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The Continuous Casting of Stainless Steels

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The continuous casting of stainless steels is now an established technology, although newer processes like thin-strip casting and horizontal casting are the harbingers of an emerging era. This review examines the various aspects of the continuous casting of stainless steels. The different processes employed to manufacture stainless-steel billets, blooms, slabs, and strip are described. Fundamental knowledge pertaining to the casting of stainless steels is examined to provide a basic understanding of the important events that occur during the process. Quality problems in the cast products are discussed in terms of the mechanisms and operating design parameters that influence them.

Introduction

Stainless steel has been continuously cast for more than four decades[1]. The first major installation in North America for the continuous casting of stainless-steel slabs was established in the early 1950's at Atlas Steel in Canada[1]. Over the years, the continuous-casting process for the production of steel billets, blooms, and slabs has emerged as one of the most important technologies in the steel industry worldwide[2], particularly in the stainless-steel sector. A revolutionary development in refining in the 1970's, namely the invention of the AOD, followed by the development of similar novel processes such as the VOD, paved the way for the production of high-quality stainless steel at reduced cost. Stainless steel is now manufactured by the process route shown in Figure 1, where, following melting in an electric furnace, the molten steel is refined in an AOD or VOD furnace and then stirred to homogenize the temperature before continuous casting[3–7].

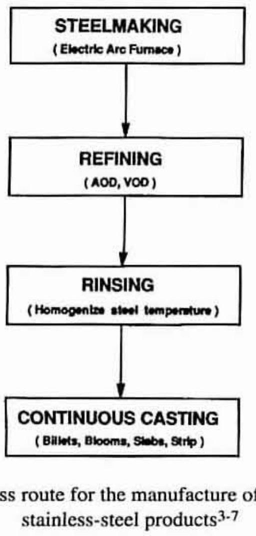

FIGURE 1. Process route for the manufacture of continuously cast stainless-steel products[3-7]

The different grades of stainless steel that are continuously cast can be classified in terms of their microstructure as ferritic, martensitic, and austenitic[3, 8–11]; these can be represented on a Schaeffler diagram[3], Figure 2. As shown in Table I[12], the stainless-steel family covers a wide range of alloy content, which makes its processing more complex than that of plain carbon grades[3,13]. The chemical reactivity, physical properties, and solidification modes differ widely for the various grades of stainless steels. Although stainless steels have been continuously cast for about four decades, the semifinished products are not entirely free from defects. Problems with respect to cleanliness, the depth and uniformity of oscillation marks, segregation and centreline porosity, surface and internal cracks, and shape defects, such as longitudinal and transverse depressions, continue to plague the industry. Although considerable progress has been made in improving the quality of semifinished sections through technological developments such as new tundish designs, and EMS in the mould and sub-mould regions, to name a few, the goal of producing defect-free products on a consistent basis has not been fully realized.

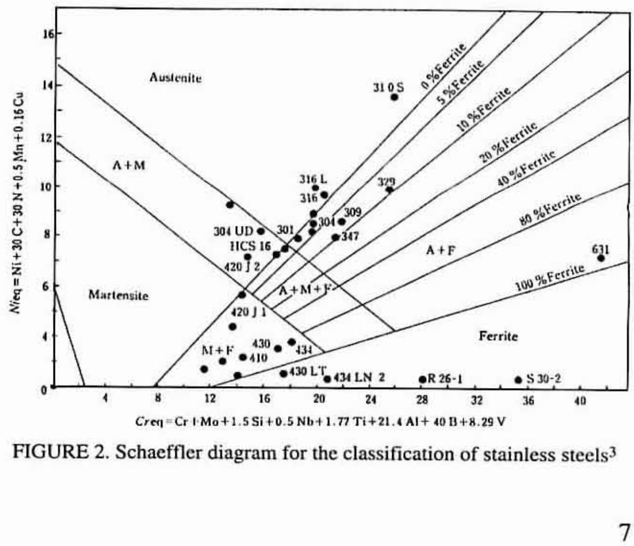

FIGURE 2. Schaeffler diagram for the classification of stainless steels[3]

TABLE I
CHEMICAL COMPOSITION OF STAINLESS STEELS[12]

Grade	Type	Composition, %				
		C	Mn	Si	Cr	Ni
Austenitic	201	0,15	5,5–7,5	1,0	16,0–18,0	3,5–5,5
	202	0,15	7,5–10,0	1,0	17,0–19,0	4,0–6,0
	304	0,08	2,0	1,0	18,0–20,0	8,0–10,5
	309	0,20	2,0	1,0	22,0–24,0	12,0–15,0
	316	0,08	2,0	1,0	16,0–18,0	10,0–14,0
Ferritic	405	0,08	1,0	1,0	11,5–14,5	
	409	0,08	1,0	1,0	10,5–11,7	0,50
	430	0,12	1,0	1,0	16,0–18,0	
Martensitic	403	0,15	1,0	0,5	11,5–13,0	
	410	0,15	1,0	1,0	11,5–13,5	
	420	0,15	1,0	1,0	12,0–14,0	
	431	0,20	1,0	1,0	15,0–17,0	1,25–2,50

Tables II to IV provide a summary of conventional and horizontal casters that process stainless steel and alloy steels in North America[14,15], Japan[15], and Europe[15], respectively. The advent of horizontal casting and strip casting marks the beginning of a period of unprecedented change with respect to the production of continuously cast semi-finished sections. These developments, which are being driven by the need to significantly reduce costs without compromising quality, will continue well into the next century and have heralded a new era in continuous casting. The horizontal continuous-casting process has been adopted extensively for the production of stainless-steel billets, as is evident from Tables II to IV. The direct coupling of the tundish to the mould, and the elimination of strand bending and unbending, make the horizontal-casting process particularly attractive for stainless steels containing reactive elements, and also for crack-susceptible grades. The single-wheel casting process developed at Allegheny Ludlum for the production of stainless-steel strip is an impressive advance in continuous-casting technology[16–19]. Twin-roll processes for the casting of stainless-steel strip have also been piloted worldwide[20–23], and commercial production by these methods is likely within the next decade.

TABLE II
CONVENTIONAL AND HORIZONTAL CONTINUOUS CASTERS PRODUCING STAINLESS AND ALLOY STEELS IN NORTH AMERICA[14, 15]

Companies	Caster type	Ladle capacity t	Annual capacity kt	Product sizes mm	Steel grades
AI Tech Watervliet NY	Billet	32	40	115 sq	Stainless
Allegheny Ludlum Brackenridge, PA	Slab	125	500	205 x 660–1320	Stainless
Armco Inc. Baltimore MD	HCC billet	50	60	100 sq to 150 x 200	302, 303, 304, 305, 306, 316, 410, 430, Nirtonic 32
Butler PA	Slab	165	900	150 – 205 x 660 – 1320	Stainless
Atlas Steel, Tracy Quebec	Slab	70	100	125 x 1320 125 x 990	300 and 400 series
Welland Ontario	Bloom billet	70	N. A.	155 sq, 145 sq and 200 x 250	Stainless, alloy, and carbon
Carpenter Tech. Reading PA	Billet	35	N. A.	125 sq to 305 x 355	Stainless, alloy, and carbon
Eastern Stainless Baltimore MD	Slab	60	150	125 x 865 125 x 1270	Stainless
J & L Speciality Products Midland PA	Slab	125	420	125-255 x 610-1320	Stainless
Lukens Steels Coatesville PA	Slab	165	660	230 x 2160	Ni–Cr–Mo grades
Washington Steel Houston PA	Slab	55	200	140 x 675–1320	Stainless

TABLE III

CONVENTIONAL AND HORIZONTAL CONTINUOUS CASTERS PRODUCING STAINLESS AND ALLOY STEELS IN JAPAN[15]

Companies	Caster type	Ladle capacity t	Annual capacity kt	Product sizes mm	Steel grades
Aichi Steel	Billet	20	N. A.	135 sq 185 sq 185 x 320	Stainless
Kawasaki Steel Chiba Works Caster 1	Slab	N. A.	N. A.	200 x 800–1280	304, 310S,430, 410, R410DH, 420J1, 420J2, 631, HCS16, 409, RU09Sr
Caster 2	Slab	N. A.	410	200, 260 x 1300–1700	
Nippon Kokan Fukuyama	Slab	40	N. A.	50–120 sq 120–220 dia.	304, 316, 321, 347, 405, 329J1, NCF825
Keihin	Bloom Billet	50	N.A.	115–250 sq 170–330 dia	
Nisshin Steel Shunan Works	Billet	N. A.	360	155 x 1030	Stainless, alloy, and carbon
Sumitomo Steel	Slab	20	156	183–336 dia	304, 316, 321, 310, 347, UNS8800, S31803

TABLE IV

CONVENTIONAL AND HORIZONTAL CONTINUOUS CASTERS PRODUCING STAINLESS AND ALLOY STEELS IN EUROPE[15]

Companies	Caster type	Ladle capacity t	Annual capacity kt	Product sizes mm	Steel grades
Avesta AB Degerfors Sweden	Thin slab	65	400	80 x 1560–2080	304L, 304, 316, 316Ti, 410, super austenitic, duplex
Boschgott Hardsgutte Germany	HCC	N. A.	200	180–350 dia.	Stainless
Imphy SA France	Billet	30	N. A.	130–180 dia.	304L, 305, 316L
Krupp Stahl Siegen Germany	Billet	50	N. A.	135–200 sq and dia.	Ferritic, austenitic, duplex
Bochum Germany	Slab	N. A.	N. A.	220–126 x 865–1650	Stainless
Terni Steel Terni Italy	Slab	180	N. A.	160 x 720–1330	Ferritic, austenitic
Thyssen Krefeld Germany	Slab	75	264	150–280 x 800–1600	305, 309, 310, 309S, 316L, 317

This paper reviews the state-of-the-art in the production of stainless steels by continuous casting, with special attention to new developments and product quality. The solidification structure and high-temperature mechanical behaviour of a variety of stainless-steel grades are examined and linked to quality problems such as segregation and crack formation. The mechanisms involved in the formation of surface and internal cracks, as well as in longitudinal and transverse depressions, are also described; and the influence of machine design and operating parameters on these defects is delineated.

Continuous Casting Processes for Stainless Steels

Conventional Continuous Casting

The conventional continuous-casting process for billets, blooms, and slabs has been the subject of detailed analyses for the past three decades. The knowledge generated is based on the results of mathematical modelling, physical modelling, in-plant measurements, and laboratory experiments, and provides important linkages among quality problems and process (operating and design) parameters[2]. Details concerning optimization of the process parameters from the viewpoint of quality products are well documented in the literature[24–27]. Numerous new technologies are being evaluated in this area to further enhance the quality of continuously cast products.

Control of steel temperature during the casting operation is very critical because of its influence on the final product quality. For example, at the start and end of casting, as well as during ladle changes, the temperature of the molten steel falls and the removal of inclusions becomes difficult[8,28]. A low-frequency channel type of induction-heating system, shown in Figure 3, has been installed on a trial basis to help maintain steel temperature; its beneficial effect has been seen on the quality of slabs cast at the start and end of heats[8,28].

Inclusions smaller than about 80 μm cannot be removed easily in the tundish by flotation[29]. Therefore, ceramic foam filters are being evaluated for removing inclusions and for improving the cleanliness of steel[30,31]. The mechanism for removing inclusions with these filters is based on a simple screening action, which involves solid-state sintering[30,31]. The inclusions absorbed are Al_2MgO_4 spinels and oxides of Ca, Al, Si, Ti, and Mn[30,31]. However, the benefits of this technology have not been assessed completely; the filters are expensive to utilize and also tend to clog during the operation.

Another interesting development is the electromagnetic brake that has been employed to decelerate the molten streams issuing from the submerged nozzle. This reduces the severity of impingement of the liquid metal against the solidified shell formed at the narrow face of the mould, as well as the velocity of the molten metal following the impingement[8]. A beneficial effect on fluctuations in metal levels and on the internal quality of slabs (inclusions and pinholes) has been observed[8].

Horizontal Continuous Casting

Horizontal continuous casters have been utilized for the production of square and round billets. In this process, liquid steel flows from a ladle into a tundish, which is connected directly to a water-cooled copper mould via a refractory assembly, Figure 4[32]. The refractory joint, or breakring, is a critical component of the horizontal-casting machine. Numerous breakring materials have been tested to reveal that boron nitride is preferable to alumina, while sialon material has also been tried successfully[33]. The fit of the boron nitride breakring inside the copper mould must be sufficiently tight to prevent the penetration of liquid metal and also to minimize any ring motion during the casting process[34].

The mould is stationary while the strand is withdrawn intermittently, through a sequential pull–push–pause motion, to prevent sticking of the solid shell to the mould[32]. In another design, the mould–tundish assembly is oscillated and the strand is withdrawn continuously, in a way very similar to the conventional casting process[32,35]. This technique has been tried successfully for low-alloy steels and austenitic stainless steels, and also for crack-sensitive and segregation-prone alloys such as ferritic stainless grades, Cr–Ni valve steels, and others[35]. The frictional force between the mould and the solid shell of stainless steel is larger than in the casting of plain carbon steel[34]. Thus, the casting of stainless steels is difficult without lubrication, and has led to the development of a self-lubricating mould coated with nickel-containing dispersed solid lubricant (e.g. polycarbon monofluoride); then stainless steels have been cast smoothly[34].

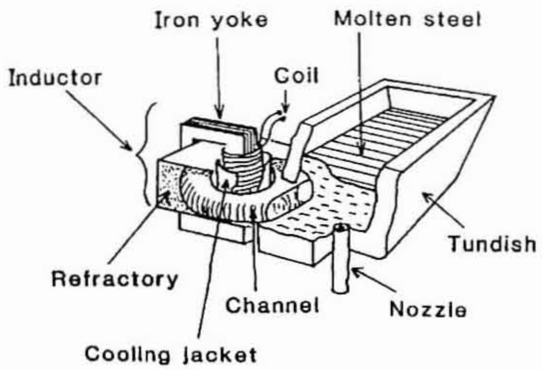

FIGURE 3. Schematic sketch of a channel type of induction-heating system[28]

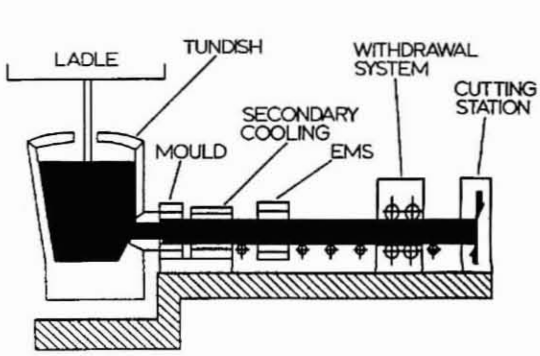

FIGURE 4. Schematic diagram of a horizontal continuous-casting machine[32]

The horizontal-casting process offers numerous advantages over the conventional casting process. The direct, air-tight mould–tundish connection is important in the continuous casting of stainless steels because it prevents the oxidation of reactive elements such as Ti or Al[36–41]. In addition, mould flux is not required and the entrapment of mould slag is therefore eliminated. In horizontal-casting machines, the strand is not subjected to bending and unbending[35,37–39], so that cracking problems related to these events are eliminated. Machine designers claim that the cost of installation of horizontal casters is lower than that of conventional machines owing to their smaller space and height requirements[35–38,42]; the operating and maintenance costs are also reported to be lower. The lower height and the absence of an open tundish–mould stream offer increased operator safety[39,42].

Notwithstanding the advantages offered by the horizontal continuous-casting process over its conventional counterpart, the application of this process has been restricted largely because of technological limitations. An important constraint is the working life of the refractory breakring that connects the mould to the tundish, although new materials are being evaluated to overcome this problem. Moreover, the cost of the withdrawal system for the horizontal caster is higher than for conventional continuous-casting machines. Finally, the witness marks on horizontally cast billets may be sites of cracking during hot working[32].

Strip Casting

Strip casting has attracted the attention of steelmakers because it allows the elimination of at least part of the rolling operation, which leads to a reduction in energy consumption and capital expenditure[20–22]. There are two kinds of strip-casting machines that are being evaluated: single-roll and twin-roll. Allegheny Ludlum is involved in the development of the single-roll casting process for the production of stainless-steel bands[16–19]. Research conducted by them has examined process parameters and their relationships with product-quality concerns such as dimensional control, edge quality, surface roughness, and internal soundness. Twin-roll casters for the production of stainless-steel strip are also being developed[20–23]. Various aspects of the casting process, such as the castability of alloys, solidification behaviour, microstructure, and product quality, have been examined to optimize the operating and design parameters[20–23,43].

Fundamental Aspects of Stainless-Steel Casting

Chemical Reactivity

Stainless steels contain a relatively large proportion of reactive elements that have a high affinity for oxygen and nitrogen. Thus, the role played by the shrouding of the molten metal in the continuous casting of stainless steels is critical to minimize operating problems such as nozzle blockage and breakouts, and to enhance product quality. Moreover, the casting of stainless steel requires a superior mould-flux technology since a wide variety of complex compounds are formed between the reactive solutes in the stainless steel and the constituents of the mould powder.

Reaction Products

In plain carbon steels that are aluminium-killed, alumina inclusions are the primary deoxidation products in the molten metal[13]. However, in stainless steels containing aluminium and titanium, it is common to find complex corundum-type inclusions such as $(Cr–Al)_2O_3$ or spinel-type oxides such as $MnTi_2O_4$ or $MnCr_2O_4$. Occasionally, Al_2O_3 (alumina) and $FeO–Al_2O_3$ (hercynite) inclusions are also observed[13]. In grades containing high concentrations of titanium, carbide or carbonitride inclusions such as Ti(C,N) are present in the molten metal as microscopic suspensions[9,13]. Since a wide variety of complex compounds are encountered in the casting of stainless steels, it is almost impossible to have a general-purpose mould flux that can handle all the different grades and temperatures efficiently.

Shrouding

Ladle-to-tundish and tundish-to-mould shrouding is necessary to minimize chemical interaction between the molten metal and the atmosphere. Shrouding facilitates a better surface quality in the final product, and also reduces the severity of operating problems such as tundish skulling and nozzle clogging[7,13,44]. The introduction of an inert gas such as argon through tundish stopper rods and ladle-to-tundish shrouds further enhances the quality of the casting operation by minimizing the buildup of solid inclusions in the nozzles[13]. However, precise control of the gas flow (and pressure) is required since excessive flow promotes agitation in the mould and causes the entrapment of mould flux in the final product; on the other hand, inadequate flow (or pressure) leads to poor flushing of the non-metallics, which causes nozzle clogging[13].

Chemical Interaction between Mould Flux and Molten Steel

During casting, the properties of the mould flux change owing to the absorption of non-metallic inclusions and direct chemical reaction between the solutes in the steel and the mould flux, as indicated earlier[45]. In a study by Lindenberg and Loh, a number of mould fluxes were tested for their crystallization behaviour and chemical interaction with various grades of molten high-alloy steels[45]. The extent of interaction between the mould flux and the molten metal was found to depend on the difference in chemical potential between the two phases. In the case of aluminium-killed or titanium-containing steel grades, the difference between the oxygen potential of the mould flux and the molten steel is large, and results in the reduction of less-stable oxides, reoxidation of the melt, and transfer of the oxides of Al, Cr, and Ti to the flux phase[9,13]. Chemical analysis of the metal adjacent to the mould flux revealed an increased carbon content due to the absorption of the element from the mould flux[45]. Such interaction and mass exchange depend not only on the thermochemical properties of the mould flux but also on the operating parameters. For example, deep oscillation marks that form with a long mould oscillation stroke are usually accompanied by a high local concentration of carbon, sulphur, and non-metallic inclusions[45].

Solidification and Structure of Stainless Steel

Stainless steels fall in the range of the δ–γ phase fields in the Fe–Cr–Ni ternary system, very close to the transition from the peritectic to the eutectic reaction[9,46]. As illustrated in Figure 5, these phase fields include the formation of primary ferrite, the formation of primary ferrite followed by a three-phase (L, δ, γ) reaction, the formation of primary ferrite and austenite, and the formation of primary austenite[46]. It should be emphasized that the structure of the final product, and the structures present during and immediately after solidification, may be different from one another. For example, some austenitic stainless steels contain a large proportion of ferrite during and after solidification. The composition of the steel, a balance between ferrite stabilizers (Cr, Si, Mo, Nb, Ti, Al) and austenite stabilizers (Ni, C, N, Mn, Cu, Mo), governs the solidification behaviour. In continuous casting, the critical ratio of Cr_{eq}/Ni_{eq} at which the solidification mode changes from primary austenitic to primary ferritic solidification is around 1,5 for austenitic stainless steels[47].

It has been reported that fully ferritic stainless steels, as in the case of plain carbon grades, solidify initially to form the classic chill zone, which then gives way to a columnar–equiaxed pattern with increasing distance from the surface of the cast section, Figure 6[13]. On the other hand, with fully austenitic grades, the structure is essentially columnar to the centre of the cast section[13]; a typical macrostructure of an austenitic stainless steel is shown in Figure 7[13]. Owing to the large size and directionality of the columnar grains, the fully austenitic grades tend to be hot short[13]. Small controlled amounts, about 2 to 6 per cent, of delta ferrite in the fully austenitic structure refines the size of the columnar grains and improves the hot-working characteristics considerably[13,44].

The effect of secondary EMS (below the mould) on the ratio of the equiaxed zone (REZ) in the cast structure has been studied by Hasegawa *et al.*[7]. The REZ is an important quality parameter since it is directly linked to the severity of ridging, a surface problem that occurs during the press forming of cold-rolled stainless-steel sheets[7,48,49]. Ridging is frequently observed in type 430 stainless steels as narrow raised areas running parallel to the rolling direction[50]. The ridging problem is more severe in stainless-steel sheet rolled from continuously cast slabs than in that produced from ingots. Studies have indicated that ridging is related strongly to the presence in hot-rolled sheet of elongated columnar grains, which appear as a band-like structure oriented parallel to the rolling direction. Increasing the REZ reduces the severity of the ridging problem. Figure 8 shows a schematic diagram of the solidified structure of an 18 per cent chromium stainless-steel slab cast with secondary EMS and superheat levels greater than 20°C. The EMS resulted in the formation of banded equiaxed grains that prevented the growth of columnar grains[7]. EMS was not effective in the case of superheats lower than 20°C, at which point the cast structures were similar for both the stirred and the unstirred slabs[7]. Figure 9 summarizes the effect of EMS and tundish superheat on the REZ.

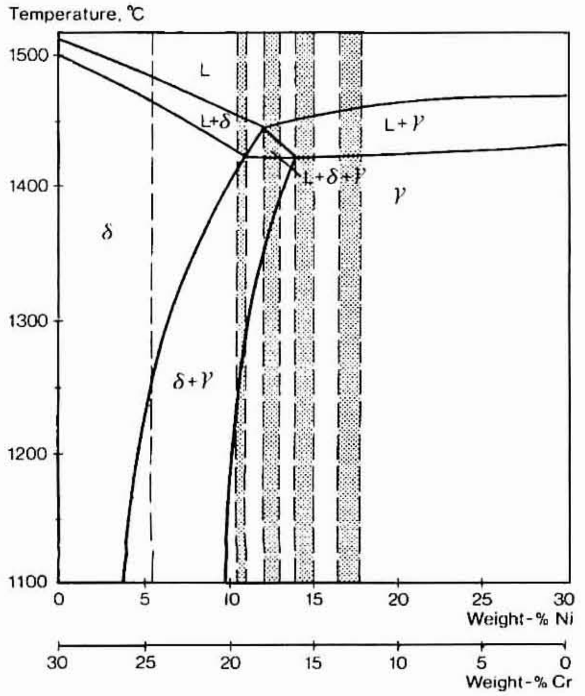

FIGURE 5. Phase diagram of the Fe–Cr–Ni system at 70 per cent Fe[46]

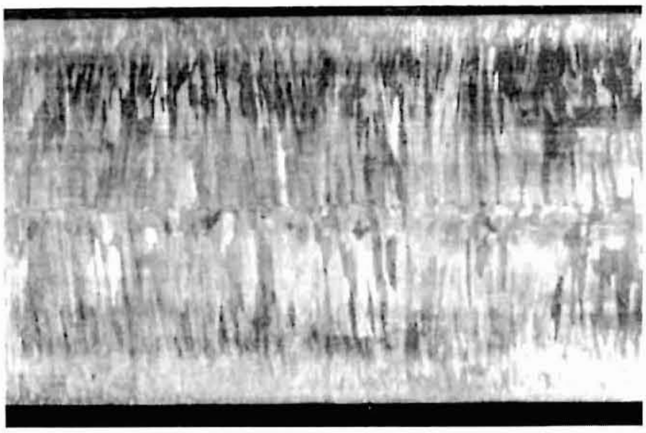

FIGURE 6. Macrostructure of type 430 ferritic stainless steel[13]

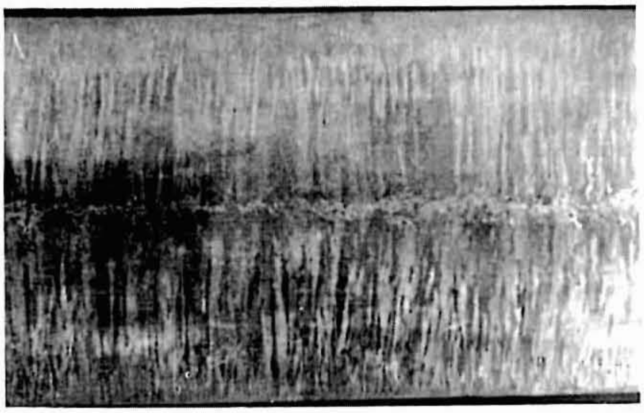

FIGURE 7. Macrostructure of type 304 austenitic stainless steel[13]

Hasegawa *et al.*[7] have attempted to explain the formation of the banded equiaxed structure with the help of the flow pattern developed during the intermittent application of EMS, Figure 10. The banded grains form at a place where the molten pool is stagnant with respect to the transverse and longitudinal directions[7]. The crystal fragments flow into this stagnant region from the lower part of the molten-metal pool and collect as a band of equiaxed grains[7]. However, this explanation has not been validated by other workers.

Research undertaken to assess the welding properties of fully austenitic stainless grades has revealed that steels having residual delta-ferrite contents of less than 2 per cent are highly sensitive to hot cracking, whereas those containing more than 6 per cent have poor hot workability[44]. The fraction of delta ferrite in a cast section can be predicted by use of a mathematical model that is based on heat transfer and the diffusion-controlled δ–γ transformation reaction[50]. Brittleness in the fully ferritic grades is related to large cast grains and a relatively high DBTT (ductile–brittle transition temperature)[13].

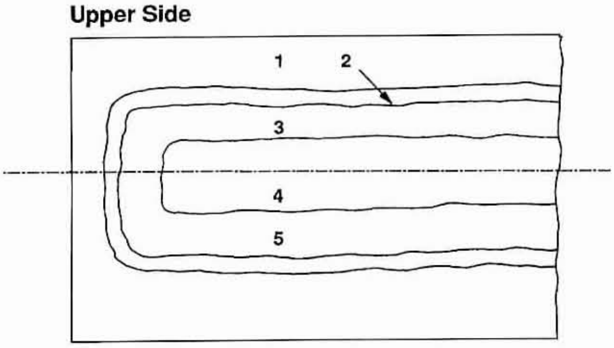

FIGURE 8. A schematic diagram[7] showing the banded equiaxed cast structure after the application of EMS with a superheat greater than 20°C

1 Chill and columnar zone
2 Banded equiaxed zone
3 Columnar or coexisting columnar–equiaxed zone
4 Equiaxed zone with fine grains
5 Equiaxed zone with some columnar grains

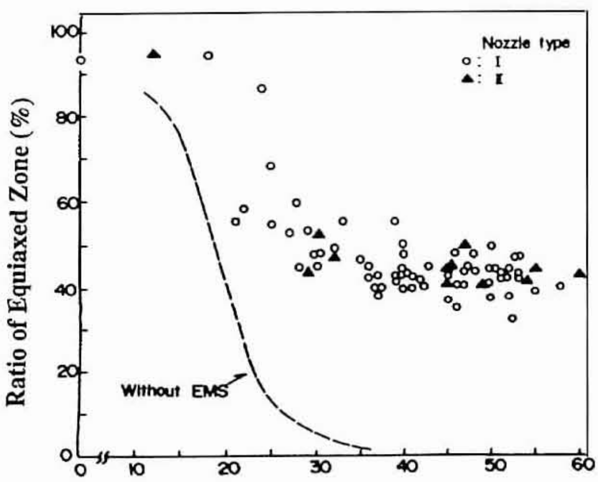

FIGURE 9. Effect of EMS and tundish superheat on the REZ in the cast structure of an 18 per cent chromium steel[7]

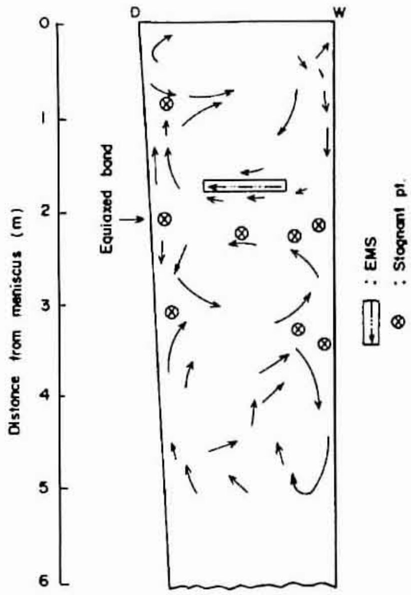

FIGURE 10. Schematic representation of the flow pattern developed during the application of EMS[7]

Cast Structure and Hot Workability

Austenitic stainless steels tend to have poor hot workability as compared with the ferritic grades because the cast structure is columnar to the centre of the section[13]. The large columnar grains give rise to anisotropy in the material properties and cause hot shortness in this grade of steel[13]. The presence of a small amount of delta ferrite in fully austenitic stainless steel has been observed to be beneficial since it refines the austenite grain size and reduces the directionality associated with the columnar structure, thereby improving the hot workability[13,44]. In the ferritic grades, since the cast structure consists of a chill zone together with the columnar–equiaxed pattern, the problem of hot shortness is less severe[13]. However, the ferritic grades are inherently brittle owing to their large grain size and relatively high DBTT[13].

Lindenberg *et al.*[44] related the cracking susceptibility of continuously cast high-alloy steel slabs to the difference between the temperatures for zero ductility and zero strength (ΔT_{ZDS}), based on the results of a series of hot-tearing tests conducted on samples solidified *in situ*. These authors modified the conventional Schaeffler diagram (valid for room temperature) to make it applicable at high temperature, as shown in Figure 11[44].

Hot Ductility

The ductility of stainless steel at elevated temperatures is important with respect to cracking susceptibility during the continuous-casting process. In stainless steels, two zones of low ductility have been identified. The first zone lies in the temperature zone within 30 to 50°C of the solidus[9], while the second zone occurs[3] at temperatures between 800 and 1150°C. In the conventional continuous-casting of steel billets, only the former is important from the viewpoint of crack formation; in conventional slab casting, however, both zones are critical.

The low-ductility zone encountered at temperatures close to the solidus arises from the presence of a liquid film, rich in solute elements, between the dendrites[51]. Cracking in

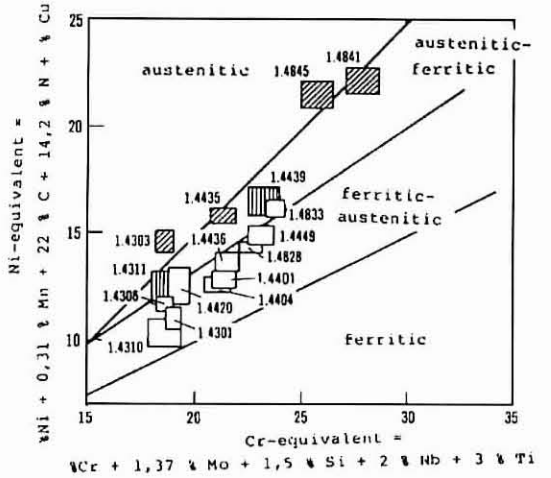

FIGURE 11. Schaeffler diagram for stainless steels at high temperatures[44] (the numbers denote the Werkstoff Numbers in the DIN specification)

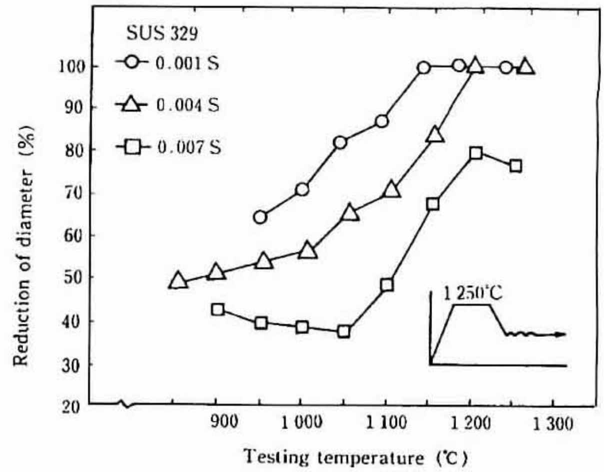

FIGURE 13. Effect of sulphur on the hot ductility of stainless steels[3]

this zone of low ductility occurs due to hot tearing. The effect of phosphorus on ductility at temperatures between 1200 and 1400°C has been studied for a high-alloy steel, and the results are shown in Figure 12. The poor ductility is attributed to segregation of phosphorus near the austenite grain boundaries[10]. Sulphur also has a deleterious effect on the hot ductility of stainless steel, Figure 13[3].

The ductility of various stainless-steel grades, characterized in terms of the reduction in the diameter of fractured tensile specimens, has been studied by Ogura *et al.*[3] in the intermediate temperature range; the results are presented in Figure 14. Thus, it is clear that stainless steels have reduced ductility at temperatures between 800 and 1150°C and, therefore, are susceptible to cracking; moreover the SUS 631 (AISI 631) grade is more susceptible to cracking than the SUS 304 (AISI 304) grade. This may be due to the presence of 1 per cent aluminium in the type 631 grade, which leads to embrittlement from the precipitation of AlN in this temperature range; this mechanism was reported by Thomas *et al.*[51]. Similar results have been published by Unger *et al.*[9] and Kinoshita *et al.*[10].

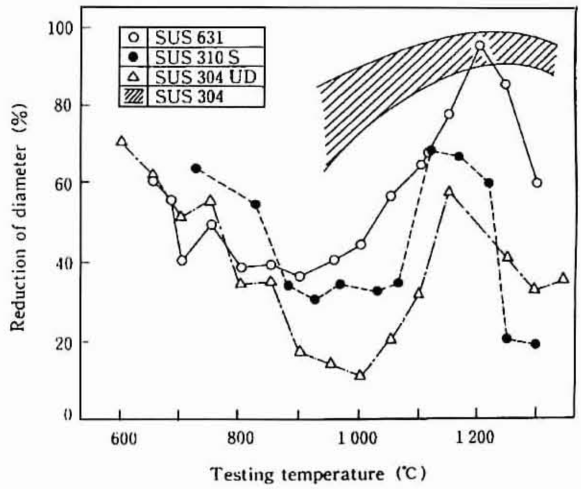

FIGURE 14. Hot ductility of stainless-steel grades[3]

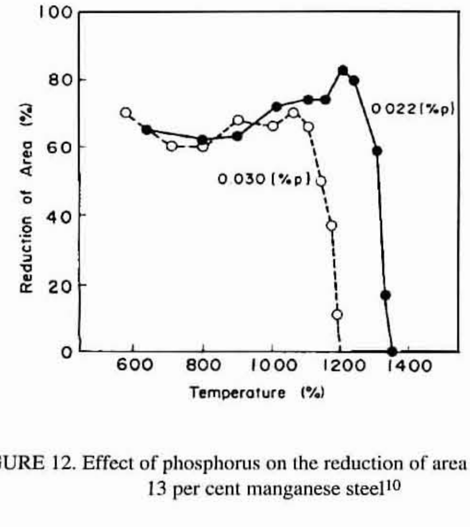

FIGURE 12. Effect of phosphorus on the reduction of area of an as-cast 13 per cent manganese steel[10]

Quality Aspects of Continuously Cast Stainless Steels

Cleanliness

Owing to the presence of reactive elements in stainless steels, a variety of inclusions, such as oxides, nitrides, and carbonitrides of Al, Ti, and Mn, form[7,9,11,44]. Oxide cleanliness is related directly to the oxygen content of the steel. The chemical composition of the oxides in stainless-steel grades AISI 304 and AISI 316 reveals a strong dependence on the titanium level and the total oxygen content, as shown in Figure 15. At higher levels of oxygen, conditions become favourable for the formation of chromium–manganese spinels, which have a deleterious effect on surface quality. Hasegawa *et al.*[7] have classified the surface defects arising from inclusions in titanium-containing stainless steels based on their morphologies, Table V. The effect of titanium and nitrogen on the formation of type A defects is shown in Figure 16, where the product of nitrogen and titanium is seen to be critical[7].

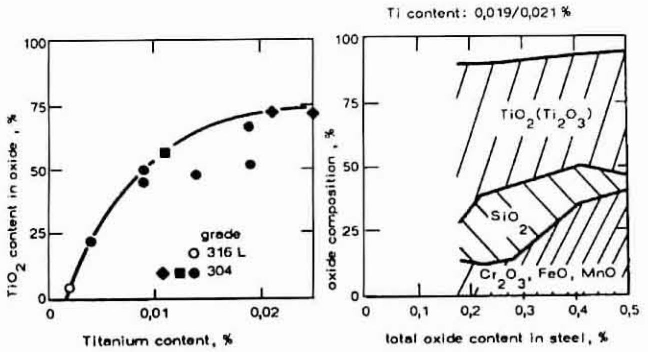

FIGURE 15. Oxide composition as a function of the titanium and total oxygen contents of steel[9]

TABLE V
INCLUSION -RELATED SURFACE DEFECTS IN TITANIUM-CONTAINING GRADES[7]

Type	Morphology
A	Rough surface with clusters of subsurface blowholes filled with mould slag
B	Clusters of alumina and titanium nitride
C	Blowholes (not clustered) filled with mould slag
D	Entrapped scum

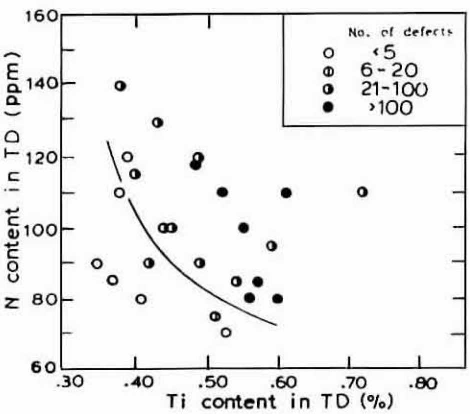

FIGURE 16. Effect of titanium and nitrogen on the frequency of type A defects in stainless steel[7]

In addition, the temperature of the molten steel in the mould influences the formation of this defect. Based on water-model experiments, it was found that the inclusions accumulated at the meniscus are dependent on the shape of the SEN (submerged entry nozzle)[7]. Temperature measurements in the mould revealed that the meniscus region closest to the SEN had the lowest temperature, which assisted in the accumulation of titanium nitride inclusions[7]. The accumulated inclusions further reduced the temperature of the meniscus, causing freezing of the liquid steel and the formation of a solid crust[7].

Skin laminations and seams are other inclusion-related surface-quality problems[52]. They tend to be more severe in the first slabs of a heat[52]. The skin laminations are related to the entrapment of refractories, flux, or any exogenous materials[52]. The seams are fine, straight lines consisting of oxides of chromium, manganese, silicon, and aluminium, with lengths up to 50 mm[52].

In horizontal casting, the problem of inclusions is less severe because of the direct mould–tundish coupling. The distribution of inclusions in the cast product is interesting because, owing to their low density, more inclusions are found in the upper portions than in the lower part of the cast billet section[53,54]. Water-model studies on horizontal moulds have revealed forward flow in the lower regions and reverse flow in the upper zone of the liquid pool in the mould[54]. The reverse flow apparently entrains inclusions of alumina and titanium nitrides, which become entrapped by the advancing solidification front[54].

Oscillation and Witness Marks

Deep oscillation marks are not desirable because they may lead to cracks, local segregation, and the entrapment of inclusions[8]. In addition, non-uniformity in the depth of oscillation marks worsens with increasing depth of the marks[8]. Hence, it is essential to minimize the depth of oscillation marks. Figure 17 shows the beneficial role of high oscillation frequency and short stroke length in producing shallow oscillation marks[55]. However, as can be seen in Figure 18, these conditions also lead to a reduction in the consumption of mould flux, which could result in a sticking problem[55]. This happens because, at a higher oscillation frequency, the amount of molten slag entering the mould–shell air gap is reduced. The inflow can be increased by the application of a less-viscous slag with a lower freezing point[56].

Witness marks on the surface of a cast section are characteristic of the horizontal-casting process, where the strand is withdrawn intermittently. The mechanism of witness-mark formation has been described by Lima *et al.*[32]. The depth of the witness marks, which corresponds to the thickness of the solid shell formed in the vicinity of the breakring during strand withdrawal[53], is important, and needs to be minimized since each mark is a plane of weakness that may cause surface cracking during hot working[32].

The depth of witness marks on stainless and carbon steels has been reported for various operating horizontal-casting machines, Table VI[32]. Witness marks are found to be

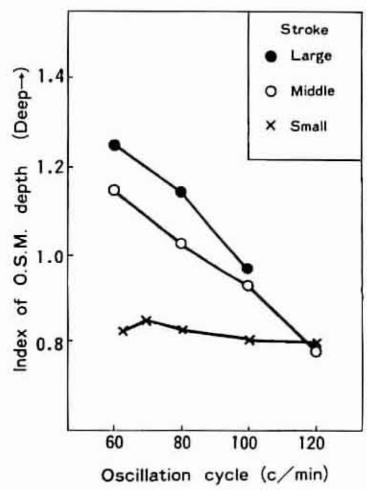

FIGURE 17. Impact of oscillation frequency and stroke length on the depth of oscillation marks in type 430 stainless steel[55]

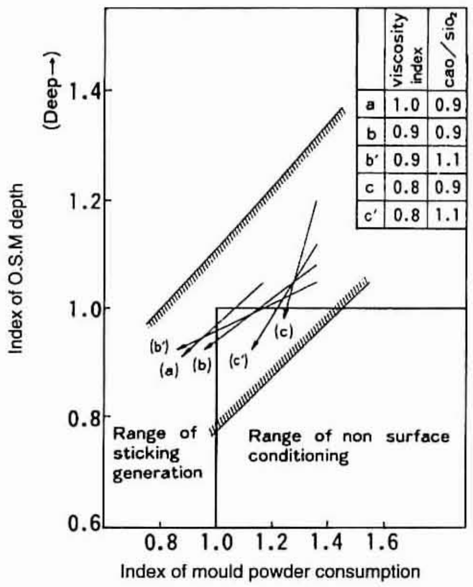

FIGURE 18. Consumption of mould flux as a function of depth of oscillation marks in type 430 stainless steel[55]. (Note: the arrow shows the trajectory of the frequency from 60 cycles per min to 120 cycles per min. The arrowhead corresponds to 120 cycles per min. Stroke length is kept constant.)

slightly deeper in stainless steels than in carbon steels[32]. In addition, the witness marks are deeper on the lower side of the strand than on the upper side[53] because, it is postulated, the former experiences a higher heat extraction owing to better mould–shell contact; therefore the shell growth at the breakring is greater[53]. This argument is further supported by measurements of secondary dendritic-arm spacing, which is found to be larger adjacent to the upper side[53].

TABLE VI
DEPTHS OF WITNESS MARKS REPORTED FOR DIFFERENT CASTING MACHINES[32]

Type of machine	Steel grade	Withdrawal frequency cycle·min^{-1}	Depth of primary marks mm
Horicast	Carbon	50	≈4
Davy McKee–NKK (1984)	Carbon	200	≈2
Horicast	Stainless	25	≈4
Davy McKee–NKK (1988) (improved mould)	Stainless Carbon Carbon	150 25 150	≈1 ≈2 ≈0
Kobe Steel	Stainless Stainless	30 45	5* 3*
Armco	Stainless	25	3,5
Technica–Guss (1985)	Stainless	220	1,5
Steel Casting	Carbon	100	0,3
Engineering Pilot Caster (1985)	Carbon Stainless Stainless	150 100 150	0,10 0,70 0,65

*Cold shut index – no absolute value given

Since the depth of witness marks is related directly to the thickness of the solid shell formed against the breakring, operating parameters that influence shell growth are important[32]. Many investigators have reported the beneficial effects of a higher superheat and an increased withdrawal frequency in reducing the depth of witness marks[32,42,53]. An increase in the withdrawal frequency reduces the time available for solidification of the primary shell, whereas higher superheats reduce the thickness of the solid shell by remelting[53] or by decreasing the rate of solidification[40]. However, high superheat is not a recommended solution since it increases the severity of depressions on the billet surface, Figure 19[57].

The design of the breakring is very critical to the formation of witness marks[33,34,40,41]. Boron nitride has been found to be a better material than alumina because of its superior surface finish and low wettability by molten steels[34]. Sialon-based breakring material has also been used and been found to be beneficial in reducing the depth of witness marks[34]. The difference in the inner diameter between the mould and the refractory nozzle must be small to reduce the discontinuity of the solidification structure beneath the witness marks[40,41]. The thickness of the breakring is important; a thinner breakring deleteriously affects the depth of witness marks[32,33]. Mould design and operating parameters that influence the temperature of the triple point of solidification (mould–breakring–steel junction) are critical in the generation of deep witness marks[32].

The beneficial effect of EMS on the depth of witness marks has been reported[53]. Mould stirring reduces the depth of witness marks on both the top and bottom surfaces[53]. The effect is believed to be due to the liquid steel washing the solidification front and promoting an increased remelting of the solidified shell.

Segregation and Centreline Porosity

Segregation of solute elements having distribution coefficients less than unity (e.g. C, S, P, Mn) occurs on both a micro- and a macro-level during the continuous casting process[49]. Microsegregation, which arises due to the freezing of solute-rich liquid between dentrites, is not normally critical in continuously cast products; on the other hand, macrosegregation, generated on a larger scale by fluid motion, can cause quality problems in the cast product[49].

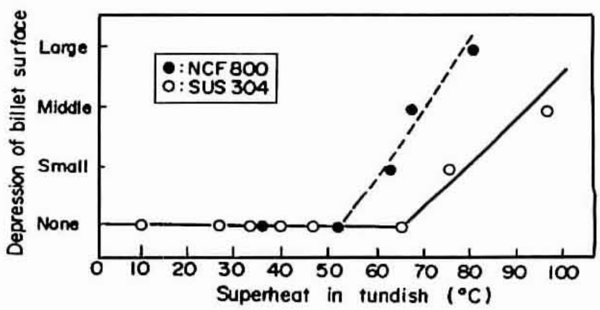

FIGURE 19. The effect of tundish superheat on the generation of depressions on the billet surface[57]

Macrosegregation in continuously cast billets and blooms has been related to operating parameters that influence the cast structure, such as superheat, strand dimensions, and steel composition[49]. It has been found that the severity of centreline segregation and porosity can be reduced by increasing the REZ[49].

In continuously cast slabs, the problem is linked not only to the cast structure but also to bulging of the slab close to the bottom of the liquid pool[49]. During bulging, solute-rich liquid moves into the strand core and generates macrosegregation. Thus, maintenance problems, such as poor roll alignment, inadequate roll pitch, improper hydraulic roll pressure, and roll eccentricity, are critical[49]. The application of soft reduction at the pool bottom is also beneficial in minimizing the segregation problem.

Segregation is also associated with oscillation marks[45,58]. The segregation of carbon and sulphur has been observed near the surface of slabs[45]. Takeuchi and Brimacombe reported positive segregation of phosphorus and manganese along subsurface hooks adjacent to oscillation marks in austenitic stainless-steel slabs[58]. They also observed positive segregation of nickel and silicon at the overflow region of hooks adjacent to oscillation marks, as well as at the bottom of oscillation marks without hooks[58]. The segregation is caused by the transport of solute-rich liquid to the surface of the slab by overflow or by bleeding[58]. The severity of the segregation problem increases with deeper oscillation marks; an increase in oscillation frequency will obviously reduce the problem[58].

The beneficial effect of EMS in minimizing segregation has been studied by numerous authors[7,44]. EMS in the mould modifies the structure primarily by dissipating the superheat[49]. Beyond the mould, the EMS affects the cast structure by reducing the thermal and concentration gradients ahead of the solidification front[49].

The beneficial effects of EMS on segregation and central porosity in horizontally cast billets has been reported by many workers[37,38,53]. Figure 20 shows the macrostructure of a round section of a 304 stainless-steel grade both with and without mould stirring. In the non-stirred case, the columnar grains grow towards the centre, forming bridges and large cavities[53]. Stirring results in finer equiaxed grains and a reduced central segregation[53]. The effect of the intensity of EMS on the REZ next to the lower and upper sides is shown in Figure 21 for the AISI 304 grade[53]. The REZ increases steadily with stirring intensity, but then reaches a plateau[53], possibly owing to the complete dissipation of superheat in the mould. The EMS improves the central segregation but also creates negative segregation zones in the cast section[53]. Mould stirring gives a wider REZ with a lower negative segregation than with secondary stirring. A combination of mould and secondary stirring gives the best result. Ishizaka *et al.* employed a three-stage EMS system and found a remarkable effect on the REZ and also on the minimization of internal cracks[33].

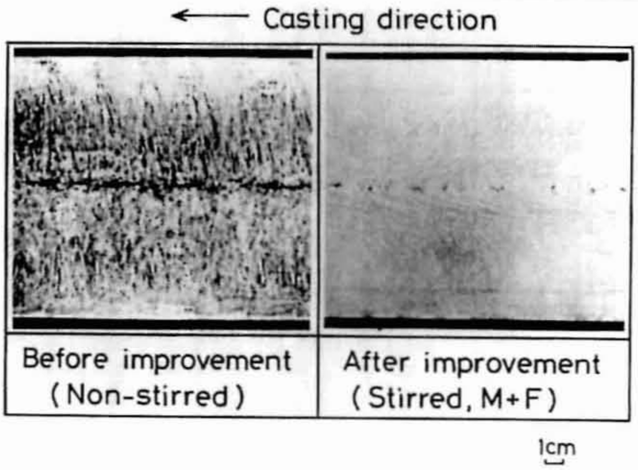

FIGURE 20. Macrostructures of a round section of AISI 304 grade (with and without EMS)[53]

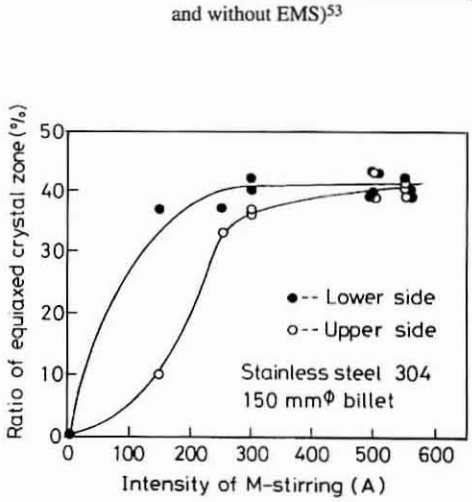

FIGURE 21. Effect of intensity of EMS on the REZ[53]

Cracks

Internal cracks

All internal cracks in continuously cast steel products form in the high-temperature zone of low ductility within about 50°C of the solidus temperature, where the microsegregation of solutes like sulphur and phosphorus creates liquid films between dendrites; therefore, the concentration of solutes such as sulphur and phosphorus in steel is critical to crack formation. Table VII summarizes the important points related to the generation of internal cracks in sections produced by the conventional continuous-casting process.

In slab casting, the important internal cracks are bulging-related cracks, straightening or bending cracks, and cracks under depressions and corners. Bulging of the broad faces of a slab gives rise to triple-point cracks, radial streaks, and centreline cracks; their detailed mechanisms have been published elsewhere[60]. Straightening or bending cracks form due to excessive tensile strains near the solidification front during straightening or bending on a liquid core. In billet casting, the main internal cracks include midway cracks, off-corner cracks, straightening or bending cracks, centreline cracks, and diagonal cracks; the mechanisms of formation of these problems have already been published[59,60].

Lindenberg *et al.*[44] have correlated the internal cracking susceptibility of ferritic stainless-steel slabs with their high-temperature mechanical properties. Figure 22 shows the relationship between the frequency of internal cracks (due to bulging and cracks under corners and depressions) and

TABLE VII
INTERNAL CRACKS IN CONVENTIONAL CONTINUOUS CASTING

Type	Causes	Influencing factors
Midway cracks	Surface reheating in or below the sprays[60]	Spray design; mould parameters (if billet has dark or bright patches at mould exit); steel composition (Mn/S ratio and P content) and superheat
Diagonal cracks	Asymmetrical cooling in the sprays or the mould[60]	Thermo-mechanical behaviour of the mould; adverse mould–shell interaction; deep and non-uniform oscillation marks; spray design and maintenance; steel composition
Pinch-roll cracks	Squeezing on a strand with liquid core[60]	Excessive pinch-roll pressure; steel composition and superheat
Straightening or bending cracks	Large deformation near the solidification front due to straightening or bending	Excessive bending or straightening strains; steel composition and superheat
Off-corner cracks	In billets, bulging of the solid shell and hinging at off corners[59]	Thermo-mechanical behaviour of the mould; adverse mould–shell interaction; deep, non-uniform oscillation marks; steel composition
	In slabs, buckling of the solid shell due to squeezing of end plates against the narrow faces[62, 63]	Heat extraction at the meniscus; copper-plate thickness; mould-coating thickness or conductivity; cooling-water velocity; cooling-channel configuration; mould-flux composition
Centreline cracks (ghost lines in slabs)	In billets, due to sudden decrease in the centreline temperature at the point of complete solidification[60]	Spray cooling near the point of complete solidification; steel composition and superheat
	In slabs, bulging of the wide face[60]	Roll gap; spray cooling; steel composition
Triple-point cracks	In slabs, bulging of the wide face[60]	Roll gap, steel composition

the temperatures for zero ductility and zero strength, ΔT_{ZDS}; a higher ΔT_{ZDS} increases the frequency of internal cracking[44]. ΔT_{ZDS} was calculated from the results of hot-tearing tests carried out at different temperatures on steel samples solidified *in situ*[44]. Figure 23 shows the results of the tests for a ferritic stainless steel containing 13 per cent chromium. Lowering the surface temperature of the slabs from 1100 to 900°C improves the strength of the strand and reduces the severity of bulging-related cracks[44].

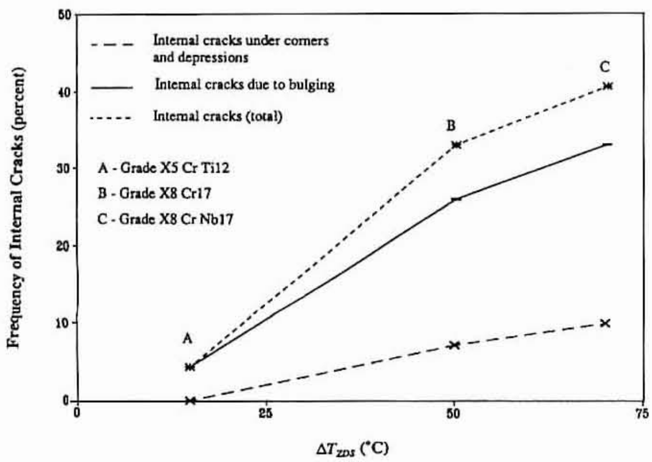

FIGURE 22. Effect of ΔT_{ZDS} on the frequency of internal cracking[44]

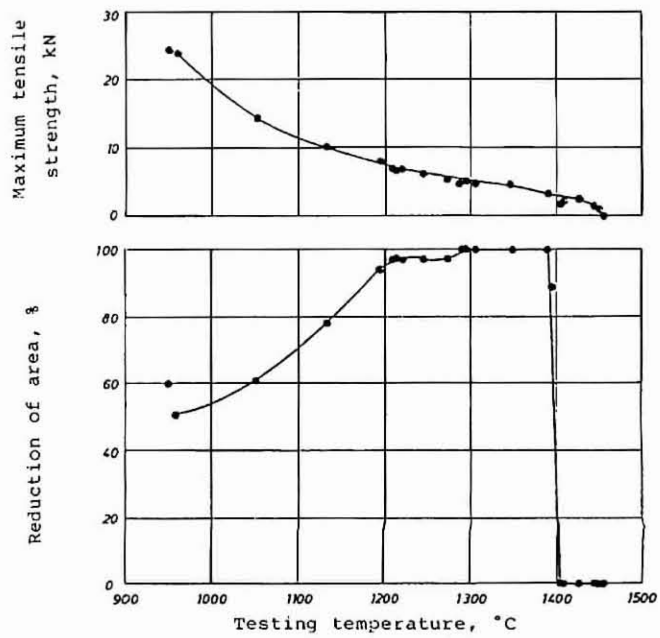

FIGURE 23. Hot ductility and maximum tensile strength of a 13 per cent chromium steel solidified *in situ*[44]

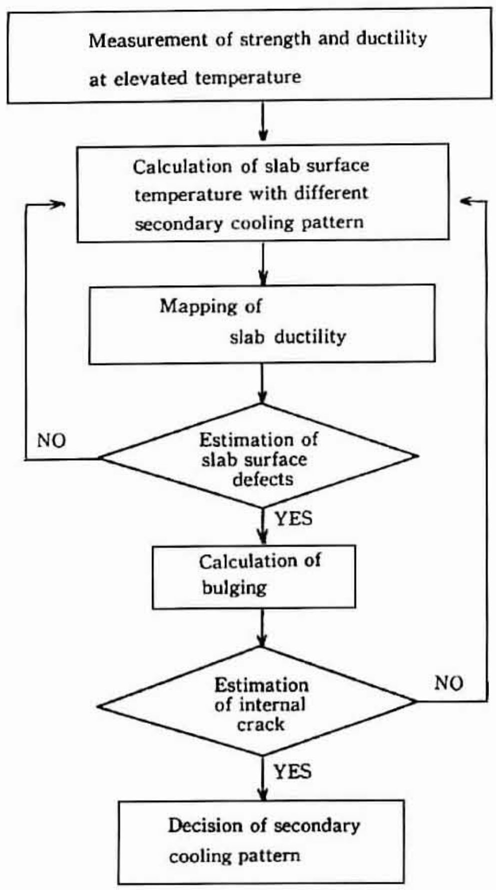

FIGURE 24. A methodology for the determination of slab cooling to minimize cracking[3]

With martensitic grades, susceptibility to internal cracking increases with increasing carbon content[44]. As with low-alloy steels, cracking susceptibility increases sharply when the carbon content exceeds the value for the peritectic reaction[44]. This is explained by the fact that the ΔT_{ZDS} increases significantly beyond the peritectic point[44]. In austenitic stainless steels, susceptibility to hot cracking is related to the cast structure and the amount of delta ferrite present, as mentioned earlier.

Surface cracks

The main surface cracks observed in continuously cast steels include longitudinal, transverse, and star cracks. The important points related to surface cracks in shapes produced by the conventional continuous-casting process are summarized in Table VIII.

Stainless-steel slabs of AISI 310 grade are more susceptible to transverse surface cracking than AISI 304 grade because of the lower ductility of the former[9]. Slabs of AISI 631, a martensitic grade, are also prone to transverse cracks[9]. In both cases, the poor ductility is attributed to segregation of sulphur at the grain boundaries[9]; a reduction in the sulphur level minimizes the generation of surface cracks. In addition, the AISI 631 grade has a high aluminium content, which aggravates its low-ductility problem because of the precipitation of AlN at the grain boundaries. The cracking tendency can also be reduced by straightening of the cast section at surface temperatures above 950°C or below 750°C so that the low-ductility zone is avoided completely. A flow chart, shown in Figure 24, outlines the methodology for determining the secondary cooling pattern to minimize the cracking problem (surface cracks and internal cracks due to bulging)[3].

TABLE VIII
SURFACE CRACKS IN CONVENTIONAL CONTINUOUS CASTING

Type	Cause	Influencing factor
Longitudinal midface cracks	In slabs, due to tensile strains generated in the mould and upper sprays[60]	Mould disorders – alignment, taper, oscillation, lubrication; overcooling in the upper sprays; steel temperature and composition
	In billets, stream impingement on a face due to cocked stream, localized reheating of the strand surface in the mould[64]	Stream alignment; scratch or gouge marks on the inner surface of the mould wall
Longitudinal corner cracks	In slabs, situated just off the corners, caused by bulging of the narrow face in the mould[60]	Mould support conditions
	In billets, non-uniform cooling in the mould or the sprays[60]	Corner radius; presence of corner key-holes; mould alignment; thermo-mechanical behaviour of the mould; adverse mould–shell interaction; deep, non-uniform oscillation marks; spray design and maintenance; steel composition
Transverse midface and corner cracks	In slabs, large surface gradients in the spray zone or at the straightener within the temperature range 700 to 900°C[60]	Spray cooling; steel composition (precipitation of complex intermetallic compounds of Al, Nb, Ti)
Star cracks	Scraping of copper from the mould wall[60, 61]	Chromium or nickel plating; machine alignment

In conventionally cast slabs, the transverse cracks are generated in the secondary-cooling zone, or beyond it, at the straightener owing to embrittlement at lower temperatures caused by precipitation of compounds such as AlN, Ti(C,N) etc.[3,60]. In conventionally cast billets, the transverse cracks are related to sticking or binding in the mould[61]. In horizontally cast steel billets, transverse cracks are observed in the vicinity of the witness marks and are related to the pull time[34]; the mechanism in the generation of transverse cracks has been described by Nakai *et al.*, who propose that there is a critical shell thickness below which transverse cracks form[34]. A reduction in the pull time or the introduction of a 'push-back' step in the cycle leads to the formation of a thicker shell and therefore minimizes the problem of transverse cracks[34].

Longitudinal cracks in conventionally cast slabs are related to the nature of the mould–shell interaction, which depends on mould cooling, taper, and lubrication. The role of mould lubrication in the generation of this quality problem is significant. In stainless steels, particularly those containing aluminium and titanium, the composition of the mould flux changes significantly during the casting of a heat[3]. For example, during the casting of the AISI 631 grade, which contains about 1 per cent aluminium, the softening temperature of the molten flux increases with increasing slag basicity because of chemical interaction between the mould flux and the molten steel[3]. Aluminium in the molten steel reduces the SiO_2 content of the mould flux and therefore increases its basicity[3]. The high frequency of longitudinal cracks has also been linked to the melting rate of the mould flux, which is related to the morphology of the carbon in it[45].

In conventionally cast billets, longitudinal corner cracks are generated because of non-uniform cooling in the corner regions of the mould, which are often caused by an excessive corner radius. Longitudinal surface cracks have been observed in rounds cast by the horizontal-casting process[53]. These cracks originate from non-uniform shell growth in the mould[53]. Mould stirring has a beneficial effect since it enhances the formation of a uniform solid shell[53]; increasing the intensity of mould stirring reduces the frequency of the cracking problem[53].

Star cracks in conventionally cast slabs arise due to the scraping of copper from the mould walls[60,63]. The copper penetrates the slab surface and causes hot shortness in localized regions. These cracks are roughly 1,5 to 3,0 mm deep and appear in clusters in the pattern of a star[60]. Chromium plating of the copper mould prevents the penetration of copper into the slabs and therefore eliminates star cracks[60]. Nakano *et al.* have found that precipitation-hardened copper moulds having a layer of electroformed nickel (about 3 mm thick) increase the grinding yield of the slabs and improve the mould life; this happens because the nickel layer reduces mould wear[63].

Depressions

Longitudinal depressions

Longitudinal depressions, 2 to 5 mm deep, have been observed on the broad face of conventionally cast type 304 stainless-steel slabs at off-corner locations[61]. They are associated with bulging of the narrow face or are caused by buckling of the solid shell resulting from squeezing of the end plates against the narrow faces[61,62]. Buckling of the solid shell at the off-corner of the broad faces generates a tensile strain close to the solidification front and a subsurface crack; therefore, it is common to find a crack below or at the base of a surface depression. A similar mechanism has been proposed for the generation of off-corner internal cracks in billets[59].

The formation of longitudinal depressions in slabs has been related to the behaviour of the slag rim at the meniscus; proper heat-flow conditions near the meniscus will help minimize this quality problem[62]. Mahapatra *et al.*[62] have found that variables important for controlling the heat extraction at the meniscus are copper-plate thickness, mould-coating thickness or conductivity, cooling-water velocity, cooling-channel configuration, and mould-flux composition.

Transverse depressions

Transverse depressions have been observed in AISI 304, 316, and 321 grades, being more severe in the 304 steel[65]. On the other hand, in resulphurized type 304 and 316 grades, transverse depressions are not a problem; similar behaviour is exhibited by 0,1 per cent carbon steels containing high levels of sulphur[65].

Wolf has attributed the formation of transverse depressions in austenitic stainless steels and plain carbon steels to local overcooling of the strand during initial solidification that is followed by contraction due to 'plastic hinge effect' and rebending[65]. Austenitic stainless steels with Cr_{eq}/Ni_{eq} around 0,55 tend to be sensitive to the formation of depressions because of a large local shrinkage associated with the δ–γ transformation at the end of solidification; this phenomenon is very similar to that observed in 0,1 per cent plain carbon steels[65]. However, this theory may not adequately explain the generation of surface or subsurface cracks below these depressions. Samarasekera and Brimacombe[66] postulate that transverse depressions in billet casting are related to sticking or binding in the mould as a result of which the withdrawal system pulls the strand and generates longitudinal tensile stresses and strains. Depending on the magnitude of the stress, the solid shell may flow plasticly and form a depression on the billet surface (similar to necking in a tensile test)[66].

Examination of the shell below a transverse depression in austenitic stainless steel revealed a zone of locally reduced heat flow and retarded shell growth[65]. A local enrichment in ferrite at the depression site was also observed[65]. As mentioned earlier, excessive ferrite is not desirable in austenitic steel since it lowers its hot workability.

In billet casting, transverse depressions can be minimized by operating with proper taper, lubrication, and oscillation characteristics; the thermomechanical behaviour of the mould, i.e. excessive distortion, may also cause adverse mould–shell interaction[67]. According to Wolf, the frequency of depressions can be reduced by ensuring a low heat flux near the meniscus, which produces a thinner initial shell; he has suggested that this condition can be achieved by operating with higher casting speeds, higher superheats, and an optimum slag-film stability, corresponding to minimum heat flux and friction[65]. The application of soft mould cooling with the help of a hot top mould has also been proposed by the same author as a potential method to reduce depressions in austenitic steels[65].

Acknowledgments

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