INCLUSIONS IN CONTINUOUS CASTING OF STEEL

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ABSTRACT

This paper first reviews the sources of inclusions in continuous casting of steel including both indigenous and exogenous inclusions, focusing on reoxidation, slag entrainment, lining erosion and inclusion agglomeration on linings. Secondly, the resulting defects in continuous cast steel products are reviewed, such as flange cracked cans, slag spots, and line defects on the surface of rolled sheet. Thirdly, the current "state-of-the-art" in the evaluation of steel cleanliness is summarized, discussing over 30 different methods including direct and indirect methods. Finally, this paper reviews operating practices to improve steel cleanliness at the tundish and continuous caster.

Key Words: Steel, Inclusions, Defects, Slab Caster, Plant Measurement, Review, Detection Methods

INCLUSIONS AND DEFECTS

1. Introduction

The ever-increasing demands for high quality have made the steelmaker increasingly aware of product "cleanliness" requirements. Non-metallic inclusions are a significant problem in cast steels that can lead to excessive casting repairs or rejected castings. Ginzburg and Ballas reviewed the defects in cast slabs and hot rolled products, many of which are related to inclusions. [1] The mechanical behavior of steel is controlled to a large degree by the volume fraction, size, distribution, composition and morphology of inclusions and precipitates, which act as stress raisers. The inclusion size distribution is particularly important, because large macroinclusions are the most harmful to mechanical properties. Sometimes a catastrophic defect is caused by just a single large inclusion in a whole steel heat. Though the large inclusions are far outnumbered by the small ones, their total volume fraction may be larger.[2]

Ductility is appreciably decreased by increasing amounts of either oxides or sulphides. [3] Fracture toughness decreases when inclusions are present in higher-strength lower-ductility alloys. Similar property degradation from inclusions is observed in tests that reflect slow, rapid, or cyclic strain rates, such as creep, impact, and fatigue testing. [3] **Figure 1** shows that inclusions cause voids, which can induce cracks. [4] Large exogenous inclusions may cause trouble in the form of inferior surface, poor polishability, reduced resistence to corrosion, and in exceptional cases, slag lines and laminations. [5] Inclusions also lower resistance to HIC (Hydrogen Induced Cracks). [6] The source of most fatigue problems in bearing steel are hard and brittle oxides, especially large alumina particles over 30µm. [7-10) 11)] **Figure 2** [7] indicates that lowering the amount of large inclusions by lowering the oxygen content to 3-6ppm has extended bearing life by almost 30 times in comparison with steels with 20 ppm oxygen. To avoid these problems, the size and frequency of detrimental inclusions must be carefully controlled. Especially there should be no inclusions in the casting above a critical size. **Table I** shows some typical restrictions on inclusions in different steel application. [12]

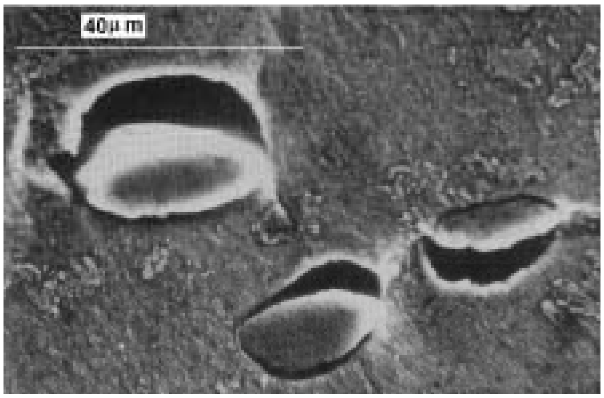


Fig.1 Effect of inclusion deformation on linking between adjacent voids

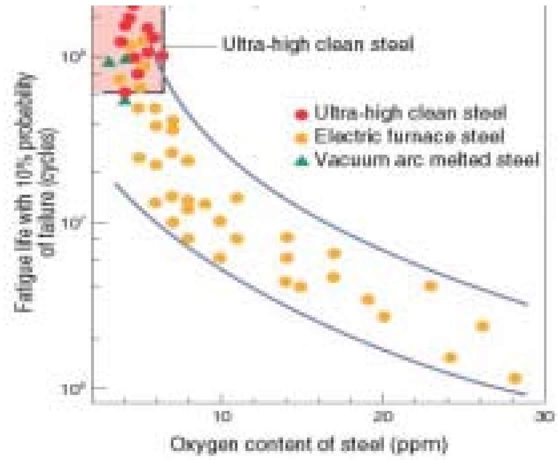


Fig.2 Relation between fatigue life and oxygen content of bearing steels

Table 1. Typical steel cleanliness requirements reported for various steel grades

Steel product	Maximum impurity fraction	Maximum inclusion size
Automotive & deep-drawing Sheet	[C]≤30ppm, [N]≤30ppm [13]	100µm [13, 14]
Drawn and Ironed cans	[C]≤30ppm, [N]≤30ppm, T.O.≤20ppm [13]	20µm[13]
Line pipe	[S]≤30ppm [15], [N]≤35ppm, T.O.≤30ppm [16], [N]≤50ppm[17]	100µm[13]
Ball Bearings	T.O.≤10ppm[15, 18]	15µm[16, 18]
Tire cord	[H]≤2ppm, [N]≤40ppm, T.O.≤15ppm[16]	10µm[16] 20µm[14]
Heavy plate steel	[H]≤2ppm, [N]30-40ppm, T.O.≤20ppm[16]	Single inclusion 13µm[13] Cluster 200µm[13]
Wire	[N]≤60ppm, T.O.≤30ppm[16]	20µm[16]

Although the solidification morphology of inclusions is important in steel castings, the morphology of inclusions in wrought products is largely controlled by their mechanical behavior during steel processing, i.e., whether they are "hard" or "soft" relative to the steel matrix. The behavior of different types of inclusions during deformation is schematically illustrated in **figure 3**. [19] "Stringer" formation, type (b) and (c), increases the directionality of mechanical properties, adversely affecting toughness and ductility in particular. The worst inclusions for toughness and ductility, particularly in through-thickness direction properties of flat-rolled product, are those deforming with the matrix, like (d) in Fig. 3.

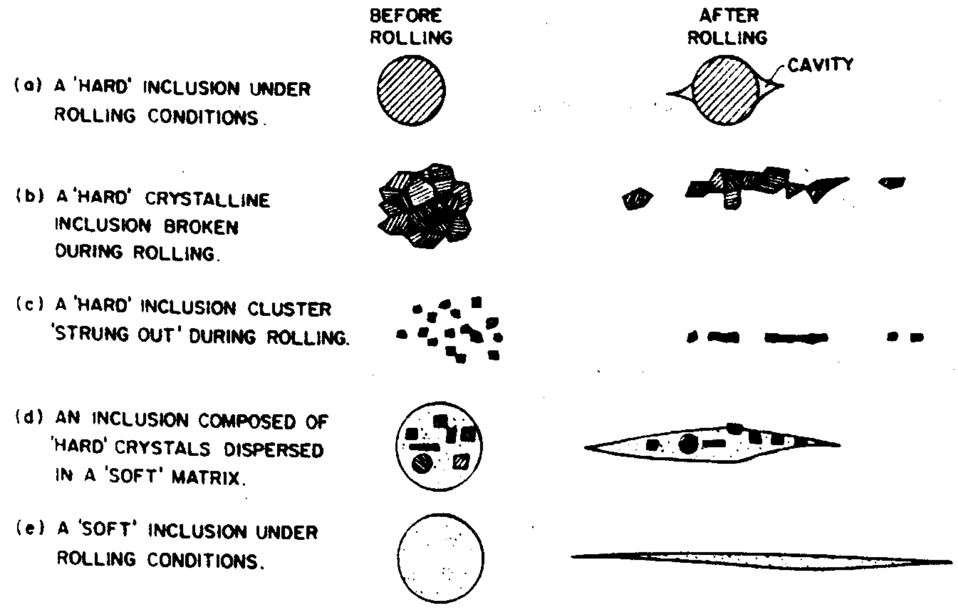


Fig. 3 Schematic representation of inclusions morphologies before and after deformation. [19]

Steel cleanliness is an important topic that has received much attention in the literature. An extensive review on clean steel by Kiessling in 1980 summarized inclusion and trace element control and evaluation methods, especially for ingots. [20] More recent reviews of this topic have been made by Mu and Holappa (1992) [21] and by Cramb (1999) [14] which added extensive thermodynamic considerations. McPherson and McLean (1992) reviewed non-metallic inclusions in continuously casting steel, focusing on the inclusion types (oxides, sulfides, oxysulfides, nitrides and carbonitrides), inclusion distributions and methods to detect inclusions in this process.[22] Zhang and Thomas (2003) reviewed detection methods of inclusions, and operating practices to improve steel cleanliness at the ladle, tundish and continuous caster. [12] The rest of this report is an extensive review on inclusions in steel continuous casting, their sources, morphology, formation mechanisms, detection methods, and the effect of various continuous casting operations.

2. Inclusions in Steel

Non-metallic inclusions in steel are termed as indigenous inclusions and exogenous inclusions according to their sources.

2.1 Indigenous Inclusions

Indigenous inclusions are deoxidation products or precipitated inclusions during cooling and solidification of steel.

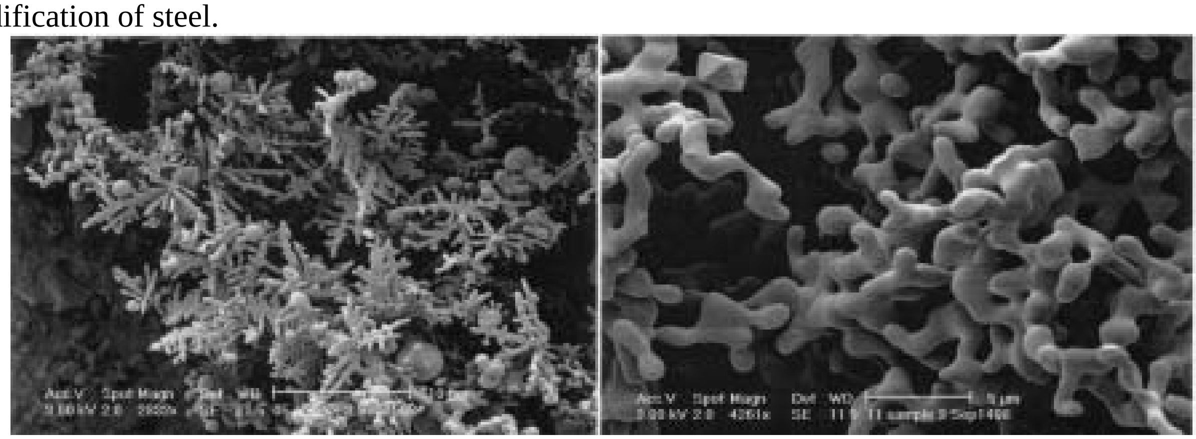


Fig. 4 Dendritic and clustered alumina inclusions (left), and coral-like alumina inclusions (right) formed during deoxidation of pure iron [42]

1) Deoxidation products [23-29) 30-34) 6, 35-41)]

Alumina (Al_2O_3) inclusions in LCAK steel, and silica (SiO_2) inclusions in Si-killed steel are generated by the reaction between the dissolved oxygen and the added aluminum and silicon deoxidants are typical deoxidation inclusions. Alumina inclusions are dendritic when formed in a high oxygen environment, as pictured in **figure 4**[42)]**.**

Cluster-type alumina inclusions from deoxidation or reoxidation, [42, 43)] as shown in **figure 5**[43)], are typical of aluminum killed steels. Alumina inclusions easily form three dimensional clusters via collision and aggregation due to their high interfacial energy. Individual inclusions in the cluster can be 1 -5 microns in diameter [39-41)].Before collision, breakup or aggregation with other particles, they may be in the shape of flower plate[44)] or (aggregated) polyhedral inclusions[45, 46)] (**figure 6**[44)]). Alternatively coral-like alumina inclusions (**figure 4**[42)]) are believed to result from "Ostwald-ripening" [39-41, 47-51)] of originally dendrtic or clustered alumina inclusions.

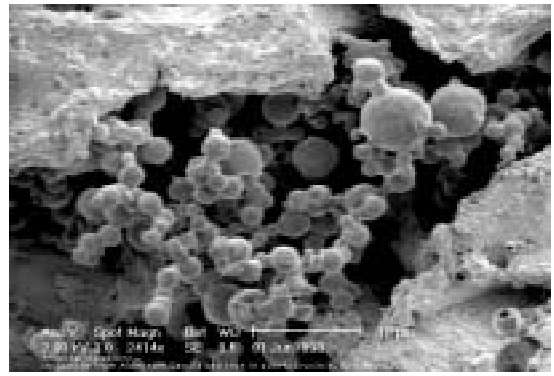


Fig. 5 Alumina cluster during deoxidation of low carbon steel by aluminum [43)]

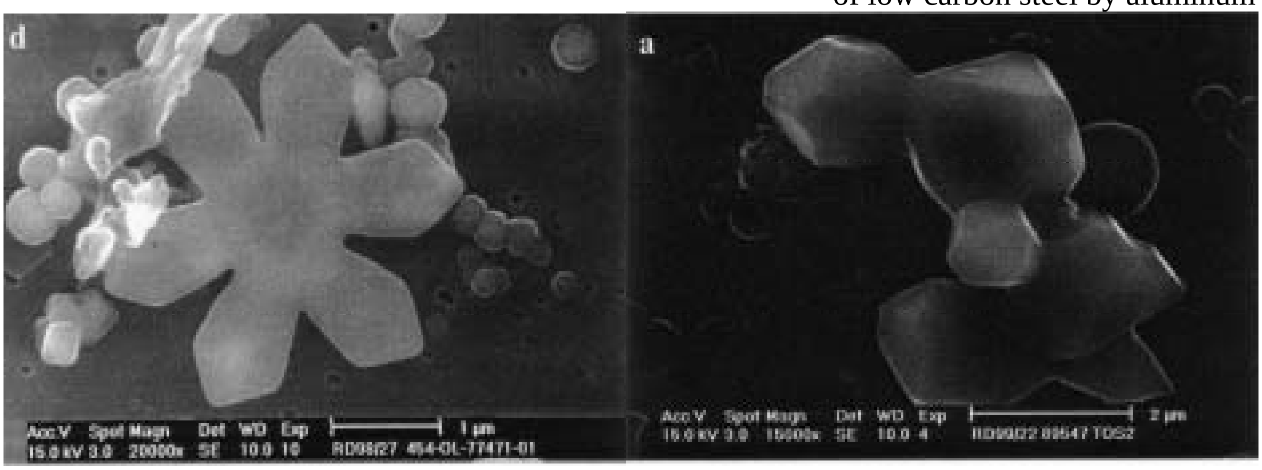


Fig. 6 Alumina inclusions formed during the deoxidation of LCAK steel (left: flower-like plate alumina; right: aggregation of small polyhedral particles) [44)]

Silica inclusions are generally spherical owing to being in a liquid or glassy state in the molten steel. Silica can also agglomerate into clusters as shown in **figure 7**[45, 52)].

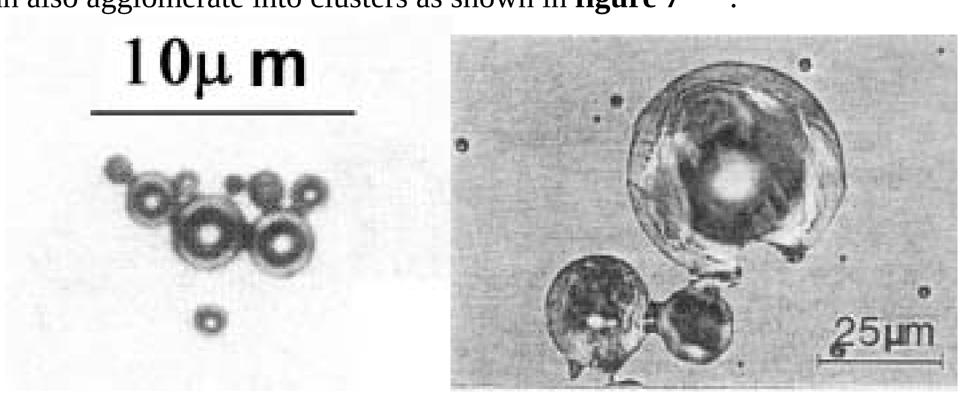


Fig. 7 Agglomeration of round silica inclusions [45) 52)]

2) Precipitated inclusions form during cooling and solidification of the steel [10, 33, 53-59)]

During cooling, the concentration of dissolved oxygen/nitrogen/sulfur in the liquid becomes larger while the solubility of those elements decreases. Thus inclusions such as alumina[59)], silica, AlN[54)], and sulphide precipitate. Sulphides form interdendritically during solidification, and often nucleate on oxides already present in the liquid steel. [60] These inclusions are normally small (<10μm).[53] **Figure 8** shows SEMs and TEMs of AlN inclusions in high Al ingot that are (a) plate-like, (b) feathery, (c) branched rod-like, and formed both during and after solidification of the matrix. [54]

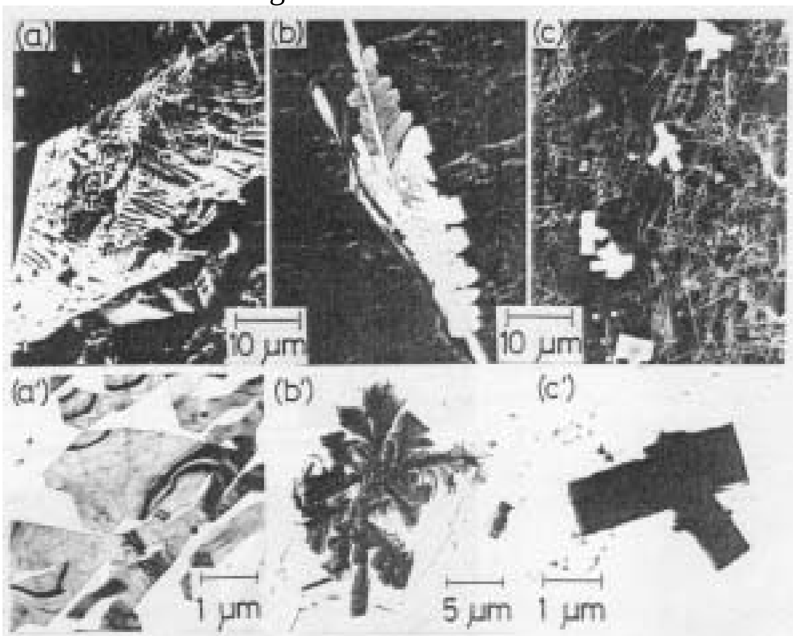


Fig. 8 SEMs and TEMs of ALN inclusions in high Al ingot ((a)(a') plate-like, (b) (b') feathery, (c)(c') branched rod-like). [54]

2.2 Exogenous inclusions

Exogenous inclusions arise primarily from the incidental chemical (reoxidation) and mechanical interaction of liquid steel with its surroundings (slag entrainment and erosion of lining refractory). In machining, they produce chatter, causing pits and gouges on the surface of machined sections, frequent breakage, as well as excessive tool wear. The frequency of exogenous inclusions in steel is exemplified in **figure 9** [61] by Slime extraction.

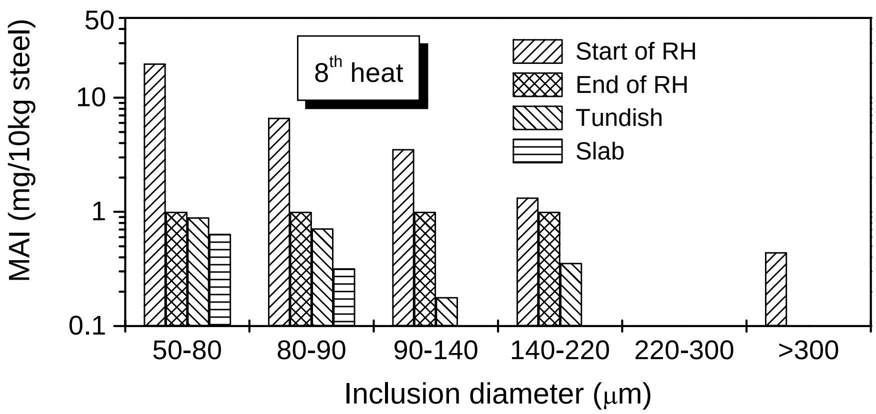


Fig. 9 Size distribution of large inclusions in a continuous casting slab [61]

Exogenous inclusions have the following common characteristics:

i). Large size: Inclusions from refractory erosion are generally larger than those from slag entrainment. [62]

ii). Compound composition/ multiphase, cause by the following phenomena:

- Due to the reaction between molten steel and SiO_2, FeO, and MnO in the slag and lining refractory, the generated Al_2O_3 inclusions may stay on their surface;

- As exogenous inclusions move, due to their large size, they may entrap deoxidation inclusions such as Al_2O_3 on their surface (Fig.10 right and Fig.11 right);
- Exogenous inclusions act as heterogeneous nucleus sites for precipitation of new inclusions during their motion in molten steel (Fig.11 left);
- Slag or reoxidation inclusions may react with the lining refractories or dislodged further material into steel.

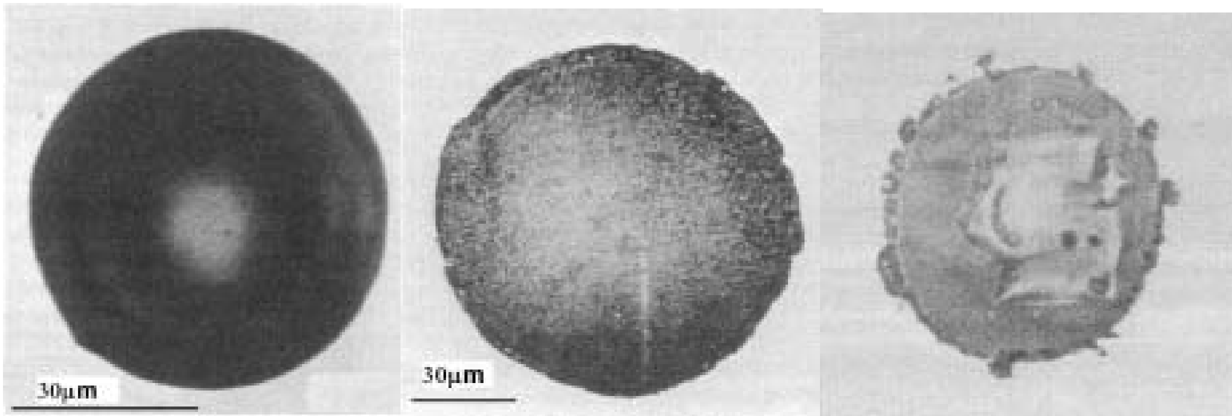
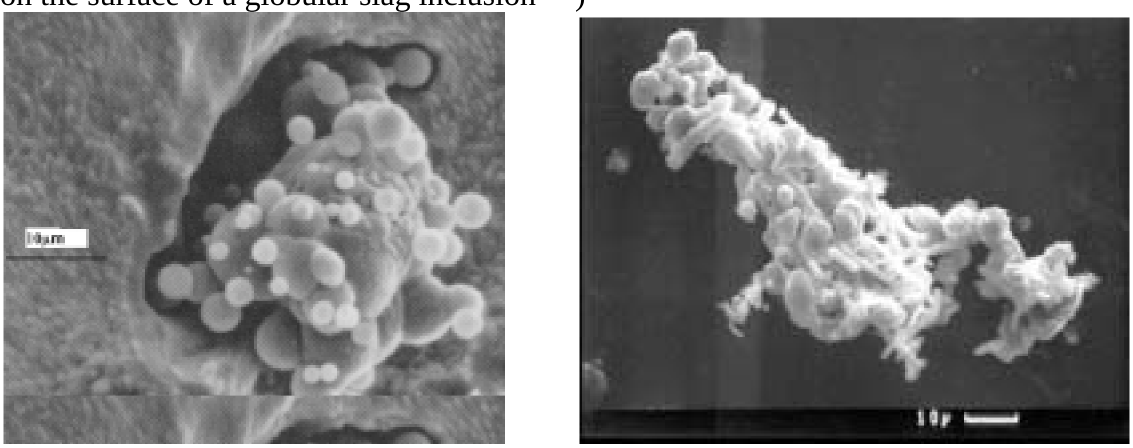


Fig.10 Typical exogenous inclusions in deep-drawing steel(Left: Vitreous inclusion (either alumina silicate or calcium-alumina silicate) [45]; Middle: Opaque inclusion (either alumina silicate or a mixed oxide phase which is very probably of exogenous origin) [45]; Right: Crystals of alumina on the surface of a globular slag inclusion [53])



(a) (b)

Fig.11 Inclusion clusters in LCAK steel (a[63], b[43])

iii). Irregular shape, if not spherical from slag entrainment or deoxidation product silica. The spherical exogenous inclusions are normally large (>50μm) and mostly multiphase, but the spherical deoxidation inclusions are normally small and single phase.
iv). Small number compared with small inclusions;
v). Sporadic distribution in the steel and not well-dispersed as small inclusions. Because they are usually entrapped in steel during teeming and solidification, their incidence is accidental and sporadic. On the other hand, they easily float out, so only concentrate in regions of the steel section that solidify most rapidly or in zones from which their escape by flotation is in some way hampered. Consequently, they are often found near the surface.
vi). More deleterious to steel properties than small inclusions because of their large size.

One question that overrides the source of these inclusions is why such large inclusions do not float out rapidly once they are in the ingot. Possible reasons are:

- Late formation during steelmaking, transfer, or erosion in the metallurgical vessels leaving insufficient time for them to rise before entering the casting;

- The lack of sufficient superheat [64];
- The fluid flow during solidification induces mold slag entrapment, or re-entrainment of floated inclusions before they fully enter the slag;

Exogenous inclusions are always practice related and their size and chemical composition often lead to the identification of their sources, and their sources are mainly reoxidation, slag entrainment, lining erosion and chemical reactions.

1). Exogenous inclusions from reoxidation

The most common form of large macro-inclusions from reoxidation found in steel such as alumina cluster are shown in Fig.4 and 5. Air is the most common source of reoxidation, which can occur in the following ways:

- Molten steel in the tundish mixes with air from its top surface at the start of pouring due to the strong turbulence. Oxide films on the surface of the flowing liquid are folded into the liquid, forming weak planes of oxide particles.
- Air is sucked into the molten steel at the joints between the ladle and the tundish, and between the tundish and the mold;
- Air penetrates into the steel from the top surface of the steel in the ladle, tundish, and mold during pouring.

During this kind of reoxidation, deoxidising elements, like Al, Ca, Si, etc, are preferentially oxidized and their products develop into non-metallic inclusions, generally one to two magnitudes larger than deoxidation inclusions [65] The solution to prevent this kind of reoxidation is to limit the exposure of air to the casting process: 1). Shrouding by inert gas curtain utilizing a steel ring manifold or porous refractory ring around the connections between the ladle and the tundish, and between the tundish and the mold; 2). Purging some gas into the tundish before pouring, and into the tundish surface during pouring; [66] 3). Controlling gas injection in the ladle to avoid eye formation.

Another reoxidation source is SiO_2, FeO, and MnO in the slags and lining refractories. By this reoxidation mechanism, inclusions within the steel grow as they near the slag or lining interface via $SiO_2/FeO/MnO+[Al] \rightarrow [Si]/[Fe]/[Mn]+Al_2O_3$. This leads to larger alumina inclusions with variable composition. This phenomenon further affects exogenous inclusions in the following ways:

- This reaction can erode and uneven the surface of the lining, which changes the fluid flow pattern near lining walls and can induce further accelerated breakup of the lining;
- A large exogenous inclusion of broken lining or entrained slag can entrap small inclusions, such as deoxidation products, and also act as a heterogeneous nucleus for new precipitates. This complicates the composition of exogenous inclusions.

To prevent reoxidation from slag and lining refractory, keeping a low FeO, MnO, and SiO_2 content is very important. It was reported that high Al_2O_3 or zirconia bricks containing low levels of free SiO_2 are more suitable.[67]

2). Exogenous inclusions from slag entrainment [62, 68) 69]

Any steelmaking or transfer operations involving turbulent mixing of slag and metal, especially during transfer between vessels, produces slag particles suspended in the steel. Slag inclusions, 10-300 μm in size, contain large amounts of CaO or MgO [64], and are generally liquid at the temperature of molten steel, so are spherical in shape (**figure 10** [45, 53] and **figure 12**[61]). Using a "H-shaped" tundish and pouring it through two ladles diminishes slag entrainment during the ladle change period [70] For steel continuous casting process, the following factors affect slag entrainment into the molten steel:

- Transfer operations from ladle to tundish and from tundish to mold especially for open pouring;
- Vortexing at the top surface of molten steel. [71] The vortex when molten steel is at low level can be avoided in many ways such as shutting off pouring before the onset of vortexing.
- Emulsification and slag entrainment at the top surface especially under gas stirring above a critical gas flow rate. [72]
- Turbulence at the meniscus in the mold; [72-75]

- Slag properties such as such as interfacial tension and slag viscosity. [76)]

As an example, mold slag can be entrained into molten steel due to: 1) turbulence at the meniscus ((1) in **figure 13**); 2) vortexing ((3) in Fig.13)[77)]; 3) emusification induced by bubbles moving from the steel to the slag ((2) and (4) in Fig.13) [78)] ; 4) sucking in along the nozzle wall due to pressure difference ((5) in Fig.13); 5) high velocity flow that shears slag from the surface ((1) in Fig.13); 6) level fluctuation ((2) in Fig.13)[79, 80)] .

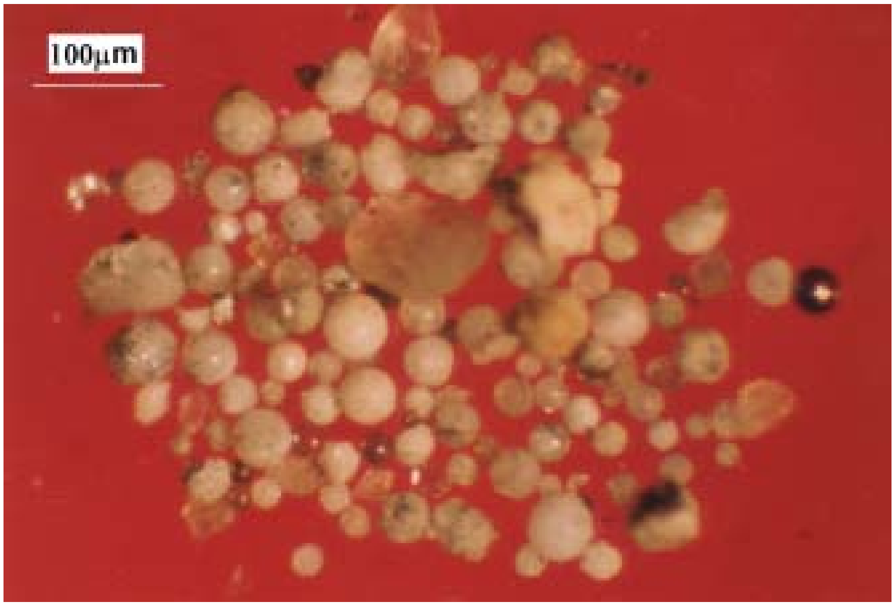


Fig.12 Slag inclusions in ladle steel extracted by Slime method [61)]

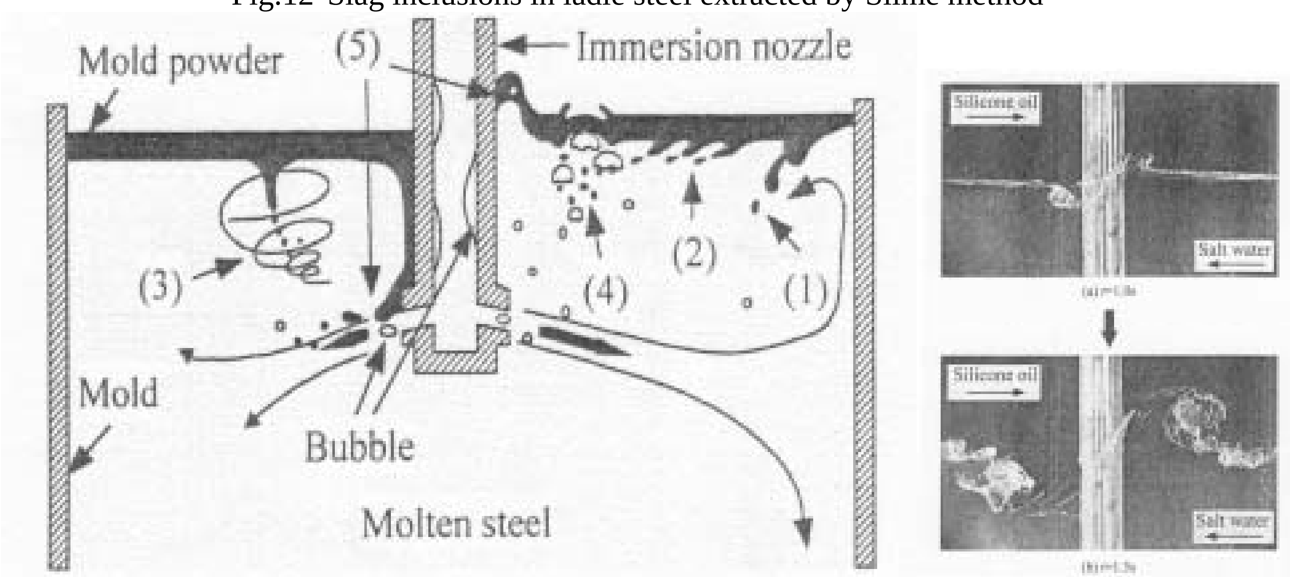


Fig. 13 Schematic of mold powder entrapment (left) and interface deformation near cylinder (right) [81)]

The interfacial tension between the steel and the molten casting powder determines the height of the steel meniscus, and the ease of flux entrainment. [82)] Specifically an interfacial tension of 1.4N/m for a lime-silica-alumina slag in contact with pure iron yields a meniscus height of about 8 mm (0.3in). The interfacial tension is reduced to a low value by surface-active species such as sulphur, or by an interfacial exchange reaction such as the oxidation of aluminum in steel by iron oxide in the slag. The very low interfacial tension associated with a chemical reaction can provide spontaneous turbulence at the interface, through the Marangoni effect. Such turbulence can create an emulsion at the interface, creating undesirable beads of slag in the steel.

3). Exogenous inclusions from erosion/corrosion of lining refractory

Erosion of refractoies, including well block sand, loose dirt, broken refractory brickwork and ceramic lining particles, is a very common source of large exogenous inclusions which are typically solid and related to the materials of the ladle and tundish themselves. They are generally large and irregular-shaped [46, 83-86], as shown in **figure 14**[46]**.** Exogenous inclusions may act as sites for heterogeneous nucleation of alumina and might include the central particle pictured in Fig. 10 and 11**,** or aggregate with other indigenous inclusions as shown in **figure 11b** [43]. The occurrence of refractory erosion products or mechanically introduced inclusions can completely impair the quality of otherwise very clean steel.

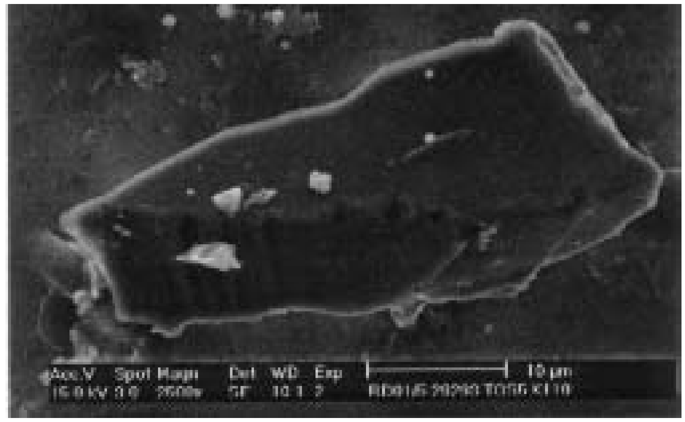


Fig.14 Typical exogenous inclusions from lining refractory

Some researchers did immersion experiments of lining samples into a melt (steel melt [87-92] or slag melt[93-95]) to investigate the erosion process. It was reported that "glazed refractories" and "reaction layers at the surface of bricks" formed with molten steel at 1550-1600^{o}C. [90, 94, 96] Large inclusion clogs on the surface of the lining can also be released into the molten steel. **Figure 15** shows the build-up at the ladle side-wall. [97]

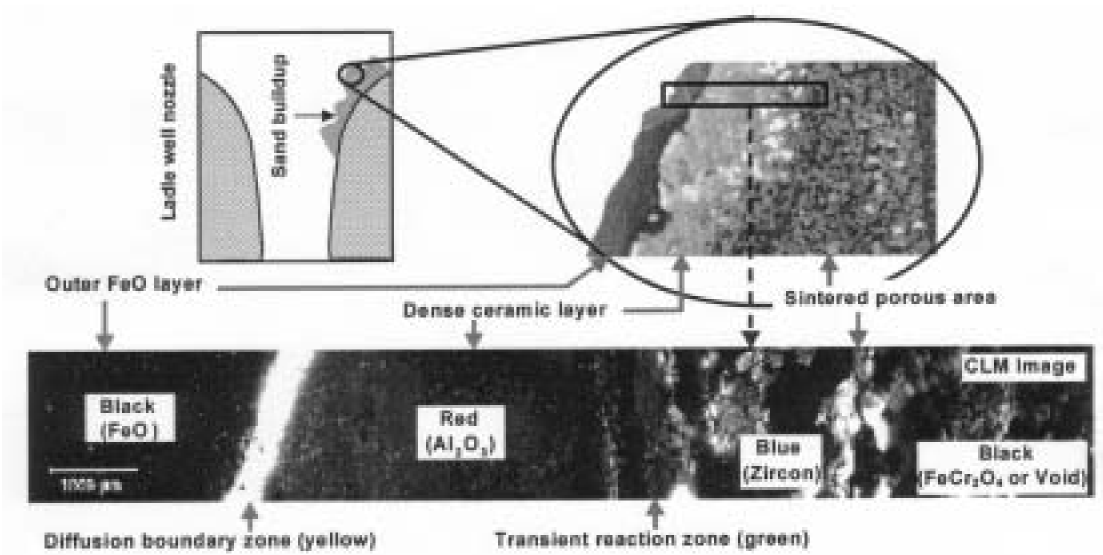


Fig.15 Ladle sand buildup block [98]

Lining erosion generally occurs at areas of turbulent flow, especially when combined with reoxidation, high pouring temperatures, and chemical reactions. The following parameters strongly affect lining erosion:

- Some steel grades are quite corrosive (such as high manganese and grades that are barely killed and have high soluble oxygen contents) and attack lining bricks.
- Reoxidation reactions, such as that the dissolved aluminum in the molten steel reduce SiO_2 in the lining refractory, generating FeO based inclusions which are very reactive and wet the lining materials, leads to erosion of lining refractory at areas of high fluid turbulence. The extent of this reaction can be quantified by monitoring the silicon content of the liquid steel. This oxygen may also come from carbon monoxide, when carbon in the refractory reacts with binders and impurities. [99]

- Brick composition and quality. Brick quality has a significant effect on steel quality. The results of corrosion tests on various brick materials with high manganese steel are illustrated in **figure 16**. [67] At Kawasaki Steel Mizushima Works, three types of materials (high Al_2O_3, Al_2O_3-SiC-C, and MgO-C with a wear rate of 1.0, 0.34, 0.16 mm/heat respectively) have been adopted at the slag line, where the refractory tends to be damaged by erosive tundish flux and slag, and the MgO-C brick shows the highest durability among the three.[100] Manganese oxide preferentially attacks the silica containing portions of the refractory. Very high purity Al_2O_3 and ZrO_2 grains can withstand attack by manganese oxide. [87]

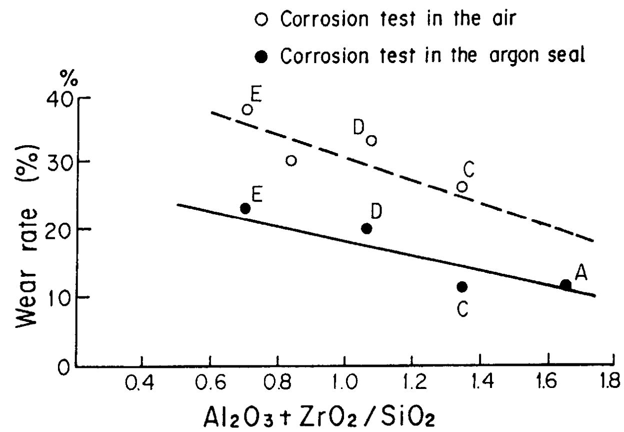


Fig.16 Effect of brick materials on wear rate (high manganese steel)

- Rapid refractory erosion from high manganese steels can be constrained by: 1). Using very high purity (expensive) ZrO_2 or Al_2O_3 refractories [67, 87]; 2). Minimizing oxygen by fully killing the steel with a strong deoxidant such as Al or Ca, and preventing air absorption. Silica-based tundish linings are worse than magnesia-based sprayed linings (Baosteel[101], Saarstahl Steelworks Volklingen GmbH [102], Bethlehem Steel Coporation [103], Inland Steel[104], and some steel plants in Argentina [105]). High alumina refractories were suggested as being the most promising. Incorporating calcia into the nozzle refractory may help by liquefying alumina inclusions at the wall, so long as CaO diffusion to the interface is fast enough and nozzle erosion is not a problem.[99, 106-108] Nozzle erosion can be countered by controlling nozzle refractory composition, (eg. avoid Na, K, and Si impurities), or coating the nozzle walls with pure alumina, BN, or other resistant material.[99, 109] The refractory at the surface of the shroud walls should be chosen to minimize reactions with the steel that create inclusions and clogging.
- Excessive velocity of molten steel along the walls in the tundish, such as the inlet zone. A pad can be used to prevent the bottom of the tundish from erosion, as well as controlling the flow pattern. It has been suggested that liquid steel velocities over 1m/s are dangerous with regard to erosion. [110]
- Excessive contact or filling time and high temperature worsen erosion problems. During long holding period in the ladle, the larger inclusions can float out into the ladle slag. However the longer the steel is in contact with the ladle lining, the more tendency there will be for ladle erosion products. Solutions are based upon developing highly stable refractories for a given steel grade, developing dense wear resistant refractory inserts for high flow areas and preventing reoxidation. [62]

4). Exogenous inclusions from chemical reactions

Chemical reactions produce oxides from inclusion modification when Ca treatment is improperly performed.[3, 6, 111-113] Identifying the source is not always easy, as for example, inclusions containing CaO may also originate from entrained slag.[111]

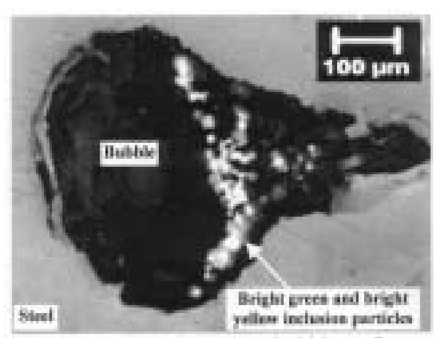


Fig. 17 Inclusion clusters on a bubble surface

2.3 Inclusion Agglomeration and Clogging

The agglomeration of solid inclusions can occur on any surface aided by surface tension effects, including on refractory and bubble surfaces as shown in **figure 17** [98]. The high contact angle of alumina in liquid steel (134-146 degrees) encourages an inclusion to attach itself to refractory in order to minimize contact with steel. High temperatures of 1530°C enable sintering of alumina to occur. [52, 63, 114, 115] Large contact angle and larger inclusion size favor the agglomeration of inclusions (**figure 18**[25]). Due to collision and agglomeration, inclusions in steel tend to grow with increasing time (**figure 19**[52]) and temperature [116]. Inclusion growth by collision, agglomeration and coagulation in ingot was investigated by many researchers.[114, 116-121] Taniguchi and Kikuchi reviewed the collision mechanisms of particles in fluids. [118] The numerical simulation of inclusion nucleation starting from deoxidant addition and growth by collision and diffusion from nano-size to micro-size is reported.[39, 40]

The fundamentals of alumina sintering into clusters [52, 63, 114, 115] needs further investigation, though some researchers used fractal theory to describe the cluster morphology (features).[120, 122] The most obvious example of inclusion agglomeration on the surface of lining refractories is nozzle clogging during steel continuous casting and this will be discussed later.

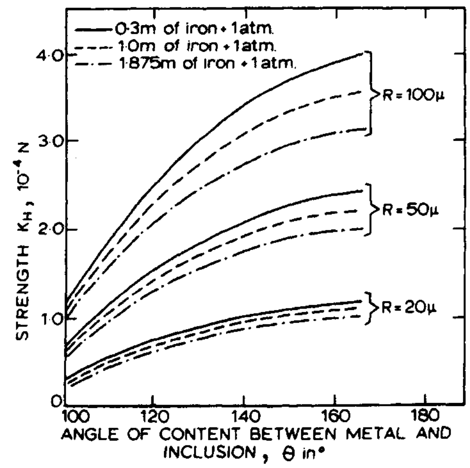


Fig.18 Effect of the angle of contact, radius, and pressure on the strength of two solid particles immersed in steel

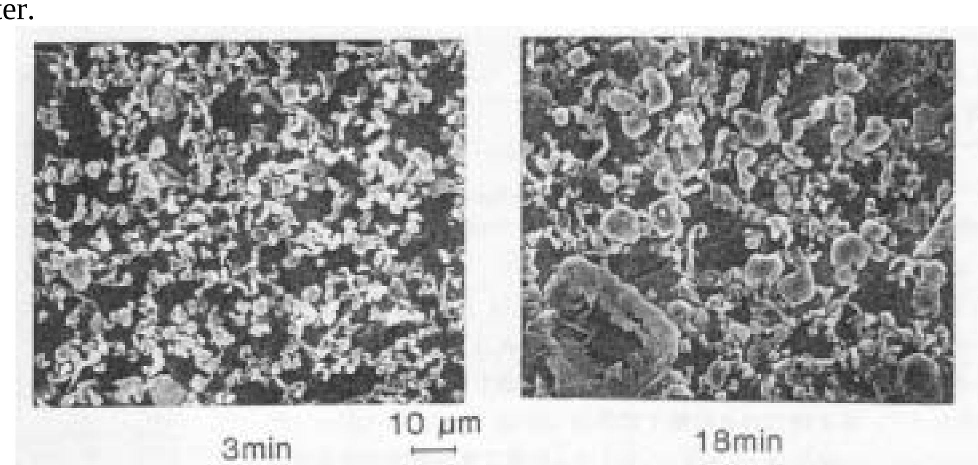


Fig.19 Comparison between inclusions in molten steel obtained at 3 min and 18min after the addition of aluminum in RH degasser [52]

2.4. Effect of fluid flow and solidification on inclusions

Inclusion distribution in continuous casting steel is affected by fluid flow, heat transfer and solidification of the steel. A popular index for inclusion entrapment is the critical advancing velocity of the solidification front, which is affected by the following parameters: inclusion shape, density, surface energy, thermal conductivity, cooling rate (solidification rate[83]), and protruding conditions of the solidification front[83]. It is reported that entrapment is controlled by drag and interfacial forces (Van der Waals force).[123-127] It was suggested that the faster the solidification rate, the greater the probability of entrapment. The probability of entrapment decreases with increasing solidification time, less segregation, smaller protrusions on

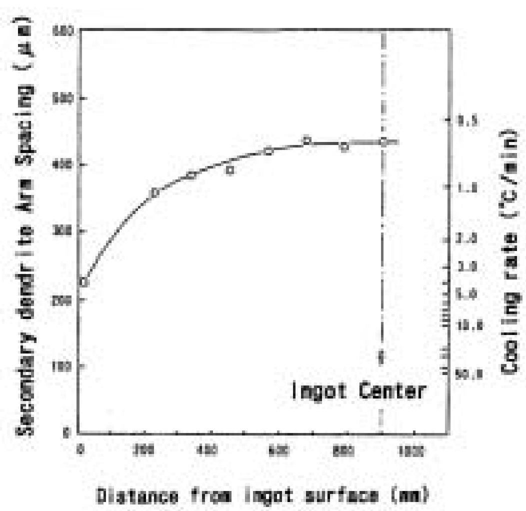


Fig.20 Secondary dendrite arm spacing of 1800mm ϕ ESR ingot

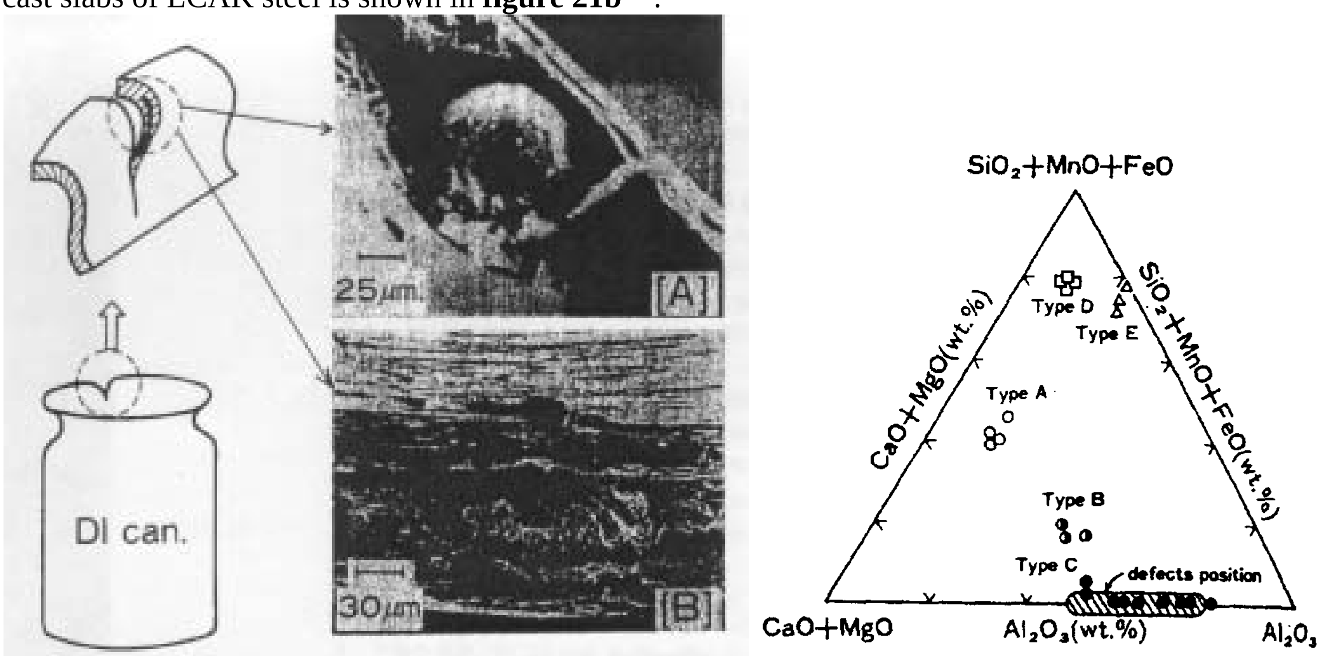
the solidification front. [83] The dendrite arm spacings have a big effect on the entrapment of inclusions, is related to the phenomena of pushing, engulfment or entrapment. [127] **Figure 20** shows how the secondary dendrite arm spacing increases with time and distance from the surface of an ESR ingot. [128] Particles, smaller than the arm spacing are easily entrapped when they touch the front.

3 Defects in Steel Products

Inclusions can generate many defects in the steel product. Three books (sections) have discussed defects in steel products in depth. British Iron and Steel Research Association compiled surface defects in ingots and their products in 1958 [129], and defined the causes of continuous casting defects in 1967[130]. Ginzburg and Ballas reviewed the defects in cast slabs and hot rolled products, many of which are related to inclusions. [1] Some of the defects in steel products are related to the process of rolling such as scaling defects. [1] Here, only defects related to inclusions from continuous casting casting are reviewed.

3.1. Flange Cracked Cans [97, 131-134]

LCAK steel cans suffer from cracked flanges due to lack of formability, while axels and bearings suffer fatigue life problems. Inclusions causing flange cracks in manufacturing (drawing and ironing) cans are typically 50-150 µm in size, and are CaO-Al_2O_3 in compositions (**figure 21a** [132]). The main source of these inclusions is continuous casting tundish-slag, which is spattered into the molten steel during ladle changing.[132] The composition of this defect compared with other inclusions in continuous cast slabs of LCAK steel is shown in **figure 21b**[132].



(a) (b)

(a) Inclusions morphology and composition (inclusion A and B: CaO 15-30%, Al_2O_3 65-85%, SiO_2 <3.6%, MgO < 1.0%, Na_2O2-8%.) (b) Phase relation of inclusions extracted from cast slabs (Frequency of inclusion types in CC slab: type A (Ca-Al-Si-(Na)-O) 25%, type B(Ca-Al-Si-(Na)-O):10%; Type C: (Ca-Al-(Na)-O):26%; type D(Si-Ti-Ca-Al-Mn-O):32%; type E: (Si-O):8%) [132]

Fig.21 Inclusions originating frange cracks in draw and ironing [132]

Byrne and Cramb [97, 133, 134] reported two types of exogenous inclusions in this defect. The first contains strong traces of calcium, magnesium, aluminum and oxygen (from slag, or the erosion and entrapment of the build-up materials found on the ladle walls and in nozzle clogs). The second contains strong traces of calcium, sodium and aluminum and weaker traces of magnesium and oxygen (from mold slag).

2). Slag spots on cold rolled sheet [97, 98, 133-135)]

Two types of exogenous slag spots have been observed. The first [97, 98, 133, 134)] contained calcium, magnesium, aluminum and oxygen and the second [97, 133, 134)] contained calcium, sodium, magnesium, aluminum and oxygen. Slag spots are chemically similar to the inclusions found from the flange crack studies. An example of slag spot on a cold rolled sheet is given in **figure 22** [98)].

3). Line defect on cold rolled sheet

Line defects appear on the surface of finished strip product, with several tens of micrometers to millimeter width and as long as 0.1-1 meter [136)]. This surface defect is believed to result from nonmetallic inclusions caught near the surface of the slab (<15mm from the surface). This defect is also called slivers, or called pencil pipe if coupled with elongated bubbles. Slivers plague LCAK steel sheet for automotive applications, causing both cosmetic surface imperfections and formability problems. There are three major types of line defects (slivers) on cold rolled sheets from steelmaking and casting sources: (a) iron oxide [97, 133, 134)], (b) alumina [97, 133, 134, 137, 138)] and (c) exogenous oxide inclusions. [84, 95, 97, 98, 133, 134, 136-138)] Examples are given in **figure 23, 24**, and **25**. Some slivers was found from mold slag entrainment, such as at Inland Steel,[104)] National Steel,[139)] and Kawasaki Steel.[100)], by using tracer (SrO_2) studies [97, 133, 134)], by using La as a tracer [137)], and by composition comparison between sliver and mold slag [138)]. Mold fluxes not melting homogenously tend to have several phases with areas of high melting and low viscosity oxides, which are available for entrapment. Mold fluxes during strand start-up do not immediately supply the necessary liquid layer essential for lubrication, and consist of a combination of dry powder, semi-molten and molten flux instead. This combination is readily entrapped in the first slab. [140)]

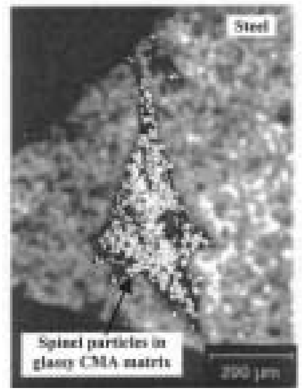


Fig.22 A slag spot defect on a cold-rolled sheet

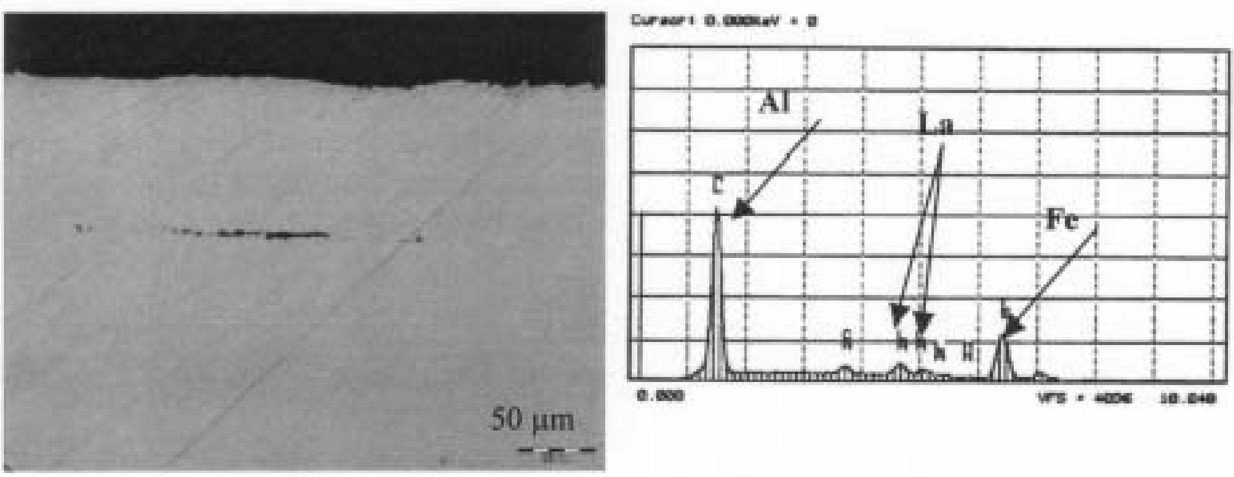


Fig.23 Pencil pipe defect detected below the surface of a rolled sheet as observed on a cross section and its chemical composition [137)]

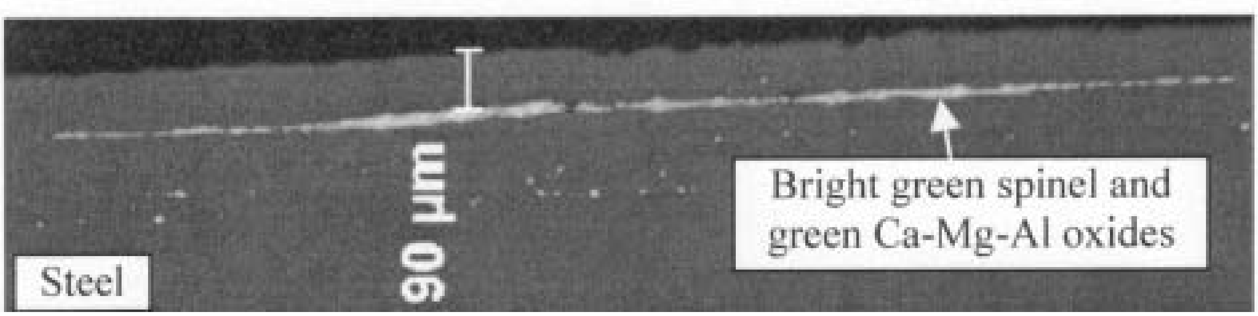


Fig.24 Inclusion sliver in the longitudinal section of a sheet product [98)]

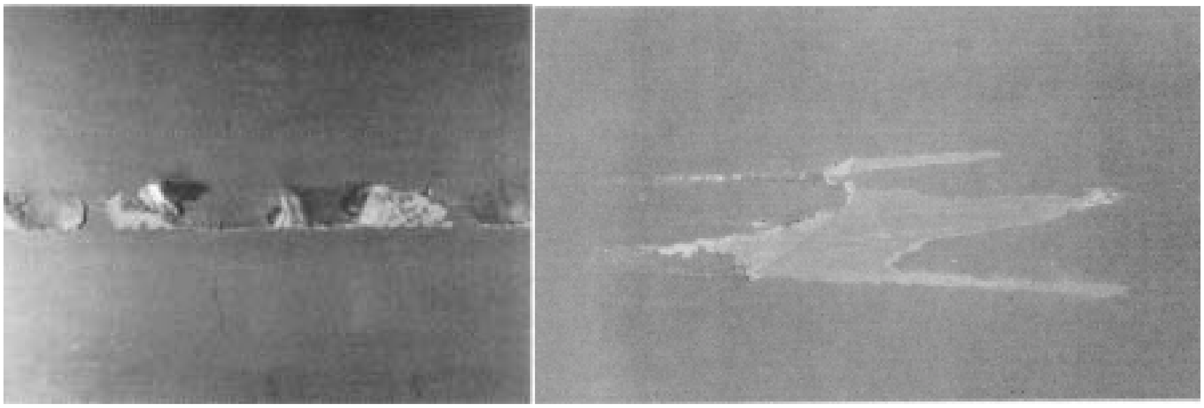


Fig. 25 Very serious sliver defects (Left: T-304 (stainless steel first slab) sheet [140], right: [136])

If hard particles exist within the inclusions in these line defects, such as galaxite, chrome-galaxite or spinels, then polishing the sheet may dislodge some of them and cause scratch marks. [84] If sliver defect is very severe as shown in Fig.25, the outer steel layer may tear off. **Figure 26** [95] shows a casting defect in rolled steel found at the pickler, and a photomicrograph of the inclusions which caused it. EPMA detection show this defect is from entrained mold slag.

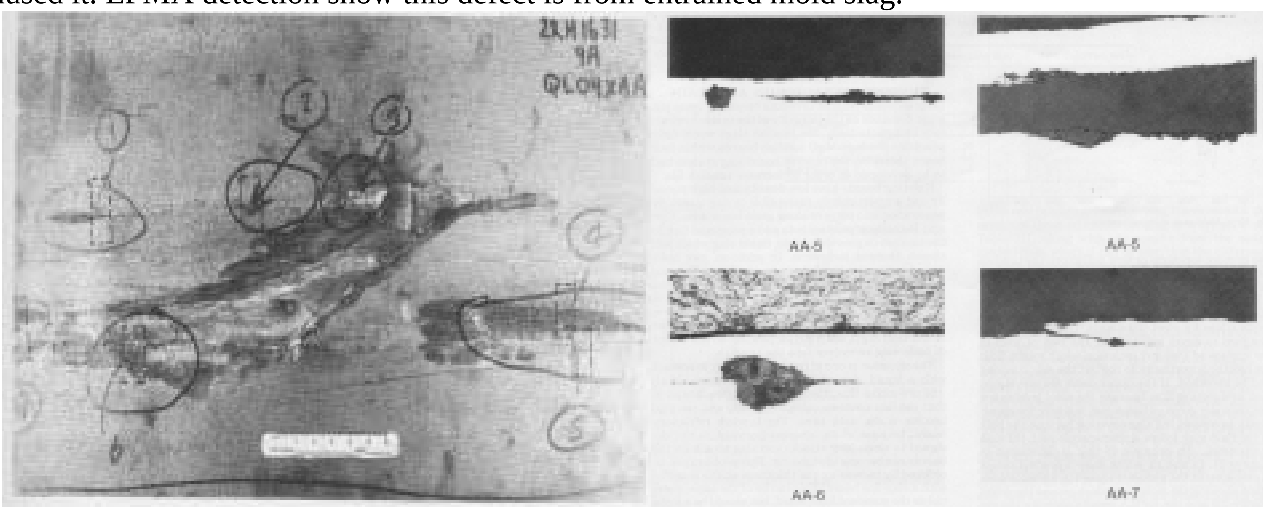


Fig.26 Defective pickle line material and Photomicrograph of inclusions found in sample locations 5-7 (Composition of 6: Si. Fe, Al, Ca, Na, O)[95]

A serious pencil pipe defect called pencil blister defects on the finished product [136] is a tubular shape surface defect, with a smooth slightly raised surface, typically ~1mm wide and 150-300mm long [136, 137] (**figure 27**[136]). It is believed to form during annealing when an entrapped bubble elongated into a gas pocket expands, and inclusions attached to the surface of the bubble during its motion through molten steel usually worsen this defect. An example of a bubble attached with inclusions is shown in Fig. 17. [98] Zhang and Taniguchi did an extensive literature review [141, 142] and water model study [143] on the interaction between inclusions and bubbles in molten steel.

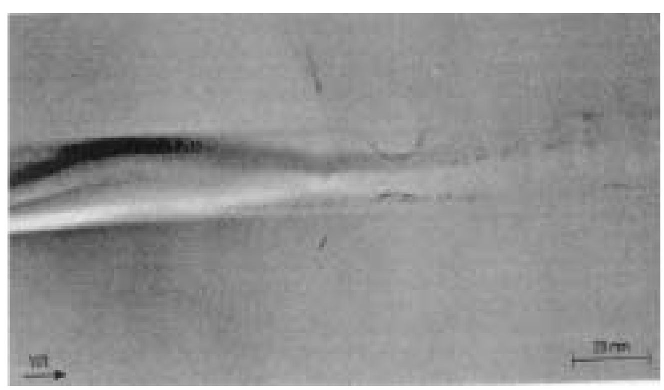


Fig.27 Typical pencil blister defect on the surface of a sheet

METHODS TO DETECT INCLUSIONS

The amount, size distribution, shape and composition of inclusions should be measured at all stages in steel production. Measurement techniques range from direct methods, which are accurate but costly, to indirect methods, which are fast and inexpensive, but are only reliable as relative indicators. Dawson et al reviewed 9 methods in 1988 by dividing them into two categories of "off-line" methods and "online" methods. [144-151)] Zhang and Thomas reviewed around 30 methods to detect inclusions in steel. [12)] Several recent methods are reviewed and added here.

1. Direct Methods

There are several direct methods to evaluate steel cleanliness, which are summarized as follows.

1.1. Inclusion Evaluation of Solid Steel Sections

Several traditional methods directly evaluate inclusions in a two-dimensional section through solidified product samples. The last five of these methods add the ability to measure the composition of the inclusions.

1) Metallographic Microscope Observation (MMO) [20, 145, 152)]: Examples are as shown in Fig.7 and 10. This method is can only reveal the 2-dimensional section of an inclusion, however, inclusions are 3 dimensional in nature.
2) Image Analysis (IA)[5, 20, 153)]: This enhancement to MMO improves on eye evaluation by using high-speed computer evaluation of video-scanned microscope images to distinguish dark and light regions based on a gray-scale cutoff.
3) Sulfur Print[2, 101)]: This popular and inexpensive macrographic method distinguishes macro-inclusions and cracks by etching sulfur-rich areas. It is subject to the same problems as other 2-D methods.
4) Scanning Electron Microscopy (SEM) [42, 43)]: This method clearly reveals the three-dimensional morphology and the composition of each inclusion (Fig.4-6, 8, 11 and 14). Composition can also be measured with Electron Probe Micro Analyzer (EPMA).[154)] Extensive sample preparation is required, however, to find and expose the inclusion(s).
5) Optical Emission Spectrometry with Pulse Discrimination Analysis (OES-PDA)[2, 18, 155, 156)]: The OES method analyzes elements dissolved in liquid steel. Inclusions cause high-intensity spark peaks (relative to the background signal from the dissolved elements), which are counted to give the PDA index.[157)]
6) Laser Microprobe Mass Spectrometry (LAMMS)[158)]: Individual particles are irradiated by a pulsed laser beam, and the lowest laser intensity above a threshold value of ionization is selected for its characteristic spectrum patterns due to their chemical states. Peaks in LAMMS spectra are associated with elements, based on comparison with reference sample results.
7) X-ray Photoelectron Spectroscopy (XPS)[154)]: This method use x-rays to map the chemical state of individual inclusions larger than 10μm.
8) Auger Electron Spectroscopy (AES)[154)]: This method use electron beams to map the composition of small areas near the surface of flat samples.
9). Cathodoluminescence Microscope[98)]: Under microscope, the steel or lining sample section is stimulated by a cathode-ray (energetic electron-beam), to induce cathodoluminescence (CL). The color of CL depends on the metal ions type, electric field, and stress, allowing inclusions to be detected. Examples are given in Fig.17 and 22.

1.2. Inclusion Evaluation of Solid Steel Volumes

Several methods directly measure inclusions in the three-dimensional steel matrix. The first four of these scan through the sample with ultrasound or x-rays. The last four of these volumetric methods first separate the inclusions from the steel.

1) Conventional Ultrasonic Scanning (CUS) [8, 9, 159, 160] :The transducer (typically a piezoelectric) emits a sound pressure wave that is transferred into the sample with the aid of a coupling gel. The sound waves propagate through the sample, reflect off the back wall and return to the transducer. The magnitude of the initial input pulse and the reflected signals are compared on an oscilloscope to indicate the internal quality of the sample. Obstructing objects in the path of the sound will scatter the wave energy. This nondestructive method detects and counts inclusions larger than 20μm in solidified steel samples.
2) Mannesmann Inclusion Detection by Analysis Surfboards (MIDAS)[161)]: Steel samples are first rolled to remove porosity and then ultrasonically scanned to detect both solid inclusions and compound solid inclusions / gas pores. This method was recently renamed as the Liquid Sampling Hot Rolling (LSHP) method.[2, 162, 163)]
3) Scanning Acoustic Microscope (SAM)[164)]: In this method, a cone-shaped volume of continuous-cast product is scanned with a spiraling detector, such as a solid ultrasonic system, which automatically detects inclusions at every location in the area of the sample surface, including from surface to centerline of the product.
4) X-ray Detection [83, 148, 165-167)]: Inclusions images are detected by their causing variation in the attenuation of x-rays transmitted through the solid steel. An inclusion distribution can be constructed by dividing a sample into several wafers and subjecting each to conventional x-rays to print penetrameter radiograghs for image analysis.
5) Chemical Dissolution (CD) [168) 63) 146) 42)]: Acid is used to dissolve the steel and partially extract inclusions. The inclusion morphology and composition can be detected by another method like SEM, or be fully extracted by dissolving all the steel sample. The three dimensional nature of inclusions can be revealed by this method as shown in Fig.4-6, 8, 11 and 14. The disadvantage is that the acid will dissolve away FeO, MnO, CaO, MgO in the inclusions. Thus this method is good to detect Al_2O_3 and SiO_2 inclusions.
6) Slime (Electrolysis) [101, 147, 157, 169)]: This method is also called Potentiostatic Dissolution Techniques. A relatively large (200g – 2kg) steel sample is dissovled by applying electric current through the steel sample immersed in a $FeCl_2$ or $FeSO_4$ solution. This method was used to reveal the individual, intact inclusions in Fig. 9 and 12. One disadvantage of this method is the cluster inclusions possibly break into separate particles after extraction from steel.
7) Electron Beam melting (EB)[170)]: A sample of Al-killed steel is melted by an electron beam under vacuum. Inclusions float to the upper surface and form a raft on top of the molten sample. The usual EB index is the specific area of the inclusion raft. An enhanced method (EB-EV - Extreme Value) has been developed to estimate the inclusion size distribution.[171)]
8) Cold Crucible (CC) melting[2)]: Inclusions are first concentrated at the surface of the melted sample as in EB melting. After cooling, the sample surface is then dissolved, and the inclusions are filtered out of the solute. This method improves on EB melting by melting a larger sample and being able to detect SiO_2.
9) Fractional Thermal Decomposition (FTD)[157)]: When temperature of a steel sample exceeds its melting point, inclusions can be revealed on the surface of the melt and decomposed. Inclusions of different oxides are selectively reduced at different temperatures, such as alumina-based oxides at 1400 or 1600^oC, or refractory inclusions at 1900^oC. The total oxygen content is the sum of the oxygen contents measured at each heating step.
10) Magnetic Particle Inspection (MPI) [146, 172, 173)]: This method also called magnetic leakage field inspection can locate inclusions larger than 30μm in sheet steel products. The test procedure consists of generating a homogeneous field within the steel sheet that is parallel to the sheet surface. If an inhomogeneity (such as an inclusion or a pore) is present, the difference in magnetic susceptibility will force the magnetic flux field to bend and extend beyond the surface of the sheet. The major disadvantage is poor resolution of inclusions that are close together.

1.3 Inclusion Size Distribution After Inclusion Extraction

Several methods can find 3-dimensional inclusion size distributions after the inclusions are extracted from the steel using a method from 2.1.2 5)-7).

1) Coulter Counter Analysis[174)]: This method, by which particles flowing into this sensor through its tiny hole are detected because they change the electric conductivity across a gap, measures the size distribution of inclusions extracted by Slime and suspended in water.[174)]
2) Photo Scattering Method[175, 176)]: Photo-scattering signals of inclusions (that have been extracted from a steel sample using another method such as slime) are analyzed to evaluate the size distribution.
3) Laser-Diffraction Particle Size Analyzer (LDPSA)[2)]: This laser technique can evaluate the size distribution of inclusions that have been extracted from a steel sample using another method such as Slime.

1.4. Inclusion Evaluation of Liquid

There are several approaches can be used to detect the inclusion amount and size distribution in the molten melts.

1) Ultrasonic Techniques for Liquid System [151, 177-179)]: This method captures the reflections from ultrasound pulses to detect on-line inclusions in the liquid metal.
2) Liquid Metal Cleanliness Analyzer (LIMCA) [179-181)]: This on-line sensor uses the principle of the Coulter Counter to detect inclusions directly in the liquid metal. Commonly this method is used for aluminum and other metals, and it is still under development for steel.
3) Confocal Scanning Laser Microscope [126, 182, 183)]: This new *in-situ* method can observe the behavior of individual inclusions moving on the surface of the molten steel, including their nucleation, collision, agglomeration, and pushing by interfaces. The detected alumina inclusion clustering process on a melt surface by this method is shown in **figure 28**. [182)]

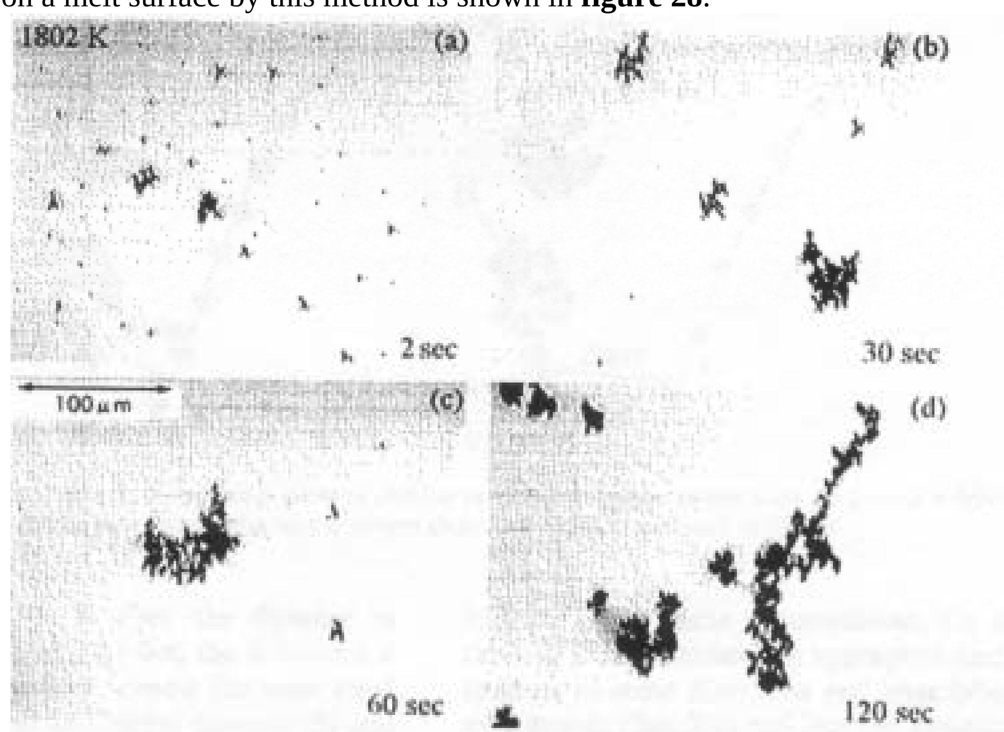


Fig.28 Alumina inclusion clustering process on a melt surface by confocal scanning laser microscope observation [182)]

4). Electromagnetic Visualization (EV) [184)]: This Lorentz-force-based detection system is used to accelerate inclusions to the top free surface of the melted sample of f metals and highly conductive opaque fluids. The technique has better resolution than other on-line methods.

2. Indirect Methods

Owing to the cost, time requirements, and sampling difficulties of direct inclusion measurements, steel cleanliness is generally measured in the steel industry using total oxygen, nitrogen pick-up, and other indirect methods.

2.1. Total Oxygen Measurement [185-187]

The total oxygen (T.O.) in the steel is the sum of the free oxygen (dissolved oxygen) and the oxygen combined as non-metallic inclusions. Free oxygen, or "active" oxygen can be measured relatively easily using oxygen sensors. It is controlled mainly by equilibrium thermodynamics with deoxidation elements, such as aluminum. Because the free oxygen does not vary much (3-5ppm at 1600^{o}C for Al-killed steel [188, 189]), the total oxygen is a reasonable indirect measure of the total amount of oxide inclusions in the steel. Due to the small population of large inclusions in the steel sample. Thus, T.O. content really represents the level of small oxide inclusions only. The T.O. measured from liquid samples roughly correlates with the incidence of slivers in the product, as shown in **Figure 29**.[187] In particular, tundish samples are commonly taken to indicate cleanliness for slab dispositioning. For example, Kawasaki Steel requires the T.O. in tundish samples <30ppm to warrant shipment of cold-rolled sheet without special inspection. [186] The T.O. levels in LCAK steel at each processing step at several steel plants are compiled in **Table 2**. Blanks in this table mean no data was available.

The following general conclusions can be derived from Table 3:

1) T.O. in LCAK steel has steadily decreased with passing years, as new technology is implemented. For example, T.O. at Nippon Steel dropped from 40-50 ppm in 1970's [190], to 20 ppm in 1990's [191];
2) Plants with RH degassing achieve lower T.O. (10-30ppm) than plants with ladle gas-stirring (35-45 ppm).
3) T.O. generally drops after every processing step: 40ppm (ladle), 25ppm (tundish), 20ppm (mold), and 15ppm (slab).

Table 2. Total oxygen (ppm) reported during various processing steps for LCAK steel

Steel Works	Refining	Ladle	Tundish	Mold	Slab	Year	Ref.
America							
Inland No.4 BOF shop	LMF	30	24	21	15	1990	104)
	RH-OB	60-80	8-30			2003	192)
Armco Steel, Middletown Works		60-105	15-40 mean 25		16.9-23.8	1991	186)
Armco Steel, Ashland Works			16.3			1993	193)
US Steel, Lorain Works					13-17	1991	194)
National Steel, Great Lake					<31-36	1991	186)
				20-40		1994	139)
			25-50 mean 40			1995	195)
Some plant in North America		20-35		20-30	10-15	1991	196)
Timken Steel, Harrison Plant				20-30		1991	164)
Usiminas, Brazil					20 (13*)	1993	185)
Dofasco, Canada			19		13	1994	197, 198)
LTV Steel, Cleveland Works			21-27			1995	199)
Sammi Atlas Inc., Atlas Stainless Steels	Gas stirring treatment	36-45	30-38			1995	187)
Lukens Steel			16-20			1995	66)

Weirton Steelmaking shop			23±10	22±12		1995	[200]
Europe							
Cokerill Sambre/CRM					<30 (20*)	1991	[186]
CRM, Belgium			20-35			1990	[201]
Mannesmannröhren-Werke, Hüttenwerk Huckingen					<20	1991	[186]
One steel Plant in Finland		48±12	32	38	17	1993	[202]
Hüttenwerke Krupp Mannesmann					10-20	1998	[80]
Dillinger, Germany	 Tank Degas	 10-15	10-15	11	 ≤15	1993 1994 2000	[203] [204] [205]
Hoogovens Ijmuiden, Netherlands			15-32			1994	[206]
British Steel, Ravenscraig Works,	DH Lime-spar injection				15.4 11	1985 1985	[79] [79]
British Steel					<10	1994	[207]
Linz, Austria					16	1994	[208]
Voest-Alpine Stahl Linz GmbH	RH	27±4		21±2		1998	[209]
	RH	25-30			25	2003	[138]
Sollac Dunkirk, France	RH		20-50			1997	[210]
Sidmar, Belgium		37				2000	[109]
	Ar stirring	40-50					[46]
	Ar stirring Low carbon Si-killed steel	40-60					[46]
Asia							
Kawasaki Steel, Chiba works,	RH	40			20	1989	[211]
Kawasaki Steel, Mizushima Works,	LF+RH KTB	30 <25-40	 34.7	 <30	26 <55	1986 1989 1991 1996	[212] [213] [186] [214]
NKK, Traditional RH	RH	17				1993	[215]
NKK, PERM for RH	PERM for RH	7				1993	[215]
NKK, Traditional VOD	VOD	33.8				1993	[215]
NKK, PERM for VOD	PERM for VOD	25.1				1993	[215]
NKK, Keihin, #1,					<20	1991	[186]
NKK, Keihin, #5,					<28	1991	[186]
Nippon Steel, Nagoya Works	RH	10-30				1989	[216]
Nippon Steel, Yawata Works	Ar stirring	82	45		44	1974	[190]
Nippon steel, Yawata works					26	1989	[191]
POSCO	RH	25-31			 <27 <10*	1993 1991 1991	[217] [186] [186]
China Steel, Taiwan	RH	<30			12	1994	[218]
Baosteel, China	CAS-OB	172.5	93		48.8	1992	[101]

	RH	72			30	1994	[101]
	RH	70	57	21-51	13.8-17.5	1995	[101]
	CAS	73-100	38-53		14-17	1999	[219]
	RH		23		10	1999	[220]
WISCO, No.1 Works, China	LF-VD	≤15				1999	[221]
WISCO, No.2 Works, China	RH	71-73			37-39	1995	[222]
	RH				30-50	1999	[223]
	RH-KTB	43-75				1999	[224]
	RH (Pressure Vessel Steel)	28-34	24-26		12-19	2000	[225]
WISCO, No.3 Works, China	RH	35-41	26-37		13-22	1999	[221]
Panzhihua Iron and Steel (Group) Co., China	RH-MFB	20-24				2000	[226]
	Ar stirring				15.2	2000	[227]
Maanshan Iron & Steel, China	ASEA-SKF	18-24				2000	[35, 228]

(* ultra clean steel).

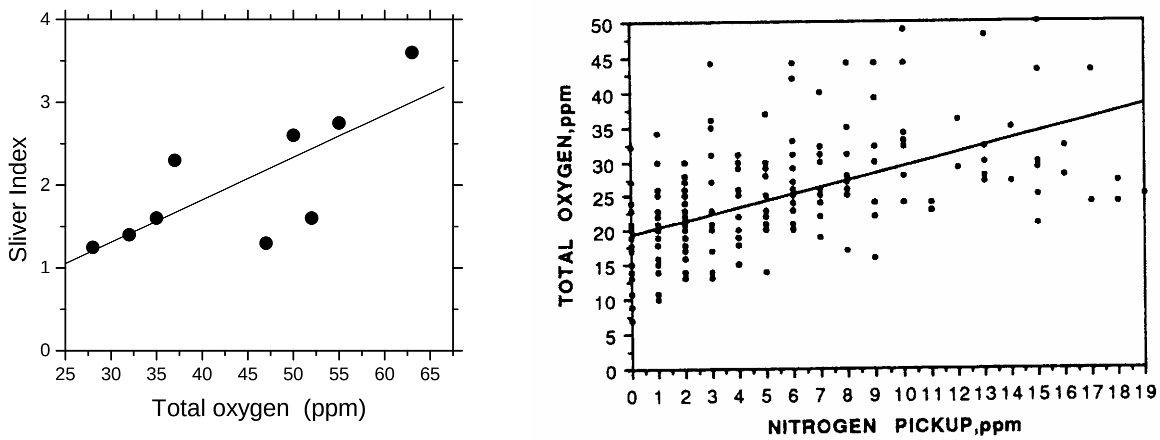


Fig.29. Relationship between T.O. in tundish and sliver defect index for product[187], and relationship between nitrogen pickup and total oxygen

2.2. Nitrogen Pickup

The difference in nitrogen content between steelmaking vessels is an indicator of the air entrained during transfer operations. Nitrogen pickup thus serves as a crude indirect measure of total oxygen, steel cleanliness, and quality problems from reoxidation inclusions. For example, Weirton restricts nitrogen pickup from ladle to tundish to less than 10 ppm for critical clean steel applications.[200, 229] . Note that oxygen pickup is always many times greater than the measured nitrogen pickup, due to its faster absorption kinetics at the air steel interface.[230] In addition, nitrogen pickup is faster when the oxygen and sulfur contents are low. [194, 203] Thus, to reduce nitrogen pickup, deoxidation is best carried out after tapping. Plant measurements confirm this, as nitrogen pickup reduced from 10-20ppm for deoxidation during tapping to 5ppm after tapping. [231]

Tables 3 [79, 101, 104, 193, 197, 203, 220-222, 229, 230, 232-236] summarize minimum nitrogen pick-up and nitrogen contents measured in LCAK steel at every processing step for several steel plants. Measurements in the tundish and mold were excluded because they tend to be high due to sampling. These two tables reveal the following conclusions:

① Nitrogen in LCAK steel slabs is about 30-40ppm at most steel plants. It is controlled mainly by the steelmaking converter or electric furnace operation, but is affected by refining and shrouding operations.

② Nitrogen pick-up is deceasing with passing years, owing to new technology and improved operations. For example, at Sollac Dunkirk Works, nitrogen pick-up from tundish to mold decreased from 9ppm in 1988, to 1ppm in 1992.
③ Generally, nitrogen pick-up can be controlled at 1-3 ppm from ladle to mold. With optimal transfer operations to lessen air entrainment, this pickup can be lowered during steady state casting to less than 1ppm. Nitrogen pick-up is discussed further in the Transfer Operations section of this paper.

Table 3. Nitrogen pickup (ppm) reported at various steel plants

	Ladle→tundish	Tundish→mold	Ladle→mold	Year	
Bethlehem Steel Corp.			~10	1986	237)
			<0.7	1989	
Dofasco	<1	0.3		1992	197)
		0.52		1995	232)
Weirton Steel			4~10 <5	<1993 1993	229) 229)
Armco, Ashland works		2		1993	193)
Inland steel, No.4 BOF shop	3			1990	104)
	1-2			2003	192)
US Steel, Fairfield Works	4 7.5			1995 >1995	233) 233)
IMEXSA Steel, Mexico			5	1996	235)
Sollac Dunkirk, France	 3 0.5-1.3	9 1		1988 1992 <1995 1995	234) 234) 234) 234)
Dillinger Steel, Germany			5	1993	203)
British Steel, Ravenscraig Works, England	3	1.8		1985	79)
CST (Companhia Siderurgica de Tubarao), Brazil			0.9-1.3		238)
Nippon Steel, Nagoya Works, Japan	0-2			2000	230)
Baosteel, China			1-5 1.5	1995 1999	101) 220)
WISCO, No.2 Works, China	 3-4	 4.3-5.5	3.8-9.3	1995 1999	222) 236)
WISCO, No.3 Works, China			0-5	1999	221)

2.3 Concentration Measuremen

For LCAK steels, the dissolved aluminum loss [239] also indicates that reoxidation has occurred. However, this indicator is a less accurate measure than nitrogen pickup because Al can also be reoxidized by slag. The silicon pickup, manganese pickup can be also used to evaluate the reoxidation process.

2.4 Lining Refractory Observation [87-90, 93-95]

Analysis of the lining refractory composition evolution before and after operations can be used to estimate inclusion absorption to the lining and the lining erosion. Also, the origin of a complex oxide inclusion can be traced to lining refractory erosion by matching the mineral and element fractions in the slag with the inclusion composition.[101)]

2.5 Slag Composition Measurement

Firstly, analysis of the slag composition evolution before and after operations can be interpreted to estimate inclusion absorption to the slag. Secondly, the origin of a complex oxide inclusion can be traced to slag entrainment by matching the mineral and element fractions in the slag with the inclusion composition.[101)] These methods are not easy, however, due to sampling difficulties and because changes in the thermodynamic equilibrium must be taken into account.

2.6 Tracer Studies for Determining Exogenous Inclusions from Slag and Lining Erosion [83, 95, 97, 110, 132, 240-244) 137)]

Tracer oxides can be added into slags and linings in ladle, tundish, mold, or ingot trumpet, and top compound. Typical inclusions in the steel are then analyzed by SEM and other methods. If the tracer oxides are found in these inclusions, then the source of these inclusions can be decided. Several tracer studies are summarized in **Table 4.**

Table 4 Tracer oxides were carried to positively identify exogenous inclusions sources

Researchers	Description	Year	Ref.
Mori et al	La2O3 oxide added to steelmaking furnace slag	1965	245)
Middleton et al	Cerium oxide (CeO_2) to sand; Furnace slag: Ba; Ladle refractory: Zr, and Ba; Nozzle sleeves: Ba	1967	110)
Ichinoe et al	La was plugged into aluminum to be added in the mould	1970	83)
Benko eta l	Ba was added into slag and lining to trace the origin of exogenous oxide inclusions	1972	240)
Zeder et al	La to ladle lining, Yb to stopper-rod in ladle, Sm to trumpet bricks, Eu to spider bricks, Ho to runner bricks.	1980	241)
Komai et al	SrO to tundish slag for the continuous casting of low carbon Al-killed steel	1981	132)
Cramb et al	BaO added to ladle slag; CeO_2 added to tundish slag; To study the slag entrainment during continuous casting	1984	69)
Byrne et al	Barium oxide (BaO) added to the ladle slag; Cerium oxide (CeO_2) added to the tundish slag; Strontium oxide (SrO_2) added to the mold slag	1985	97)
	Cerium oxide (CeO_2) added to the ladle shroud cell and the tundish slag	1988	95)
Burty et al	La was added into steel during RHOB after Al-killing, then 5 minutes stirring, to evaluate reoxidation, understand clogging at SEN, and inclusion floating to top slag.	1994	242)
Zhang et al	BaCO3 to ladle slag, SrCO3 to tundish slag, La2O3 to mold slag for CC production of LCAK steel.	1995	243)
Zhang et al	La2O3 to ingot mold powder. 17 of 28 analyzed slag inclusions had the composition of mold power.	1996	244)
Rocabois et al	La was added into steel during steel refining after Al-killing to study the origin of slivers defects	2003	137)

2.7 Submerged Entry Nozzle (SEN) Clogging

Short SEN life due to clogging is sometimes an indicator of poor steel cleanliness. The composition of a typical clog during LCAK steel continuous casting is: 51.7% Al_2O_3, 44% Fe, 2.3%

MnO, 1.4% SiO_2, 0.6% CaO, which shows that nozzle clogs are often caused by a simultaneous buildup of small alumina inclusions and frozen steel.[109] Thus, SEN clogging frequency is another crude method to evaluate steel cleanliness. The cause and prevention of SEN clogging was reviewed by Kemeny [246] and Thomas [99].

3. Final Product Tests

The ultimate measure of cleanliness is to use destructive mechanical tests to measure formability, deep-drawing, and / or bending properties of the final sheet product, or fatigue life of test specimens or product samples. Other sheet tests include the Hydrogen Induced Crack test and magnetoscopy.[161] Another example is the inclusion inspection method in ultra-sonic fatigue test. [247] These tests are needed to reveal facts such as the potential benefit of very small inclusions (< 1μm), which should not count against cleanliness.

The previous discussion shows that there is no single ideal method to evaluate steel cleanliness. Some methods are better for quality monitoring while others are better for problem investigation. Thus, it is necessary to combine several methods together to give a more accurate evaluation of steel cleanliness in a given operation. For example, Nippon Steel used total oxygen measurement and EB melting for small inclusions, and Slime method and EB-EV for large inclusions.[157] Usinor used total oxygen measurement with FTD, OES-PDA, IA and SEM for small inclusions, and Electrolysis and MIDAS for large inclusions.[157] Baosteel employed total oxygen measurement, MMO, XPS, and SEM for small inclusions, Slime and SEM for large inclusions, nitrogen pickup for reoxidation, slag composition analysis to investigate inclusion absorption and slag entrainment.[101]

Because exogenous inclusions can originate from a combination of several sources, methods for their prevention are not likely to be simple. It is only through the correct combination of all these sources and removal mechanisms that the incidence of large non-metallic inclusions in steels can be reduced. For detecting exogenous inclusions in steel, the following methods are suitable: Ultrasonic Scanning, Microscope Observation, Sulfur Print, Slime (Electrolysis), X-ray, SEM, Slag Composition Analysis, and Refractory Observation.

CONTINUOUS CASTING OPERATIONS FOR CLEAN STEEL

Continuous casting operations control steel cleanliness. For example, a systematic study of inclusion removal found that ladle treatment lowered inclusions by 65~75%; the tundish removed 20~25%, although reoxidation sometimes occurred; and the mold removed 5~10% of the inclusions.[210] Tundish operations greatly affect steel cleanliness, as covered in reviews by McLean[248] and Schade[249]. The following important factors are discussed here: tundish depth and capacity, casting transitions, tundish lining refractory, tundish flux, gas stirring, and tundish flow control.

1. Top Slags

The top slags in the ladel and tundish provides several functions:

- insulate the molten steel both thermally (to prevent excessive heat loss) and chemically (to prevent air entrainment and reoxidation[235]).
- absorb inclusions to provide additional steel refining.

A common tundish flux is burnt rice hulls [250], which is inexpensive, a good insulator, and provides good coverage without crusting. However, rice hulls are high in silica (around 80% SiO_2 [101]), which can be reduced to form a source of inclusions. They also are very dusty and with their high carbon content, (around 10% C [101]), may contaminate ultra low carbon steel.

Basic fluxes (CaO-Al_2O_3-SiO_2 based, and SiO_2<10%) are theoretically much better than rice hulls at refining LCAK steels, and have been correlated with lower oxygen in the tundish. [198, 213] For example, the T.O. decreased from 25-50ppm to 19-35ppm with flux basacity increasing from 0.83 to

11, measured at Kawasaki Steel Mizushima Works.[213)] POSCO Gwangyang Works developed this kind of basic fluxes, by this technique, the total oxygen in mold was reported to be lowered, and coil defect was decreased. [250)] More likely, the basic flux was ineffective because it easily forms a crust at the surface,[101)] owing to its faster melting rate and high crystallization temperature. This crust results in the evolution of an open slag-free eye around the ladle shroud during teeming, which not only provides an excessive area for reoxidation, but also allows a significant radiative heat loss and discomfort for operators on the ladle platform. Also, basic fluxes generally have lower viscosity, so are more easily entrained. To avoid these problems, AK Steel Ashland suggested a two-layer flux, with a low-melting point basic flux on the bottom to absorb the inclusions, and a top layer of rice hulls to provide insulation, which lowered T.O. from 22.4ppm to 16.4ppm.[193)]

2. Tundish Depth, Capacity and Flow Control Devices

The tundish flow pattern should be designed to increase the liquid steel residence time, prevent “short circuiting” and promote inclusion removal. Tundish flow is controlled by its geometry, level, inlet (shroud) design and flow control devices such as impact pads, weirs, dams, baffles, and filters. Deep tundishes with a large capacity increase the residence time of liquid steel and particles, so encourage inclusion removal[251)]. Deep tundishes also discourage vortex formation, enabling more time for ladle transitions before slag entrainment becomes a problem. Tundish size for LCAK steel has gradually increased worldwide over the past 20 years, typically reaching 60-80 tons with over 70 inches depth. [95)]

If properly aligned, and perhaps together with weir(s) and dam(s), a pour pad can improve steel cleanliness, especially during ladle exchanges. [199, 252)] For example, adding the pour pad at LTV Steel decreased alumina during ladle transitions from 48 to 15ppm.[199)] At Lukens Steel, T.O. decreased from 26ppm (with a domed pad) to 22ppm (with a hubcap pad).[66)] At POSCO, steel cleanliness was improved by putting 77 holes in their dam, making it act as a partial filter.[217)] At Nisshin Steel, a similar technique was used, and steel cleanliness improved too. [253)] Baffles combined with an initial tundish cover lowered the average T.O. in the tundish during steady state casting from 39±8 to 24±5 ppm.[198)] Ceramic filters and CaO filter are very effective at removing inclusions.[217, 254-257)]. However, their cost and effective operating time before clogging usually make their use prohibitive.

Injecting inert gas into the tundish from its bottom improves mixing of the liquid steel, and promotes the collision and removal of inclusions. [201, 258, 259)] At Lukens Steel Company, this technology was employed and successfully lowered T.O. to 16 ppm in tundish.[66)] The danger of this technology is that any inclusions-laden bubbles which escape the tundish and become entrapped in the strand would cause severe defects. It was reported that oxide area fraction (10^{-3}%) of steel in tundish decreases 25% by this technique compared with those without this technique. [201)]

3. Casting Transitions

Casting transitions occur at the start of a casting sequence, during ladle exchanges and nozzle changes, and at the end of casting. They are responsible for most cleanliness defects.[260)] Inclusions are often generated during transitions and may persist for a long time, thus contaminating a lot of steel.[120)] The sliver defect index at the beginning of the first heat was found to be 5 times higher than that at the middle of the first heat and over 15 times that of successive heats.[100)] During these unsteady casting periods, slag entrainment and air absorption are more likely, which induce reoxidation problems.

A “self-open” ladle opens on its own without having to lance the nozzle. Lancing requires removing the shroud, which allows reoxidation, especially during the first 25 to 50 inches of the cast. Lanced-opened heats have total oxygen levels around 10 ppm higher than self-open heats.[66)] Carefully packing of the ladle opening sand helps to realize ladle self open. Ladle sand is also a source of reoxidation because of high silica contained.[261)]

Figure 30 indicates that the first heat has more total oxygen than the intermediate heats. [198)] One improvement during ladle transitions is to stop the flow of liquid into the mold until the tundish is filled and to bubble gas through the stopper to promote inclusion flotation.[195)] Another improvement is to open new ladles with submerged shrouding. With this measure, T.O. was decreased at Dofasco from 41±14ppm to 31±6 ppm with more consistent quality throughout the sequence.[198)]

At National Steel, for example, T.O. in tundish during transitions is 50-70 ppm, compared with only 25-50ppm at steady state.[195)] At other plants, the difference is only 3ppm. Lukens reports transitions to have only 19.2 ppm, relative to 16ppm at steady state[66)] and Dofasco reports T.O. of 27±5 ppm during transitions and 24±5 ppm during steady casting[198)]. At Nippon Steel, the nitrogen pickup in tundish is 5-12ppm during start period of teeming and decreases to 0-2ppm after 12.5min teeming (steady casting state).[230)]

Near the end of a ladle, ladle slag may enter the tundish, due in part to the vortex formed in the liquid steel near the ladle exit. This phenomenon requires some steel to be kept in the ladle upon closing (eg. A four tonne "heel"[104)]). In addition, the tundish depth drops after ladle close, which disrupts normal tundish flow and may produce slag vortexing, slag entrainment, and increased total oxygen in the mold, as reported by Dofasco.[198)]

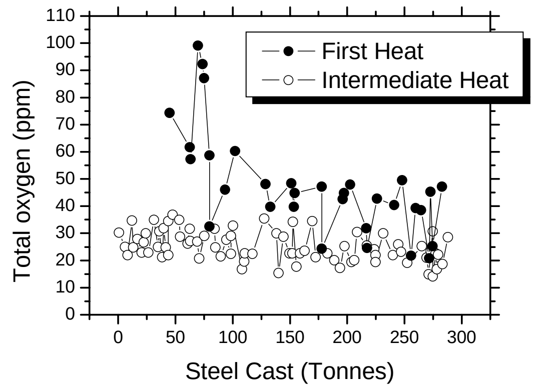


Fig.30 The T.O. content in Tundish versus time for different heats

4. Shrouding, Argon Protection, and Sealing

Steel shrouding from ladle to mold includes ladle slide gate shrouding, ladle collector nozzle, ladle shroud connection, tundish well block, top plate of the tundish slide gate. [237)] McPherson and McLean reviewed various aspects of tundish-to-mold transfer operations, focusing on shroud design variations.[262)]

Using an optimized shrouding system greatly lowers reoxidation during transfer operations. For example, using a ladle shroud lowered nitrogen pickup from 24 to 3 ppm relative to open pouring at Bao Steel.[101)] At US Steel Fairfield Works, replacing the tundish pour box with a ladle shroud and dams lowered nitrogen pickup (ladle to tundish) from 7.5ppm to 4ppm, and also lowered slag entrainment during transitions.[233)] At British Steel Ravenscraig Works, improving the shroud system from ladle to tundish, lowered the nitrogen pickup there from 14 ppm to 3 ppm.[79)] Shrouding the ladle to tundish stream at another plant lowered the dissolved aluminum loss from 130ppm to only 70ppm and to lower the T.O. increase by 12 ppm.[263)] When pouring without shrouds, which is common in billet casting, the turbulence of the casting stream is very important. A smooth stream entrains much less oxygen than a turbulent or "ropy" stream.[264)] To produce a smooth stream between tundish and mold in these operations, and the metering nozzle edges must be maintained and high speed flow in the tundish across the nozzles must be avoided. A protective tundish cover with carefully sealed edges also helps, lowering T.O. from 41.5 to 38 ppm.[187)]

A variety of inert gas shrouding systems are also available to help.[262, 263)] Total oxygen in the slab (LCAK Steel) can be lowered from 48.3ppm to 28.6ppm by shrouding between the ladle and the tundish, and to 23.0ppm by this shrouding plus argon sealing. [265)]

It is very important to carefully seal the joints in the shrouds, both to improve cleanliness and to prevent clogging. Improving the bayonet system between the ladle nozzle and ladle shroud, lowered the nitrogen pickup there from 8 to <1 ppm.[197)] Stiffening the SEN holder and increasing its maintenance lowered initial nitrogen pickup from 1.8ppm to 0.3 ppm.[197)]

Inert gas can protect the steel from air reoxidation in many ways. To combat air entrainment at the beginning of a cast, the tundish can be purged with inert gas (to displace the air) prior to ladle opening,[66)] which lowers both the total oxygen and the nitrogen pickup during startup.[203)] Argon injection to pressurize the shrouds can help to prevent the liquid steel from air reoxidation through any joints or leaks.[99)] Guidelines for minimum argon gas flow to ensure positive pressue inside the nozzle are provided elsewhere.[266)] In addition, flooding the joints with argon gas ensures that any leaks aspirate inert gas and not air. Injecting argon into the tundish stopper rod and improved sealing decreased nitrogen pickup from tundish to slab from 5 ppm to 1.8ppm; lowered T.O in slab from 31ppm to 22ppm, decreased the size of alumina clusters in the slab, and the decreased clogging.[79] Elsewhere, argon injection through the stopper rod lowered the number of inclusions detected by MIDAS method by 25-80%.[80] Injecting Ar gas purge through upper plate of the sliding gate lowered the amount of 50-100μm sized inclusions from 3 to 0.6 per cm^2, and lowered 100-200μm macroinclusions from 1.4 to 0.4 per cm^2. [267]

5. Clogging and New Techniques at SEN

The nozzle is a one of the few control parameters that is relatively inexpensive to change, yet has a profound influence on the flow pattern and thus on quality. [251, 266, 268] Nozzle parameters include bore size, port angle and opening size, nozzle wall thickness, port shape (round vs square vs oval), number of ports (bifurcated *vs* multiport), and nozzle bottom design (well vs. flat vs. sloped), and submergence depth [269]. Both too large and too small submergence depth increases problems with longitudinal cracks and transverse depressions. [269]

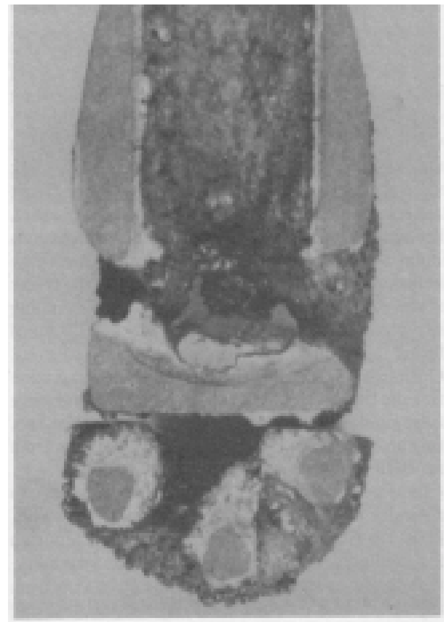


Fig.31 Example of clogging at SEN of continuous casting

Examples of the SEN clogging are shown in **figure 31** [97, 133, 134] and **32**[192]. Alumina inclusions clogged in an SEN is shown in **figure 33** [42, 46]. Snow and Shea found the occurrence of corundum (Al_2O_3)covering the bore surface of nozzles used to teem Al-killed steel ingot early in 1949. [270] Duderstadt et. al. (1967) [271] found that nozzle blockage occurred with high levels of Al (0.0036%) and that nozzle sectioning revealed dendritic growth of alumina from the nozzle wall onto the bore. Farrell and Hilty (1971) [272]observed clogs os Al, Zr, Ti and the rare earths. Many other researchers experimentally investigated nozzle clogging by alumina inclusions in steel, such as Schwerdtfeger and Schrewe (1970) [273], Steinmetz and Lindberg (1977) [274], Saxena et. al. (1978) [275], Byrne and Cramb (1985) [97, 133, 134], Dawson (1990) [276] , Fukuda et. al. (1992) [277], Tiekink et. al. (1994) [278], Tsujino et al (1994) [89], Ichikawa et. al. (1994) [279], Fuhr et al (2003) [280], and the cause and prevention of SEN clogging were extensively reviewed by Kemeny [246] and Thomas [99].

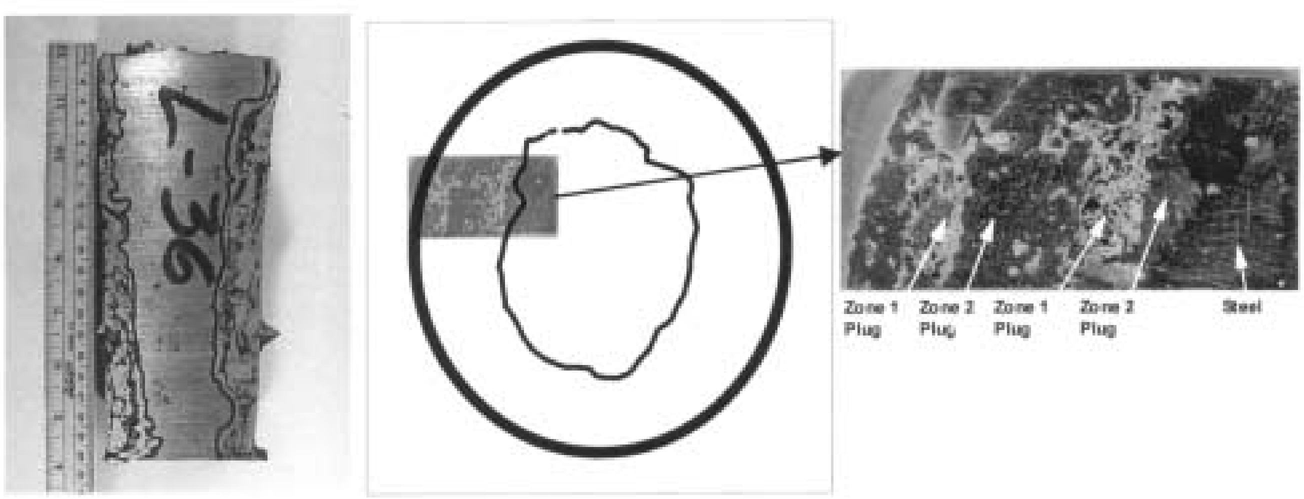


Fig.32 Example of SEN nozzle clogging (longitudinal and transverse. [192]

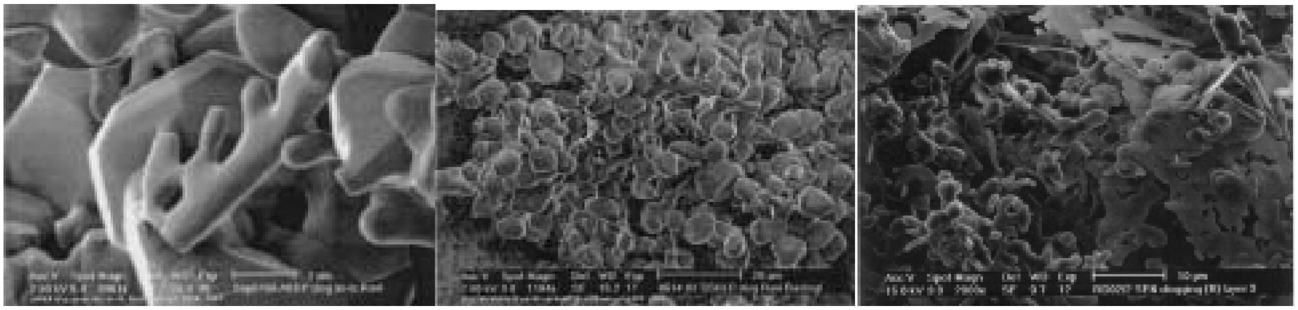


Fig.33 Inclusions clogged at SEN during the continuous carting of LCAK steel (left and middle: sphere-like cluster [42]; right: dendritic cluster and plate-like clusters [46])

Nozzle clogs are caused by reoxidation, or by the accumulation of solid oxides or sulfides, such as alumina (Al_2O_3) and cacium sulfide (CaS) in the steel.[101, 109, 111, 231, 281] In addition to interfering with production, tundish nozzle / Submerged Entry Nozzle clogging is detrimental to steel cleanliness for many reasons. Firstly, dislodged clogs either become trapped in the steel,[101] or they change the flux composition, leading to defects in either case. Secondly, clogs change the nozzle flow pattern and jet characteristics exiting the nozzle, which disrupt flow in the mold,[80] leading to slag entrainment and surface defects. Thirdly, clogging interferes with mold level control, as the flow control device (stopper rod or slide gate) tries to compensate for the clog.

The cure for this problem includes improving steel cleanliness by improving ladle practices, implementing smooth and non-reacting refractories and controlling fluid flow though the nozzle to ensure a smooth flow pattern. Changing from a 3-plate slidegate system to a stopper rod system reduced clogging at Dofasco.[232] Many practices can be used to minimize clogging, which are reviewed elsewhere.[99, 246] In addition to taking general measures to minimize inclusions, clogging via refractory erosion can be countered by controlling nozzle refractory composition, (eg. avoid Na, K, and Si impurities), or coating the nozzle walls with pure alumina, BN, or other resistant material.[99]

There are several new techniques at SEN reported to improve the fluid flow pattern and inclusion removal, such as swirl nozzle technique, step nozzle technique, multiports nozzle, and oval offset bore throttle plate.

1). Swirl nozzle techinque [282-285) 286-292]

A fixed blade placed at the upstream end of the SEN induces a swirl flow in nozzle. Centrifugal force generated by the swirling flow in the nozzle can distribute molten steel equally to its two spouts. Since a molten steel stream with centrifugal force has the maximum velocity in the vicinity of the wall inside the nozzle, it tends to flow out of the upper part of the spout. Thus, velocity distribution that tends to have higher values toward the lower part of the spout with a conventional nozzle can become uniform. (figure 34 [290]) It was reported that by using this swirl nozzle at CC, the defect ratio of final products (coils) has decreases to ¼ of conventional nozzles, and casting speed has risen by 30%. [292] Its price is only 20% higher than the conventional nozzle, so is cheaper than using a Electromagnetic Brake[293]. This swirl flow pattern can also be generated by the Electromagnetic Stirring at nozzle [294], which can also improve the solidification structure of the cast metal as well.

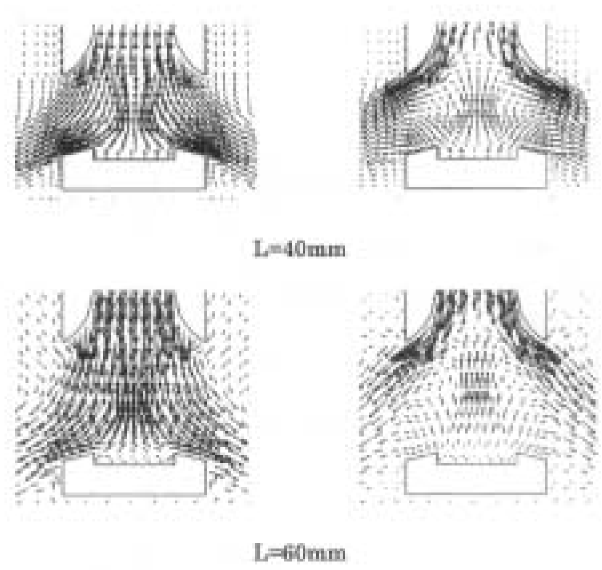


Fig.34 Velocity vector at the SEN outport by conventional nozzle (left) and swirl nozzle (right) (L is the height of SEN outport with a width of 38mm)

2). Step nozzle [295-299)]

Due to the sliding gate of SEN, the flow pattern at the outports of conventional SEN is uneven or biased as shown in figure 35. This biased flow pattern (swirl flow at outports of SEN) increases the impingement of the jet, and therefore worsens inclusion removal to top surface. [299)] By using inner annular steps these biased flow in mold can be weakened as shown in Fig.35. The calculation suggests that the removal fraction of 50µm inclusions to the top surface of the mold is 2% with the conventional SEN, but increases to 7% doe the Stepped SEN. [299)]

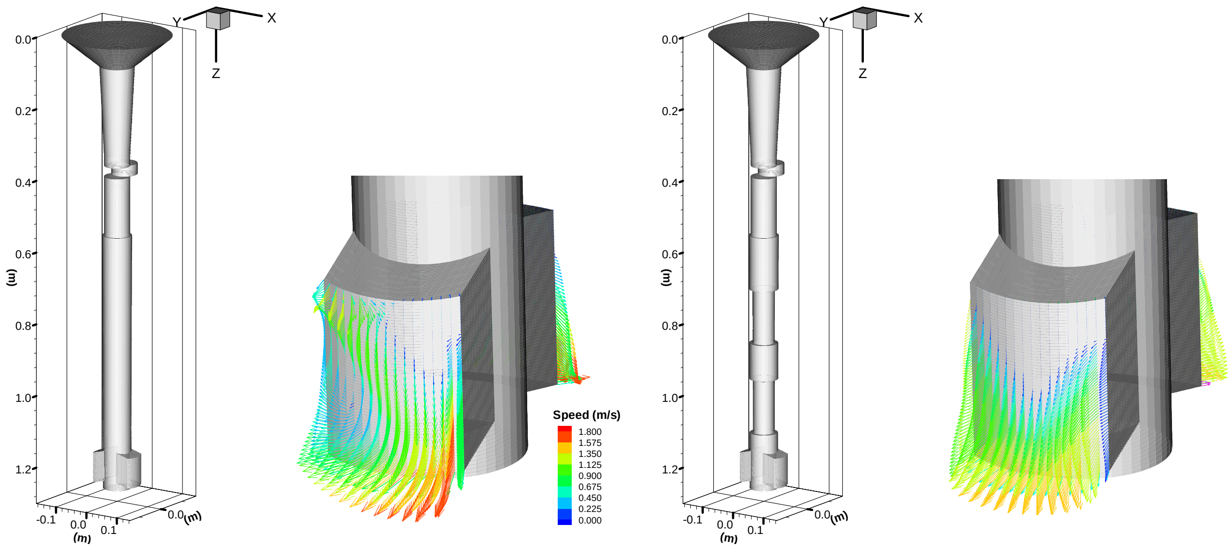


Fig.35 Fluid flow pattern at outlet ports of the conventional SEN (left) and Step SEN (right)[299)]

3). Oval offset bore throttle plate [300, 301)]

In the conventional system, gate throttling results in a highly skewed and biased flow in the tundish-to-mold flow channel both upstream and downstream of the gate. These effects are significantly alleviated in the Offset Bore system (**figure 36**). The Offset gate design extracts the fluid more centrally from the tundish well nozzle. Thus, the system is less sensitive to any build-up on the walls of the well nozzle, which extends the useful life of the tundish well nozzle, allowing longer tundish sequences. In practice it has also been found that clogging within the plates of the Offset Bore gate is significantly reduced as compared to the conventional gate.

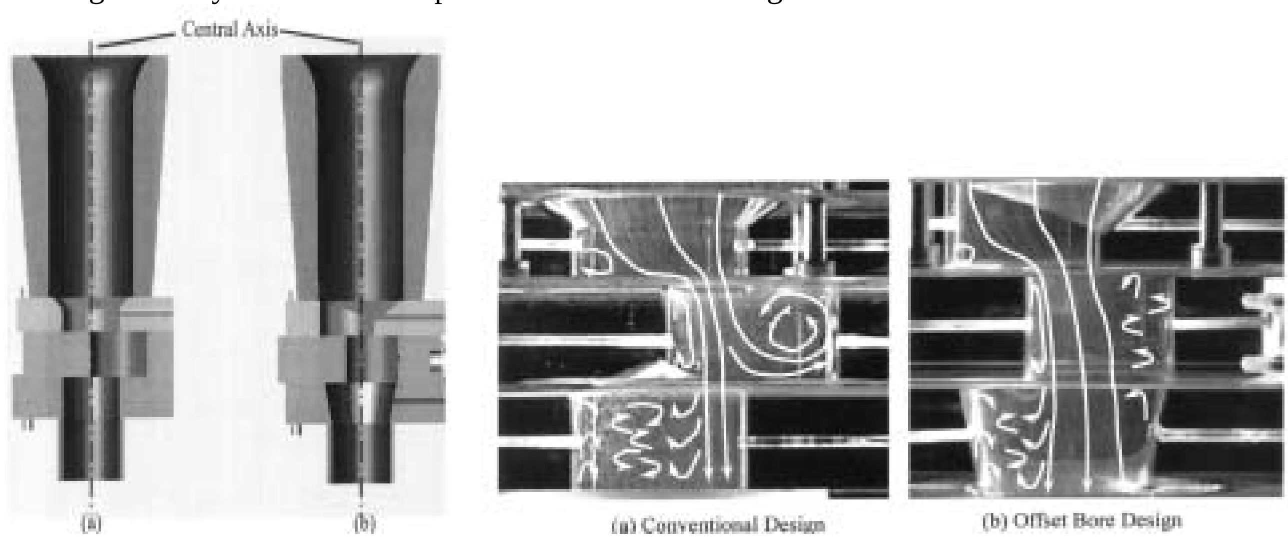


Fig.36 Comparison of gate designs (left two) and flow pattern near gate (right two) between conventional design and Offset Bore Design [300, 301)]

4). Multiple outports

It is well known that the surface velocity of the mold has a big effect on slag entrainment and top surface fluctuation. Many defects are related to the surface velocity of the mold. Thus decreasing the surface velocity is very important to improve the steel cleanliness. This task can be targeted by using multiple outports at SEN. As shown in Figure 37 [302], addition of a bottom hole at SEN lowers the momentum of the side jets so it is possible to get a good steel flow and meniscus condition even under high throughput that is better stabilized[303].

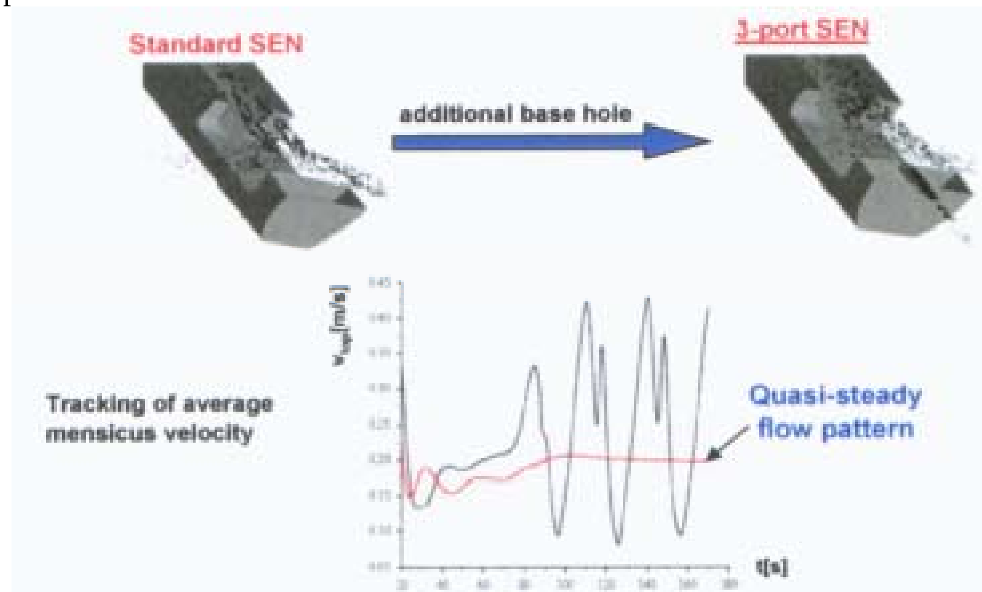


Fig.37 Stabilation of the mold flow by using a bottom hole at SEN [302]

6. Mold and Caster Operations

The continuous casting mold region is the last refining step where inclusions either are safely removed into the top slag layer or they become entrapped into the solidifying shell to form permanent defects in the product. In 1985, Mcpherson used the words "Mold Metallurgy" to emphasize the importance of the mold to improve steel cleanliness.[79] The mold flow pattern is very important to avoid defects because it affects particle transport: removal to the top slag or entrapment by the solidifying shell.

6.1. Top surface Control

Directing too much flow towards the top surface generates surface defects, due to transients, turbulence at the meniscus, and inclusion problems from slag entrainment. However, decreasing surface flows too much can also generate problems. These include surface defects due to the meniscus region becoming too stagnant, and a greater fraction of incoming inclusion particles being sent deep before they can be removed into the slag. Thus, a balance must be found in order to optimize the flow parameters to avoid defects.

The most obvious source of surface defects is the capture of foreign particles into the solidifying shell at the meniscus. If the steel jet is directed too deep or has too little superheat, then the liquid surface will have very little motion and will become too cold. This can lead to freezing of the steel meniscus, which will aggravate the formation of meniscus hooks.[304] This allows inclusions and bubbles to be captured, the latter forming pinholes just beneath the surface of the slab. For example, decreasing surface velocity below 0.4 m/s has been measured to increase surface pinhole defects.[305] To avoid these problems, the flow pattern should be designed to exceed a critical minimum velocity across the top surface, estimated to be about 0.1-0.2 m/s.[306]

Slag entrainment is less likely with deeper nozzle submergence and slower casting speed. To avoid shearing slag in this manner, the surface velocity must be kept below a critical value. This critical velocity has been measured in water – oil models as a function of viscosity and other parameters.[76, 306-311]. Entrainment is more difficult for shallower slag layers, higher slag viscosity, and higher slag surface tension.

A maximum limit of the argon gas injection flow rate into the nozzle was reported as a function of casting speed, beyond which mold slag entrainment will take place.[231]

Increasing casting speed tends to increase transient turbulent fluctuations, and worsens the extent of flow pattern asymmetries. This in turn worsens detrimental surface turbulence and level fluctuations.[312] Improving internal cleanliness often requires limiting the maximum casting speed, such as employed by Inland to avoid pencil pipe defects.[313] Lower casting speed and avoiding variations in casting speed both reduce the rate of slivers.[187] More precisely, it is important to lower the liquid mass flow rate in order to control the jet velocity exiting the nozzle.[313]

6.2. Fluid flow pattern

The mold flow pattern is controlled by adjustable parameters such as nozzle geometry nozzle submergence depth, argon gas injection rate, and the application of electromagnetic forces [314]. It also depends on parameters which generally cannot be adjusted to accommodate the flow pattern, such as the position of the flow control device (slide gate or stopper rod), nozzle clogging, casting speed, strand width, and strand thickness. All of these parameters together form a system that should be designed to produce an optimal flow pattern for a given operation.

Bubbles injected into the nozzle and mold have five effects related to the steel quality control:

- Helping to reduce nozzle clogging;
- Helping influence and control the flow pattern in the mold;
- Generating serious top surface fluctuation even emulsification if gas flow rate is too large;
- Capturing inclusions as they flow in the molten steel.[78, 142, 315, 316]
- Bubbles entrapped solid oxide particles captured by solidified shell eventually lead to surface slivers or internal defects.[78]

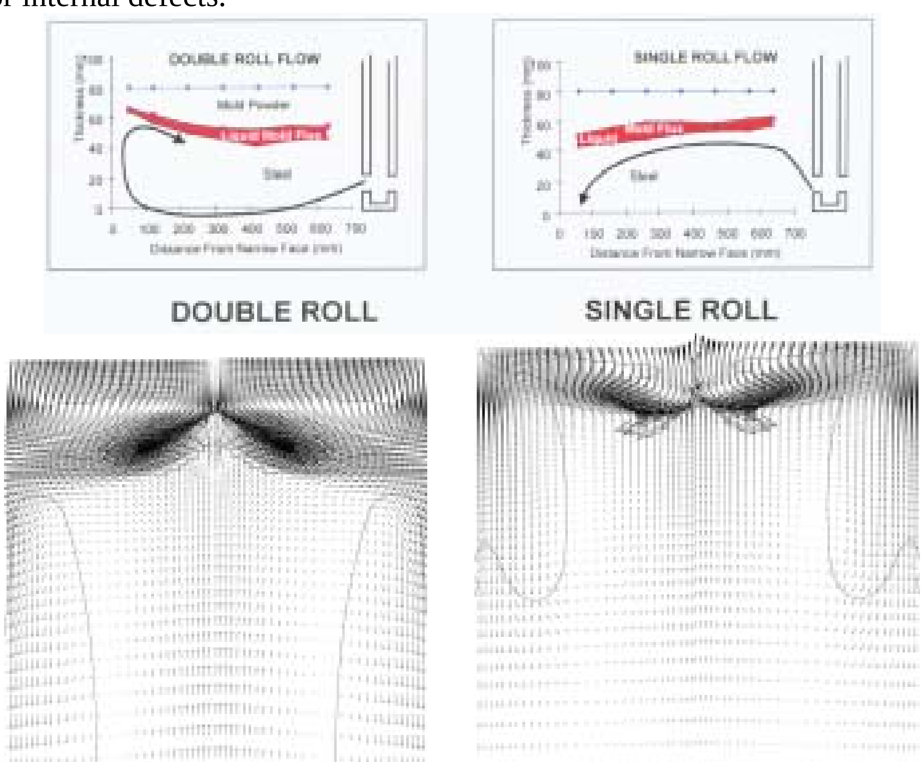


Fig.38 Typical steel mold flow patterns and corresponding top surface shape and flux layer behavior (left: 4.0 SLPM, 3.7%gas; right:6.3 SLPM, 8.6%gas) [324]

Figure 38 shows that low gas flow tends to double-roll flow pattern, while a high argon flow rate induces single-roll flow.[314, 317] This phenomena has been studied as early as in 1983. **[318]** To maintain a stable double-roll flow pattern, which is often optimal, the argon should be kept safely below a critical level. [317, 319, 320] Excessive argon injection may generate transient variation of the jets entering the mold, introduce asymmetry in the mold cavity,[307] and increase surface turbulence. Argon gas bubbles may also be trapped in the solidifying steel shell to form blister defects, such as pencil pipe in the final product.[78, 313, 321]

It was observed that inclusion entrapment varies from side to side, which suggests a link with variations in the transient flow structure of the lower recirculation zone, and the asymmetrical flow pattern, which could be induced by nozzle clogging as shown in **figure. 39**,[80] by turbulence as investigated by Thomas et al (mathematical simulation) [322] and Gupta (water model)[323], and by excessive argon gas injection[307]. It is especially important to keep nearly constant the liquid steel level in the mold, powder feeding rate, casting speed, gas injection rate, slide gate opening, and nozzle position (alignment and submergence).

Electromagnetic forces can be applied to the molten metal in a number of ways to substantially alter the flow pattern in the strand. [314] Timken Harrison Plant reports that electromagnetic stirring of outer strands can improve the steel cleanliness, lowering T.O in the billet from 30ppm to 20 ppm.[164] Another example is the electromagnetic brake (EMBR),[293] which bends the jet and shortens its impingement depth, to lessen the likelihood of capture by the solidified shell deep in the strand.

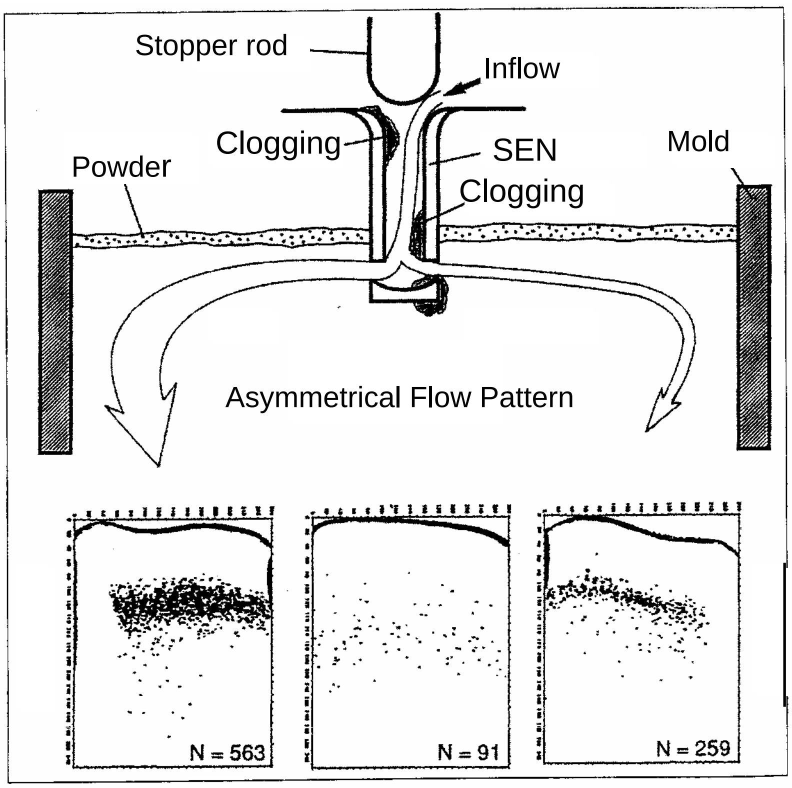


Fig.39 Asymmetrical contamination of a continuous cast slab due to an asymmetrical flow from the SEN clogging (N=inclusion index by using MIDAS)[80]

6.3. Caster Curvature

Curved mold machines are known to entrap more particles than straight (vertical) mold casters,[267, 325] because the particles gradually move upwards towards the inside radius while they spiral with the liquid in the lower recirculation zone [321] (**figure 40** [136]). Most particles are captured 1-3 m below the meniscus, independent of casting speed,[321, 326] which corresponds to a specific distance through the strand thickness.[315] Often, inclusions concentrate at surface and one-eighth to one-quarter of the thickness from the top of the inside radius surface,[61, 251, 281] (**figure 41** [61]).[186] **Figure 42** shows the difference of inclusion and pinhole distributions along the slab thickness between curved (S-type) and vertical bending (VB-type) caster. The vertical bending caster has fewer inclusions and pinholes, which are distributed deeper, relative to the curved caster. [267] Particle entrapment defects such as pencil pipe can be lessened if at least the top 2.5m section of the caster is straight (vertical).

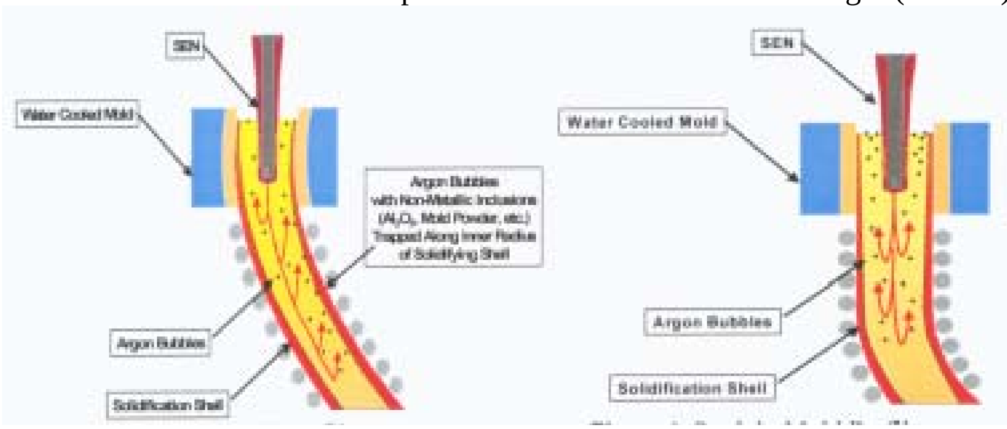


Fig.40 Schematic of fluid flow and inclusion motion in a curved caster and vertical bending caster [136]

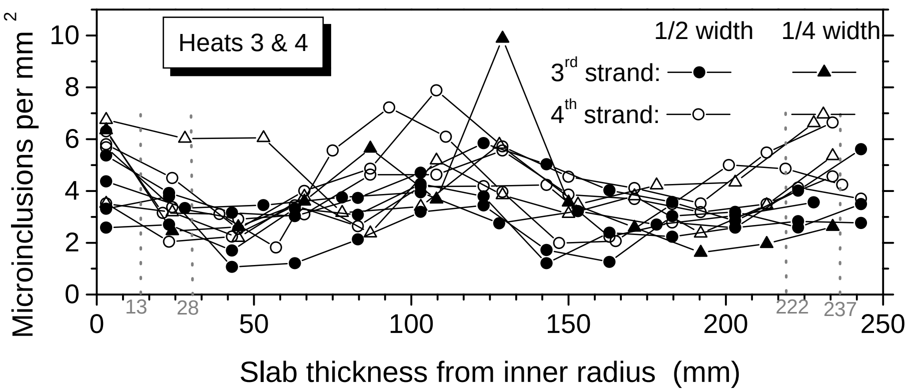


Fig.41 Inclusion distribution along the thickness of continuous casting slabs [61]

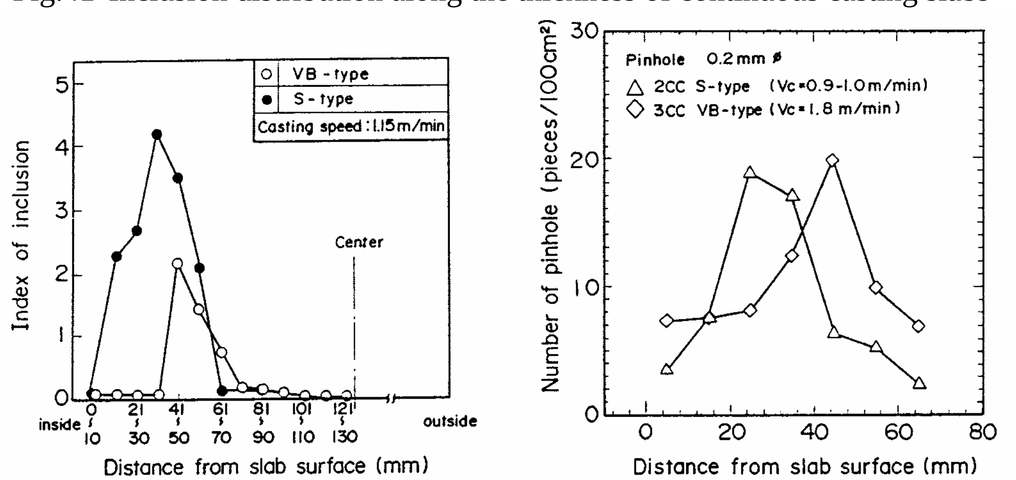


Fig.42. Effect of caster curvature on steel cleanliness (left: inclusion distribution; right: pinhole distribution. VB-type: vertical bending type; S-type: Curved type) [267]

SUMMARY

This paper first reviews the effect of inclusions on steel qualities. Next, the sources and morphologies of indigenous inclusions and exogeneous inclusions are reviewed. Indigenous inclusions are from deoxidation and precipitation during cooling and solidification process. The main sources of exogenous inclusions are steel reoxidation, slag entrainment and lining erosion. Thirdly, the different methods to evaluate inclusions are reviewed, including both direct and indirect methods. There is no single ideal method to measure steel cleanliness, so it is best to couple several methods together to give a more accurate evaluation. Many plants control total oxygen content and nitrogen pickup in Low Carbon Al-killed steel, which are summarized for many plants. Finally, operation practices to improve steel cleanliness at the tundish, transfer, and caster are reviewed. Tundish operations should employ a large, deep vessel with a nonreactive lining and a stable basic flux cover. It should be optimized with flow controls such an impact pad to remove inclusions, especially during transitions. Transfer operations should employ self-open ladles with optimized, nonreactive refractory shrouds, argon gas protection, sealing and care to avoid reoxidation, slag entrainment and nozzle clogging. Mold operations should optimize casting speed, nozzle geometry, gas injection, submergence depth, and electromagnetic forces in order to maintain a stable mold flow pattern that encourages inclusion removal while avoiding the creation of new defects. The top portion of the caster should be vertical to minimize inclusion and bubble entrapment on the inside radius.

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