a unit responds only to the steel metal level since eddy currents are not generated in the slag or powder. Hence this method appears to allow the highest control of accuracy which has been quoted as ± 3 mm. Figure 6.4 shows this arrangement.

This method also has the advantage that a single source/detector is used and is not an integral part of the mould. The same detector can be

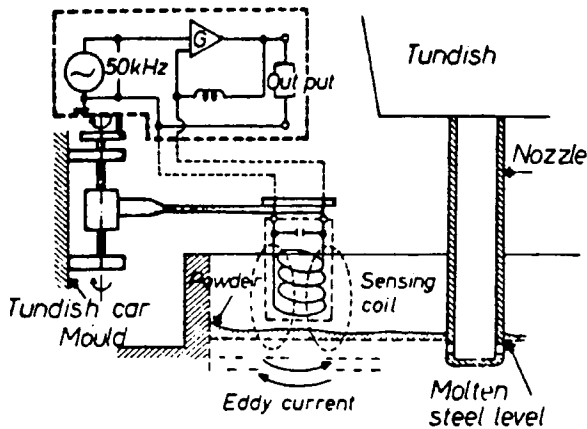


Figure 6.4 Schematic diagram of the eddy current mould metal level detector.²

used for several moulds and has a significant benefit in maintenance terms since each mould has to be equipped with instrumentation for each of the other two methods.

Thermocouple System. The steel metal level can be detected by the output from an array of thermocouples inserted into the copper plate. Figure 6.3(b) shows the arrangement. To obtain a measurable response time the thermocouples need to be near the hot working surface of the copper plate and this impairs mould life. Therefore this system is not as widely used as the radioactive or eddy current systems.

In each case for slab and bloom casting the output signal from the level detector is compared with the required set point and this control provides a signal to adjust the sliding gate valve or stopper rod so that the teeming rate can be changed to maintain the correct metal level in the mould. An hydraulic actuator is used to adjust the sliding gate valve or the stopper rod whichever method is in use. In billet casting where metering nozzles are used to control the flowrate from the tundish to the mould the level signal is used to continually control the withdrawal speed to maintain mould level control.

6.1.3 Secondary Cooling Water Control

The secondary cooling distribution and intensity is designed to produce a particular surface temperature profile both down and around the strand at a particular casting speed.

Examples of specific temperature profiles down the mid broad face of a slab strand were shown in Figure 4.5. This was for 'soft' and 'hard' cooling respectively at a casting speed of 0.8 m/min. Provided the casting speed

remains constant the required limits of surface temperature demanded by the steel grade can be maintained but during casting there are occurrences when it is necessary to change the casting speed. At start of cast it is necessary to increase the casting speed in predetermined steps and at the end of casting again a predescribed pattern of casting speeds is used during 'capping off' and strand run out.

In addition casting speed often has to be reduced during ladle changeover and if tundish changing is practised then the strand will be stopped for a short period. A further requirement to change speed is associated with potential breakouts. If the breakout warning system predicts a sticker type breakout then the system either stops the strand for a predetermined time or reduces the casting speed followed by a preset build up again to normal casting speed (see Section 6.2.3).

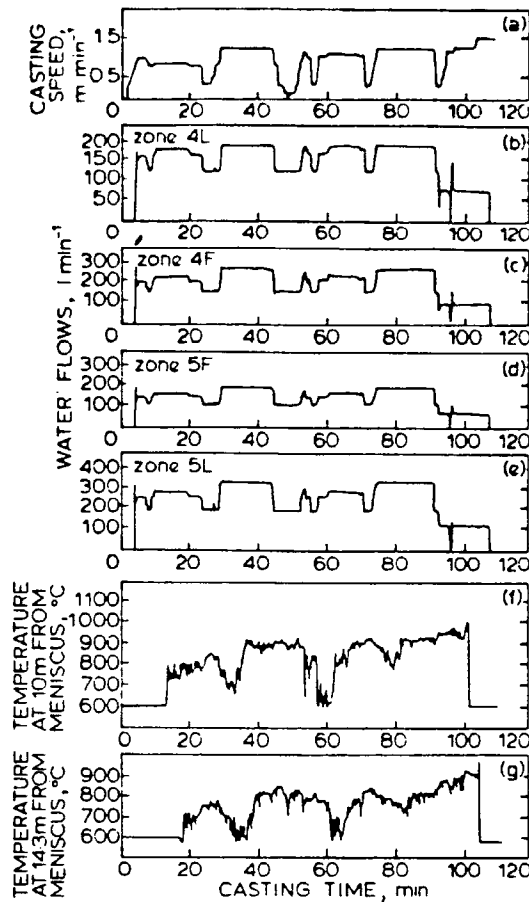


Figure 6.5 Effect of casting speed changes on surface temperatures.

Early secondary cooling control systems merely reduced the water flow rates in each zone proportionally to the casting speed. This however is quite inadequate since the surface temperatures in various points of the strand respond differently due to the thermal condition of the strand at the position in question.

Figure 6.5³ demonstrates that, when the water flow rates in each zone are reduced in proportion to the casting speed reductions, the surface temperatures are also reduced.

Dynamic secondary cooling control systems have been developed so that the correct amount of water (or air mist) is applied to each part of the strand according to the thermal history of that part. To enable this to be done the strand is divided up into a discrete number of transverse slices or elements. Each element of a predetermined length is tracked down the strand by integrating the casting speed with time and the correct amount of water is applied to that element dependent on its lifetime. To achieve the correct surface temperature throughout the strand the heat transfer coefficients and hence water quantities are determined as a function of time using the off-line heat transfer and solidification model as described in Section 3.4.1.

The procedure is as follows:

- for the required casting speed the secondary spray cooling water flow rates are determined for each spray zone to achieve a required surface temperature distribution throughout the stand.
- the heat transfer coefficients and water flow rates are calculated as functions of time.
- These functions are stored in the process control computer and the appropriate water flow rate is then applied to particular tracked elements of the solidifying strand according to the 'life-time' of that element to enable the correct surface temperature to be achieved throughout the solidification time of that particular element irrespective of any changes or variations in casting speed.

Figure 6.6(a) shows an example of a bloom strand divided into 40 transverse elements each 200 mm in length and Figure 6.6(b) shows the relationship between heat transfer coefficient and time to achieve a particular surface temperature profile.⁴

The heat transfer vs time curve is determined using the off line solidification model to maintain the same surface temperature profile which exists at the normal casting speed. It provides, in the form of an equation, the required heat transfer from any element depending on the 'life time' of that element. When changes of casting speed occur the control system can

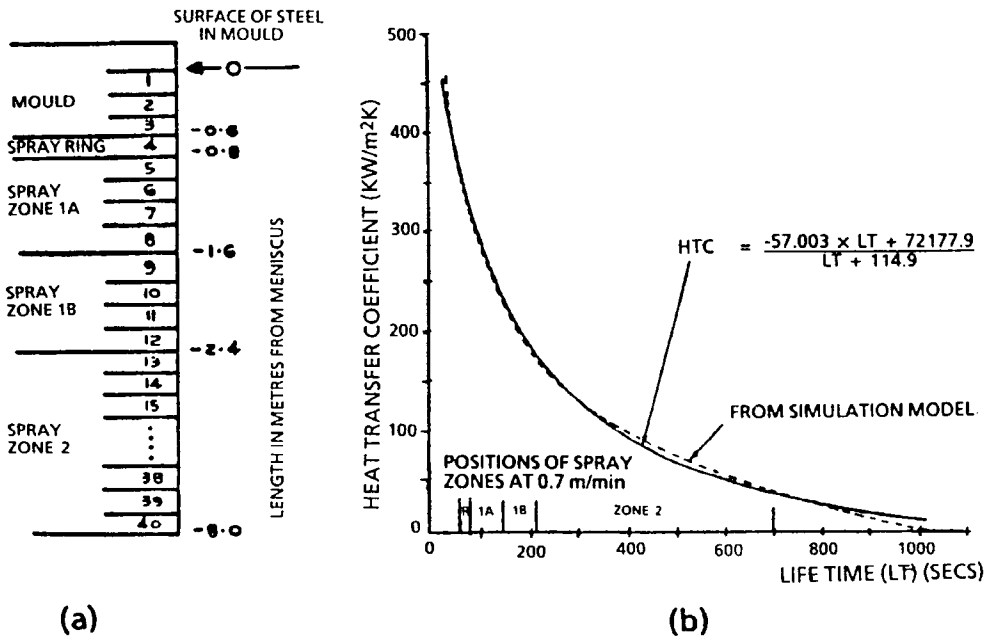


Figure 6.6 Details of automatic secondary cooling control on a bloom machine showing (a) schematic diagram of the individual elements and (b) heat transfer coefficient against time.

then adjust the cooling water flow rates to ensure that each element receives the appropriate amount of cooling as determined by the curve in Figure 6.6 (b).

6.1.4 Automatic Start of Casting

In most slab and bloom machines casting is started manually. When the steel in the tundish reaches a predetermined level the operator opens the stopper or sliding gate valve. The mould is filled to a particular level and then the strand withdrawal is started and the casting speed gradually increased according to a predetermined pattern. When the operating casting speed is reached then the operator switches to automatic level control.

For smaller strand cross-sections such as small bloom or larger billet casters automatic start up systems have been developed since nozzle opening and mould filling is a difficult task particularly for inexperienced operators. In such systems, the stopper or sliding gate opens when the tundish weight reaches a certain level. The mould fills until the mould level measuring system detects the metal level rising in the mould when the mould level control system takes over the operation. However, diffi-

culty arises with several of these mould level measuring systems because the detectors only operate over a limited length of the mould. In such cases the operation is facilitated by the inclusion of an array of thermocouples inserted in the copper plates and distributed up the length of the mould. This gives the mould level control system advance information of the filling rate and enables the control system to adequately respond to achieve automatic control. Sometimes the advance information is obtained by the use of a laser system looking into the mould and which again operates over the full length of the mould. However, in this case good access into the mould is required for the laser beam.

6.1.5 Automatic Mould Powder Feeding

The mould powder is usually manually fed into the mould by the operator using a small rake at specific intervals of time. However many attempts have been made at developing automatic systems thus eliminating further manual operation particularly during steady state casting. Several methods are now in operation, the simplest being a tube feeder which uses pelletised powder and the level of the powder in the mould controls the feed rate. More sophisticated systems monitor the top surface of the powder in the mould with temperature sensors and when the top surface temperature reaches certain levels discrete amounts of powder are added. Some of these systems detect the hottest regions and apply the powder at these regions by the use of a robot.

6.2 On-Line Monitoring Systems

Several systems will be described which are used to monitor or detect certain aspects of the process during operation. Several of these are used to detect deviations from optimum practice and can, therefore, be used for assessing quality of the as-cast product. Such systems will be described in 6.4.2

6.2.1 Detection of Slag from the Ladle

With covered tundishes and shrouded teeming between ladle and tundish it is extremely difficult for the operators to know when ladle slag emerges from the ladle when it is nearly empty. Any overflow of ladle slag during ladle emptying causes an undesirable build up of slag in the tundish during long sequencing and systems have been developed to detect when slag commences to flow through the sliding gate nozzle. A common method of slag detection is by inserting small electromagnetic coils behind

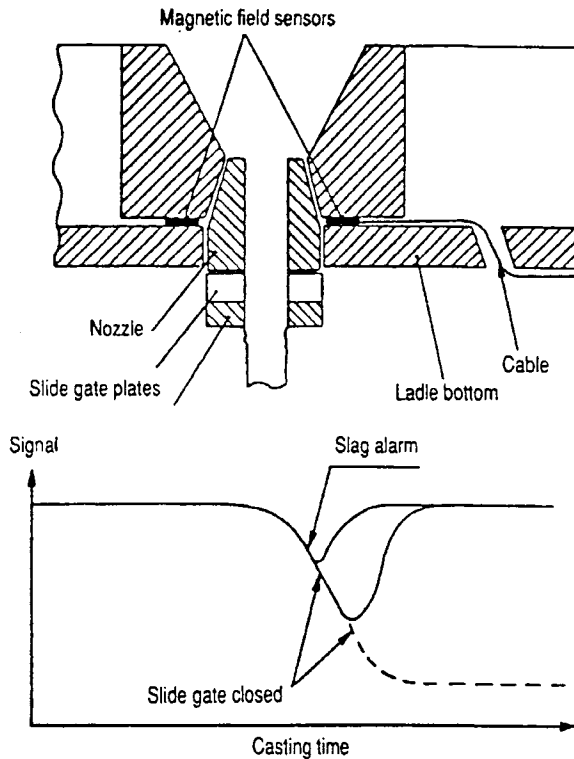


Figure 6.7 Basic principles of an electromagnetic slag detection system.

the upper part of the nozzle in the ladle. Figure 6.7 shows a schematic diagram of such an arrangement.⁵

It should be noted that the change in signal is not instantaneous since the slag is gradually entrained in the steel as a vortex forms in the low level of remaining steel in the ladle. As the amount of slag increases the signal changes due to the differing response of steel and slag to the electromagnetic field. At a predetermined signal level the operator closes the sliding gate nozzle or this can be done automatically by providing this signal to the ladle to the tundish teeming control system.

6.2.2 Continuous Tundish Temperature Measurement

Over many years the steel temperature in the tundish has been measured at discrete intervals of time during the casting operation. This is done by the use of special probes with temperature measuring devices on the end. These are quickly destroyed due to the high temperature but not until the thermocouple has produced 'plateau' output signal providing the steel

temperature. In more recent times temperature measuring systems have been developed which measure the temperature continuously in the tundish thus eliminating the need for an operator to carry out the manual measurements described above. The aim is to obtain a continuous temperature measuring system which will last at least the life of the tundish which may be around 10 heats.

6.2.3 Mould Thermal Monitoring (MTM) and Sticker Breakout Prediction

The use of thermocouples inserted in the mould copper plates was described in Section 3.1.2. This was for early investigatory purposes but it was soon realised that information from thermocouple arrays in the mould copper plates had considerable potential to provide valuable information about the thermal conditions in the mould. Such information could serve as a direct indication of the distribution and variability of the heat transfer in the mould and of the mould powder performance, which in turn could be related to the risk of surface defects or sticker type breakouts (see later).

After further investigatory work in the mid 1980s on a rounds bloom caster⁶ to study the causes of longitudinal cracking a real time thermal monitoring system was installed on this caster to enable control of the process to reduce the incidence of this defect. Since that time the complex software for mould thermal monitoring has been developed along with the reliability of the thermocouples and consequently many slab casters and some bloom casters are now equipped with sophisticated mould thermal monitoring sys-

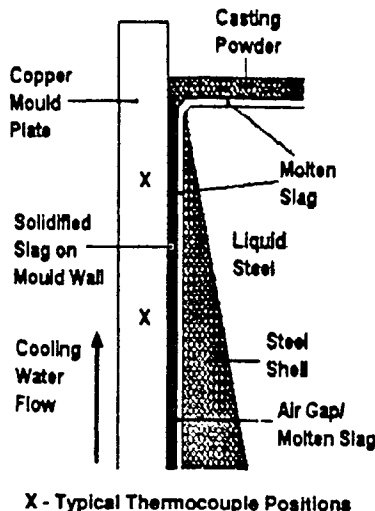
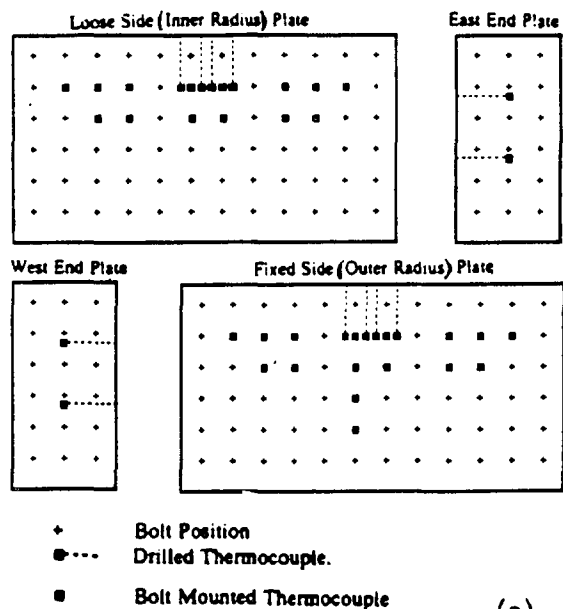
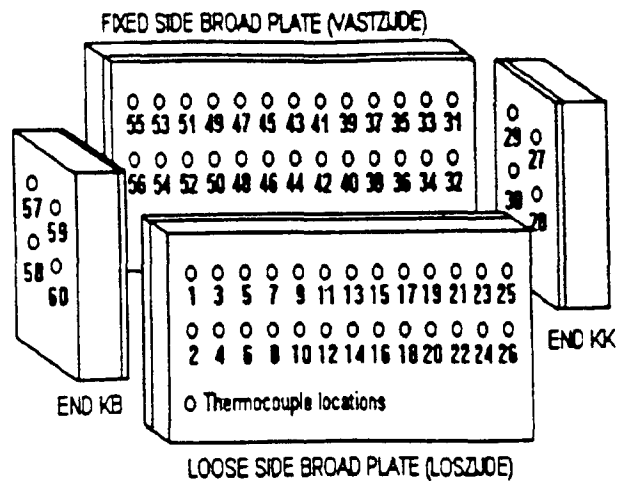


Figure 6.8 Typical themocouple positions in the copper plates



(a)



(b)

Figure 6.9 Schematic diagrams of the thermocouple positions for (a) a twin strand slab caster for plate products⁸ and (b) a twin strand slab caster for strip products.⁹

tems.^{7,8,9} In such systems, rows of thermocouples are inserted around the complete mould perimeter at two levels down the mould. Figure 6.8 shows the schematic arrangement for an individual thermocouple pair installed in this manner, and the copper mould/strand interface.

The top row is usually about 80 mm below the meniscus level while the bottom row varies between 200 mm and 250 mm depending on the mould length and casting speed. The thermocouples are now all installed through the mould plate fixing bolts which sometimes dictates the exact position of the two rows of thermocouples.

Figure 6.9 shows typical thermocouple positions for a twin strand slab caster for plate products and those for a high speed twin slab caster for strip products. Figure 6.10 shows the system schematic configuration for the twin strand slab caster referred to in Figure 6.9 (a).

The mould thermal monitoring systems are usually installed on dedicated powerful micro-computers which may be networked to works-wide computer systems giving wider communications possibilities. A typical non-networked system is depicted in Figure 6.10. Data acquisition units are distributed around the plant at appropriate locations close the the source of signals with data transfer achieved by high speed serial line communications.

MTM Software. The MTM computer is equipped with software to perform real-time monitoring, configure all aspects of the system and perform some data playback functions. The package is completely menu driven, some menus being accessible only from the local systems keyboard; for example those related to configuration of system operating parameters. Functions are also included to allow testing of the system off-line.

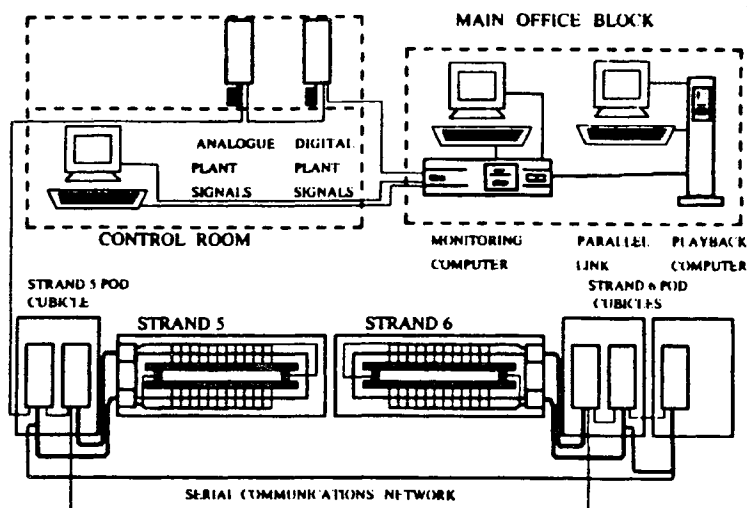


Figure 6.10 MTM system schematic.

System Configuration. The system configuration menu is password protected as the adjustable parameters fundamentally affect the system performance. These parameters include functions for data entry to define moulds and mould plates within the system and to update data for existing moulds and plates.

As new copper plates are prepared for mould thermal monitoring and existing plates are re-profiled to correct wear, the thickness of copper between the thermocouple tip and the hot face of the plate must be measured as this affects thermocouple sensitivity. A menu provides access to a series of functions for informing the system of which moulds and which plates within the mould are in use. In this way, the system can track the plates in use and all mould related information is passed to the main monitoring program by definition of a mould identity alone. The software adjusts alarm levels automatically to compensate for individual thermocouple sensitivity when detecting sticker breakouts and measuring thermal variability.

Several parameters are available to fine tune the sensitivity of sticker breakout detection and to define alarm conditions for MTM parameters for each mould plate. These parameters are arranged in carpet diagrams, several versions being available to allow optimisation, if necessary, for different steel grades or casting conditions. Changing of parameter sets can be made on-line. There is also a facility to adjust detection of start and end of cast via a comparison of mould cooling water outlet temperature and the mould thermocouple temperatures, if a digital in-cast mode signal is available.

Other configurable aspects include plant voltage conversion to engineering units, colours and display range defaults and definition of the variability assessment period. These assessment periods can be length based, for example one metre, or a constant time.

Operation. In operation the program scans the data acquisition system, logging the raw data every second and performing calculations. Indices to represent thermal variability for entire mould plates and regions of the broad plates are generated by calculating means and standard deviations for the thermocouple data every minute during logging. The raw data and calculated results are displayed in several formats.

Most thermal variability results are displayed as scrolling bar charts in 'maximum and minimum' format which update after each minute of data logging. The most recent data are to the right of the screen and the oldest to the left. For each assessed period of data logging and calculation, the greatest and least values of thermocouples variability for each broad plate are displayed. For uniform heat transfer across the width of the plate, these values should be similar and should be low. Figure 6.11 shows a typical display approximately 25 minutes after start of cast. Initial high

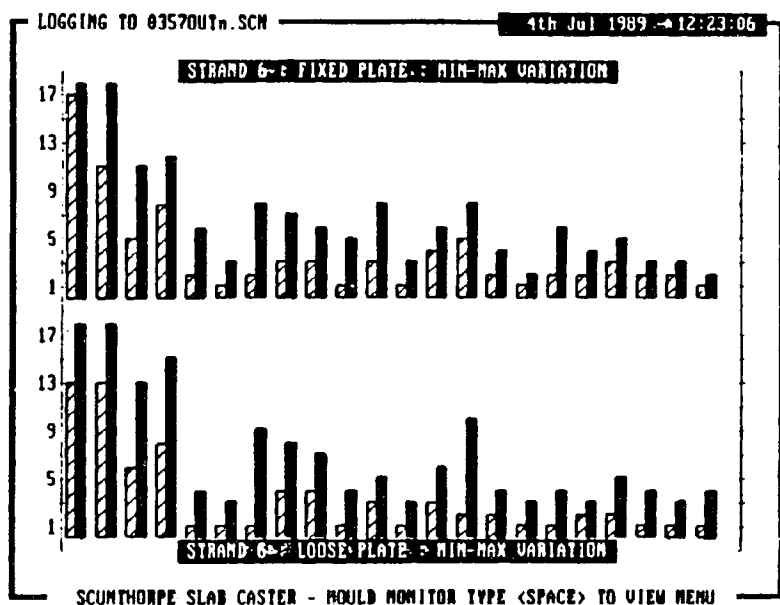


Figure 6.11 Bar chart temperature display.

variability during mould fill and strand start gradually falls away. Other displays of similar format detail end plate variability and symmetry.

A high resolution graphics screen is provided to view the temperatures recorded by the thermocouples and selected plant signals as traces over a selectable time-base. This provides a means of quickly examining thermocouple behaviour to aid detection of damaged thermocouples and to check the characteristic pattern in the event of a sticker breakout alarm.

Other screen displays are available which show actual temperature values, plant casting signals, average mould heat transfer and general system diagnostics information.

For each sequence monitored, the data scanned each second are logged to files on the computer's hard disk. In addition, the results of the calculations of means and standard deviation and variability indices are recorded. Files to describe start of cast and the system performance are also generated.

The effect of carbon content on heat transfer in the mould was discussed in Section 3.1.2.3 when it was demonstrated that the mould heat transfer was much more erratic at levels of around 0.1%. Figure 6.12 shows the difference between the thermal variability indices for both 0.16% and 0.10% carbon levels respectively as shown by the mould thermal monitoring equipment.

Prevention of Sticker Breakouts. A sticker breakout is caused by the breakdown of lubrication in the mould with a consequent rupture of the solidifying shell near the meniscus. A further very important function of

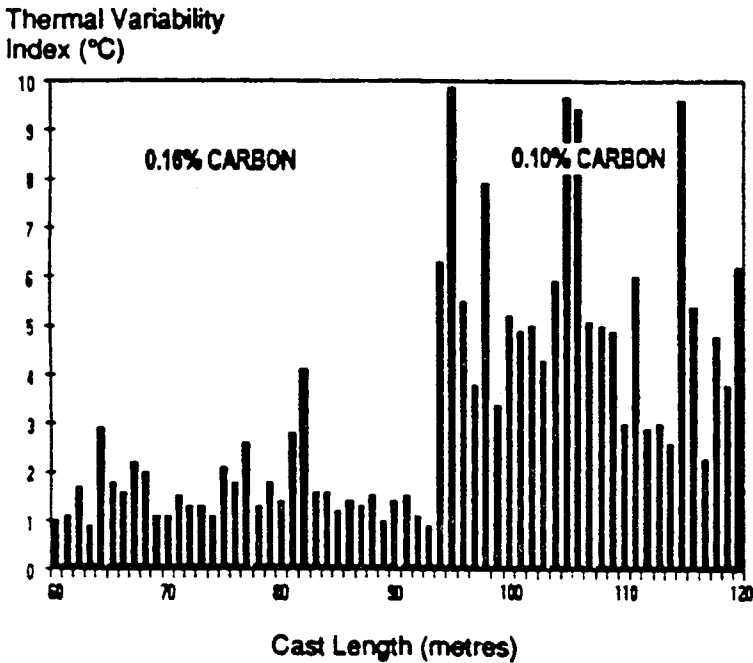


Figure 6.12 Thermal variability index for 0.16% and 0.10% carbon steels.

the MTM system is to detect the onset of such a situation and give a warning so that the operator may intervene to avoid the propagation of the ruptured shell. This is done by stopping the strand and allowing the casting speed to be again built up slowly to enable the ruptured skin to heal by further solidification. On some plants this corrective action is carried out automatically and indeed some systems avoid complete strand stoppage and merely reduce the speed to a low level.

The initial rupture of the shell near the meniscus occurs due to the thin shell above sticking to the mould when lubrication is not adequate. The shell which sticks to the mould wall continues to gain in thickness while the thin shell at the ruptured position partially resolidifies but continues to rupture and this propagates down the mould. The thickening shell at the top of the mould causes a rapid reduction in temperature at the position of the higher thermocouple while the thin part of the shell, which remains thin due to continual rupturing and resolidification, causes the lower thermocouple temperature reading to increase. The temperatures from the two thermocouples consequently cross and when this occurs an alarm is activated and the corrective action applied either manually or automatically. Figure 6.13 shows a schematic diagram of the mechanisms described above and also indicates how the thermocouple temperature

patterns are used to detect the event. The algorithms employed in the software, however, need to be more complex than this because crossovers of the nature described are relatively frequent and do not always correspond to sticking. It is important that such false alarms are not issued in such cases as unnecessary interruptions to the casting operations are undesirable.

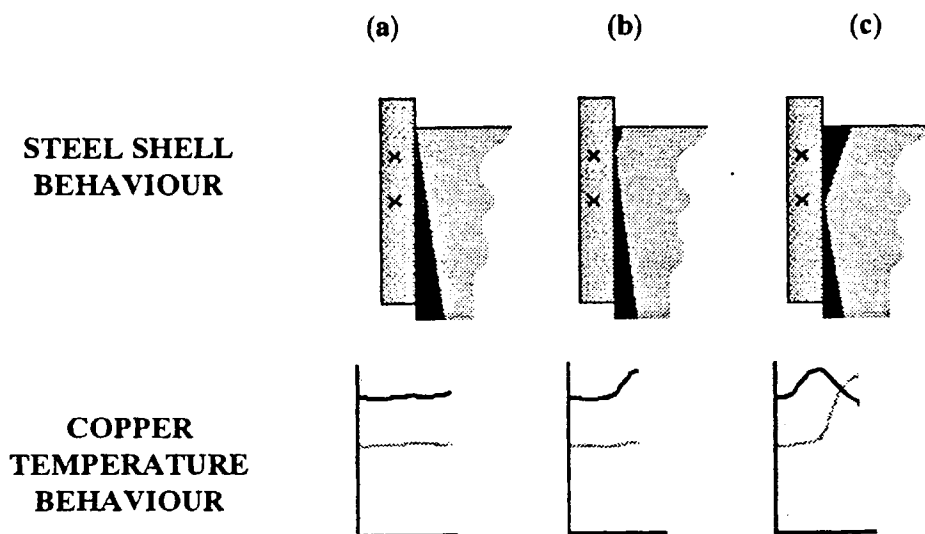


Figure 6.13 Sticker breakouts – mechanisms and detection.

The events as illustrated in Figure 6.13 are as follows:

- (a) During normal casting, shell thickness increases down the length of the mould to the mould exit. For several possible reasons, the shell can stick to the copper plate at the meniscus.
- (b) The shell below the stuck portion is torn on each successive oscillation cycle and a thin region propagates down the length of the mould. The upper thermocouple temperature rises as the thin area passes its position.
- (c) The thin region continues down the mould and approaches the position of the lower thermocouple. This temperature starts to rise. During this time the steel shell above the tear continues to thicken because of continuing crystallisation from the stuck position. As a result the temperature of the upper thermocouple falls. An alarm is sounded on recognition of this behaviour thus facilitating prevention of the otherwise inevitable breakout.

6.2.4 Mould Oscillation Monitoring

In Section 3.1.1.3. it was emphasised that movements of the mould in the directions other than the direction of casting must be less than 0.2 mm. Additionally the quality of the sinusoidal waveform needs to be accurately maintained. Deviations in both lateral movements and the quality of the waveform can occur due to wear or deterioration of the oscillating equipment and therefore many plants install on-line monitoring equipment to continuously check the oscillation performance. On-line measurements are required because the true performance can only be determined when the machine is under load (mechanical and thermal).

Figure 6.14 shows the principles of an on-line mould oscillation monitoring system which continuously displays appropriate data. The information from such a system can be used for a quality prediction system (see Section 6.4.2).

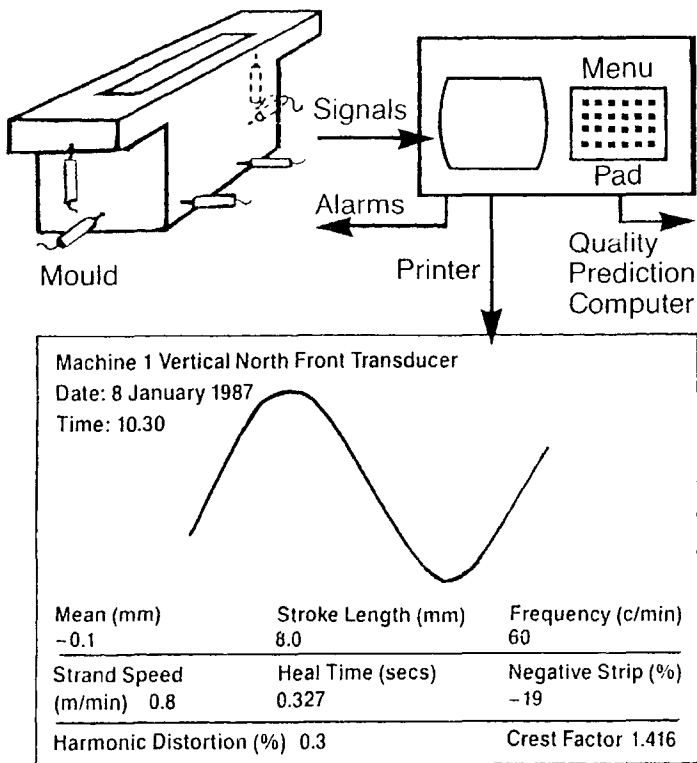


Figure 6.14 Mould oscillation monitoring equipment and displays.¹⁰

6.2.5 Spray Water Monitoring

Poor spray distribution cannot be directly measured during casting. Mis-aligned spray nozzles can be detected by visual inspection between casts or by the special equipment monitor described later (Section 6.3.2) Nozzle blockages or loose hoses, however, can invariably be detected by accurate on-line monitoring of the pressure and flow rate of each spray header¹⁰. Since flow rate is controlled the changes in pressure indicate leakage or blockage. If the pressure during casting increases then nozzle blockage is occurring. If, however, pressure decreases then this would indicate leakage. A large decrease could mean a connecting hose had burst or become disconnected.

6.3 Off-Line Measuring Systems

Many important engineering parameters cannot be measured during casting. These are:

- Mould geometry
- Strand support geometry
- The distribution of spray water

Equipment developed to carry out comprehensive measurements of these parameters during maintenance periods or between casts will be described.

6.3.1 Mould Geometry Measurements

Special equipment using transducers are used to rapidly measure mould geometry, the main measurements being the mould internal dimensions down the length of the mould. Such measurements indicate the degree of mould wear. Additionally equipment has been developed to rapidly measure end plate taper. For billets and blooms the taper of all four mould faces are measured.

6.3.2 Strand Condition and Spray Water Distribution Monitoring

Sophisticated equipment has been developed, and used regularly for many years,^{10,11} to comprehensively check the mechanical state of all the strand support equipment and which also is capable of measuring the spray water distribution. Such measurements are made by the use of equipment the same size and shape as a dummy bar head. This equipment

contains a variety of measuring devices and at the end of casting the dummy bar head is replaced with this unit which is then driven up the strand (or down in the case of a top fed dummy bar) and then withdrawn down the strand. A range of measurements are made and recorded on a small data logging unit which is installed in the instrumented head. When the unit is completely withdrawn the data can then be transferred to a dedicated computer/data logging system which can display the data and information in a form which is readily understood, and acted on, by the maintenance engineers.

6.3.2.1 Measuring Head

Figure 6.15 shows a diagram of such a unit. The quick release chain link enables the normal dummy bar head to be quickly replaced by the strand condition monitoring unit. The typical measuring functions of this equipment are

- **Roll Gap Measurement.** 5 pairs of transducers to enable measurement of the roll gaps at 5 positions along the roll length.
- **Roll Bend.** 2 additional pairs of roll gap transducers located in line with the central gap transducers.
- **Roll Rotation Monitors.** Two sensors to identify seized rollers
- **Backface Alignment.** Inclinometers located on each end of the measuring head to measure the angle of inclination between adjacent rollers

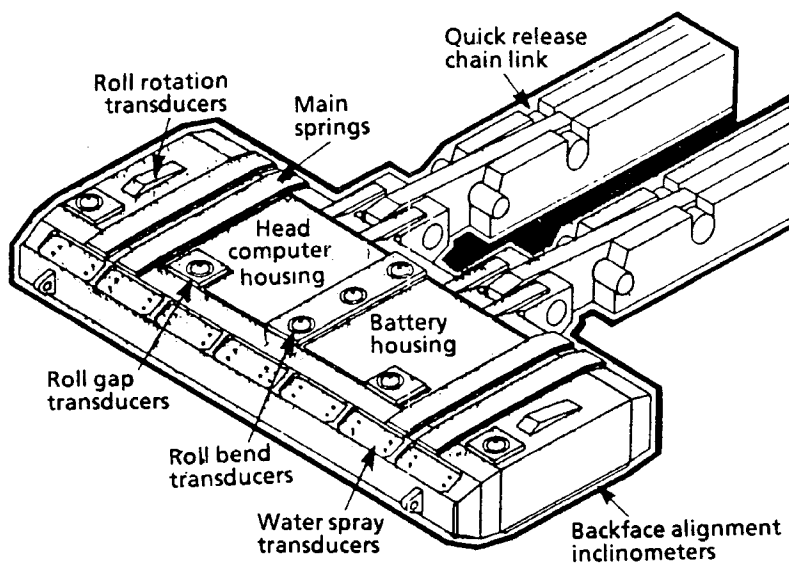


Figure 6.15 Automatic strand condition monitor for slab casting machines.

- **Water Spray Monitors.** 12 sensors are mounted on each side of the 'nose' of the measuring head. These are suitable for quick routine assessment of either water or air/mist distribution.

The number of measuring transducers can vary according to the specific size and design of any particular machine.

6.3.2.2 Computer Hardware

There are 3 computers associated with this measuring facility. These are:

- **In-Head Computer.** The in-head computer (see Figure 6.15) is situated in the measuring head and is battery powered. This computer collects and stores the data during each run through the casting machine. The computer enclosure is fully sealed and pressure tested to ensure reliable operation in the caster.
- **Portable Computer.** Battery powered and used for calibration of the head and for data transfer between the in-head and main computer.
- **Main Computer.** The main computer is typically an IBM PS2 or equivalent. The measured data can be displayed on a VDU and transmitted to a printer for a hard copy.

6.3.2.3 Computer Software

- **In-head Computer.** The computer is switched on by remote control when the measuring head has been driven up to just below the mould. The software will enable the in-head computer to: identify roll numbers; measure and record the outputs of all sensors as the head travels through the caster.
- **Portable Computer.** Communicates with the in-head and main computers to: calibrate the sensors; collect and verify data; download to main computer.
- **Main Computer.** This computer formats and displays data in tabular or graphical form on VDU or printer for hard copy.

The above equipment was developed by British Steel Technical and a licence for supply was obtained by Sarclad International. Other systems fulfilling similar functions have also been developed.

6.4 Quality Control Systems

Quality control for surface defects is largely carried out on the cold semis by visual inspection which can be:

- (a) on the as-cast surface
- (b) after proof scarfing
- (c) after full face scarfing

The extent of each type of defect is quantified by a grading system which could, for example, be from 1 to 5 the defect incidence being worse as the grading number increases.

Internal quality is assessed by cutting a small slice from each strand for each ladle and then sulphur printing or microetching the machined and polished surface of the cross-section. Again the severity of each defect is graded by a numerical system.

As the need to increase the amount of continuously cast semis, which can be hot charged or directly rolled, has prevailed over recent years much effort has been directed at quantitatively inspecting the surface of the as-cast semi in-line and whilst still hot. Another approach is to monitor the casting process in detail and using the vast amount of information available relating defects to compositional, operational and engineering parameters (as described in Chapter 4) and then predict whether the surface quality will be adequate for hot charging and further processing without surface rectification. Each of these approaches will be discussed separately.

6.4.1 On-Line Hot Surface Inspection

Considerable effort worldwide over the past decade has been directed to the development of various systems for the inspection of the surfaces of hot as-cast products and many inspection systems have been installed on production plants.¹²

The various systems can be categorised according to the physical techniques used and Figure 6.16 illustrates these various categories.¹³

Such systems should be capable of the following:-

- flaw detection at temperatures $> 900^{\circ}\text{C}$
- detection of defects $> 1.0\text{ mm}$ deep and 20 mm long
- Ability to detect and mark the defect location
- Indicate defect type
- Flaw detection at roller table speeds up to 90 m/min

In order to avoid spurious readings, the surface of the continuously cast material has to be descaled up stream for most types of defect detection.

The optical system is probably the most widely used system and Figure 6.17 shows a particular optical system¹⁴ whereby the slab is illuminated with a mercury lamp at a particular angle and the reflected light is viewed

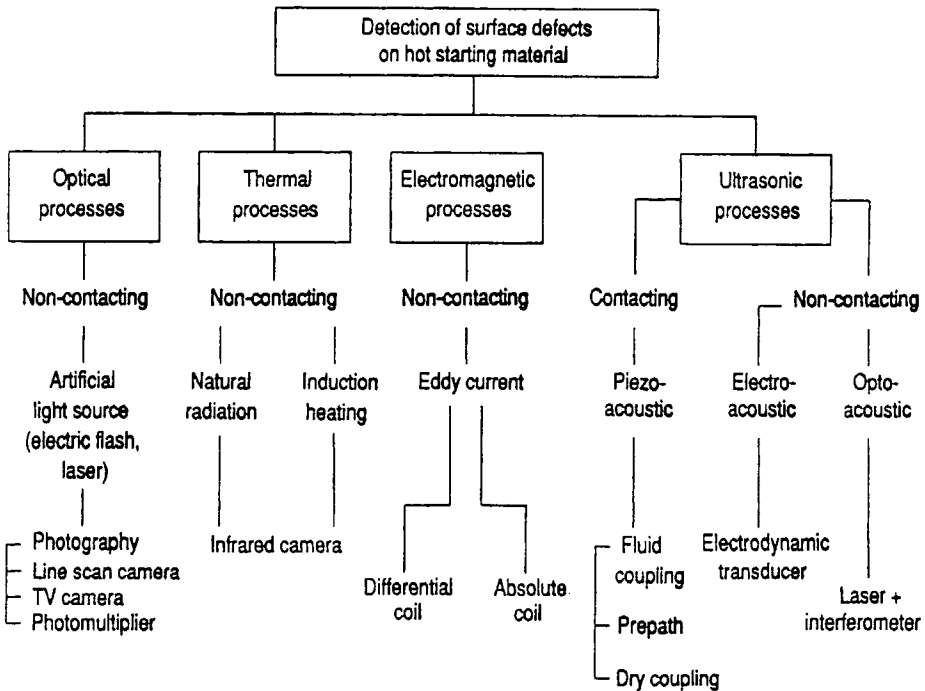


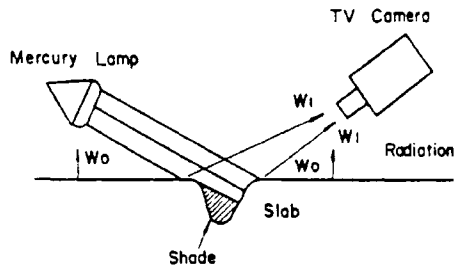
Figure 6.16 Hot surface inspection methods.

by a TV camera. Figure 6.17(a) illustrates the principle of how a surface defect will appear as a shadow on the TV screen.

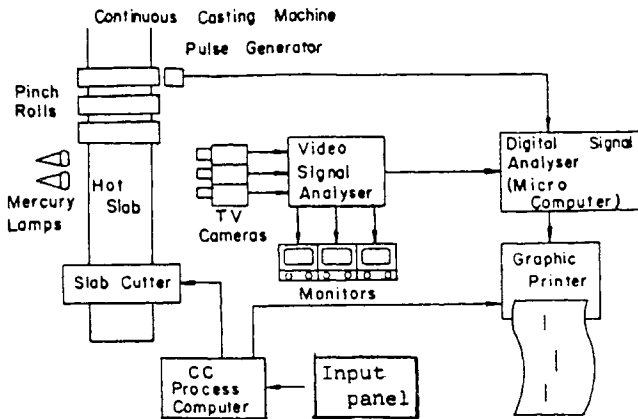
The comprehensive inspection of the surface for all types and sizes of defects, however, would require a range of systems. Any one system can only deal with specific types of defects and invariably can only detect the more gross examples. For example, eddy current equipment for the detection of transverse corner cracks can only reliably detect cracks greater than a certain length and depth. Finer cracks could be detected by using smaller heads but then the area of inspection becomes limited. Similarly optical systems using rapid image processing techniques can only recognise cracks above a particular size. Many small defects, some of which are sub-surface, would be extremely difficult to detect with any equipment.

The comprehensive inspection of all types and sizes of undesirable defects, therefore, would need a range of technically complex and expensive systems and which would require considerable maintenance to achieve an acceptable availability and performance. Even so, many defects such as slag spots and pinholes would remain undetectable.

The possibility of having systems to comprehensively inspect the internal quality of the as-cast material is even more difficult.



(a)



(b)

Figure 6.17 TV inspection system for hot slabs showing (a) the principle of detecting the reflected image of a defect and (b) a schematic diagram of the inspection system.

6.4.2 On-Line Quality Prediction Systems

Due to the difficulties in the direct detection of as-cast defects much effort has been directed to the development of on-line predictive grading systems. Predictive on-line quality control systems have been described^{15,16} and these attempt to assimilate all the relevant factors, including specially monitored parameters by incorporating these into a central computer system.

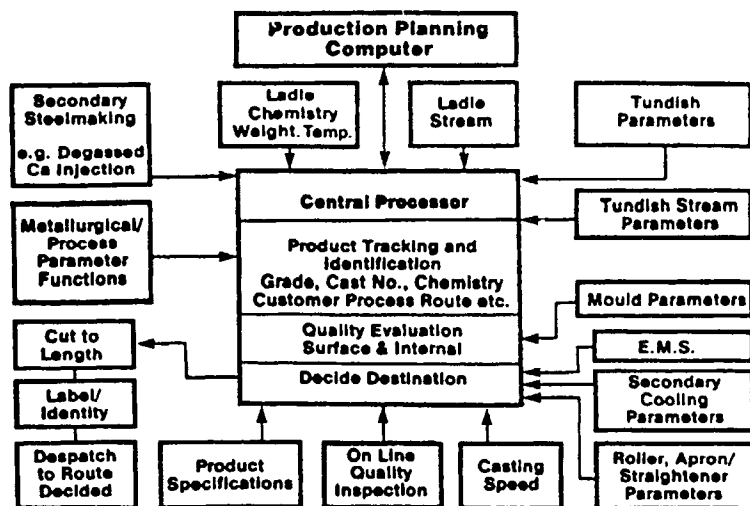


Figure 6.18 Schematic diagram of quality prediction system.

Figure 6.18 shows a schematic diagram of what is required of a comprehensive on-line predictive quality control system.

The software and logic of such a system would rely heavily on the type of data and relationships which were described in some detail in Chapter 4 and that arising from the on-line and off-line monitoring systems described in Sections 6.2 and 6.3. The mould thermal monitoring information is fundamental to surface quality and therefore is an invaluable input to on-line predictive grading.

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SUMMARY

Over the last quarter of a century the method of converting liquid steel to the solid state has changed dramatically. The traditional method was to teem steel into individual ingot moulds and then reheat the resulting ingots in soaking pits prior to rolling them on a primary mill to various semi products such as billets, blooms and slabs. This short monograph describes the development of the continuous casting process which is now used to cast over 80% of the western world's steel production directly and continuously to these semi-finished products. In 1970 the corresponding amount was 5%. This alternate method has many advantages, the most important being improved yield, reduced energy consumption and a reduction in manpower, thus reducing production costs significantly. The process also produces improved and more consistent steel quality. This book is intended to provide a detailed account of how continuous casting technology has developed over the years and give details of plant component design, solidification control and metallurgical quality of the as-cast semi-finished products. The emergence of more advanced technology to further reduce process costs is also described.

Chapter 1 gives the historical background to the continuous casting of steel and describes some of the more important developments of the process over the last 25 years and provides in general terms a brief description of the principles and details of a continuous casting plant. The evolution of machine design is also discussed and the benefits in terms of improved yield and reduced energy consumptions are detailed.

Chapter 2 is concerned with the liquid steel supply to the continuous casting machine. Control of steel composition and temperatures to within tight limits is essential whilst the ladles containing the liquid steel must arrive at the caster at the correct time. Brief examples are given of the secondary steelmaking process routes to achieve specified chemistries whilst on-line control systems to predict liquid steel temperature during the process routes are described. The methods of pouring the liquid steel from ladle to tundish and tundish to mould are also outlined.

Chapter 3 gives details of the various machine components such as the mould, the strand support systems, secondary cooling, strand straightening and strand withdrawal. Several fundamental details of the process are described in each case and the control of the solidification process by acquiring knowledge of the heat transfer data during each stage of the process is discussed fairly extensively. Consideration is also given to roller design and performance. The final part of this chapter is concerned with

mathematical models which have been developed to enable rapid and accurate simulation of the process. The major models described are the solidification model and models to estimate strand deformation and to calculate roller temperatures and deflections.

Chapter 4 is dedicated entirely to the quality of the as-cast semi product and separately describes surface and internal defects. The effect of various chemical, process and engineering parameters on the various types of surface and internal defects are discussed at some length. The role of electromagnetic stirring of the liquid pool within the strand on product quality is also described.

Chapter 5 deals with special processes and emerging technologies in continuous casting. The special processes described are horizontal casting and the casting of beam blanks for section products. Also included is a brief summary of the world wide research on emerging technologies on thin slab and strip casting which has assumed the terminology of 'Near Net Shape Casting' since it produces a cast section which is nearer the final product dimensions thus giving the potential for fewer processing steps and hence reduced costs.

The final section, Chapter 6, concentrates on process control and process monitoring. Closed loop control systems described include liquid steel level control in the tundish, mould metal level control, automatic start-up and the control of the secondary water spray cooling. On-line monitoring systems included are slag detection, mould thermal monitoring, mould oscillation monitoring and spray water monitoring. The important ancillary equipment to comprehensively measure the strand support geometry is also described in some detail. The final part of this chapter discusses quality control and, in particular, on-line hot surface inspection and on-line quality prediction systems

The author hopes that this overview of this relatively new steelmaking process will be of benefit to students who are studying appropriate engineering and science courses and give them an insight into this casting technology and how this has progressed rapidly over the last 25 years. Similarly it should be of benefit to production, engineering and technical personnel already working in the steel industry.

Inevitably, with such a wide scope of technology to cover, there will be particular items omitted or not discussed in sufficient detail and the author is aware that improvements could be made. Other specialists in this field are welcome to submit any suggestions, modifications or additional subject matter which could be included should any further edition be issued.

INDEX

Index Terms

Links

A

Air ingress	33	34	
Air gap formation	8	49	50
Air mist cooling	63	66	67
Argon Shrouding	33	48	
Argon Stirring	24	26	28
Automation	177		
mould metal level	179	182	
on-line predictive grading	201		
powder feeding	186		
secondary cooling	182		
start of casting	185		
tundish metal level	179		

B

Basic oxygen steelmaking (BOS)	13	16	24	
Beam blanks	156	162		
Bending	3	13	15	76
multi point	78			
Billet and/or bloom casting	2	10	15	35
	38	48	50	59
	130	149		
Breakout	13	41	114	193
	194			

<u>Index Terms</u>	<u>Links</u>			
Break ring	158	160		
Bulging	8	59	68	82
	142	144		
C				
Calcium				
aluminates	28			
sulphides	28			
treatment	26	27		
Carbon	23	24		
effect on heat transfer	53	54	97	
effect on internal cracks	124	139		
effect on longitudinal facial cracks	97			
Casting powders	53	95	97	108
affect on heat transfer	53	107		
affect on longitudinal facial cracks	95	97		
Central porosity	121	127	129	
Centreline segregation				
macrosegregation	126	129	144	
semi-macrosegregation (or 'V' segregation)	128	129	135	
Chemical composition	22	95	96	
aluminium	34	98	99	
carbon	23	24	52	54
	97	102	117	124
	131	135	139	193
manganese/sulphur ratio	101	102	119	139
niobium	98	99		
phosphorus	23	100		
silicon	23			

Index Terms

Links

Chemical composition (*Cont.*)

sulphur	23	24	25	34
---------	----	----	----	----

	100	101	102	
--	-----	-----	-----	--

vanadium	99			
----------	----	--	--	--

Cleanness	23	26	30	
-----------	----	----	----	--

Columnar structure	121	124		
--------------------	-----	-----	--	--

Cracks

centerline	121	144		
------------	-----	-----	--	--

intercolumnar (or interdendritic)	121	139	142	
-----------------------------------	-----	-----	-----	--

longitudinal corner	95	151		
---------------------	----	-----	--	--

longitudinal facial	95	97	101	103
---------------------	----	----	-----	-----

	104	111	119	150
--	-----	-----	-----	-----

star	95			
------	----	--	--	--

transverse corner	95	99		
-------------------	----	----	--	--

transverse facial	95	99	105	
-------------------	----	----	-----	--

triple point	121			
--------------	-----	--	--	--

D

Definitions

beam blanks	162			
-------------	-----	--	--	--

billet	2			
--------	---	--	--	--

bloom	2			
-------	---	--	--	--

cast strip	169			
------------	-----	--	--	--

slab	2			
------	---	--	--	--

thin slab	165			
-----------	-----	--	--	--

Dendritic structure (*see* columnar structure)

Deoxidation	24	25	26	33
-------------	----	----	----	----

Diagonal cracks	151			
-----------------	-----	--	--	--

Index Terms

Links

Direct charging (*see* hot changing)

Dual spray system

67

Dummy bar

11

12

197

E

Electromagnetic brake (EMBR)

137

138

Electromagnetic stirring (EMS)

129

 billets and blooms

130

 horizontal casting

161

162

 slabs

134

Energy

19

20

44

Equiaxed structure

121

135

136

Evolution of machine design

13

14

15

F

Ferrostatic pressure

8

58

69

Foot rolls

58

151

Free cutting steels

24

G

Grain refined steels

98

99

119

H

Hazelett process

157

166

168

Heal time (negative strip)

3

7

41

44

49

112

113

195

Heat transfer

 convective

62

 mould

7

44

Index Terms

Links

Heat transfer (*Cont.*)

radiative	62			
secondary cooling	8	63		
support rolls	69	70		
Horizontal casting	15	156	158	
Hot charging	20	167		
Hydrogen	24	32		
Hydrogen-induced cracking (HIC)	137			

I

Ingot casting	1	18	19	20
In-line rolling	167			
Inclusions	26	27	28	48
	95	96	103	121
	129	136	137	138
Internal cracks	121	139	151	

L

Ladle	9	10	28	32
car	9	10		
changing	10			
furnace	23	24	28	29
turret	9	10		
Liquid core length	17	81		
Liquidus temperature	81	122	136	
Longitudinal facial cracks	96	97	101	103
	104	119		
Longitudinal corner cracks	95	151		

Index Terms

Links

M

Mini-ingot formation	127			
Mould				
construction	38			
cooling	8			
copper	8	40	41	
design	37	38		
friction	13	78	160	
geometry	196			
heat transfer	7	37	44	
length	40			
lives	39			
maintenance	39			
materials	40	41	160	
metal level control	35	105		
multi stage	58			
oscillation	40	41	42	48
	112			
oscillation monitoring	195			
powders	48	53	91	95
	97	107		
plating	40			
thermal monitoring	188			
taper	43	44	49	
tubular	38			
twin/triple	17	44		
variable width	16	43	44	
Multi-nozzle system	66			
Multi-roll drive	77	78		

Index Terms

Links

N

Negative strip (or heal time)	3	7	41	44
	112	113	195	
Nitrogen	23	25	35	98
	99			
Nitrogen pick-up	25	33		
Nozzle clogging	28	34		
Nozzles				
metering	33	35	48	182
spray	8	60	63	
submerged entry	11	22	31	34
	44	47	48	

O

Oscillation	40	41	42	48
	112			
Oscillation marks	114			
Ovality	150			
Oxygen	26			

P

Partition coefficients	140			
Pinch roll unit	77			
Pinholes	104	105	107	134
Plate mould	38	40		
Pouring stream shrouding	9	10	32	
Process control computer system	178			
Production rate	16	17	44	

Index Terms

Links

R

Rape seed oil	7	107	109	
Reduction in area	98	99		
Refractory materials	21	24	27	32
	34			
Reoxidation	27	28	33	34
	103			
Rhomboidity	150			
Roll				
alignment	85	86	141	
cooling	69	70		
designs	68	69	88	89
friction	78			
gap measuring device	142	197	198	
material	71			
measurements	197			
Permanent bending	69	90		
Rotation transducers	197			
split (or divided)	61			
wear	72			

S

Secondary cooling				
air mist	63	67		
design	65			
heat flux	65			
impact density	64			
multi-nozzle	66	148		
single nozzle	66	148		
spray nozzles	8	63		

<u>Index Terms</u>	<u>Links</u>			
Secondary cooling (<i>Cont.</i>)				
twin nozzle	66	148		
water only	63	66		
Segregation				
centerline macrosegregation	129	140	144	
intercolumnar (or interdendritic)				
macrosegregation	140	142	143	
microsegregation	129			
negative segregation (or white				
bands)	132	133		
V segregation (or spot segregation)	128	135	140	144
Sequence casting	10	22		
Shape defect	150	151		
Sheet	135			
Shrinkage cavity	121	127	129	
Shrouding	9	10	11	32
tube	9	32	33	
gas	11	35		
Slag detection	186	187		
Slag spots	104	105	106	
Sliding gates	9	32	33	
Slitting	17			
Soft reduction	127	129	137	144
	147			
Solidification	11			
columnar (or dendritic) structure	121	125	127	128
equiaxed structure	121	135	136	
solidification constant	16			
solidification model	16	18	80	184
solidification rate	16	80	81	

Index Terms

Links

Spray Cooling (*see* secondary cooling)

Star cracks 96

Starting chain (*see* dummy bar)

Stirring systems (*see* electromagnetic stirring)

Stopper rod 10

Strand

friction 78

guide section 58 59

machine cooling water 63

maintenance 61

secondary cooling 8 62

straightening 11 13 14 72

support grids, plates 59

support, slab strands 59 60 61

taper 127 129 137 144

145

walking beam supports 59

with air mist 63 67

withdrawal force 79

withdrawal 77

Straightening 11 13 14 72

continuous 75

multi point 13 75 76

single point 13 75 76

strains/strain rates 73

Strains

bulging 82

misalignment 82

straightening 73 87

Index Terms

Links

Strip casting	156	169		
Stroke length	112	113		
Submerged entry nozzle (SEN)	11	22	31	33
	34	44	47	48
Sulphur	23	24	25	34
	100	101	103	
Superheat	121	122	125	133
	136			
Support rolls	8	58	68	87
Surface defects	95			

T

Taper				
mould	43	44	49	196
strand	127	129	137	144
	145			
Temperature control				
ladle	28			
surface	100	120	182	
tundish	28			
Thin slabs	156	165		
Torch cutting	11	18		
Transverse cracks	98	99	105	119
Tubular moulds	38			
Tundish	10	30		
bath level	35	179		
changing on-the-fly	10			
flow control	33	34	179	180
flow patterns in tundish	31			
influence on cleanness	30	31		

Index Terms

Links

Tundish (*Cont.*)

metering nozzles	35	182		
refractory lining	32			
size	30			
sliding gates	33	35		
stopper rods	10	31	33	34
	35			
weirs and dams	30			

Twin and Triple casting	17	44		
-------------------------	----	----	--	--

V

Vacuum degassing	23	24	25	26
	28			
V-segregation (or spot segregation)	128	135	144	
Variable width mould	16	43	44	

W

Walking beams	59			
---------------	----	--	--	--

Water

cooling channels	37	38	50	51
impact density	64			
machine	63			
mould cooling	37	50	52	
roll cooling	63	68	88	
secondary cooling	62			
sprays nozzles	8	62	148	
velocity	37	38		
water quality	37			

Wide flange beams	162			
-------------------	-----	--	--	--

<u>Index Terms</u>	<u>Links</u>			
Withdrawal rolls	9	11	77	78
Withdrawal forces	79			
Y				
Yield	19	44		