Original Article

ANALYSIS AND VERIFICATION OF PROCESS VARIABLES AS CAUSES FOR MACROINCLUSIONS AND SCRAPPING IN A SPECIAL STEEL MELT SHOP

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Abstract

The technology used in manufacturing steel for mechanical constructions has made great progress in recent years, resulting in a remarkable reduction of the impurities in special steel. One of these impurities is known as macroinclusion, the presence of which can cause serious defects in the steel structure. In a melt shop, where the semi-finished product is formed, there are several variables that can cause the formation of impurities in the steel and must be controlled. Therefore, by analyzing the influence of the primary melt shop variables, including: the iron and manganese oxides of the ladle slag (FeO+MnO), the stopper rod level variation and the argon pressure in the shroud between ladle and tundish in continuous casting; it was possible to establish a relationship between scrap generation and these process variables, through the creation of an investigation method. As result it was possible to identify the scrapping relationship with the presence of high FeO and MnO contents in the slag, during ladle furnace starting operations, along with stopper rod level variation in the tundish.
Keywords: Macroinclusions; Clogging; FeO+MnO; Steelmaking.

1 INTRODUCTION

The manufacture of steels free of impurities has been a great challenge for the steelmaking industry. This requires knowledge about the metallurgical phenomena involved in the formation, growth and agglomeration of nonmetallic inclusions, which can be deleterious to the quality of the final product. These impurities can affect the mechanical properties of the steel. Although generated during the steel manufacturing process (being classified as endogenous or exogenous), these inclusions can cause clogging phenomenon in submerged entry nozzles (SEN) [1,2], also affecting the productivity of the melt shop.

Macroinclusions are, in most cases, inclusions of great size, usually of exogenous origin (slag entrapment), with an average diameter greater or equal to 50 micrometers. Generally, they cause defects in the manufacturing process or in the beginning of application. They are responsible for crack formation, due to their different deformability from steel, which compromises the quality and product application [3].

The present work has as first objective to establish a relationship between scrapping, based on the presence of macroinclusions and the variables considered as some of the main causes for the formation of these impurities in the product: iron and manganese oxides in the ladle slag (FeO+MnO), stopper rod variation level and shroud argon pressure in continuous casting (CC). The mentioned variables have been studied [4,5] in order to avoid or at least minimize the formation of macroinclusions and deepen knowledge about the chemical profile of inclusions.

The second objective of the present research is to determine if the degree of the studied variables is enough to justify the weight of the scrap material, making it possible to establish a correlation between theory and the production process and create a methodology to demonstrate this possibility. The macroinclusion formed in steel bars with considerable scrapping throughout the steelmaking process is also chemically characterized.

Inclusions could be defined as nonmetallic or intermetallic phases dispersed in a metallic matrix [6,7]. When significant amounts of large inclusions (e.g. 50 μm-150 μm) are present in the product, problems related to defect tend to occur. Sometimes, only a single large inclusion can cause a catastrophic failure, hence the need for tight control over the presence of these particles [8].

The number of inclusions depends directly on the oxygen content in the steel. For inclusions of 5 μm diameter,

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the difference in the number of inclusions for a total oxygen content between 1 to 50 ppm can be 100 times greater, assuming in this case all oxygen is in the form of Al_2O_3 inclusions. When taking into account inclusion morphology, inclusions aligned and elongated as small isolated particles get worse the strength properties and fracture toughness of the steel, as an example [9].

One of the main sources of inclusions in steelmaking is slag transfer from the electric furnace to the ladle, which contains high FeO and MnO contents. These liquid oxides react with the dissolved aluminum, originating solid alumina. The higher the content of these constituents in the ladle, the greater the reoxidation potential and consequently the greater the amount of alumina inclusions, making the steel less clean [1,10,11].

Recently, various studies [12-16] about how to overcome the problem of inclusions accumulation in bottlenecked regions of the casting flow (clogging) were reported. Bielefeldt et al. [17] studied calcium treatment of inclusions at a laboratorial scale to transform them into calcium aluminates of lower melting point and greater deformability. Avillez et al. [18] characterized inclusions with the intention of creating a correlation among different types to characterize internal steel cleanliness, considering different elaborations and deoxidation practices employed in the steels used as samples.

Another factor that may interfere in the degree of steel cleanliness is the shroud argon pressure. During casting, reoxidation of the steel may occur with the filling of the tundish, the exposed surface of liquid upon transfer from the ladle to the tundish (TD), or even from the TD to the course of the mold. When the metal is transferred from the ladle to the TD, the liquid jet contracts and expands, generating pressure in the shroud. Under these conditions of transfer intensity of the liquid jet, if the sealing system is not perfectly functional, atmospheric air can enter into the tube and cause reoxidation [8].

Air suction may occur between the slide gate and tundish, while the amount of air absorbed by the porous ring (where the argon is injected) depends on the level of inert gas which, if it is too high, can draw oxygen into the refractory and, if it is too low, allow the contact of the liquid steel with the atmosphere, which will reoxidize the steel and generate inclusions. There are shrouds with and without argon injection on the superior point of contact with the ladle. Argon is capable of making this region inert by ejecting mainly N_2 and O_2 from the atmospheric air around the ladle. In this scenario, the nozzle tip is immersed in the steel to approximately 20 cm, according to Gomes [19].

2 MATERIALS AND METHOD

2.1 Material

SAE 1050 steel was studied in this work and it was chosen because of its manufacture process in the steel industry and forming being critical. It is a medium carbon steel of wide application in the manufacture of shafts (automotive components) of any size. Table 1 shows the range of acceptable chemical composition of this material.

2.2 Study of the Elaboration Process of SAE 1050 Steel

In this study 12 heats were monitored, with 3 samples of steel and slag being taken throughout the process to obtain the results (P as steel and E as slag):

- Beginning of ladle refining: E-LFi and P-LFi.
- Final of ladle refining: E-LFf and P-LFf.
- Beginning of CC: E-CC and P-CC.

Figure 1 shows where which sample was taken in each production step inside the melt shop (considering ladle furnace and the continuous casting machine).

The heats were named as: A, B, C, D, E, F, G, H, I, J, K and L. Heats that showed scrap were B, E, I and K. The scrapping index was elaborated by the weight of refused material over the quantity of ingot steel.

The following variables were considered and their limits stipulated by the historic process control of the plant and are shown below:

- Iron and manganese oxides in the ladle slag (%FeO+%MnO), with a max limit of 6%, in mass for E-LFi and 1,5% for E-CC.
- Stopper rod level variation in CC tundish, limited to 5 mm;
- Argon pressure in shroud between ladle and tundish in continuous casting, between 100 and 1000 bar.

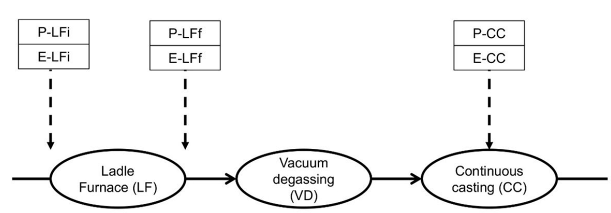

Figure 1. Scheme of sample collection steps.

Table 1. Chemical composition of SAE 1050 steel (weight %) [20]

	C (%)	Mn (%)	Si (%)	P (%)	S (%)
Minimum	0.48	0.6	0.035	-	-
Maximum	0.55	0.9	0.15	0.04	0.05

Other information of interest to this work:

- Ladle capacity of 60 tons.
- Three strands continuous casting machine.
- The billet section analyzed was square 155 mm x 155 mm.
- The refractory lining of the ladle was made of MgO-C and the tundish composed of MgO.
- Stopper rod cap made of MgO.
- The base of the submerged entry nozzle was made of alumina, while the region of contact with the mold slag was composed of zircon.

PIMS (Plant Information Management System) software was also used to verify the stopper rod variation and estimate the steel cleanliness with the inclusions retained on the SEN.

2.3 Equipments used in sampling

Samplers (lollipop type) used for the collection of steel and slag were from the manufacturer Heraeus Electro-Nite. The sampler used to take samples from the tundish contained a quartz tube and its extremity was positioned at 45 degrees from the bath surface, while samples from the ladle were considered good as they contained an appropriate combination of three main variables: penetration, immersion depth and time of immersion. Ultrasound equipment was used to evaluate defects due to the presence of macroinclusions in the bars. This equipment inspected 100% of the bars and had 6 heads of 5 MHz, with a detection limit of defects from 50 mm of the bars tip (detection depth). It is a widely used tool for detecting internal discontinuities, among them macroinclusions (MI), by allowing the analysis of a relatively large volume of the product, along with being able to demonstrate the distribution of inclusions. In addition, in case of automation of the system, it may be a relatively quick inspection technique. On the other hand, the greatest limitation of the technique is that it does not enable the determination of the type of inclusion detected.

Figure 2 shows the highlighted region where the presence of an MI defect was detected by an ultrasound inspection. In this region a marking was made on the bar to indicate where the section analyzed should be cut for further laboratory analysis.

The steel bar section was cut, just after its analysis by microscope. Sample cuts were carried out using diamond discs, where the flat surface was later grinded by grain sizes of 120, 220, 400 and 600 mesh. After grinding, the samples were cleaned in an ultrasonic bath for 5 minutes and polished with diamond paste. At each change in grinding grain size, the samples were washed and dried so that there was no contamination on the polishing cloth.

The MI chemical analyzes were carried out in a Scanning Electron Microscope by Zeiss, model LEO 440, with an EDS probe (20 kV and focus in 20 mm), using INCA software (that allows users to acquire an X ray spectrum from a specified point or area - Oxford X ray system) and detection by secondary and backscattered electrons.

The X ray spectrometer equipment was used for chemical analysis of the slag samples. For the steel analyses, an optical emission spectrometer was used. The X ray equipment model was PW2600, by Philips.

3 RESULTS AND DISCUSSION

3.1 Study of the Elaboration Process of SAE 1050 Steel

3.1.1 %FeO+%MnO contents in ladle slags

Figure 3 shows the %FeO+%MnO evolution obtained in slag samples throughout the process.

E-LFi indicates the %FeO+%MnO in the ladle at the beginning of the secondary metallurgy stage, while E-LFf indicates this value immediately before the ladle leaves towards vacuum degassing. E-CC stands for the content of the oxides in a continuous casting sample.

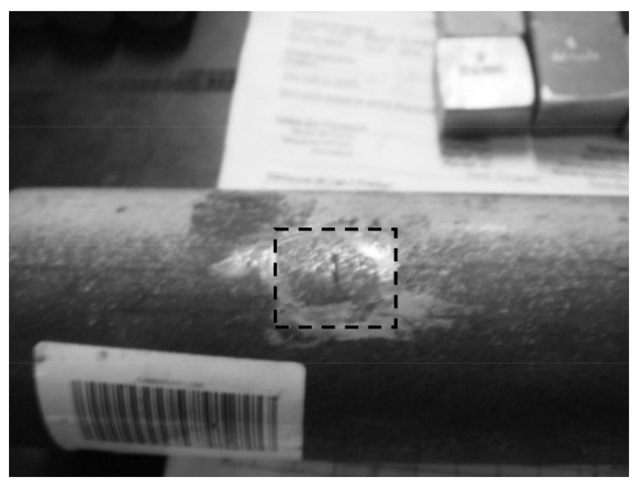

Figure 2. Bar with type MI defect marking after being inspected.

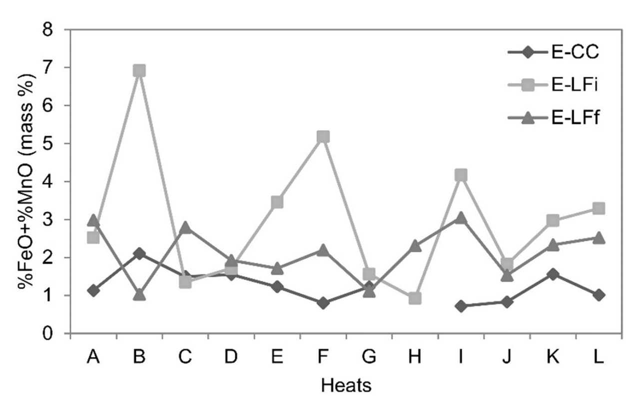

Figure 3. Results of %FeO+%MnO analysis in slag samples during the process.

With data obtained by analysis, heats B, F and I showed a percentage of oxides (FeO+MnO) close to 6%, in mass in sample E-LFi, when taking into consideration this variable. This indicates slag is being dragged from the Electric Arc Furnace (EAF) to the ladle. In some cases, the expected order of contents for each step of the furnace slag was not followed, like in heats A and B, where the FeO+MnO content is not reduced gradual from E-LFi to E-LFf and E-CC.

The E-CC analysis importance is due to the fact that this is the last sample taken from liquid steel in CC, not having much more time for actions related to inclusion removal, in the case a high amount of %FeO+%MnO is confirmed.

Results for E-CC indicate heat B with oxides content superior to the considered limit (~1.5%, in mass), along with heats D and K being slightly over this maximum. In heat H, E-CC was not collected during the steel production process. A similar study was conducted by Andersson et al. [21]. In their work they concluded that the model described could be used for future work on dynamic modeling of slag/metal reactions if the initial FeO content is less than 3-4% (by weight), while in this work the restriction is higher.

3.1.2 Variation of the stopper rod level

Figure 4 shows the stopper rod level control and argon pressure graphs in PIMS software.

The stopper rod consists of a refractory rod located inside the tundish, controlling the steel flow from this reservoir to the mold. In the heat K, a variation in the final of CC process was verified. This variation was not enough for clogging, but indicates that the steel is not clean, confirming the presence of MI in this heat (demonstrated on item 3.4). This kind of steel flow mechanism was also studied by other authors. For example, homogeneous flow was studied by Odenthal et al. [22] and is important in order to have a clean steel.

According to Contini et al. [2] with regards to the application of a computational fluid dynamic model, different stopper rod openings were evaluated to visualize the steel behavior and relate it to the inclusion deposition rate. This evaluation corroborates to the present study where it explains the relationship between a higher position of the stopper rod to a higher inclusion deposition rate. Figure 4 shows heat K demonstrating stopper rod elevation at the end of the heat.

3.1.3 Argon pressure in shroud between ladle and tundish in CC

All the heats presented Argon pressure values in the range of approximately 100 to 900 bar (represented by the lower line on Figure 4). For heats without air or argon entrapment, the inclusion formation was not verified. According to the first graph of a study [23], CC is stressed with complete shrouding (which also happened in heats monitored within this present paper) of the oxygen contact in low alloy carburized steels. Under such conditions, it seems to be that the inclusion formation was difficult.

3.2 Equipments used in sampling

Heat K, the one that showed the higher variation of stopper rod, presented the following final chemical composition (in mass percentage), Table 2.

The steel was produced under the specification of SAE 1050.

Figure 5 shows the EDS results for the encountered MI.

This sample presented clogging trace elements, so the type of inclusion could be concluded as being constituted of an oxysulfide (Ca-O-S). Also, the size of the inclusion found

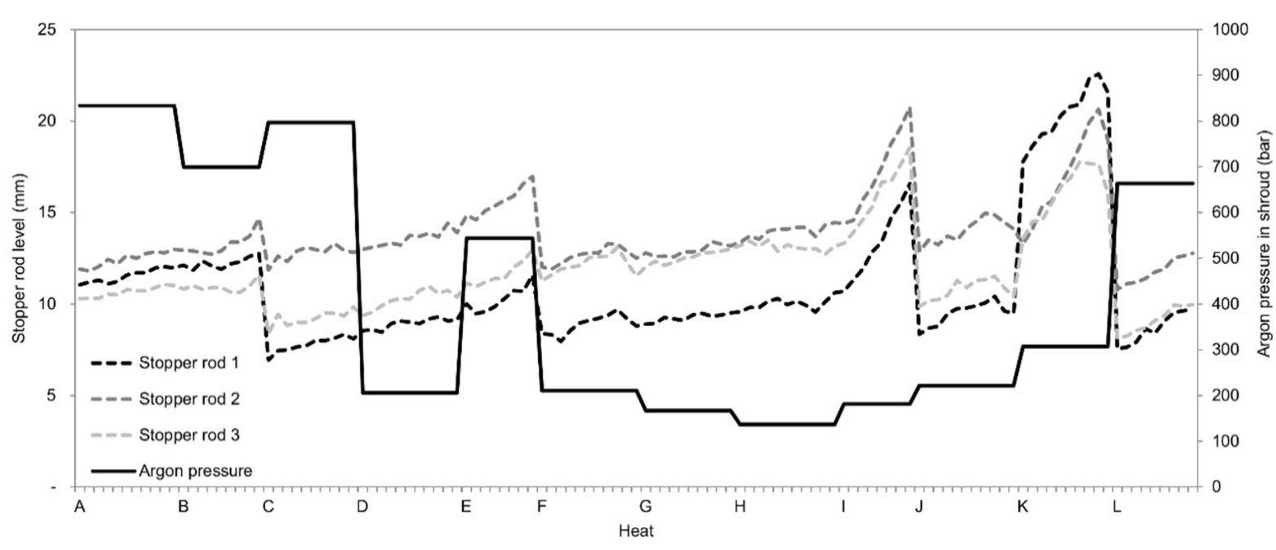

Figure 4. Stopper rod curve variations for the three strands.

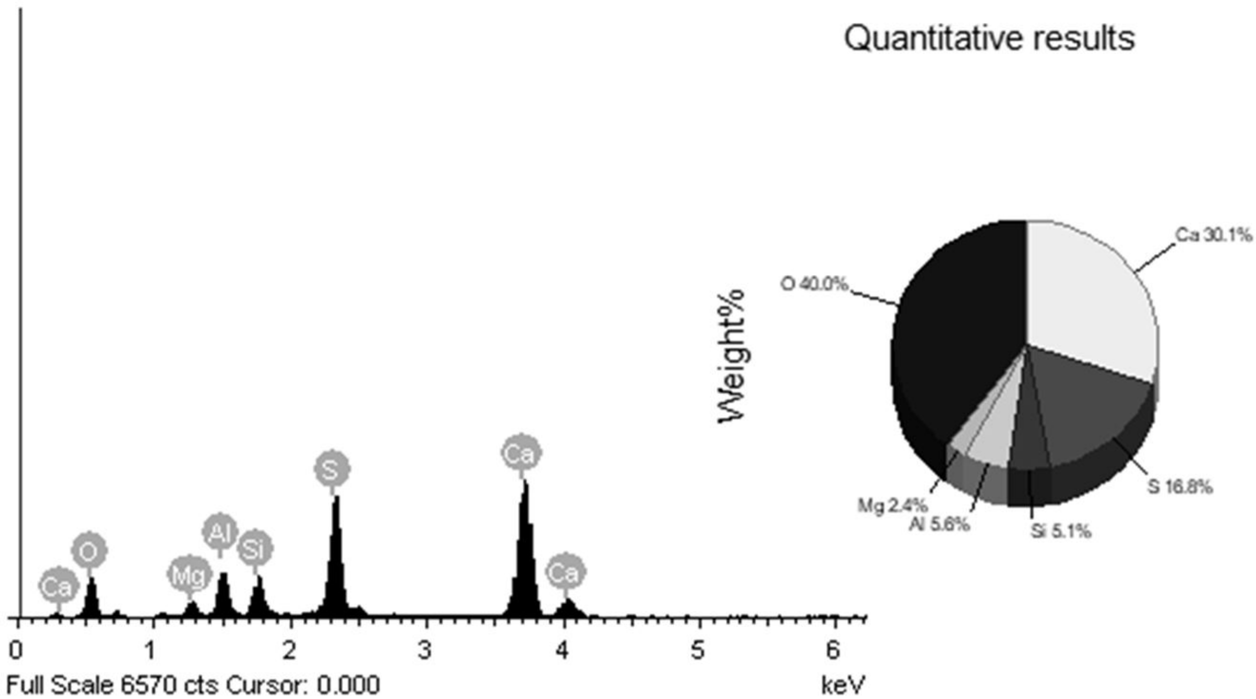

Figure 5. Chemical analysis of the inclusion formed in heat K sample.

Table 2. Steel elemental analysis (mass %).

	C	Mn	P	S
Value	0.53	0.77	0.014	0.019
Maximum of SAE 1050	0.55	0.90	0.040	0.050

in the steel bar analyzed in the SEM was about 1.2 mm, appearing on the surface, according to Figure 6.

Heat K inclusions were the only inclusions characterized chemically, as the heat showed a scrapping index of 6%, and was the only one that presented a stopper rod level variation over 10 mm. The scrapping percentage values are presented as follows:

- Heat B: 96% of scrap.
- Heat E: 1% of scrap.
- Heat I: 4% of scrap.
- Heat K: 6% of scrap.

Other heats (A, C, D, F, G, H, J and L) did not present a scrapping process.

The following heats presented the following variables as non-standard values for the steelmaking process:

- Heat B: %FeO+%MnO content in E-LFi and in E-CC.
- Heat K: %FeO+%MnO content in E-CC and stopper rod level.

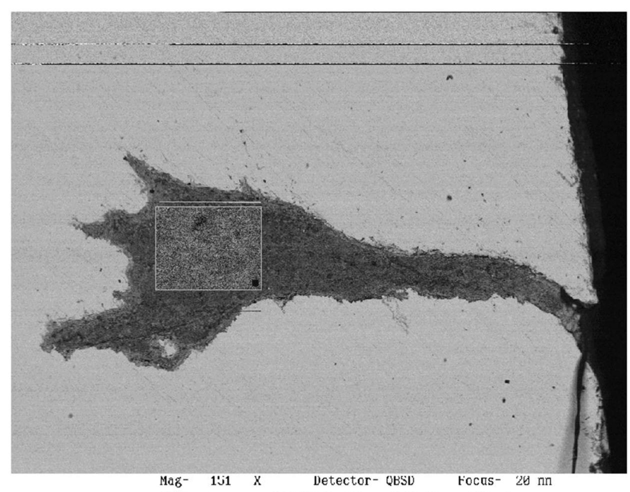

Figure 6. SEM image of macroinclusion contained in scrap bar after inspection.

Figure 7 shows the relationship between the number of variables classified as not acceptable (out) in the process (in X axis) and the percentage of scrap weight (Y axis) for the heats followed by the production of SAE 1050 by calculating the Pearson coefficient, which indicates a measurement of the linear correlation between two variables.

The correlation coefficient (represented by R^2) indicates the degree of linear relationship that exists between two variables, in the percentage case of scrapping and the number of variables "out of limits". If $R^2 = 1$ there is a perfect positive correlation. With the result of R^2 being 0.39 ($R = 0.63$), the correlation is considered moderate [24].

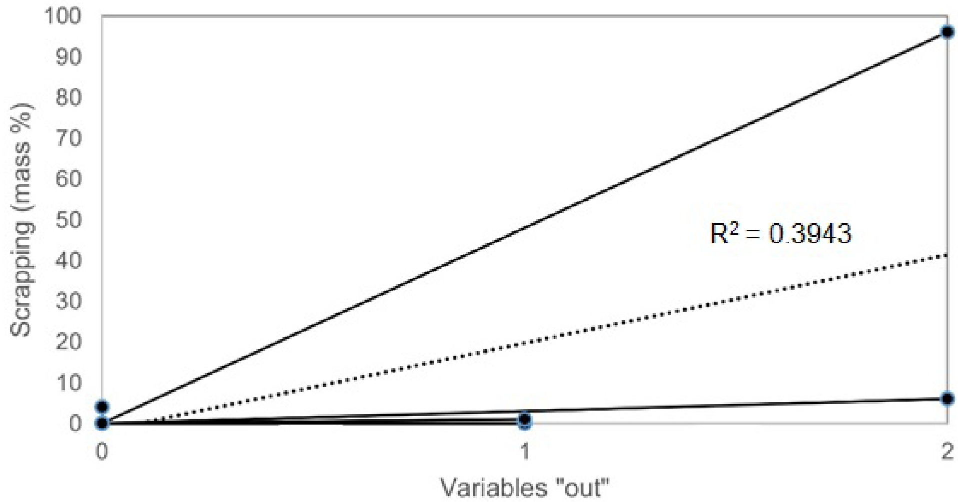

Figure 7. Correlation between the sum of process variables and the scrapping index.

4 CONCLUSIONS

After experimental result analysis and compared with the information contained in literature, it was possible to establish the following conclusions:

- It was possible to create a methodology that indicates a correlation when establishing a relation between the scrapping and the analyzed variables of the work;
- The heats B, D and K showed %FeO+%MnO levels above the maximum limit, among which those scrapped were heats B and K;
- Heat B also presented a content above the limit for %FeO+%MnO for sample E-LFi, indicating a tendency of correlation between scrapping for SAE 1050, once in this heat the scrapping index was very high;
- Heat K showed variation in the stopper rod level over 10 mm on the final CC process, not characterizing clogging, but indicating an incomplete cleanliness of the steel. Also, through the chemical characterization, identification was made of the formation of inclusions of the oxysulfide type (melting point > 2500°C), harmful to castability.

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