BACKGROUND OF CONTINUOUS CASTING BILLET DEFECTS: FORMATION MECHANISMS AND FAST & EFFECTIVE DETECTION with 5 WHYS METHOD

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Abstract

Continuous Casting (CC) is a process that transforms molten steel into a solid product, primarily in the form of slabs, blooms, or billets. It is one of the advanced steel-making technologies that produce casting products of a specific cross-section suitable for the final product to be manufactured at the desired length. The CC process requires strict adherence to operational procedures, technological norms, and advanced production and control techniques. However, despite these measures, defects in CC products cannot be entirely eliminated. The formation and type of defects depend on various factors such as the condition of the CC machine equipment, the shape and size of the casting product, the quality of the steel, casting temperature and speed, mold and mold oscillation, primary and secondary cooling conditions, phase transformation, and the quality and material properties of the casting powder.

A defect in a CC product can be defined as a deviation in appearance, shape, size, macrostructure, and/or chemical properties when compared to the specifications given in technical standards or other existing normative documents. Post-casting defects in CC products can be detected by visual inspection of the surface on the cooling platform, visual reinspection of the surface quality on the rolling platform, or through chemical analysis and macrostructure inspection of test samples in laboratories.

Defects that occur during the solidification and cooling process in CC products can lead to defective products, reduced efficiency, and sales loss in subsequent processing of the main material. To prevent these losses, it is necessary to analyze the causes of defect formation using preventive metallurgy technologies and intellectual knowledge. Additionally, separating the defective product from the main material, defined as defect-free, and immediately addressing the issue through appropriate intervention in the CC process is essential. However, a defect is not always the result of a single unique cause. Often, a defect results from multiple interacting causes that depend on a varying number of

parameters. Similar defects may have one or more different causes, and different defects may have one or more common causes.

Defects in CC products arise during the production process due to various factors including material-related factors, casting speeds and temperatures, mold taper, mold oscillation, casting powder, the segregation coefficient of dissolved elements, phase transformation, and mechanical and thermal stresses. Mechanical stresses occur due to friction, ferrostatic pressure, tensile & straightening operations, and pressure. Thermal stresses arise from non-uniform cooling in the mold and/or secondary region. Controlling the water flow impacting the surface of the initially solidified semi-product and minimizing reheating of the product can reduce thermal stresses.

In this study, crack formation in the CC process was evaluated as a phenomenon occurring during production, influenced by the interaction of three main factors that clearly alter the quality of the final product: i) the chemical composition of the steel, ii) the control of process parameters, and iii) the development of microstructure. These parameters were explained using the "5 Whys" analysis technique.
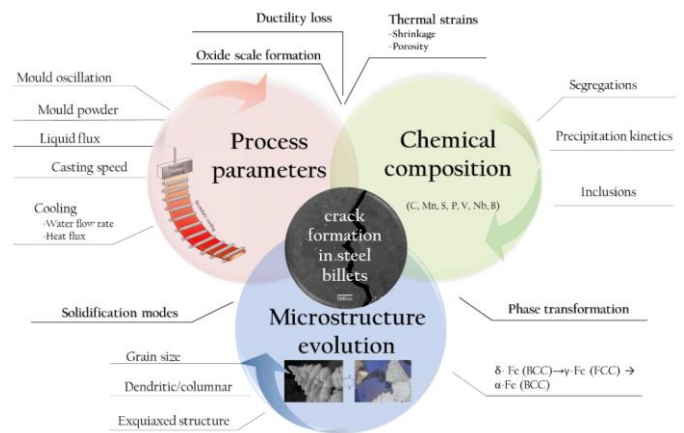

Figure 1. Factors affecting crack formation in steel billets during continuous casting process

1. Introduction

1.1. Continuous casting (CC) process: influential parameters and surface defects

The Continuous Casting (CC) process is a production method where molten steel solidifies/cools into long products, influenced by numerous parameters. To meet quality requirements in production activities, steel manufacturers must be fully competent in all machine/process/operator parameters, particularly steel analysis. Therefore, innovative, digital applications that allow for real-time monitoring of quality results are preferred. These applications enable enterprises to achieve maximum quality production, reduce the ratio of defective products/waste in steel production, and provide cost advantages through continuous improvement.

Key surface defects that occur primarily on or just beneath the semi-finished surface include longitudinal cracks, transverse surface cracks, transverse corner cracks, depressions, gas cavities, and macro-inclusions. The crack formation mechanism in continuous casting is closely related to the high-temperature strength of the steel. During solidification, tensile stresses caused by mechanical or thermal sources in the low ductility zones (when surface temperature is >1340°C and 800°C < surface temperature < 900°C) can lead to cracks on the product surface or within the interior if they exceed a certain value, depending on the steel quality. Except for longitudinal and transverse surface cracks, all other surface cracks begin during the solidification phase. Some cracks propagate to the surface, while others remain within the subsurface, beneath the shell. Since cracks form on the solidification surface, their location and depth indicate the stage in the solidification process where the crack initiated. Surface cracks typically occur on the upper surface of the billet and in the upper parts of the machine (mold and bending unit - S path), while internal cracks occur in the lower parts of the machine (straightening unit).

The tensile stress causing a specific crack is always perpendicular to the direction of the crack. In other words, longitudinal cracks are created by transverse tensile stresses, while transverse cracks are caused by longitudinal tensile stresses.

2. Crack Formation

2.1. Longitudinal cracks

Longitudinal cracks form in the direction of steel extraction/flow. The presence of this defect results in the rejection of the CC product. The primary causes of longitudinal cracks are:

✓ Uneven/homogeneous primary cooling in the mold.

✓ Turbulent flow of molten steel and sudden variability in the meniscus level in the mold (level control).

✓ Uneven or excessively intense secondary cooling.

✓ Molds with high thermal variability, inconsistent coating thickness, and advanced wear along their length, leading to deformation and improper tapering.

✓ Casting of molten steel at excessively high temperatures.

✓ High casting speed.

✓ Use of casting powder with unsuitable properties and insufficient lubrication.

✓ High concentrations of P, S, Pb, and Cu.

✓ Malfunctioning machine calibration.

✓ Tensile and straightening stresses.

✓ Irregular oscillation.

✓ Bulging of the shell that is insufficiently resistant to ferrostatic pressure.

These cracks typically occur very close to the corners of the surface and are usually about 1-2 mm deep. Although many studies have linked these cracks to rhomboidity, they can also occur without rhomboidity. The most critical cause of longitudinal surface corner cracks is a large mold corner radius. In molds with large corner radii, stress development during solidification occurs on the surface and at the corners, leading to cracks in these areas. To prevent the influence of the mold corner radius on the formation of such cracks, the ratio between the billet edge length and the corner radius should be a minimum of 1/10. Another contributing factor is insufficient mold taper. Immediately after solidification begins, the billet shrinks (the carbon content plays a significant role here, as low-carbon steels shrink more, creating an air gap), and the billet moves away from the mold wall. During this initial solidification phase, the shell is thin and weak. If there is insufficient taper, the heat transfer rate decreases due to shrinkage, preventing the shell from developing properly. The shell cannot withstand the stresses caused by ferrostatic pressure, leading to crack formation. High casting speed and temperature, which can cause the formation of a shell with insufficient strength and thickness, also contribute to these cracks. Additionally, a deformed mold and misalignment of the mold and sub-mold rollers play roles in the formation of these cracks.

Figure 2. Longitudinal cracks

3. Causes of Crack Formation

3.1. Steel Chemistry

High levels of P, S, and other trace elements (tramp elements, such as Cu, Ni, As, Pb, Sn, Sb, Mo, Cr, N, H) in the cast can significantly weaken the shell, leading to cracks in the oscillation marks when combined with mechanical stress.

The main factors influencing the formation of corner cracks and transverse corner cracks include the percentages of C, Cu, Sn, and Pb, the Mn/Si and Mn/S ratios, roller/role adjustments, mold taper, casting powder, lubrication practices, mold friction, mold oscillation practices, fluctuations in mold levels, tundish temperature, the intensity of secondary cooling, and casting speed.
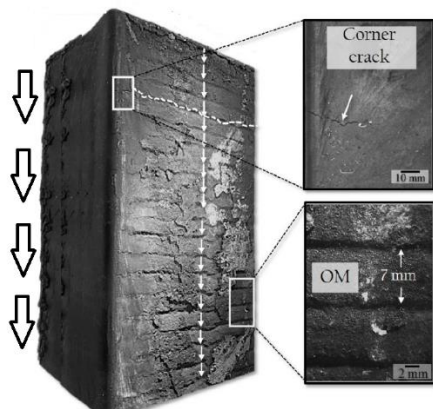

Figure 3. Oscillation marks and cracks formed on a steel billet during continuous casting.

There is a close relationship between the formation of corner cracks and transverse corner cracks and the chemical composition. If all other factors are controlled and no issues are present, meeting the following conditions can prevent crack formation.

$$\frac{\%C}{10} + \%S \leq 0,05$$
$$\%Mn \geq 15 \times \%S$$
$$\%P + \%S + \%As \leq 0,075$$

"Copper-Equivalent Factor" = %Cu + 10*%Sb + 5*%Sn + 2*% As - %Ni

Copper is fully soluble in steel, and the only economically viable solution to reduce its concentration is dilution. Additionally, copper has a very negative impact on the surface of the steel, as it promotes hot shortness during hot rolling, forging, and casting processes. Since copper does not easily form intermetallic compounds with oxides, sulfides, or carbides in steel, it tends to accumulate and precipitate in copper-enriched regions. The low solubility of copper in surface scales and austenite triggers the formation of these regions. A copper-rich liquid phase forms under the scale, which moves towards the grain boundaries, leading to a loss of ductility and ultimately intergranular fracture. Other alloying elements can increase or decrease the degree of hot shortness caused by copper, making the situation very complex. For example, antimony, tin, and arsenic increase the hot shortness caused by copper, while nickel reduces it. Each of these elements represents the hot shortness caused by copper as shown in the above equation as the copper equivalent factor.
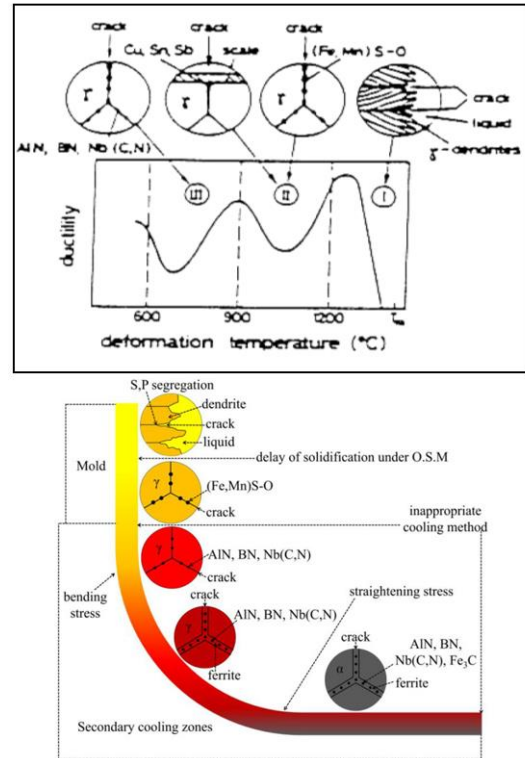

Brittleness observed in the intermediate critical temperature range (1200 – 900°C) increases further with the precipitation of low-melting S and O compounds along the grain boundaries and the enrichment of elements such as Cu, Sn, and Sb beneath the surface. Given the temperature range, it is easy to conclude that these cracks are not mold-related. Another critical temperature range where the risk of intergranular crack formation is high is the low temperature range (900 - 600°C). Here, brittleness is known to result from AlN precipitation at austenite grain sizes, making the control of Al and N levels in steel important. This mechanism, which occurs at low temperatures, especially leads to surface and subsurface cracks.

For brittleness in both the intermediate (1200 – 900°C) and low temperature regions (900 - 600°C), the fundamental condition is the presence of precipitation at the grain boundaries, which is directly related to austenite grain size. It is inevitable for the steel solidified in the meniscus region to be fine-grained, but at later stages, the cooling rate must decrease to a degree that allows grain growth, which increases the risk of crack formation. At temperatures in the 600-900°C range, elements such as Al, Nb, and V precipitate at the grain boundaries, significantly reducing ductility.

The formation mechanisms of transverse corner cracks and transverse surface cracks share similar

characteristics.
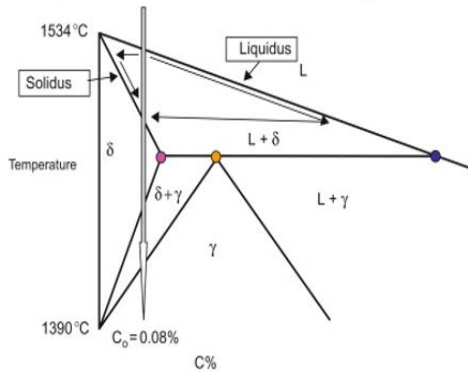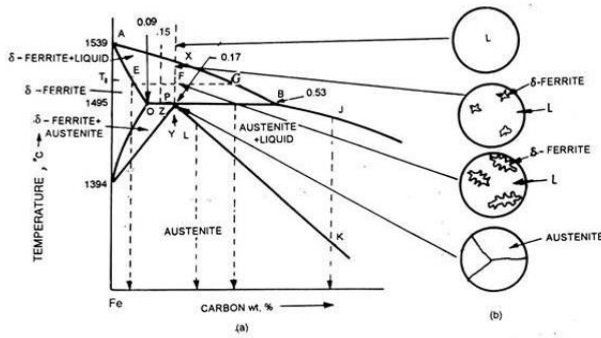
During continuous casting processes, the susceptibility of low-alloy steel billets to surface cracking is significantly dependent on carbon content, with a maximum range of 0.06 – 0.17% (referred to as the middle range, exhibiting low crack formation tendency). This characterization has been studied in relation to the peritectic reaction during solidification in the mold. For carbon content in the range of 0.17 – 0.25%, the initially solidified shell is irregular due to the shrinkage occurring during the transformation of δ-ferrite to austenite. This shrinkage leads to a significant decrease in heat transfer due to the lack of close contact between the metal (initial shell) and the mold wall. As a result, the temperature gradient between the liquid steel and the thinner parts of the irregularly solidified initial shell is quite low. The thin metal is close to its solidification temperature and has low strength and/or ductility, making it sensitive to cracking. Additionally, the local cooling delay in the thin parts of the irregularly solidified initial shell leads to the formation of larger austenite grains in the surface region of the steel. This condition can be noted as the second factor contributing to high transverse cracking susceptibility.
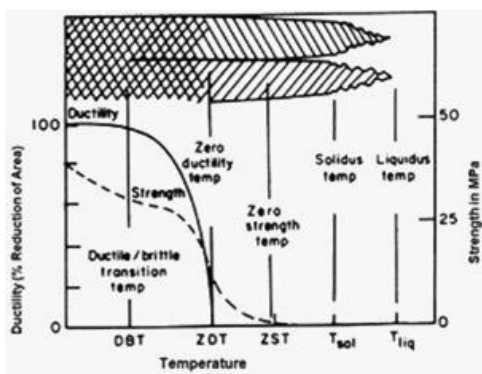
During the continuous casting process, the mechanical properties of steel at high temperatures play a crucial role in crack formation. It is known that crack formation occurs in the semi-solid-liquid (mushy) region, which exhibits low plastic properties. This is because brittleness is at its maximum in this region.

Many cracks in steel produced by continuous casting occur in this mushy region of low ductility. Cracks form and propagate along the interdendritic regions within this zone. The level of mechanical properties obtained within the solidifying shell is related to the volume fraction of the solid phase to the liquid phase in the mushy zone. The threshold for crack formation is at least 90% solid phase by volume in this region. Under these conditions, it reaches a stage where the liquid cannot infiltrate. As the dendrites are very close to each other, they prevent liquid penetration, creating a more solid region. This temperature is referred to as the "liquid impenetrable temperature" (LIT).

As the steel begins to fully solidify, the liquid film that forms between dendrites disappears, reducing crack susceptibility. The temperature at which solidification is complete is known as the "zero ductility temperature" (ZDT). Thus, the brittle temperature range of the steel is between the ZDT and the LIT. Additionally, it is essential to consider the chemical composition and the development of microsegregation in the solidifying matrix. These factors affect the solidification temperature and, consequently, the volume fraction of the solid phase at given temperatures. The relationship between the volume fractions of austenite and δ-ferrite phases influences solidification. This relationship is crucial, particularly if the δ-ferrite to austenite transformation occurs within the brittle temperature range, impacting crack susceptibility.

In steels containing 0,17% C, the δ-ferrite to austenite transformation occurs in the final stages of solidification. In steels with 0,06% C, this phase transformation happens after solidification is complete. For steels containing up to 0,25% C, the phase transformation occurs during solidification.

As a result, for steels with less than 0,17% C, the phase transformation occurs after solidification in temperature regions where ductility is present. Therefore, these steels exhibit greater resistance to stresses occurring during the phase transformation. In the brittle temperature range, only stresses due to thermal contraction are influential. For steels containing 0.17% to 0.25% C, the phase transformation occurs during solidification. Consequently, the combined stresses due to phase transformation and thermal contraction occur within the brittle temperature range, increasing crack susceptibility.

The positions of characteristic temperatures (ZDT and LIT) vary according to the content of dissolved trace elements in the steel. Among these elements, S is the most significant, along with others like P, N, and H.

The brittle temperature range increases with higher sulfur content. This is because, during the final stage of solidification, sulfur segregation occurs, causing localized changes in the solidification temperature and increasing thermal stresses. For instance, in a steel type containing 0.30% C, the brittle temperature range is 25°C with 0.01% S but approximately 80°C with 0.08% S.
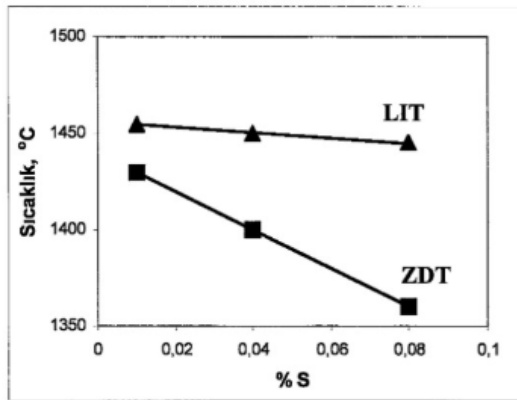

The Effect of Sulfur Content on the Brittleness Temperature Range in Steel Containing 0.30% C

Based on this information, the sulfur content in steel during casting is crucial for preventing or reducing the severity of cracks in billets. Therefore, sulfur should be minimized as much as possible under operating conditions, except in some specific steel grades. In secondary steel production, sulfur refining is achieved through ladle metallurgy, as previously explained. Hence, identifying and optimizing the factors affecting sulfur removal is the most critical activity for preventing crack formation on the billet surface and within its internal structure.
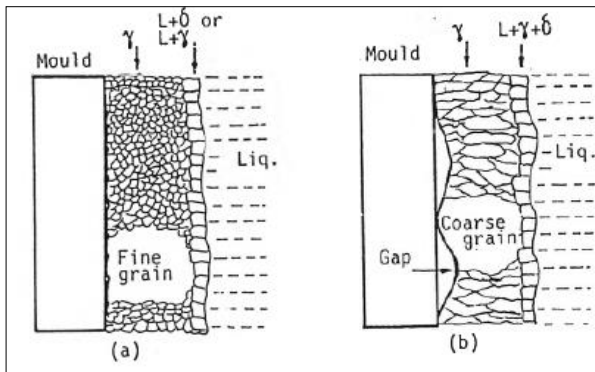
The effects of irregular solidification and metallographic changes, along with carbon content, are shown on the side. The schematic representation illustrates the difference in austenite grain size between (a) low-carbon steels and (b) medium-carbon steels due to uneven solidification in the mold.
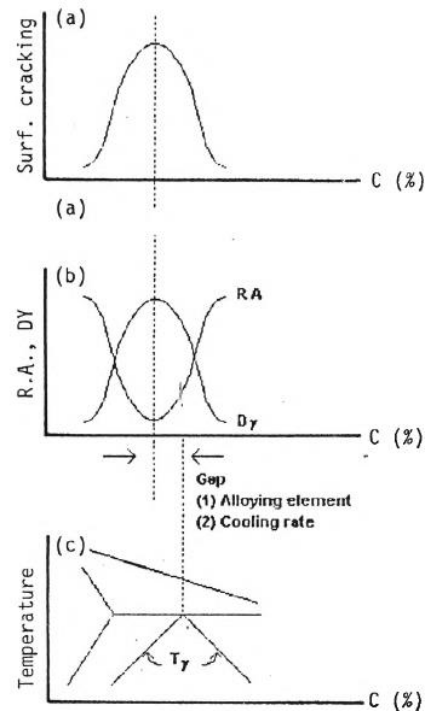
On the other hand, as known for low-carbon steels, when there is good mold contact and appropriate cooling conditions, the austenite grain structure will also be good accordingly. Although the carbon content corresponding to the maximum austenite grain size matches the carbon content associated with maximum surface cracking susceptibility, there is significantly less frequency of crack formation at the peritectic point of 0.18% C in the Fe-C diagram. This reduction in carbon content at the peritectic point can be explained by the effects of alloying elements such as Mn, Si, Ni (the influence of these elements can be described using the carbon equivalent (CE) and this relationship can be utilized). The carbon content, which is dependent on the austenite grain size, corresponds to a value where ductility is low and is also in good harmony with changes in austenite formation temperature as shown on the side in the Fe-C diagram. Diagram indicating (a) steel surface cracking frequency, (b) ductility (RA), and γ grain size (Dγ) in relation to carbon content, and (c) their association with the peritectic transformation.

3.2. Phosphorus & Sulfur

Temperature, the oxidizing power of the slag, and its basicity are factors affecting the distribution of phosphorus and sulfur between the metal and the slag. After phosphorus and sulfur are oxidized from the metal and absorbed into the slag, an increase in metal temperature, a decrease in the system's oxygen potential, and a reduction in the slag's basicity can result in the return of phosphorus and sulfur from the slag back into the metal. This phenomenon has been observed in practice under certain conditions. The primary reasons for the return of phosphorus and sulfur to the metal include a decrease in the slag's basicity, the addition of deoxidizing elements to the system before the complete removal of the slag, and the subsequent reduction of the system's

oxygen potential. By addressing these factors, up to 90% of the phosphorus and sulfur in liquid metal can be transferred to the slag with a single slag treatment, provided the initial phosphorus and sulfur content is not excessively high.

In steel production, the primary source of hydrogen is moisture found in the furnace atmosphere, furnace charge materials, or furnace and ladle refractories. Carbon boiling is crucial for the removal of hydrogen from steel; hydrogen atoms diffuse into rising CO gas bubbles within the metal bath, enter these bubbles as H_2 gas, and thus exit the metal. Following deoxidation, the absence of carbon boiling results in insufficient hydrogen removal from the metal, and the drop in oxygen concentration increases the equilibrium hydrogen concentration. This highlights the critical importance of water and water vapor, particularly after deoxidation.

A summary of the effect of alloying elements on hot ductility (HD) and transverse cracking (TC) on microalloyed steels can be observed in Table 2, which shows the positive (+) and negative (-) effect from different alloying elements.

Table 1. Effect of alloying elements on crack susceptibility during continuous casting

Element	HD (+)	HD (-)	TC (+)	TC (-)	Remarks
Nb		✗			*Formation of fine Nb (C,N) precipitates, promote low ductility failures. *Additions of 0.01% has a detrimental effect on transverse cracks formation. *Nb steels with S levels of <0.005% increase crack susceptibility in Nb steels. Additions of Ti in Nb steels increase ductility.
V	✓				*Little effect on transverse cracking. At high content of N (0.025%), cracks can accur in 0,15%V steels. *In thin slabs (50mm), VN steels are reported to have better surface quality than Nb steels.
Ti		✗	✓		*Ti additions of 0.01-0.06% are required to reduce transverse cracks *0.15%Ti was reported to decrease volume fraction of TiN *Generally, Ti addition is considered beneficial to surface quality of steel slabs and reduce the risk for crack formation during straightening.
N		✗		✗	Nitrides are considered to be detrimental for cracking formation.
Al		✗		✗	Transverse cracking problems can arise when the Al levels are >0.03%Al. It has been found AlN precipitates on the surface of intergranular failed specimens which indicate possible detrimental effect.
S		✗		✗	Due to either segregation in grain boundaries or fine sulphies precipitation. Recommended to keep low amount of S.
P	✓		✓	✗	0.02%P is recommended for Nb steels. t can be detrimental at >0.04%P. Segregation of P promotes boundary liquid films and inter-granular failures.
B	✓		✓		Slow cooling rates during CC promotes better ductility between 850-1050☐ and lower ductility between 850-950°C. Ref the effect of boron... B retard the formation of pro-eutectoid ferrite and increase grain boundary cohesion beneficial for hot ductility. Steels containing 0.002% B improves ductility of steels Combination 0.004% B with 0.002% Ti imporvest ductility significantly.
Cu		✗			CuS precipitation responsible for poor ductility. Additions of N prevent crack formation. Cu levels must not exceed 0.15% Cu.

4. Operational results

Table 2. Analysis of Transverse and Corner Crack with 5 Why method

WHY? WHAT IS THE SOURCE OF DEFECT? WHY DOES THE DEFECT OCCUR?	HOW TO PREVENT THE DEFECT?	HOW TO DETECT THE DEFECT?	WHAT ARE THE DEFECT REMOVAL METHODS?	WHAT ARE THE EFFECTS OF THE DEFECT ON THE FINAL ROLLED PRODUCT?
- Incorrect oscillation settings. - Solidifying liquid steel getting caught on irregularities inside the mold. - Deformation of the mold (excessive tapering, wall wear). - Very high steel temperature. - Non-uniform secondary cooling water. - Severe localized cooling of the strand. - Incorrect mold lubrication. - Dirty inner surface of the mold.	- Calibration (centering) of the mold with the "S" curve. - Absence of scratches and wear on the mold surface. - Appropriate liquid steel temperature. - Keeping unwanted elements (S, Sn, Cu, Zn, Pb) in the steel under control.	- It is very difficult to detect defects during casting. Only large cracks can be identified. - Grinding in a direction parallel to the cracks can easily reveal the defect. - Inspection performed after acid etching the surface provides very good results.	- If transverse surface cracks occur in one cast, this defect persists throughout the entire casting. - If the cracks are not deep, the entire semi-finished surface and corners should be cleaned by grinding or scarfing. If the cracks are deep, the semi-finished product is scrapped.	- Transverse billet cracks cause large cracks on the surface of the rolled product. - On bar products, cracks appear jagged, like a saw blade. - Large cracks can lead to significant rolling problems and may result in the billet breaking or snapping during rolling.

Table 3. A breakout in the continuous casting process can be caused by several factors

WHY? WHAT IS THE SOURCE OF DEFECT? WHY DOES THE DEFECT OCCUR?	HOW TO PREVENT THE DEFECT?	HOW TO DETECT THE DEFECT?	WHAT ARE THE DEFECT REMOVAL METHODS?	WHAT ARE THE EFFECTS OF THE DEFECT ON THE FINAL ROLLED PRODUCT?
• Excessive slag in the steel and slag adhesion between the mold and the first shell/billet, • Low tundish level and slag leaking into the mould. • Insufficiency/excess of lubrication, • Excessive use of casting powder, • Steel/slag adhesion at the mouth of the mold, • Mold deformation, • Mold cooling water not at appropriate flow rate, • Casting temperature is too high, • High casting speed, • High casting speed due to zirconia nozzle expansion. • Casting flow does not flow into the mold center, • 1st and 2nd stage waters not having the appropriate flow rate (ring and collector) • Improper selection or clogging of the 1st and 2nd cooling water jets.	Removing slag from the mold, - Removing slag from the tundish, - Skimming the mold, - Maintaining Mn/Si ratio ≥ 3 and Al content < 0.005, - Limiting the amount of S that causes hot brittleness in the material, - Changing the mold, - Adjusting the proper mold cooling water flow rate, - Correctly controlling the casting temperature and speed, - Properly aligning the zircon mold, - Selecting and appropriately using suitable water sprinklers and nozzles, - Designing the spray cooling area so that the cooling intensity decreases from top to bottom, - Adjusting the secondary cooling water flow rate properly, keeping the water pressure high.	- The defect resulting from bleeding is easily visible during casting. - An explosion can cause the loss of the strand, leading to a severe burst. - An explosion can also cause serious damage to the machine.	- The defect necessitates grinding or material removal, often leading to the rejection of the billet.	- This defect can cause various serious surface flaws. - Material defects such as wavy edges, transverse cracks in the middle, edge cracks, and alligatoring, split ends cracks.

5. Conclusion

The Continuous Casting (CC) process is a sophisticated steel-making technology that converts molten steel into solid products like slabs, blooms, or billets. Despite strict operational procedures and advanced control techniques, defects in CC products cannot be entirely eliminated due to various factors such as equipment condition, casting parameters, steel quality, mold characteristics, cooling conditions, phase transformation, and casting powder properties.

Defects in CC products, defined as deviations from specified standards, can lead to reduced efficiency and sales loss in subsequent processing. Preventive metallurgy technologies and immediate intervention during the CC process are essential to address defects and prevent losses. It is crucial to analyze the causes of defect formation, which often result from multiple interacting factors.

In this study, crack formation in the CC process was examined, influenced by the chemical composition of the steel, process parameter control, and microstructure development. The "5 Whys" analysis technique was used to understand the root causes of defects and implement effective solutions.

Overall, continuous monitoring, analysis, and optimization of the CC process are necessary to ensure the production of high-quality steel products and minimize defects.

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