Original Article

Reduction of longitudinal cracks index in peritectic grades slabs through the steel project and casting parameters optimizations

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Abstract

The occurrence of longitudinal cracks in continuous casting steel slabs remains a recurring challenge in the steel industry, particularly for peritectic grades (0.08–0.15%C - ArcelorMittal Pecém reference), whose solidification behavior is inherently unstable. Due to the complexity of the phenomenon, its mitigation requires the combined assessment of metallurgical and operational factors. This study presents an integrated approach to reduce crack formation in slabs intended for heavy equipment ("Yellow Goods") applications. The original steel grade was located within the peritectic zone and exhibited a Ferrite Potential (FP) between 0.85 and 1.05 - considered a critical range in the literature - which increases sensitivity to defect formation. Given this condition, three new steel grades were developed and repositioned outside the critical FP range while maintaining the required mechanical properties. Simultaneously, the continuous casting process was optimized through parameter standardization and the development of mould fluxes capable of equalizing the heat flux in the mould. As a result, longitudinal cracks were completely eliminated (reduced from 10% to 0%), demonstrating the effectiveness of the proposed metallurgical and operational solution.

Keywords: Longitudinal cracks; Mould flux; Heat flux; Peritectic steel.

1 Introduction

The production of steel slabs via continuous casting is one of the essential pillars of modern steelmaking, offering higher productivity, energy efficiency, and quality control compared to conventional ingot casting processes. However, the occurrence of longitudinal cracks in slabs remains one of the main technical challenges, especially in steels with high susceptibility to segregation or unstable solidification. The presence of such cracks can compromise sheet formability, cause structural discontinuities, and directly impact the final product quality [1]. Therefore, strict control of both operational parameters and the metallurgical characteristic of the steel is essential to ensure the structural integrity of the manufactured components.

Peritectic steels present specific metallurgical challenges during solidification in continuous casting due to the peritectic transformation ($L + \delta \rightarrow \gamma$), which involves significant volume changes between phases, resulting in internal stresses and increased susceptibility to the formation of surface and subsurface cracks. This transformation, particularly in hypo-peritectic steels with carbon content between 0.08 and 0.14%, occurs abruptly under high cooling rates, promoting crack nucleation even under low strain levels [2, 3].

The formation of longitudinal cracks in slabs is associated with a combination of metallurgical and operational conditions. Among the main parameters influencing their occurrence are: casting speed, mould heat flux, immersion depth and geometry of the submerged entry nozzle (SEN), liquid steel flow pattern, and meniscus conditions [4]. High cooling rates can accelerate the peritectic transformation and generate thermal stresses before the complete solidification of interdendritic liquid, favoring crack nucleation at the ferrite-austenite interface [2]. Additionally, regions with irregular cooling or excessive turbulence at the meniscus intensify segregation and promote the development of surface and subsurface cracks along the slab [3].

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Therefore, this study proposes an investigation of the metallurgical characteristics of the original peritectic steel design, aiming to optimize its chemical composition to improve solidification behaviour, as highlighted in the literature. Furthermore, the main operational parameters of the continuous casting process are analysed, focusing on control strategies aimed at mitigating the formation of longitudinal cracks.

2 Materials and methods

In this phase of the study, analyses were conducted to identify the root causes of longitudinal cracks observed in steel slabs produced from an original peritectic steel design, as well as to propose metallurgical and operational solutions to mitigate the issue. The methodology was divided into two complementary approaches: (1) metallurgical analysis of the original and new steel's chemical composition and (2) evaluation of the control parameters in the continuous casting process.

Considering the final product application, customer requirements (mechanical properties), and the metallurgical characteristics evaluated in this study, three new steel grades were developed to reduce the occurrence of longitudinal cracks and improve castability. Table 1 presents the chemical composition of the grades: P0 (original design), PA (trial 1 – Nb + Ti), PB (trial 2 – Nb + Ti), and PC (trial 3 – V).

All three trial compositions were adjusted in terms of alloying elements to modify the solidification transformation behavior while maintaining the Carbon Equivalent (Ceq) within the customer's specified range (0.36–0.42), as calculated using the IIW formula (Equation 1). This ensured that the metallurgical modifications did not compromise the mechanical property requirements of the final product. It is important to highlight that V contributes to the Ceq value according to Equation 1, whereas Nb and Ti do not influence the Ceq calculation.

$$Ceq_{IIW} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad (1)$$

2.1 Metallurgical analysis

2.1.1 Original chemical composition Ferritic Potential (FP) evaluation

The Ferrite Potential (FP) was calculated based on the methodology proposed by Normanton (2005) [5], using the following Equations 2 and 3:

$$FP = 1,25 - 2,5 \cdot CP \quad (2)$$

$$\begin{aligned} Cp = [C] + 0,01[Mn] + 0,009[Si] + 0,02[Ni] + 0,003[Cr] - \\ 0,007[Mo] + 0,009[V] + 0,008[P] + 0,147[S] + 0,5[N] + \\ 0,007[Cu] + 0,007[Ti] + 0,05[Al] + 0,04[Nb] \end{aligned} \quad (3)$$

This index was used as a parameter to evaluate the behaviour of the chemical composition in relation to the peritectic transformation and its influence on steel solidification. The calculated average value (0,89) was compared with the critical range reported in the literature (FP between 0,85 and 1,05), which is associated with increased susceptibility to longitudinal crack formation [6].

Figure 1 shows the tendency of defects in Fe–C alloys as a function of Ferrite Potential (FP). Figure 2 presents a pure Fe–C diagram, where the critical zone would correspond to Ca = 0.08% and Cb = 0.16%. However, in practical situations, steels contain alloying elements that influence the determination of these values and modify the phase diagram [7].

2.1.2 Phases diagram simulation – ThermoCalc

Phase diagram simulations were performed using Thermo-Calc software to evaluate the positioning of each steel grade (P0, PA, PB, and PC) within the peritectic transformation fields during solidification. This analysis aimed to identify the critical composition ranges (Ca, Cb, and Cc) and determine how the proposed chemical adjustments would influence the solidification path and phase transformations.

2.1.3 Development of new steel grades

New steel grades were developed to meet the final product requirements specified by the customer. These grades were re-evaluated using the same metallurgical criteria (FP and simulations) to compare their behaviour against the original design.

2.2 Evaluation of process parameters - operational data collection and analysis

A cause-and-effect analysis (Ishikawa diagram) was employed to identify the main contributors associated with the occurrence of longitudinal cracks. The potential causes were grouped into three categories: material, method, and machine.

Table 1. Chemical composition of steel designs

	C	Mn	Si	P	S	Al	Nb	V	Ti
P0	0,12	1,40	0,20	0,020	0,010	0,040	0,030	-	0,015
PA	0,15	1,45	0,35	0,020	0,004	0,030	0,013	-	0,017
PB	0,15	1,50	0,35	0,020	0,003	0,030	0,020	-	0,014
PC	0,15	1,35	0,30	0,020	0,004	0,030	-	0,068	-

The identification of these causes was carried out through brainstorming sessions combined with the practical knowledge of the continuous casting team. This collaborative approach ensured that the analysis reflected both theoretical considerations and operational experience, providing a robust foundation for selecting the most relevant process parameters to monitor and evaluate during the study.

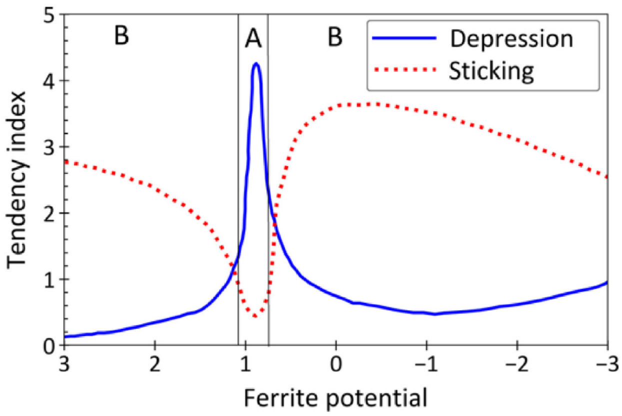

Figure 1. Ferrite potential indicator of peritectic steel behavior showing sensitivity to depressions [6].

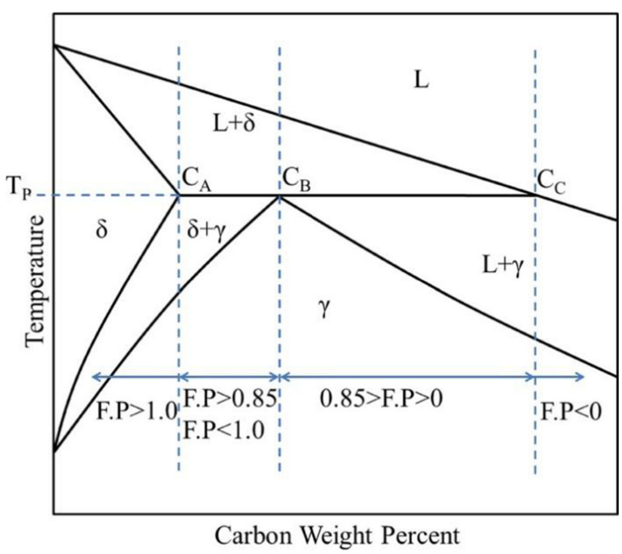

Figure 2. Demonstration of the ferrite potential in the Fe-C diagram showing the critical zone of peritectic steel [7].

In addition to the qualitative analysis, operational data from industrial casting campaigns were assessed to correlate process parameters with the incidence of slab cracking. The insights obtained from this analysis supported the definition of the optimization actions described in the following sections.

2.2.1 Evaluation of process parameters - mould cooling optimization strategy

Mould cooling conditions were evaluated with a focus on achieving uniform thermal extraction and controlling temperature gradients. The analysis included a review of water channel configurations in the mould and inspection of heat transfer surfaces. To improve heat removal balance between the wide and narrow faces, the water channels were redistributed across the mould plates, promoting a more uniform cooling pattern and reducing thermal asymmetry. Figure 3 illustrates the mould face configuration at AMP continuous casting.

A methodology was developed to optimize primary cooling based on the design study of AMP's copper mould plates. This approach aimed to equalize the water ΔT, defined as the average difference between the inlet and outlet water temperatures for each mould face. By monitoring and adjusting this parameter, thermal extraction was balanced across the mould, minimizing temperature gradients and improving casting stability. Figure 4 illustrates the thermal condition of the mould faces before and after optimization, showing the proportional ΔT for the wide faces considering the difference in water flow rate.

2.2.2 Evaluation of process parameters - review of mould flux properties

The physical and chemical properties of mould fluxes used in the casting of peritectic steels were analysed, including melting point, viscosity, sintering rate, and lubrication capacity.

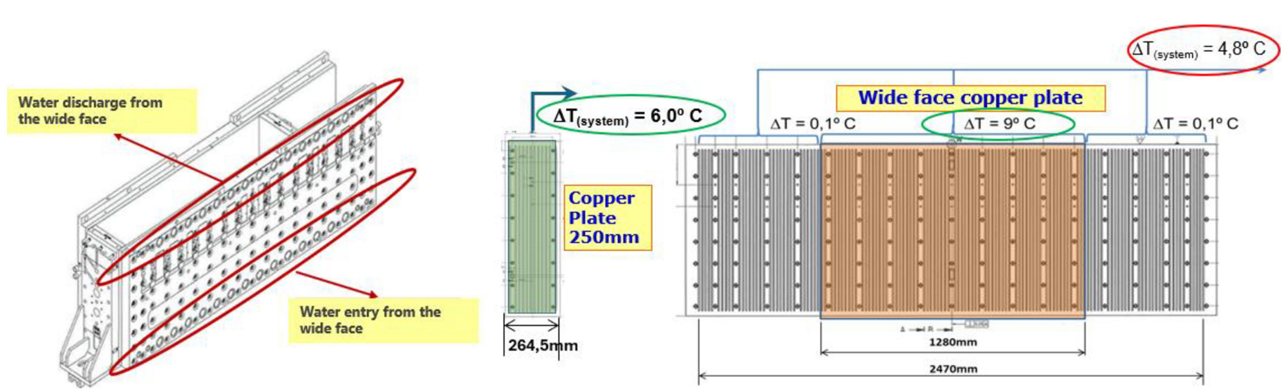

Figure 3. Primary cooling scheme showing wide and narrow mould faces.

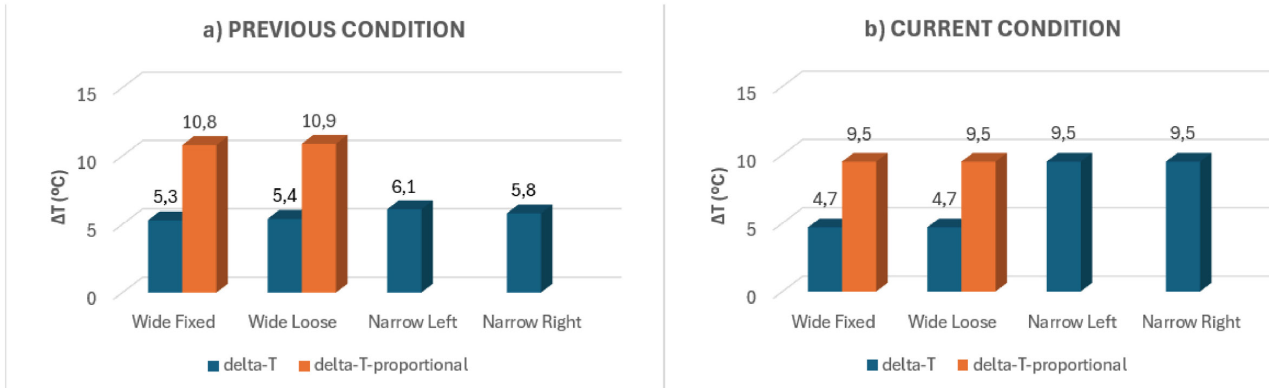

Figure 4. Comparison of (a) previous and (b) current condition of cooling water temperature variation.

The objective was to propose flux compositions better suited to the solidification regime of the studied steel grades.

As previously reported in the introduction section, peritectic steels tend to form highly irregular surfaces, which result in non-uniform heat transfer across the solidified shell inside the mould.

In practical terms, this irregularity is mainly caused by two effects: (i) deeper oscillation marks, which depend on meniscus stability, mould flux behaviour, and oscillation settings, and (ii) air gap formation between the shell and the mould. These two features change the contact between the shell and the mould and the thickness of the slag film, creating variations in local heat extraction. This leads to regions with thermal stresses in the solid layer of the slab, promoting the formation of longitudinal cracks [6]. One of the proposed controls is through the change of the characteristics of the mould flux to reduce heat transfer. The influence of mould flux on this behaviour is illustrated in the figures 5 and 6 below, showing the influence of the mould powder characteristics on the heat transfer during primary cooling.

Mills et al. [8] and Azevedo et al. [9] indicate that the use of flux agents with high basicity, high viscosity and high breakpoint temperature would be the most appropriate to produce sensitive grades to the formation of surface defects. Thus, in the AMP, one of the methods adopted for mould fluxes selection was the analysis of the T-Break point as shown in the Figure 7 [8, 9].

2.2.3 Evaluation of process parameters - operational standardization

Based on the analyses conducted, guidelines were established to standardize operational practices related to submerged entry nozzle control, argon flow rate, casting speed profile, and mould width variation criteria, aiming to enhance process consistency and stability. These practices were defined considering the expertise of AMP's continuous casting teams, ensuring that operational knowledge was incorporated into the process improvements. In case of the argon flow rate, it was limited according to best practices to maintain meniscus stability and avoid excessive turbulence, while casting speed curves were optimized to improve thermal balance.

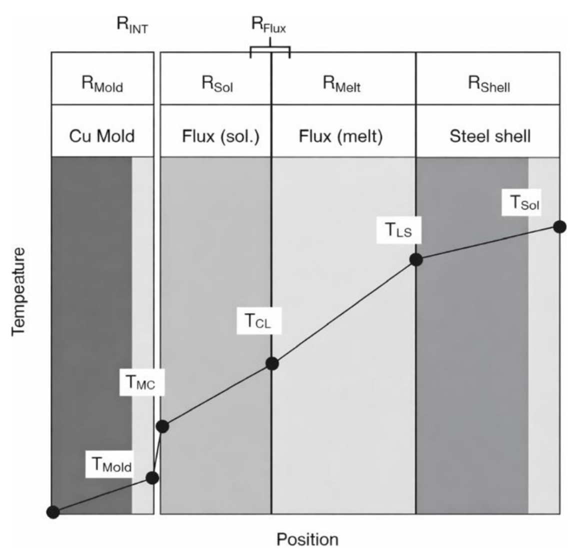

Figure 5. Slag basic characteristic of mould flux: Mould flux film thickness (thicker if viscosity is higher), Film crystallinity (higher if basicity is higher) and Interfacial resistance (higher if more crystalline) [8].

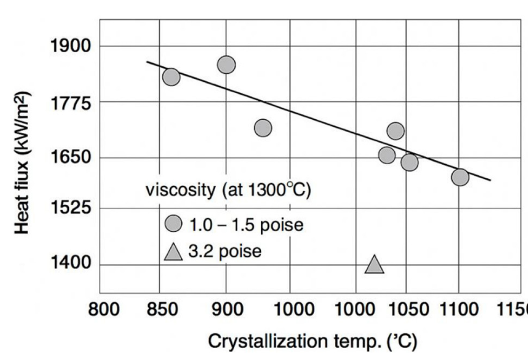

Figure 6. a) Schematic temperature Profile in caster mould. b) Actual relationship between mould flux and heat transfer [8].

2.3 Inspection and scarfing

A more rigorous inspection plan was developed to collect data and perform scarfing tests to verify the presence of longitudinal cracks before and after the implementation of corrective actions. All slabs produced were subjected to 100% hot inspection (at the end of caster machine), and additional slabs were selected based on sampling criteria (at least one slab per heat and per strand, aiming for approximately 30% of the slabs produced to be deviated) and quality events for cold inspection and scarfing. The objective was to identify the presence of longitudinal cracks and assess the effectiveness of the metallurgical and operational improvements.

3 Results and discussion

The modification of the original steel composition (P0), whose average Ferrite Potential (FP) was 0.89 (within the critical range of 0.85 to 1.05) resulted in significant improvements in thermal stability and solidification behavior with the new grades PA, PB, and PC. As discussed by Azizi et al. [6], the presence of FP within this range is associated with "depression-sensitive" steels, which exhibit more instability during solidification due to the peritectic transformation coinciding with the final stages of solidification. These new FP values were achieved by modifying the chemical composition, especially by adjusting the carbon content, which has a direct relationship and a coefficient equal to 1 in the Normanton equation.

By shifting the FP outside this critical zone, the new grades reduced thermal instability near the meniscus, promoting more uniform and continuous solidification with lower susceptibility to longitudinal crack formation.

Furthermore, Azizi et al. [6] highlight that the volumetric contraction associated with the $\delta \rightarrow \gamma$ transformation is significantly greater in peritectic steels, particularly in the 0.10 to 0.13% carbon range. This contributes to the formation of regions with high internal stress and irregular shell growth. This contraction occurs early during solidification, before the shell has developed sufficient strength to withstand the generated stresses, thus promoting crack nucleation [9].

The proposed grades were designed to move away from the critical zone of longitudinal crack sensitivity, as guided by the literature, considering the FP range. Although the target compositions were already intended to avoid the critical zone, after production, statistical analysis using ANOVA confirmed a significant difference between the P0 and the new grades, with a 95% confidence interval, as shown in Figures 8 and 9.

It is important to note that grades PA and PC were produced as trials, with intentional variation in chemical composition to evaluate mechanical properties at the customer's end. This explains the wider confidence interval observed.

A phase diagram (Figure 10) was generated using Thermo-Calc software based on the chemical composition of steel P0, allowing precise identification of the critical points Ca, Cb, and Cc. The analysis revealed that steel P0 falls within the Ca–Cb range, characterizing it as a classic peritectic steel, where the $\delta \rightarrow \gamma$ transformation occurs at the end of solidification in the solid state, promoting the formation of internal stresses and longitudinal cracks. In contrast, the new steel grades (PA, PB, and PC) were adjusted to fall within the Cb–Cc range. In this region, the peritectic transformation occurs while liquid is still present, allowing the remaining liquid to accommodate the volumetric contraction associated with the phase transformation. This behaviour significantly reduces the generation of thermal stresses and, consequently, the susceptibility to surface and internal defects during continuous casting [6].

Considering the implemented process improvements, the most critical contributors identified were: Casting speed, Mould heat flux, Immersion depth and Geometry of the Submerged Entry Nozzle (SEN), Argon flow rate, Secondary cooling strategy, Meniscus conditions, and Mould changeover timing. This comprehensive approach to process evaluation is illustrated in the cause-and-effect diagram shown in Figure 11.

The process parameter improvements were essential to achieving greater stability during continuous casting. The standardization of operational practices, combined with optimized mould cooling and careful mould flux selection, contributed to more uniform heat flux and mitigation of critical temperature gradients in the meniscus region. These actions significantly reduced localized thermal stresses, which are known to promote longitudinal crack nucleation in peritectic steels. The synergy between operational adjustments and the metallurgical redesign of grades PA, PB, and PC resulted in a more robust casting process.

The slabs produced during the trial phase were inspected and scarfed following the same sampling and scarfing standards. The incidence of longitudinal cracks decreased from 10% of scarfed slabs to 0% across all three proposed grades.

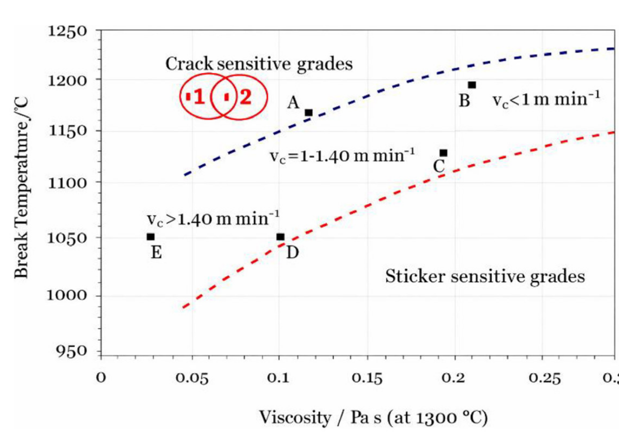

Figure 7. Relationship between viscosity and break temperature of fluxing agents, showing points 1 and 2 as being the choice of ArcelorMittal Pecém fluxing agents for this family of steel grades [10].

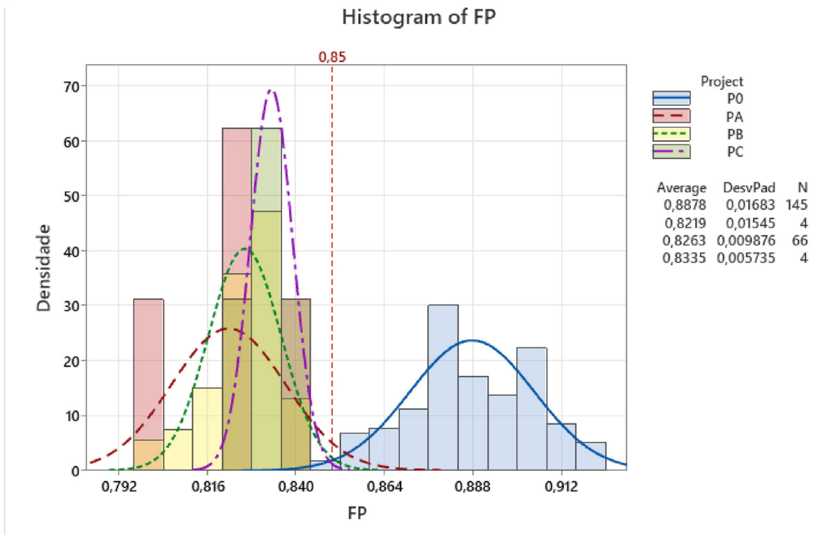

Figure 8. Normal distribution of the FP of the projects studied showing the limit considered critical (0.85).

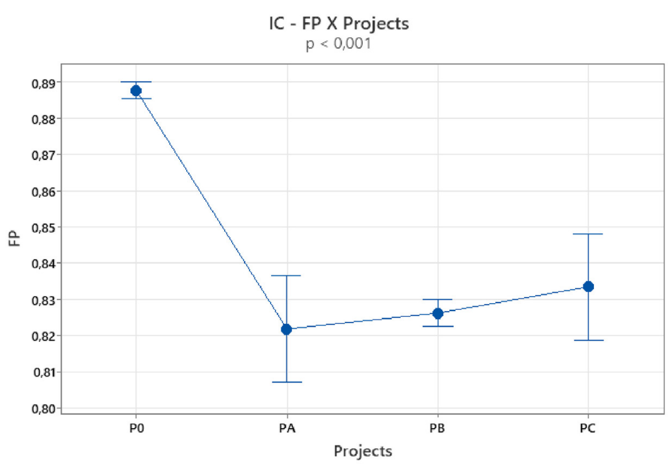

Figure 9. ANOVA analysis showing significant difference between P0 and the others projects with p < 0.001.

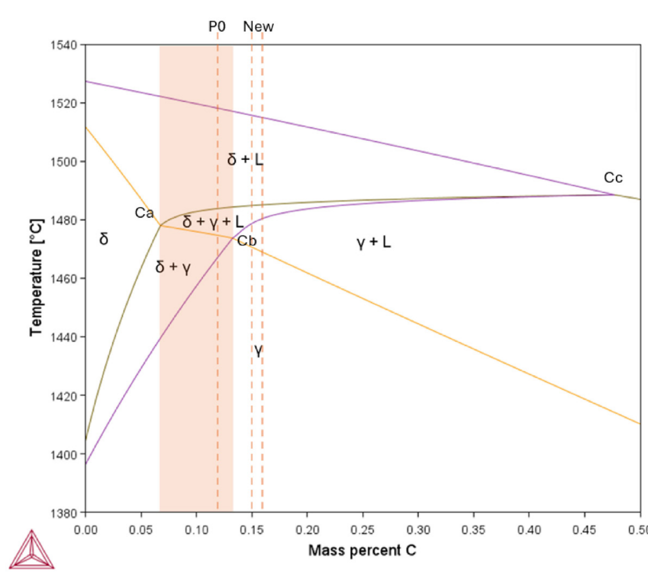

Figure 10. Simulation of phases diagram based on P0 chemical composition.

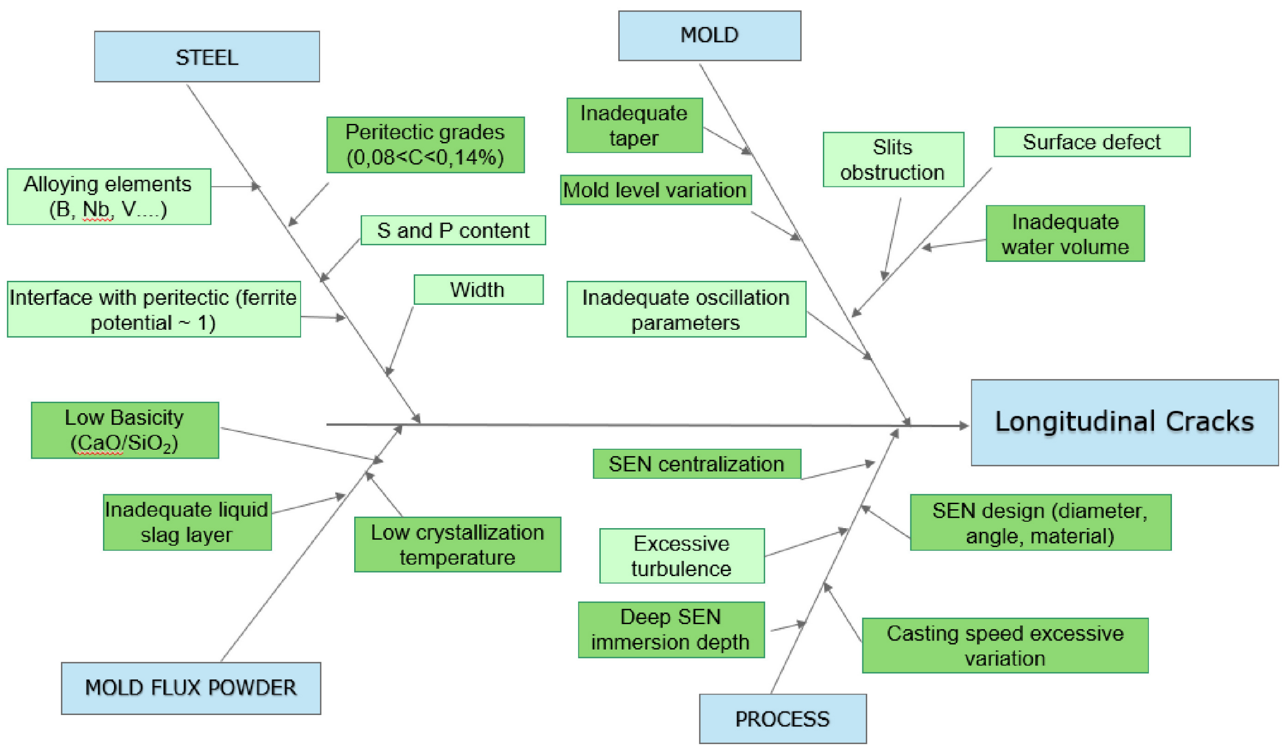

Figure 11. Ishikawa diagram with the main cause variables for longitudinal crack formation.

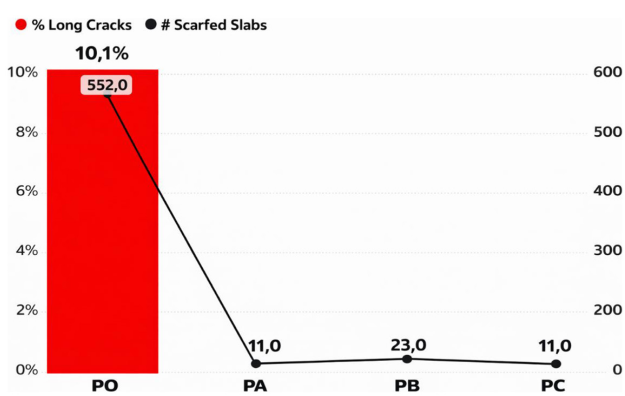

Figure 12. Result of longitudinal cracks after scarfing, showing the reduction of occurrences in the trials of the 3 new projects.

4 Conclusion

The modification of the steel's chemical composition, repositioning the new grades outside the critical FP range and the unstable peritectic zone, was essential to improving solidification stability and validating the equations used for FP calculation, as proposed by Normanton [5] and discussed by Azizi et al. [6].

The thermodynamic simulation performed using Thermo-Calc confirmed that the new grades fall between points Cb and Cc, allowing the peritectic transformation to occur while liquid is still present. This significantly reduces the generation of internal stresses.

Literature data related to the formation of non-uniform solidified shells in peritectic steels—where the mechanism of longitudinal crack initiation and propagation begins—were analysed. As a result of the analysis, the mechanisms identified in the literature were compared with the actual longitudinal crack occurrences at AMP. This comparison enabled the proposal and implementation of process adjustments discussed in this paper, aiming to improve surface quality.

Inspection of the slabs produced demonstrated the effectiveness of the applied strategies, with complete elimination of longitudinal cracks in all three new grades tested. This led to a reduction in slab rejection rates, an increase in direct dispatch, and a reduction in rework (scarfing).

Currently, all actions have been standardized and are being applied at ArcelorMittal Pecém.

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