Metallurgy and materials

Evaluation of the non-metallic compounds on secondary refining – Ruhrstahl Heraeus (RH) process

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Abstract

The purpose of this study was to evaluate the cleanliness of Interstitial Free (IF) steels produced in a Ruhrstahl Heraeus (RH) vacuum degasser by determining the level of Al_2O_3 and Al-Ti-O inclusion types generated in three different process conditions: i) steel processed without thermal intervention; ii) steel processed with chemical heating and iii) steel processed with cooling by the scrap addition. The inclusion formation and remotion during these processes were analyzed. The influence of homogenization time was also studied. The content of inclusions was measured by a Scanning Electron Microscope (SEM) with an automated counting system denoted as Automated Steel Cleanliness Analysis Tool (ASCAT). This method can provide the size and composition of non-metallic compounds. The results have shown that the Ruhrstahl Heraeus (RH) process can improve the remotion efficiency of the inclusions, such as those larger than 2.5 mm, which is due to the molten steel circulating in RH vessel. For some inclusion types, higher concentrations were detected, but their size was smaller. For a heat where it was necessary to apply chemical heating using Al addition and O injection, there was detected a higher concentration of inclusions when compared with that cooled by scrap addition. In cooling heats, there is a strong generation of small and thin inclusions (<1.0 mm) that are very difficult to be removed from liquid steel. The size of the Al_2O_3(s) type is around eight times larger than Al-Ti type inclusions.
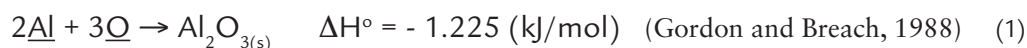
Keywords: inclusions, steel, SEM-ASCAT, Al-Ti, Al_2O_3.

1. Introduction

Advanced steels which are applied in industrial segments, such as automotive manufacture, petroleum production, civil engineering, and others, currently have strong restrictions stablished by the market requirements and inclusion levels have been rigorously considered throughout the years (Costa e Silva, 2018; Susumu and Wagatsum, 2018; Pretorius *et al.*, 2013; Zhang and Thomas, 2003; Kiessling, 1969). The Interstitial Free (IF) steels are typical examples of those with very low C and N levels; that I, around 20-30 ppm. Usually some content of Ti and/or Nb is designed for scavenge carbon and nitrogen by the formation of carbides and nitrides,

and then, these interstitial ones are avoided in the matrix (Ge *et al.*, 2011). When the control of the recrystallization and texture is required, some alloys are designed to avoid Ti in solid solution, aiming to keep some Nb instead. The C and N interstitial elements can be removed from steels using a vacuum degasser, such as Ruhrstahl Heraeus (RH) and the remaining content must form some compounds, such as carbides, nitrides and carbonitrides, making the interstices between solidified iron atoms totally free from the interstitial elements (Yadav *et al.*, 2021). Along the years, there have been a many research articles dealing with incorporating the RH process to

reduce C and N from the liquid steel to attend the high-quality requirements of the steelmaking plants around the world (Xu *et al.*, 2019; Geng *et al.*, 2015; Ende *et al.*, 2011; Kuwabara *et al.*, 1988). This process is very common for producing IF steels, and depending on the production conditions, after this step, the steel heat may be under incorrect temperature, that is, it can be lower or higher than ~ 1600 ℃. If the temperature is too low, it is necessary to reheat the liquid steel using some Al addition. The Al, when combining with O, results in a powerful exothermic reaction with enough energy to increase the temperature up to that desired following Reaction 1.

$$2\underline{Al} + 3\underline{O} \rightarrow Al_2O_{3(s)} \qquad \Delta H^\circ = - 1.225 \text{ (kJ/mol)} \quad \text{(Gordon and Breach, 1988)} \qquad (1)$$

The advantage of chemical heating is the rate of increase of temperature when it is compared with the ladle furnace (LF) system and this rate is around 7 ℃/min. However, some difficulties take place due to the nonmetallic inclusion generation, which can appear during continuous casting, causing some operational problems, such as clogging. Also, during the rolling mill step, some sliver defect type may take place. Thus, the level of inclusion at the end of the secondary refining must be a slow as possible, and knowledge about the composition, morphology, number, size, and distribution of these inclusions becomes very important in secondary refining (Ghosh, 2001). Thus, some procedures can be proposed to avoid or eliminate these inclusions.

Sometimes, the temperature becomes

very high due to uncontrollable operational conditions, and in this case, it is necessary to add scrap for cooling the steel. When scrap is added into the ladle, some exposition of the liquid alloy to the environment is very common. Thus, oxidation occur forming new compounds and process may add new non-metallic inclusions into steel. Sometimes oxides, such as FeO and Fe_2O_3, can be also reduced by Al, forming $Al_2O_3(s)$ inclusions and other complex compounds. Thus, the scrap addition can introduce a new generation of tiny inclusions. If the nonmetallic inclusions are not big enough, then it is very hard to remove them from the steel, due to the weak buoyancy and weak forces that cannot create high speed flotation. Moreover, the Ti in steel as Ti (dissolved) or combined,

as for example $xTiO_2.yAl_2O_3$, decreases surface energy between the liquid steel and inclusions, so high wettability takes place, and therefore, reduces the rate of inclusion flotation and removal (Story *et al.*, 2005). Figure 1 presents a typical industrial flow for manufacturing IF type steels. As can be seen, after the RH process, the temperature and dissolved oxygen content are measured (TO step). Depending on these measurements, an option is taken, either to add Al and oxygen to heat the steel, or if the temperature is too high, some scrap must be added to cool the heat. Sometimes neither a heating nor cooling adjustment is necessary, so the production flow will be a simpler one. Thus, these operating conditions directly change the level of cleanliness of the steel produced.
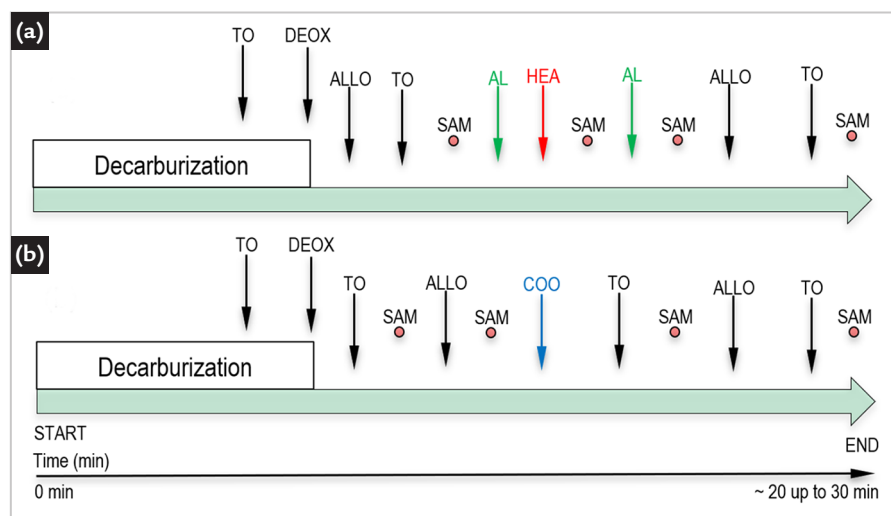

Figure 1 - Schematic flow of the RH process and actions (a) Increasing temperature using oxygen injection and (b) Reducing temperature using scrap addition. * TO: Temperature and oxygen content measurements; DEOX: Deoxidation using Al addition; ALLO: Alloy addition; SAM: Get sample; AL: Aluminum addition; HEA: Heating using oxygen injection; COO: Cooling using scrap addition. (Some steps may be excluded depending on the specific heat).

As here exposed, the presence of non-metallic inclusions, such as Al_2O_3, AlTi type and others is unavoidable in steel samples from steelmaking processes. The purpose of this study was to evaluate the influence of the deoxidation process, addition of alloys for chemical adjustment, as well as other parameters to establish ways that can lead to improvements of the steel processing operations. For this purpose, the Automated Steel Cleanliness Assessment Tool (ASCAT) technology was used to set the chemical composition and size distribution of nonmetallic inclusions into steel, and study how the temperature control routes in secondary refining has influence on the inclusion generation.

2. Experiment

For the development of this research, some studies were focused into Ultra Low Carbon (ULC)/Interstitial Free (IF) steels produced in a steelmaking plant of the ArcelorMittal group. The Interstitial Free (IF) steel grade was processed under vacuum RH system (0.4 mbar - 1.0 mbar) at temperatures around 1580 °C - 1600 °C. For this grade, high formability is required for use in the automotive industry. The weight of each cast was around 300 t. As the mass and composition of the slag carried over from Converter were always similar composition in wt%: Al_2O_3=28; CaO=48; MgO=6; SiO_2=12; FeO=6, it was considered the same influence for all experiments. The final range of the chemical composition %wt was: C: max 0.003; Si: max 0.030; Mn: 0.070~0120; P: max 0.014; S: max 0.008; Al: 0.020~0.050; N: max 0.035; Ti: 0.035~0.045. As the steel grade of the present study was an ULC type, thus calcium level was not measured. The secondary refining was done using the RH process with the following parameters: snorkel diameter 750 mm; snorkel immersion depth: 450 mm; snorkel height: 900 mm; number of argon nozzles: 16; injection flow rate in snorkel: 2,500 NL/min; nominal flux rate of steel: 180 t/min; ladle capacity: 315 t; no additional stirring system was used in ladle; All samples for analysis were obtained using a sampler "*lollipop*" design type as shown in Figure 2. The oxygen content was measured by use of the immersion sensor lance Celox® sensor. The temperature and the oxygen level measurements before and after the deoxidation step for each heat are presented in Table 1.
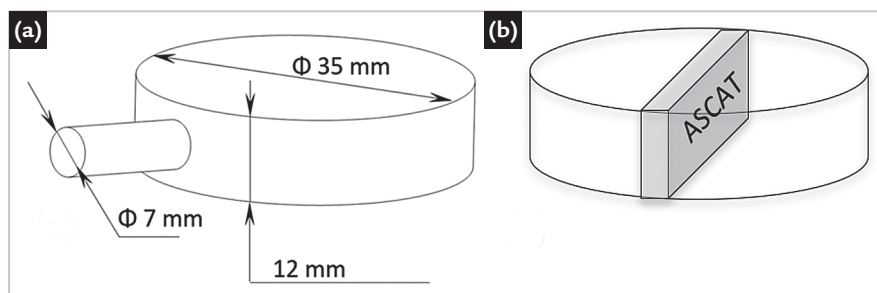

Figure 2 - Sketch of (a) the "*lollipop*" sample and (b) cut for SEM-ASCAT analysis.

In the experimental project, three different types of processing of Ti-stabilized IF steel were studied, i) steels processed without thermal adjustments – designed as N1, N2 and N3 heats; ii) steels processed with a chemical heating supply requirement using O_2 injection and Al addition – designed as H1, H2 and H3 heats; and iii) processed steels requiring cooling using scrap addition – designed as C1, C2 and C3 heats. In Figure 3 is the flowchart of the secondary refining with the identification of these steps.

Table 1 - Temperature (T) and Level of O of the samples.

Heat	Before deoxidation		After deoxidation	
	O ppm	T - °C	O ppm	T - °C
N1	454	1585	2	1602
N2	454	1580	4	1593
N3	318	1580	4	1593
H1	437	1576	2	1589
H2	419	1577	0	1585
H3	451	1585	5	1605
C1	475	1604	3	1618
C2	729	1605	3	1612
C3	329	1602	2	1603

Basically, the refining of steel starts with the decarburization process of the hot metal, where the C content of the bath is reduced, and for the IF steel production, the use of the RH process is imperative, where C and N are reduced

until there is a very lower content inside the range specification, like the example given in herein. After the decarburization, it is evaluated if it is necessary to either proceed with a cooling using scrap additions or chemical heating using Al plus oxygen injection. The third possibility happens when the heat is at the correct temperature after the deoxidation step at the end of the RH process, where the desired temperature is around ~1600 °C.
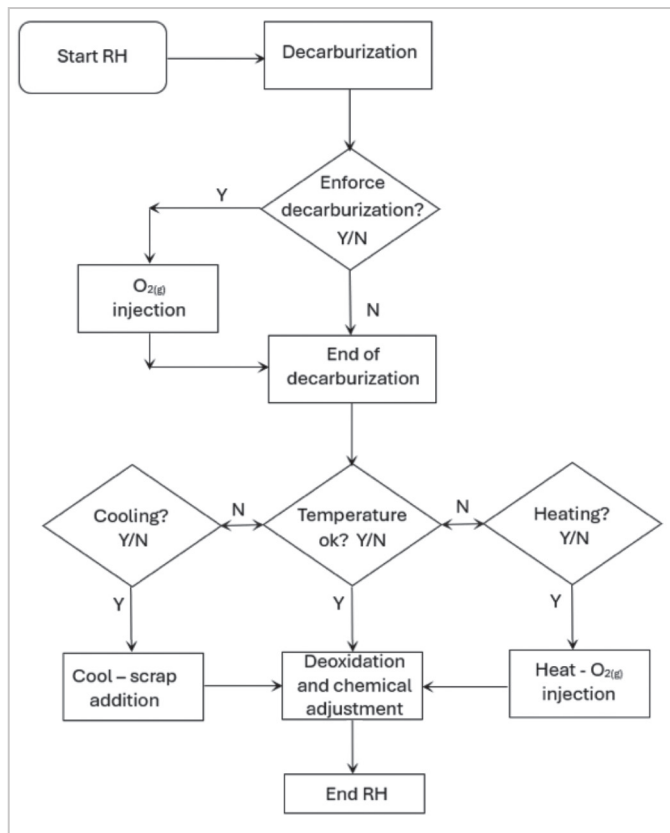

Figure 3 - Flow chart of the secondary refining - RH.

Industrial experiments were performed in a steelmaking plant and 9 heats were chosen. For each heat, the samples were taken in accordance with the plan presented schematically in Figure 4. Basically 3 samples were taken for each heat with the following schedule: 1st: after ~2-4 min; 2nd: after ~12-16 min; 3rd ~17-22min; 4th ~25 min (for one heat, an additional sample was picked due to the prolonged time of the operation). The first samples were taken after the deoxidation process, the seconds ones ~ 3 min after the heating and the last ones were taken after ferroalloy addition. However, although the schedule to get the samples was not the same in all industrial experiments, it was designed using a pattern linked to the process. That was because of the development of this project inside
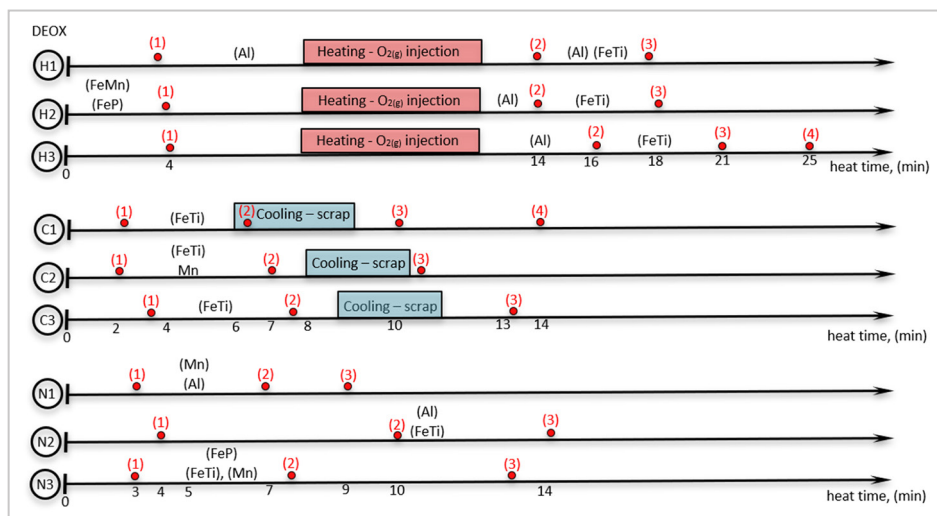

Figure 4 - Schematic flow showing the sampling during the experimental heat in the RH process.
*1, 2, 3, 4 are the sampling steps in each heat. "Hi", "Ci" and "Ni" refer to the heating (H), cooling (C),
no action (N) for each type of experiment and "i" represents the number of the heat of that group.
Al, Mn, FeP, FeTi, FeMn are aluminum, manganese, ferrophosphorus, ferrotitanium, ferromanganese additions, respectively.

of a steelmaking plant, where it is not possible to create the very stable conditions existing in laboratory procedures. But on the other hand, these conditions provide a great advantage because they represent a real production for the industrial context.

The chemical composition of the sample was determined using an optical emission spectrometer (OES) Thermo Scientific ARL 4460. The quantitative measurements of the nonmetallic inclusions were done using Scanning Electron Microscope (SEM) Trade Leica 440 and an automated counting system denoted as Automated Steel Cleanliness Analysis Tool (ASCAT). The operation's parameters were: 20 kV acceleration; current of 6 µA; distance work of 10 mm; 100 X of magnification; time or retention per inclusion of 2 s; minimum size of 1 µm. Figure 2b presents how the samples were cut to be inserted into the SEM. An area of cross-section of a 1 cm diameter was analyzed for each sample. The samples were used to study the distribution generation of the inclusions and evaluate how the process has influence on the Al_2O_3 inclusions. The level of inclusions was measured in "inc/mm²" (inclusion per millimeter square) and/or square area fraction "f" units.

3. Results and discussion

Nonmetallic inclusions are commonly found due to the reaction of the metallic impurities in the steel with oxygen, even when their content appears in trace amounts. These inclusions can become a big problem for the products leading to crack formation. This detrimental aspect can often be detected as slivers in the final product of the rolling mill process. The inclusion removal in the RH process has a strong dependence on the bubbling time and the mix up circulation of the steel in the RH vacuum chamber. Figure 5 shows the evidence of how the level of Al_2O_3 inclusions decreases as a function of time in RH. It is possible to realize that the nonmetallic inclusion content decreases drastically around 83% when compared samples taken 2min and samples taken 4min after deoxidaton process. After that, the process continues, and in a more prolonged time ~ 98% of the remotion is reached in 10 min, time that was taken the last sample after deoxidation. Thus here is shown the importance of the RH process in the cleanliness of the steel. These results suggest that longer treatmente time leads to a more efficiente process. Some inclusion may remain in the heat and come to the continuous casting. Matsuura *et al.* (2007) explains that in some industrial plants, it is very common to add Ti after ~ 2 min from the end of the aluminum deoxidation process. In this study, the Ti was added after at least 4 min. Depending on the process conditions, some inclusion with polygonal morphology may appear containing Ti until 20 mol% of Ti. This event may be hazardous, and depending on the Ti content, results in a tendency for agglomeration of inclusions with consequential nozzle clogging (Matsuura *et al.*, 2007). The experiments were conducted under the temperatures already presented in Table 1. The average temperature before deoxidation was 1585 °C and after deoxidation 1602 °C, thus the average deviation was nearly 9 °C to minimize as much as possible the influence of temperature on the inclusion formation process.
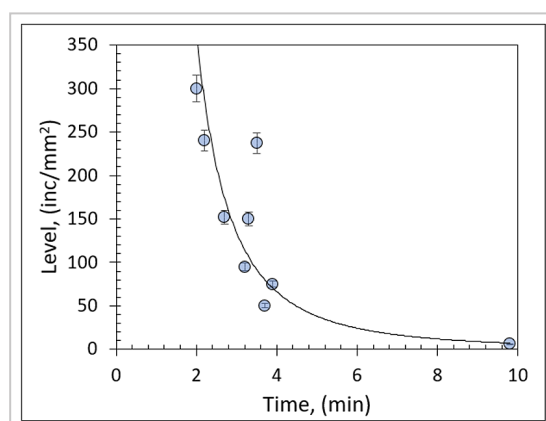

Figure 5 - Evolution of the Al_2O_3(s) inclusion level as a function of the RH process time for all nine heats.

In Figure 6, the average level of inclusions for all conditions is summarized – all nine sample. Noticed that the main inclusion type is Al_2O_3(s), and as expected, the A/Ti inclusion type was the second one with a higher level. Some other types of inclusions are present in much lower fraction, and the total content of them was less than ~ 0.6%. Some calculations of Ruby-Meyer *et al.* (2000) indicate that the alumina inclusion type is most thermodynamically stable in traditional Al-killed IF steels stabilized with Ti, and Al/Ti inclusions are present when an intense local reoxidation consumes large amounts of Al. Matsuura *et al.* (2007) stresses this concept, and explains that the Al/Ti inclusion generation happens throughout a transient reaction due to the Ti local supersaturation. In this case, some Ti oxides are formed because of the local Al content decreased by the consumption of Al during the growth of the Al_2O_3 particles, and the melt composition went to the Al_2TiO_5 or TiO_x stable regions (Matsuura *et al.*, 2007).

The measurements of the level and fraction of inclusions of all heats are presented in Table 2. The results shows that the level of inclusions decreases when total time increases. The initial number of inclusions are due to the deoxidation process performed in RH after decarburizing process and dissolved oxygen content is reduced as shown before in Table 1. For N1, N2 and N3 (N's) with no temperature adjustments, Figure 7a shows the level of Al_2O_3(s) inclusions as a function of time.
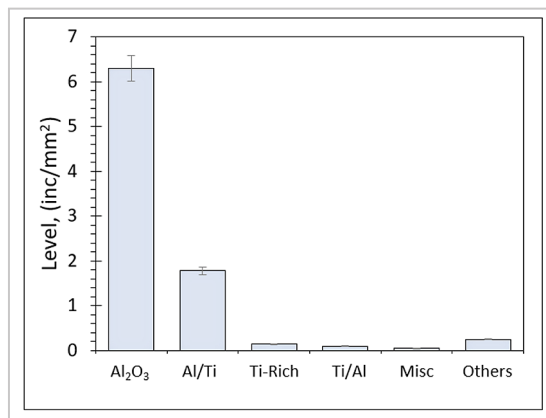
Figure 6 - Type of inclusion detected by ASCAT at the end of the RH process for all nine heats.

These experiments have shown that inclusion content always diminishes until the average level from around ~ 4 up to 8 inc/mm². However, in a comparison between Figure 7a and Figure 7b, it is possible to notice some aspects related to the fraction of the area occupied by the inclusions. When the time process delays too much, despite the amount of inclusion reductions, virtually obtain a very lower inclusion level. However, an experiment (N1) has shown that the fraction of the area occupied by the inclusions is higher, even when the content (inc/mm²) has become lower (Figure 7a). This result may be explained by the increase of the medium diameter of the inclusions due to the diffusive growing process during the RH process and/or by the nucleation event of new ones. Also, agglomeration events can take place, but this cannot increase the area of the fraction occupied by them. Indeed, Wakoh and Sano (2007) in their article explained that the growing of the inclusions may occur by Brownian/Turbulent movement collisions and/or by a diffusion process. Thus, a generalized function that can describe the growing mechanism of the inclusions may be expressed by Equation 2 (Wakon and Sano, 2007).

$$r^n = r_o^n + k.t \qquad (2)$$

Where "r" is the radius average of the inclusions at any time "t". The "r_o" represents the initial size of a new inclusion nucleus and "k" may englobe many parameters that will depend on the growing mechanism, such as specified before it would be by diffusion growing or agglomeration. The parameters that compound "k" are different in each case. In this study, there is a strong convective component due to the industrial RH process. Thus, the most probability is that the domain mechanism is the inclusion growing by agglomeration with some minor diffusion process contribution. In the RH process, the amount and inclusion area fraction can also increase a lot due to the convective flow creating new stable nucleons (Wasai and Mukai, 2002) within the liquid steel. The "n" index may define the theorical growing process mechanism, and it will be 3 for the agglomeration processes and 2 in diffusion case.

Table 2 - Level of Al_2O_3(s) inclusion type as function of time during RH process.

N1			N2			N3		
Time (min)	Level inc/mm²	f (fraction) x 10⁶	Time (min)	Level inc/mm²	f (fraction) x 10⁶	Time (min)	Level inc/mm²	f (fraction) x 10⁶
3	157	1486	4	235	2227	8	9	115
7	7	26	10	9	94	13	4	41
9	6	70	14	6	32	-	-	-
H1			**H2**			**H3**		
Time (min)	Level inc/mm²	f (fraction) x 10⁶	Time (min)	Level inc/mm²	f (fraction) x 10⁶	Time (min)	Level inc/mm²	f (fraction) x 10⁶
3	92	845	4	76	692	3	152	1718
13	45	818	13	17	151	17	13	175
18	12	147	19	3	41	21	4	48
-	-	-	-	-	-	25	6	47
C1			**C2**			**C3**		
Time (min)	Level inc/mm²	f (fraction) x 10⁶	Time (min)	Level inc/mm²	f (fraction) x 10⁶	Time (min)	Level inc/mm²	f (fraction) x 10⁶
2	237	1736	2	301	2236	4	51	309
6	19	170	7	4	18	8	6	45
10	7	33	11	9	42	13	7	38
14	6	35	-	-	-	-	-	-

Figure 7c endorses that the average size of the $Al_2O_{3(s)}$ inclusions have increased in the N1 heat. This result is in accordance with the previous results presented in Figures 7a and 7b, and since increasing fraction of the area cannot be explained by agglomeration, in this case, it is possible to conclude that some events of growing by a diffusional process and/or formation of a new stable nucleus has happened. Figure 7d presents a cluster composed by alumina particles, where its equivalent total diameter is greater than the individual particles/inclusions. Due to the agglomeration process, the measured medium size/diameter of the inclusions may be higher. Also, ASCAT calibration and procedure system may affect these results because of the setup of the software, which may be more or not sensible to disguising isolated particles/inclusions. If the setup of ASCAT is sensible enough to detect agglomeration, the amount of inclusion can decrease, keeping the area's fraction constant. Thus, a reason for this result may be due to Al addition carried out 5 min after completion of the decarburization process, as shown in Figure 4 (N1), and the time of the last sample taken. In this way, the RH process time was not sufficient for the effective elimination of the inclusions formed after the deoxidation. In other words, this condition has been favorable to the nucleation of new inclusions and growing process, but the time was not enough to enable a lower inclusions level. Yang *et al.* (2013) had a similar outcome, and they have explained that the initial number of inclusions per square unity plays a vital role in the final inclusion level. Thus, the higher the inclusion at the beginning of the process, the higher will be the inclusion content at the end of heat, taking into consideration the same among of time. When some addition is performed in the process, such as aluminum, from this point on, there is a "new start", whereupon the inclusion level increases too much, requiring more time to attain a lower level of inclusions.
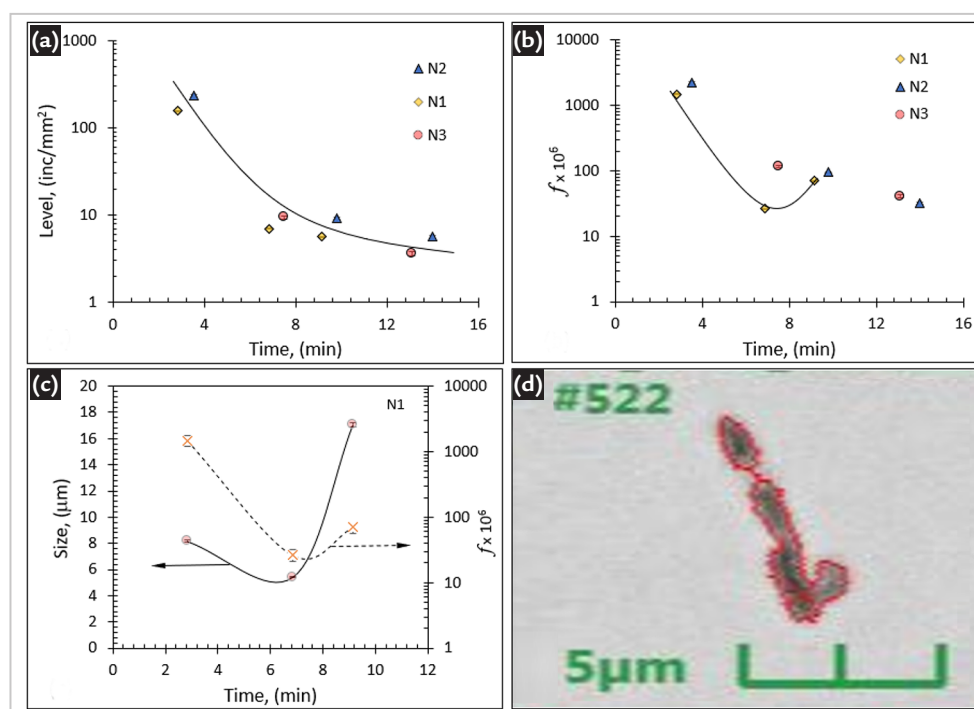

Figure 7 - Evolution of the $Al_2O_{3(s)}$ inclusion level as function of time in RH process, heats with neither scrap addition nor chemical aluminum heating (a) inc/mm² and (b) fraction of inclusions (c) Medium size and fraction of inclusion "*f*" of the inclusions in Heat 1: arrows indicates the correct axe to use for "size" and "*f*" and (d) a cluster of $Al_2O_{3(s)}$ inclusion type identified by ASCAT system.

Indeed, from long-standing experience, the RH process has been recognized not as purely for degassing, but that it also has a key role to promote inclusion remotion (Wasai and Mukai, 2002; Shirabe and Szekely, 1983). So, the high cleanliness level required by the market in a modern steel company can be obtained using this equipment. Figure 8 presents the inclusion level as a function of the time for the heats with necessary heating (H's-8a) and cooling (C's-8b). As explained before, sometimes this adjustment is unavoidable to provide the correct temperature in the subsequent step of continuous casting. Once again, as in the N's heats for all conditions, the level of inclusion is controlled by the time. Excluding any unpredicted event, the general rule is that the longer the time of the process, the lower will be the inclusion level, However, for these experiments, the maximum reduction level is limited to the medium value of ~ 8 inc/mm². Thus, the RH process decreases the inclusion level with time (Wakon and Sano, 2007) and good efficiency can be obtained throughout the inclusion coagulation associated with the correct time of the process for a level of inclusions as low as possible. The differences between the heats of the same family always can be explained. For example, as is shown in Figure 8a, the H1 heat was that which presented the higher level of inclusions observed in the last sample taken in the steel process when is compared the level of non-metallic inclusion observed in the last sample taken in H2 and H3 heats. This behavior probably occurred due three process conditions: a) the shorter time between the last sample analyzed and the end of the oxygen blowing in the metallic bath; b) Sorter time between the last sample analyzed and ferro alloy addition; c) Higher oxygen volume in order to increase de temperature of the heat H1. It is possible to conclude that the last sample analyzed of H1 heat was taken around 7min of RH circulation, while for H2 and H3, the time was ~ 10 min and 11 min, respectively. The oxygen

blowing in H1 was 103 Nm³ while for H2 and H3, the oxygen blowing was 82Nm³ and 91Nm³ respectively. In Figure 8b, plotted are the results obtained for the C's heat, where the same behavior was recognized, and the C2 heat time process was shorter with a higher level of inclusions when compared with the other C's. These levels of inclusions in IF steels are acceptable, for typical industrial applications and literature present results in same range (Yuan *et al.*, 2022).

Figure 8c presents consolidated data for all experiments, and as presented before, the common lower level of inclusions obtained was around ~ 8 inc/mm². The process that has resulted in the lowest level of inclusion in the last sample was the N3 heat with no adjustment of temperature and the value was 4.9 inc/mm². Figure 8d presents a similar results of inclusion area fraction observed in the last samples analyzed even with thermal

adjustmens performed in heats group H's and C's.. These results indicate that the RH process time helps two opposing sides. On the one hand, the duration time favors the removal of inclusions, and on the other hand, it also favors the creation of new ones by the nucleation process. The prolonged time also favors the clustering/agglomeration process, helping the trapping by the slag. For the H's heat group, the general result was an increase of the average number of inclusions per square area unit n samples taken just after the heating process and a decrease of the average number of inclusions per square observed in last samples taken with time. This behavior is associated with oxygen blown into the bath and some material additions during the process, such as Al and/or ferroalloys/others. The explanation for this result is that not only are old inclusions always growing by diffusion and/or a coalescence process and can be removed,

but also new ones are being constantly formed up to a kinetic/thermodynamic limit. When the inclusion level is very low, such as ~ 4 up to 8 inc/mm², it is extremely difficult to remove them, not only because they are very small, but also because it is difficult to cluster them and trap them in the slag because the average distance between them becomes great. The N's heat were the ones with the shortest delay time, but they reached the lowest level of inclusion. This result may be due to the absence of thermal adjustment, low level of new nucleon formation observed in last sample taken, and perhaps for the present inclusion, the growth by diffusion/agglomeration was not feasible. This same behavior was also observed for the cold heat C's.

An example is that the scrap additions can change the normal behavior of the inclusion level as a function of time. Thus, for the C's group, a very interesting result was obtained.
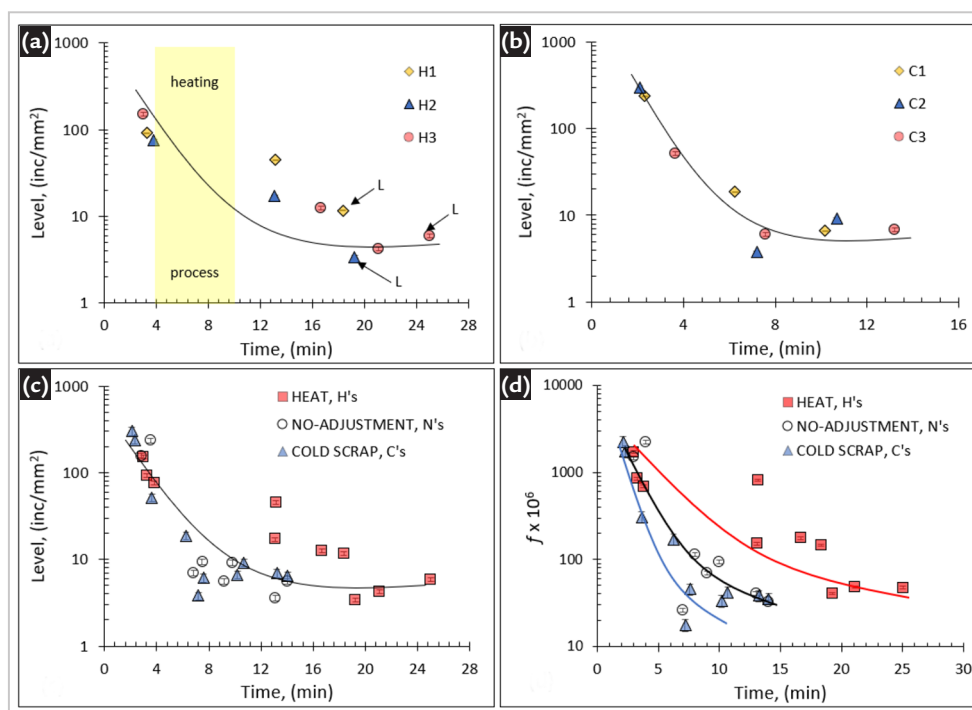

Figure 8 - Evolution of the Al₂O₃(s) inclusion level as function of time in the RH process.
(a) Heats with aluminum addition for chemical heating – H, arrows indicate last sample (L),
(b) Scrap cold heats - C, (c) and (d) comparative inclusion level and inclusion fraction, respectively for the three conditions.

The addition of the scrap near the last sample taken (C2) made the level of Al₂O₃ inclusions increase significantly as is shown in Figure 8b, where a higher inclusion level can be seen in the last C2 sample when compared with others. Figure 8d presents the fraction area occupied by the inclusions as a function of time and agglomeration takes place when time is prolonged. Thus, cold scrap and no adjustment heats were those with the

lower area occupied by inclusions, and this behavior is explained by the shorter time for the diffusion growing and new nucleation mechanisms, except that agglomeration cannot increase the fraction area (f). Figure 9a presents the results for the C2 experiment and some agglomeration was detected, as well as having the medium size that was from around ~ 6 up to 8 mm at the end of the process.

Figure 9 shows the results for the

C2 heat and they are very similar to those obtained for the N1 in Figure 7c, where it is possible to see again an increase of the medium size of the inclusions. These results pointed out that agglomeration and/or diffusional growing are a real process that can occur during the RH process after nucleation. Next, the inclusions can be removed or not by the convective flow inside the RH reactor. However, if the time is not enough, the level of inclusions

perhaps cannot be reduced significantly. Indeed, the results suggest that during this period, new inclusions can nuclei inside the liquid steel as was presented in Figure 8b and as said before, the level of inclusion increased in the C2 experiment due to the scrap addition, which can be the reason for the new nuclei formation. The difference between Figure 9a (C2 heat) and Figure 7c (N1 heat) is that for the N1 heat, the level of inclusion has decreased, which is why there is the suspicion that scrap addition can create new nucleons, and in fact, Figure 9b suggests that cold scrap heats have presented a higher inclusion level in the last sample associated with lower medium size. From these results, it is possible to establish that in fact, prolonged time can reduce the level of inclusions during the RH process, but some nucleation and growing events take place, leading to results with large inclusions without significant improvements in the inclusion content. The scrap and others material addition can lead to the nucleation of new inclusions, and in this case, more time can be necessary to avoid a high level of inclusions. In some cases, it is feasible to increase the fraction of inclusion, even when the level of inclusion reduces, which can occur due to the new nucleon formation and growth by a diffusional process.
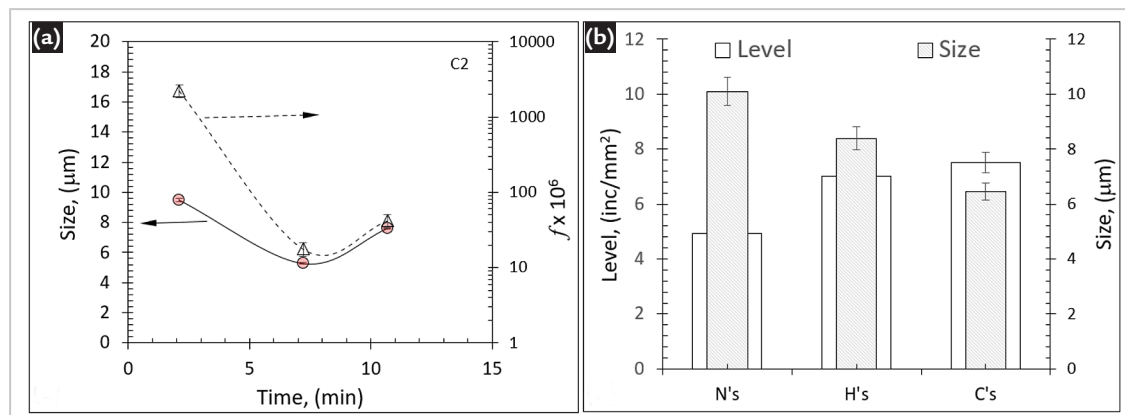

Figure 9 - Evolution of the inclusion as function of RH time process. (a) size and fraction of inclusions for C2 heat: Arrows indicates the correct axe to use for "size" and "f " and (b) Medium level and size of the inclusions for N's, H's and C's experiments.

4. Conclusions

Usually, the level of inclusions at the end of the RH process reduces with the time process. Thus, this parameter is extremely important, if the main objective is to minimize inclusion content in a steelmaking plant.

Some inclusions can agglomerate due to the Brownian/Turbulent mechanism as a function of time. They can also grow by a diffusional mechanism, and as such, the longer the time of the RH process, the lower the level of inclusions may. However, in this case, some of them may have their size increased due to these mechanisms.

Heat with the necessary reduction of the temperature using cold scrap may turn the thin inclusion formation more favorable, which will stay in the process in other steps of the steelmaking production, such as continuous casting process.

Heats without adjustments of the temperature, may present some thick inclusions in case of the shorter time of the process, since the time was not enough to remove them. Finally, even with thermal adjustments the level of inclusions at the end of all group of heats (N's, H's, C's) can be the same as long as there is enough process time to remove them.

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