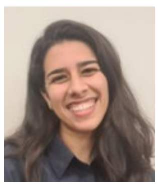
Improvements in Process Practices With a Focus on Reduction of Slivers in Ultralow-Carbon Automotive Exposed Application Grades at Ternium Brasil



The demand for high-quality clean steel requires the mitigation of non-metallic inclusions; this is particularly significant in the manufacturing of ultralow-carbon steels for automotive exposed applications. During the galvanization process, there is an increase in the probability of inclusions being revealed. Inclusions can originate from various sources such as deoxidation and reoxidation, entrapment of slag, wear of refractory materials, and undesired chemical reactions. To fine-tune a process method to meet those requirements, adjustments were implemented in the production parameters, starting from initial stages of steel production in the converter until continuous casting, aiming to mitigate the formation and entrapment of non-metallic inclusions.

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Introduction

Interstitial-free (IF) steels belong to the category of ultralow-carbon steels, their virtually absent interstitial atoms resulting from low levels of C and N. They are widely employed in the automotive industry for exposed deep-drawing applications. The occurrence of slivers in steel sheet for automotive applications causes both cosmetic surface imperfections and formability problems. Sliver defects occur as lines along the steel strip surface parallel to the rolling direction. This type of defect in steel coils can be associated with the presence of non-metallic inclusions.[1]

Non-metallic inclusions can be classified according to their origin, with those originating from the steel manufacturing process being called endogenous, and those from external sources being classified as exogenous. Endogenous inclusions are a product of the intentional addition of alloying elements for steel deoxidation, such as aluminum. Alumina inclusions are generated by the reaction between dissolved oxygen and the added deoxidant. These are microscopic inclusions. Exogenous inclusions, on the other hand, result from steel reoxidation or slag emulsification in the molten bath, and may also come from slag entrainment, flux powder, or the reaction between the metal and the refractory. They are generally macroinclusions.[2]

Table 1 provides a summary of the main sources of non-metallic inclusions and their formation mechanism.[1–6]

This article evaluates alloyed ultralow-carbon steels, aluminum-killed, produced by primary refining in a basic oxygen furnace (BOF), treated in secondary refining by Ruhrstahl-Heraeus (RH) route and, subsequently, cast as steel slabs in a continuous casting machine (CCM), as described in the diagram in Fig. 1. These slabs were cold-rolled, and their coils were 100% inspected after the galvanization process.

Discussion

Characterization of inclusions

Table 2 shows the chemical composition of the steel studied. The slabs produced with this material are cold-rolled, where their thickness is reduced to 0.6 mm. After this,

Table 1

Summary of the Main Sources of Non-Metallic Inclusions

Origin of inclusion	Formation mechanism
Deoxidation products	Generated by the reaction between the dissolved oxygen and the added deoxidant, such as aluminum
Reoxidation products	Generated when Al remaining in the liquid steel is oxidized by FeO, MnO, SiO2 and other oxides in the slag or by exposing the steel to exposure to the atmosphere
Slag entrapment	Occurs when slag from the ladle, tundish, or mold is carried over into the steel during the transfer process
Exogenous inclusions from other sources	Include particles such as pieces of refractory bricks and ceramic lining, flux powder particles

they go through the galvanization process, where the coils receive a zinc coating.

During the inspection of this material, defects typical of cold-rolled were identified, as shown in Fig. 2. These types of defects are known as material separations caused by subsurface inclusions. They have a length of 250–320 mm and a width of 8–10 mm.

Figs. 3a and 3b show subsurface inclusions under the zinc cover layer. Their size is very small (right) to small (left) being in the range of 1–10 µm. The energy dispersive x-ray (EDX) composition mapping shows a mixture of nonmetallic elements O, Ca, Si, F, Al, Mg, Zn plus the metallic elements from the steel matrix like Fe, Ti, Mn.

Figure 1

Steelmaking route.[7]

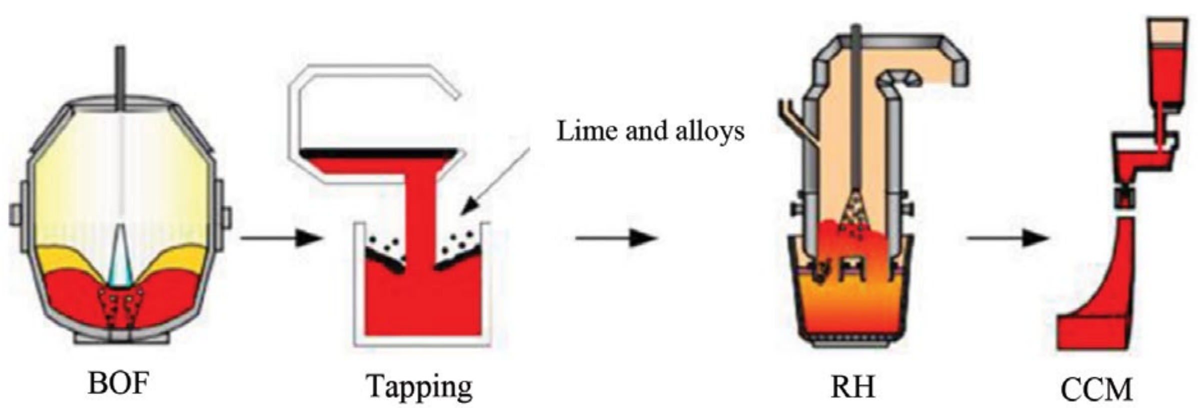


Table 2

Chemistry of Interstitial-Free (IF) Steel Grade Analyzed, wt. %

Product identification	C	Mn	S	P	Al	N	Ti	Si
Alloyed ultralow carbon	Max. 0.002	Max. 0.155	Max. 0.0090	Max. 0.0154	Max. 0.060	Max. 0.0030	Max. 0.049	Max. 0020

Figure 2

Defect images photographed at the cold rolling mill.

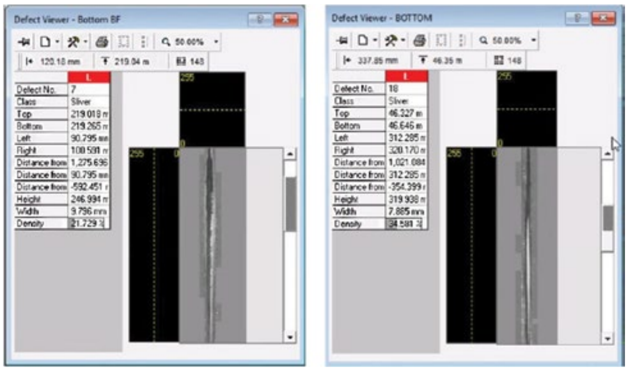
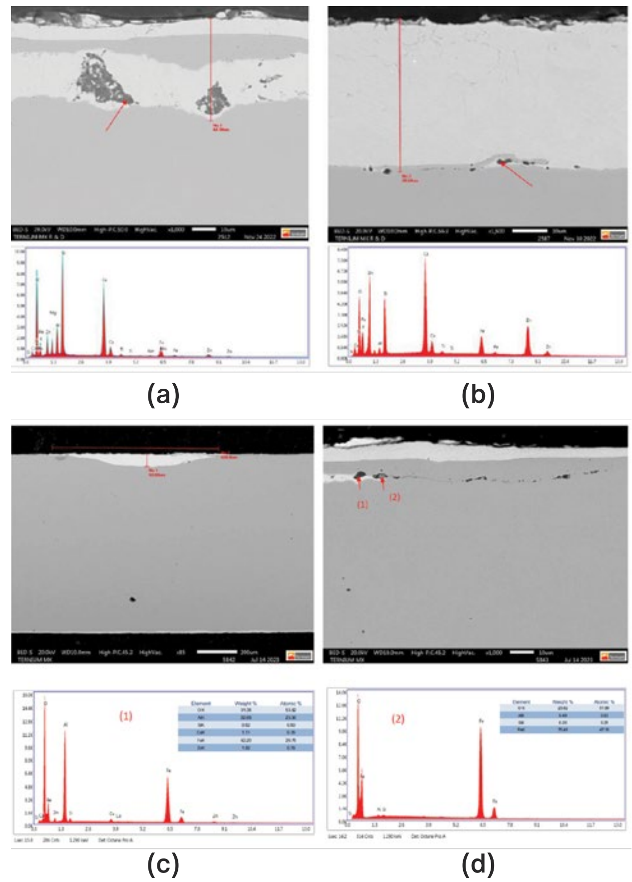


Figure 3

Defect appearance and composition.



Figs. 3c and 3d also show a mixture of nonmetallic elements O, Ca, Si, Al, Zn plus the metallic element Fe.

Thick oxidation inclusions in the melt should be concentrated in the inclusion band of the slab, which is located from 3.5 to 5.0 cm below the surface of the original slab due to the CCM vertical length. These can resurface during rolling. Although, the high contents of Ca, Si and F with low alumina and MgO in Fig. 2a and 2b indicate problems related to casting powder. On the other hand, Figs. 2c and 2d indicate a defect caused by the presence of alumina, normally associated with inclusions from ladle slag, tundish slag or reoxidation during casting.

Operational Practices Applied in the Steel Production Process

With the aim of reducing the occurrence of the presence of slivers in the galvanized material, several adjustments to the production process were carried out in order to increase the cleanness of the steel without. It is necessary to carry out scarfing on 100% of the surface of the plate to remove inclusions concentrated on the surface and subsurface of the slabs.

Production Practice Applied to the Converter Process: The passage of slag through the LD converter channel to the ladle during tapping is an important source of reoxidation. This occurs because the slag contains a high content of FeO and MnO, which are oxides that tend to react with dissolved aluminum and, consequently, generate alumina in the liquid steel, due to favorable thermodynamics, as shown in Eqs. 1 and 2. The higher content of FeO and MnO in the ladle slag, the greater potential for reoxidation and corresponding generation of alumina inclusions. Fig. 4 shows how the total oxygen in the ladle correlates with % (FeO + MnO) in the ladle slag.[2,4]

Figure 4

Relationship between the FeO+MnO in ladle slag and the T.O in of steel in ladle.

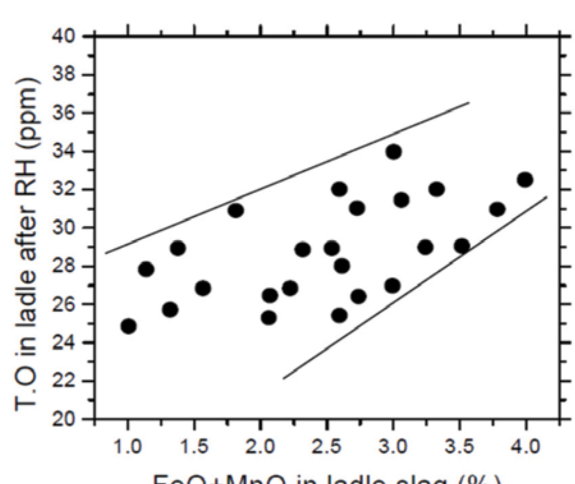


Figure 5

Study of kg/t of carryover slag at Ternium Brasil.[9]

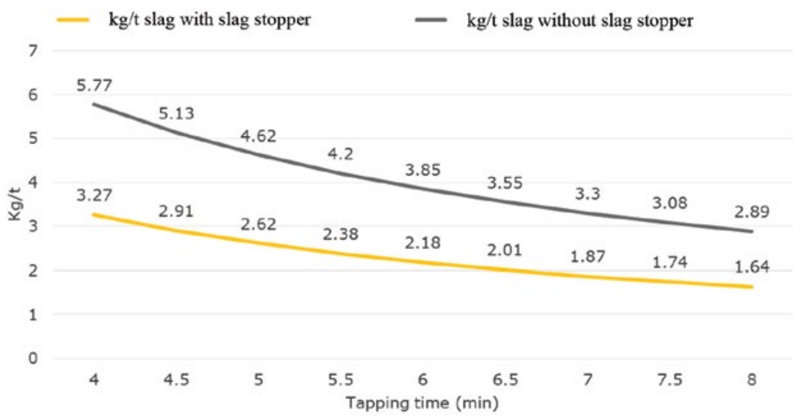
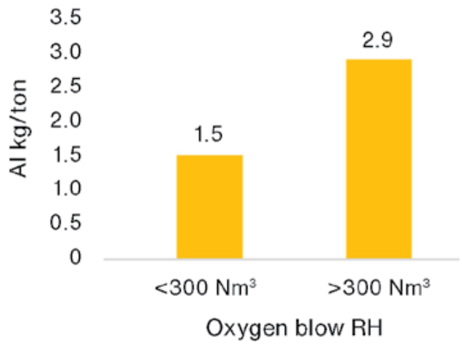


Figure 6

Comparison of total Al consumption for ULC heats with heating below and above 300 Nm^3.



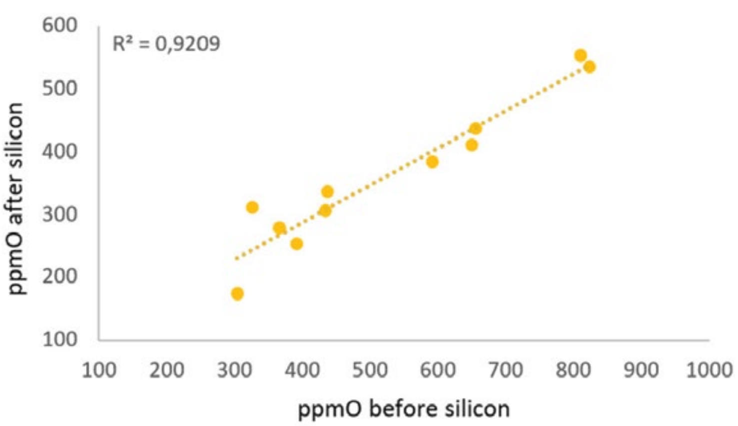
$$3FeO(l) + 2Al = Al_2O_3 + 3Fe(l) \quad \text{(Eq. 1)}$$

$$3MnO + 2Al = Al_2O_3 + 3Mn(l) \quad \text{(Eq. 2)}$$

One of the countermeasures that can be adopted to reduce contamination by FeO and MnO is to minimize the passage of slag from the converter to the ladle during tapping by using the AMEPA camera in conjunction with the slag stopper. The AMEPA camera identifies the passage of slag, and the slag stopper is then activated in order to reduce the volume of slag carryover from the converter into the ladle.

Figure 7

Correlation between ppm of oxygen before and after pre-deoxidation with silicon addition.



Tapping time is also an important process parameter, as it is correlated to the taphole life and the flow of steel and slag during tapping. This can be seen according to the study carried out at Ternium Brasil shown in Fig. 5, where it can be observed that for situations with or without a slag stopper, the volume of passing slag is greater when there is a shorter tapping time.

Production Practice Applied to the Secondary Refining Process

Practices for Reducing Alumina Inclusions Formation — At Ternium Brasil, chemical heating by oxygen lance is an inherent part of the process needed to adjust the final temperature of the bath to the continuous casting process. As the heating is by aluminothermy, it enriches the steel with alumina inclusions that could hinder the final product. To better suit the cleanliness requirements of the final application, the chemical heating in the secondary refining RH route was limited to a maximum of 300 Nm^3.

As all aluminum additions have a loss inherent to yield that generates alumina, to give extra time to the lost aluminum to float and be retained in slag, it's possible to see that average consumption of aluminum is much greater for heats > 300 Nm^3 as heating in RH is by aluminothermy (Fig. 6).

Besides that, to reduce oxygen available to form alumina inclusions, it was standardizing a practice with pre-deoxidation with silicon before complete deoxidation with aluminum. The procedure with combined silicon-aluminum deoxidation implemented aims to reduce the total oxygen and amount of alumina inclusions.

Figure 8

Boxplot of slag Fe Total for heats with and without slag DeO practice implemented.

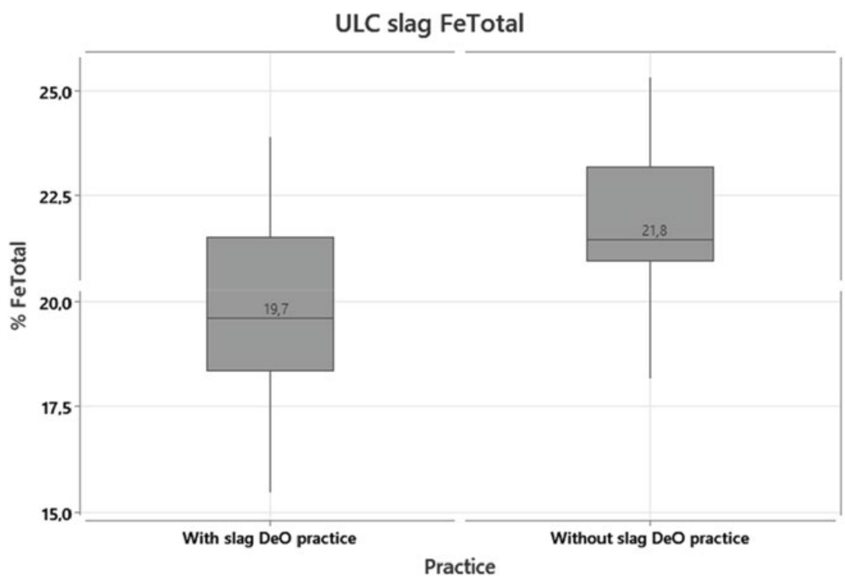


Fig. 7 shows the correlation between ppm of oxygen before and after silicon addition.

Practices for Removing Alumina Inclusions — Inclusions are mainly captured by ladle slag in the refining process. The removal of nonmetallic particles occurs in three stages: flotation in the bath, separation to the interface and dissolution into the slag. To do so, the ladle slag needs to be able to absorb those inclusions. Inclusions are considered eliminated from steel when they're completely dissolved in the slag.

Aiming to lower FeO and MnO from ladle slag, and to form a liquidus and good viscosity slag, a practice for deoxidizing slag with granulated aluminum added after tapping was implemented. Fig. 8 shows the reduction in FeTotal for slag sample taken after RH degasser, with an average reduction of 9%.

Even though the process route in question is the RH degasser facility, a slagless metallurgical route, the extra procedure was also deemed optimal to avoid the reduced but existent motionless slag-metal reoxidation reactions.

Besides that, a minimum flotation time is necessary in order float most of the inclusions as indicate in Fig. 9 by Geng Dian-Qiao et al.[10] Because of that a minimum circulation time, called "killing time," of 12 minutes after the complete deoxidation at RH degasser was applied.

To maintain optimal argon flow, the RH nozzles were checked and assured to be mostly functional, with a threshold of 14 of 16 nozzles. The inclusion flotation is stirring dependent. As Onu and Kuwabara previously demonstrated, the circulation of steel is enhanced with a higher argon injection. This operational parameter was used as an addition guarantee of proper facility performance. Eq. 3 was obtained by Kuwabara (NSC-1984) through an experimental model in a 100-ton reactor when correlating the circulation rate with operational variables.

$$Q = 11.4 * G^{\frac{1}{3}} * D^{\frac{4}{3}} * \left(\ln\left(\frac{P_1}{P_2}\right)\right)^{\frac{1}{3}}$$

(Eq. 3)

where

Q = Liquid steel circulation rate (tons/minute),

G = Carrier gas flow (Nl/minute),

D = Snorkel inner diameter (m),

P_1 = Atmospheric pressure (mbar),

P_2 = Vacuum level inside the RH (mbar).

Another important parameter for the cleanliness of steel during secondary refining treatment is the stirring time after alloy addition. The recommended time is above 10 minutes,

Figure 9

Schema of removal on inclusions at RH degasser.[10]

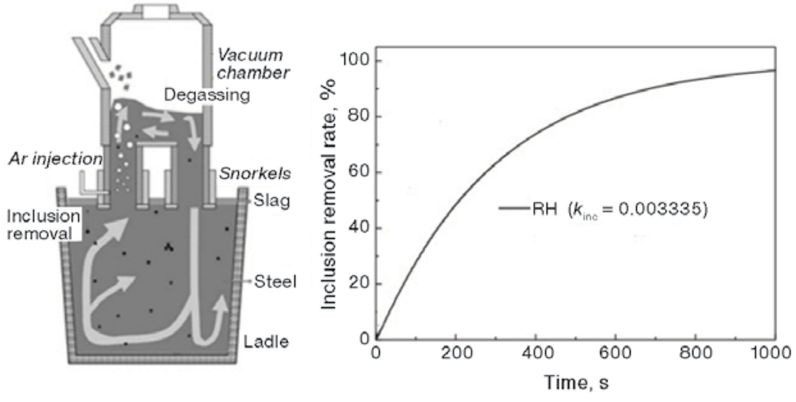


Figure 10

T.O in ladle versus ladle stirring time.[7]

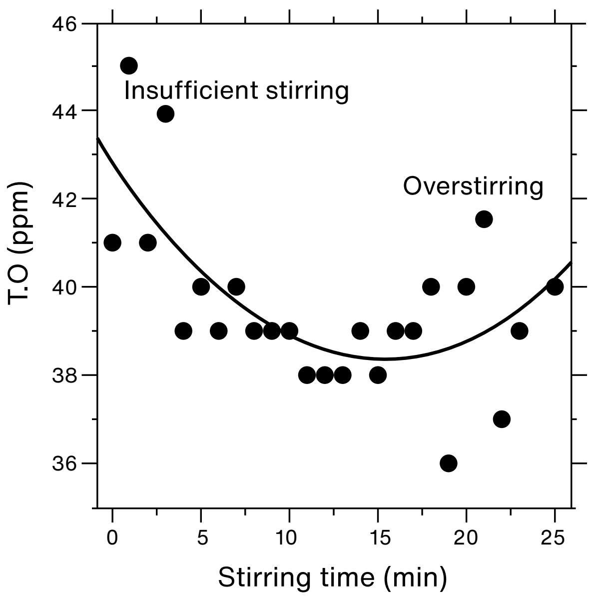
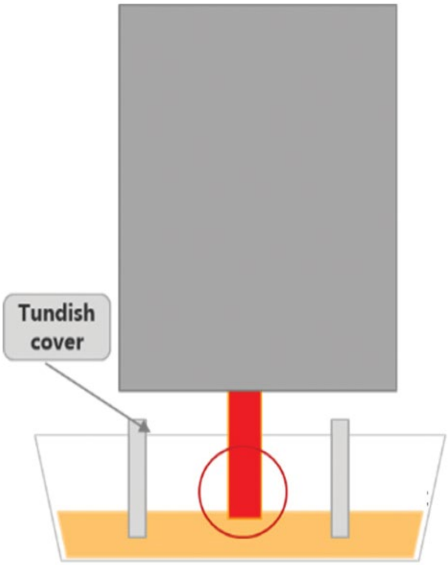


Figure 11

Schematization of the appropriate moment to begin adding covering powders in tundish.



allowing alumina inclusions to circulate toward the slag and be removed. However, there is an optimal range of circulation time, above which the effect of inclusion removal reverses, as can be seen in Fig. 10.

Production Practice Applied to the Continuous Casting Process: Considering the continuous casting process, some practices can be applied to prevent the formation of inclusions and even reduce the number of inclusions in steel by capturing them through the distributor slag. Several operational practices associated with this have been studied, such as: the use of flow modifiers in the tundish, ladle opening with a long tube immersed in the tundish during ladle changes during sequencing, lining of tundish based on magnesium instead of silica, gas bubbling in the tundish, free ladle opening without the use of oxygen, protection of the gate valve mechanism with argon, and protection of the jets with a long tube and submerged-entry nozzle (SEN).[2,4]

Analyzing the process in tundish, some key points were evaluated. At the beginning of the sequence at the tundish, the ladle needs to be in the lowest position when it is opened, therefore the immersion of the ladle shroud into the steel in tundish happens at a higher tundish weight, leading to more avoidable oxidation. Another

Figure 12

Schematization of the proper process for ladle opening during the exchange.

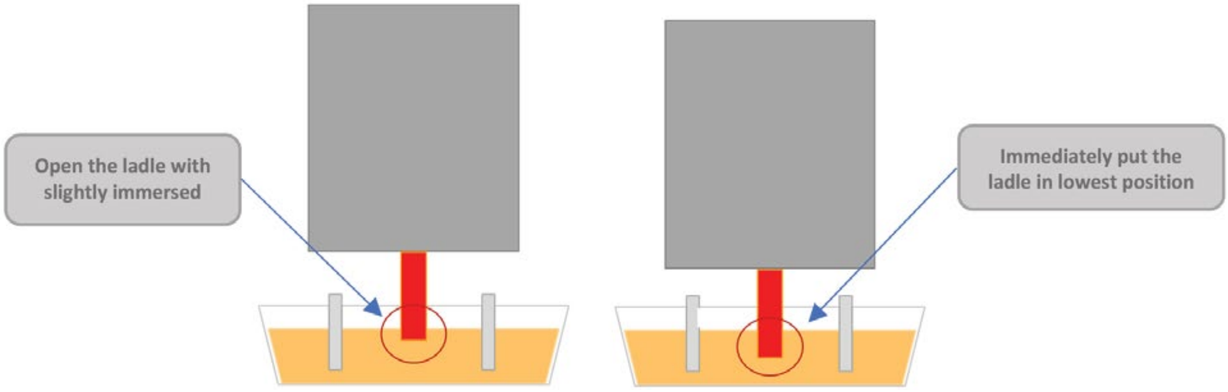
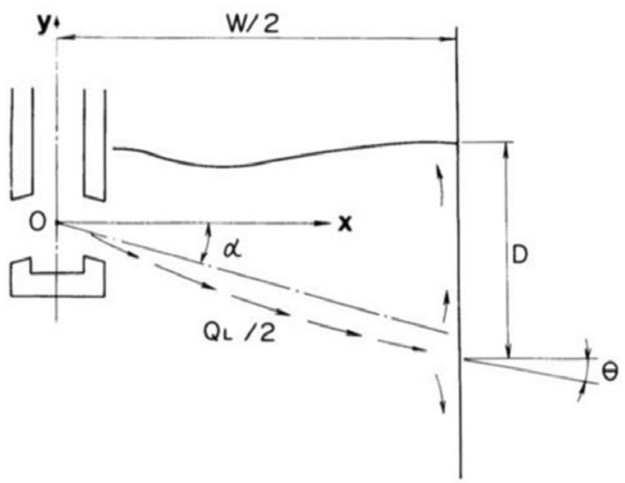


Figure 13

Diagram representing where the values used in the calculation of the F parameter are taken from Reference 8.



critical step during this phase is determining the optimal moment to begin adding the covering powder. With the ladle positioned at its lowest, the addition of tundish slag powder should commence upon immersion of the ladle shroud, as illustrated in Fig. 11.

The use of a shroud type that allows immersed opening of the ladle is extremely important. This immersion serves multiple purposes:

- Protection from oxidation: By immersing the ladle shroud into the steel bath, it helps to minimize the exposure of the molten steel to the surrounding atmosphere, thus reducing the risk of oxidation.
- Control of flow: The ladle shroud helps to control the flow of molten steel from the ladle into the tundish, ensuring a smooth and uniform transfer.
- Minimization of inclusions: Proper immersion of the ladle shroud helps to prevent the entrapment of slag and other nonmetallic inclusions, which could otherwise degrade the quality of the final steel product. Fig. 12 shows an ideal simulation of opening the ladle during a ladle change.

In addition to starting the sequence and changing the ladle, closing the ladle during the sequence is also very important. When ladles are closed manually after visual slag detection, there is a risk for uncontrolled slag carryover to the tundish. As the ladle slag of IF steel is at a relatively high FeO level, this can have a negative impact not only for the transition's slabs but for the whole sequence. For this reason, it is recommended to use a slag detection system (as closing of the ladle with AMEPA) in order to automatically close the ladle and mitigate the passage of slag to tundish.

In addition to the steel flow in the tundish, the steel flow in the mold is also very important for the control of inclusions in the produced steel slabs, especially when it comes to nonmetallic inclusions due to the presence of flux. In a study, T. Teshima et al. defined a numerical parameter that correlates factors that impact the steel flow in the mold. These factors are defined according to Fig. 13. This numerical parameter was named the F value and can be written according to Eq. 4:[8]

Figure 14

Relationship between level fluctuation at narrow side of mold between F value (a) and relationship between surface defect frequency on cold-rolled coil and F value (b).[8]

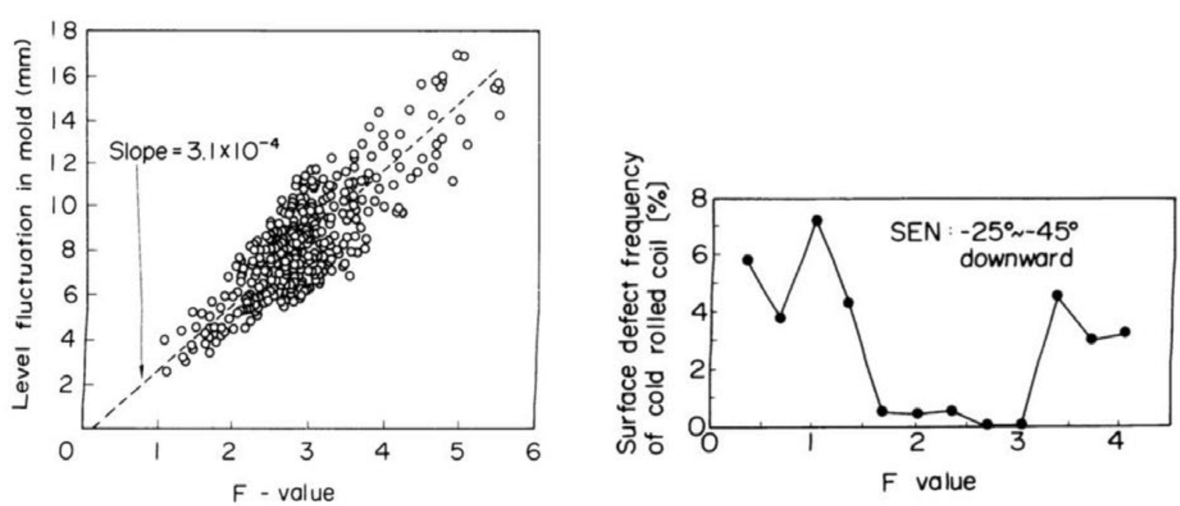


Figure 15

Evolution of the inspection result of galvanized coils.

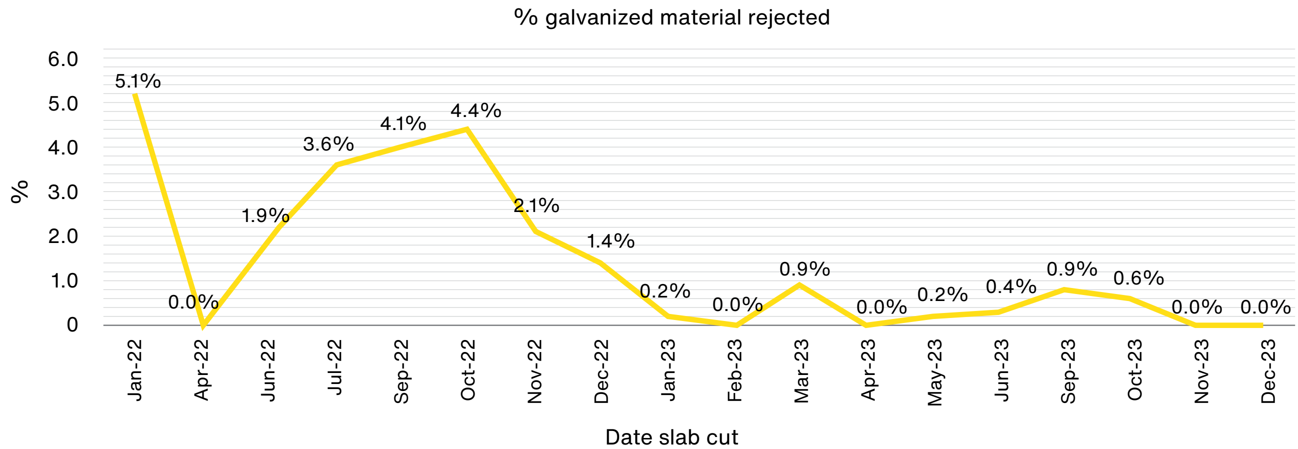
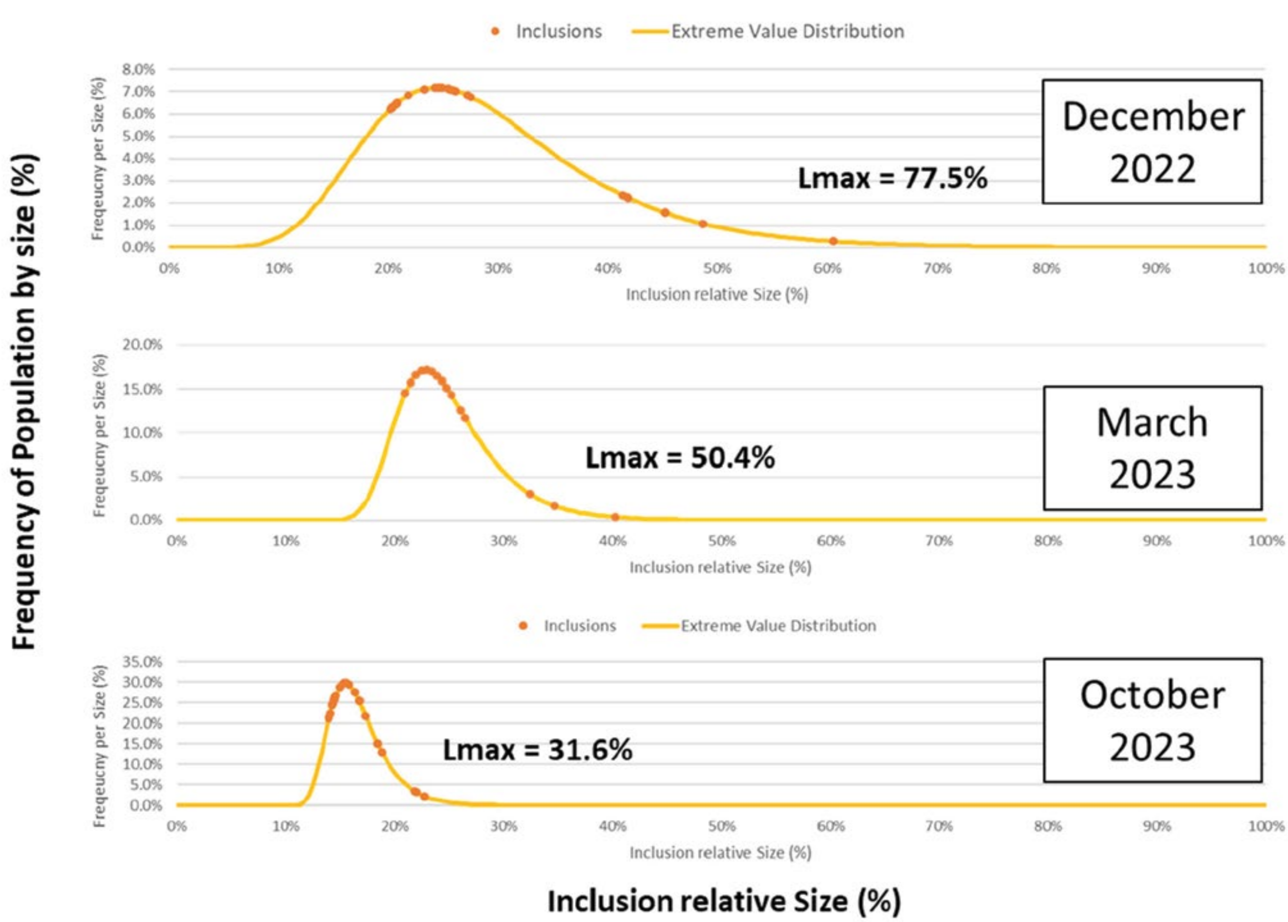


Figure 16

Gumbel Extreme Value Distribution for tundish steel samples in three different time sheets.



$$\frac{\rho Q_L v_e \left(1-\sin\theta\right)}{4} * \frac{1}{D}$$

(Eq. 4)

where

Q_L = flowrate of molten steel, m^3/second,

v_e = penetrating velocity of main steel stream, m/second,

α = outlet angle of submerged nozzle, (°),

θ = the steel stream penetrating angle, (°),

D = the distance between penetrating point at the wall and free surface, m,

ρ = density of molten steel, kg/m^3 and

W = mold width, m.

In the same study, T. Teshima et al. were able to correlate the F value with the fluctuation of the steel level in the mold on the narrowfaces and the presence of inclusions in the coils originating from the produced plates, as shown in Fig. 14.[8]

Thus, it is possible to use the F value as a reference that encompasses the type of submerged valve used, the casting speed, and the immersion of the SEN. As demonstrated in Fig. 14b), for values between 1.8 and 3, there is a significant reduction in defects found in cold-rolled coils.

Evolution of Results After Implementation of New Production Practices: If one analyzes the evolution of the rolling result on Fig. 15, it can be seen that after the application of new production rules in December 2023, the defect percentage went through a significant drop. An important point to be noted is the fact that slabs in question did not go through the scarfing process, which is usually used by mills during exposed steel production.

The steel cleanliness in the tundish was also measured by the Gumbel Extreme Value Distribution. It was used to determine the maximum alumina inclusion size in heats from December 2022, March 2023 and December 2023. The worst result of each period is shown in Fig. 16. It was considered that the upper 0.5% of the population distribution is represented by outliers. In this sampling, it is noticeable that the expected maximum alumina size reduces by considerable amounts.

Conclusions

Due to the characterization of the defect identifying traces of flux powder as well as the presence of alumina, improvement actions were necessary in the production process focused on the cleanliness of steel in all areas involved in steel production and solidification. From the analyses, it can be concluded that the actions taken to reduce the occurrence of defects caused by the presence of nonmetallic inclusions were effective, considering that there was a decrease from 5% of defects in 2022 to 0.2% in 2023.

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