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CASTING PRACTICES INFLUENCING INCLUSION DISTRIBUTIONS IN BILLETS

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Abstract

A macro-etching method has been used to analyze the distribution and amount of inclusions along billets and on cross sections. Main parameters that have been varied are holding time before casting and amount of liquid remaining after casting.
The result show that short holding times, in the order of 10 minutes, give increased amount of inclusions in the beginning of the billets, but holding times in the range from 30 to 60 minutes do not show any significant differences.
If the melt remaining in the furnace after casting is less than about 3000 kg, the inclusion density increases towards the end of the ingots.
The distribution of inclusions over the cross section of billets show that most inclusions are found in the centre of the billets, however, at increased total amount of inclusions, they tend to appear evenly over the whole cross sections.
The results are discussed based on convection in furnace and settling rates and convection at solidification front.

Introduction

The presence of nonmetallic inclusions in Aluminum DC-cast billets is a common defect, which almost can be observed in every ingot production, and it has negative effects on mechanical properties of casting products and can cause problems in extrusion processes by damaging the dies [1, 2]. Moreover, presence of these inclusions in final products are not desired when the surface appearance of products are important. Therefore, different treatments such as sedimentation, degassing units and ceramic foam filtration are being used to reduce the amount of inclusions in molten aluminum [3].
Main nonmetallic inclusions can be classified in groups of oxides, carbides, borides and nitrides in shape of particles and films [4]. The most common inclusion in aluminum melt is oxides, which originate from the thin layer of oxide that always protects the liquid aluminum in casting processes. The oxide skin is fragile, can break and be introduced into the molten metal [5].
One way to improve the cleanliness of aluminum melt is by sedimentation, which means that the melt is held in a furnace for a period of time (holding time) to allow the inclusions to settle to the bottom of the melt [6].
This work aims to examine the effect of holding time on the distribution of inclusions, as well as the effects of different amount of liquid remaining after casting. The nonmetallic inclusions along the billets were analyzed by a macro-etching method, which recently has been developed and been described in [2,7]. The method gives the actual position of inclusions in a billet, and therefore more information than what can be obtained from, e.g. LIMCA measurements, which has earlier been used to study similar effects [1, 6].

Experimental procedures

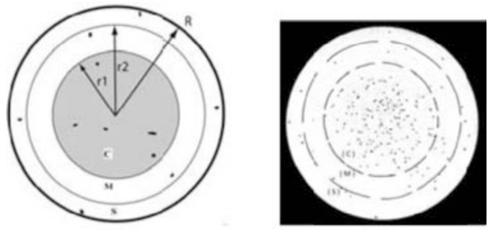
In the present work samples were collected from two cast houses. At cast house 1, after producing primary aluminum in electrolytic cells, aluminum melt is transferred to holding furnaces, while at cast house 2, first a melting furnace is charged by scrap and then, aluminum liquid is transferred through a launder to a holding furnace before start of casting. At cast house 2, two castings are done from the same charge.

Inclusion distributions were investigated in aluminum DC-cast billets. These billets were collected from castings with various holding times and different amounts of liquid remaining after casting. Table I shows the details of the samples.
The billet slices were cut transversely in different position along the billets from the bottom to the top. To analyze the inclusion distribution, the cross-section of each slice was divided into three zones with equal areas; the center (C), mid-radius (M) and surface (S). Figure 1 shows schematically the details.

Table I. Details of collected samples

Holding time [min]	Remaining melt in furnace after casting [kg]	Al alloy	Billet diameter [mm]	Cast house
30	5270	6063	152	1
60	7550	6060	152	1
25	9470	6060	152	1
10	10000	6060	178	1
85	6030	6063	178	1
80	2670	6060	178	1
30	1700	6060	178	1
40	15000	6060	228	2
35	3000	6060	228	2

A deep etching method was used to assess the amount and distribution of non-metallic inclusions over cross-sections of the samples. First, a turning machine was used to remove scratches and to obtain flat surfaces, and then the slices were immersed in a solution of 15% sodium hydroxide and etched for about 15 minutes at 338 K (65 °C). After etching, samples were washed with water and cleaned with brush to make the billet surfaces clear. Subsequently, some holes, visible by naked eyes, appear after dissolving out the inclusions during deep-etching and these etch pits (holes) represent the places of the inclusions. These holes are about 10 times larger than original inclusions [7]. To evaluate the inclusion distribution on the cross-sections of the slices, pits on the etched surface were marked, and then copies of the surfaces were printed. The inclusions appearing, as black dots, could then easily be counted.
According to the mean diameter of the etch pits, inclusions has been classified into two groups: large and small size, the large with diameters greater than 0.5 mm and small with diameters less than 0.5 mm.



(a) (b)

Figure 1. (a) Division of cross-sections [2] (b) Inclusion distribution in a deep etched sample.

Results

As was mentioned in the introduction the aim is to analyze and couple the amount, size and distribution of inclusions in the billets to different holding times and amount of melt remaining in the furnace after casting. From economical point of view and productivity, it is very important to evaluate the effect of different holding times on the settlement behavior of inclusions and find the optimum time [6]. Therefore, slices from certain various distances along the ingots from bottom (start of solidification) to top (end of casting) were cut and investigated. It should be noted that results about samples from the two companies have been presented and discussed separately due to differences in furnace design.

Samples from Cast House 1

Different Holding Times. It can be seen from figures 2 and 3, from 30 and 60 minutes holding time, that the highest number of inclusions was observed at the bottom of the billets (start of casting). The number of inclusions considerably decreases at 180 cm and remains in almost the same range at all other positions in the 30 minutes holding time casting, whereas in the 60 minutes holding time casting the number of inclusions declines towards the middle length of the billet (360 cm) and then increases again towards the end. Generally, there are very small differences between the two casting regarding level of inclusions overall in the billets. In addition, in casting with 30 minutes holding time, large inclusions (light blue bars) mainly were detected at the bottom of billet (at start of casting), while after 60 minutes holding time; they were found at both ends. Furthermore, the inclusions were concentrated to the center at all positions along the billets in both castings.

In a billet from 25 minutes holding time, two slices, from the bottom and top, were investigated, and the results are given in table II. The number of inclusions is relatively high at both bottom and top, compared to the billet from 30 and 60 minutes holding time. The number of inclusions at the bottom is significantly higher than at the top. At the bottom, the inclusion population is more shifted to the periphery. At the top, it is more concentrated to the center zone. In addition, the number of large inclusions is relatively high in both slices and especially at the bottom, but it should be noted that the positions, at which the slices were taken, were not the same as for the billets analyzed in figures 2 and 3.

Data from the casting with 85 minutes holding time is also given in table II. As it can be observed, the number of inclusions at the top of this billet is rather similar to the amount of inclusions at bottom, and also, there are noticeable numbers of large inclusions at both positions.

Figure 4 displays the results of short holding time (10 minutes). Firstly, the total amount of inclusions is higher than in the billets cast after longer holding time and a high amount of inclusions is observed at start. The results also show that most of the inclusions are located at the center of the billet in each position. It can generally be concluded that the number of inclusions reduces towards the middle of the casting from a high amount at the start and then increases again towards the end. It can also be stated that it shows a high level of inclusions along the whole billet. Furthermore, it is noteworthy to mention that large size inclusions were found in all slices.

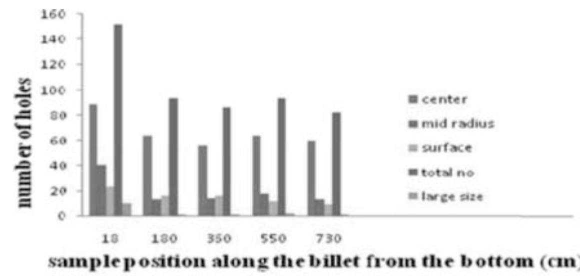


Figure 2. Inclusion distribution for 30 minutes holding time.

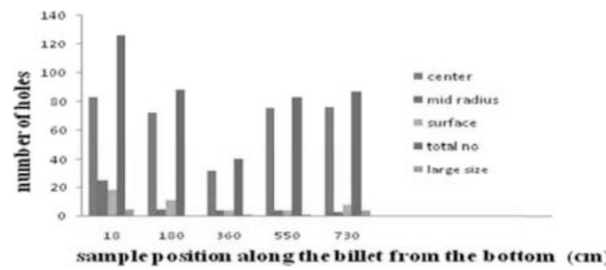


Figure 3. Inclusion distribution for 60 minutes holding time.

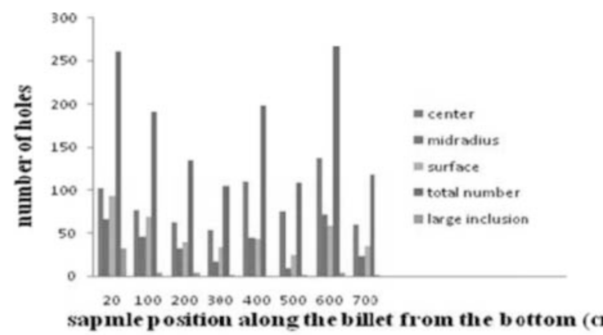


Figure 4. Inclusion distribution for 10 minutes holding time.

Table II. Inclusion distribution for 25 and 85 minutes holding time

Sample position (cm)	# (C)	# (M)	# (S)	#Total	Large size	Holding time (min)
Bottom	91	89	119	299	33	25
Top	76	50	55	181	7	25
Bottom	63	47	70	180	11	85
Top	79	56	58	193	10	85

Different amount of melt remaining after casting. In normal casting the amount of remaining liquid after casting is about 5000 kg, and it is assumed that the liquid is enriched with more inclusions at the end of a casting due to settling [1]. Samples from two castings with small amount of remaining melt were investigated and the results are shown in table III.

It can be seen that in the billet with 2670 kg of melt remaining after casting, the amount of inclusions at the end (top of billet) is substantially higher than at the bottom (start of solidification). Furthermore, relatively high numbers of large size inclusions were found in both slices. In this casting with high level of inclusions, it was found that the inclusions were distributed evenly over the whole cross sections of the billets and not in a certain zone.

It is clear from table III that in the billet with 1700 kg remaining melt, the number of inclusions in top of the billet is approximately two times higher than at the bottom and that some large inclusions were found in both ends of the billet. What also can be noted is that the total number of inclusions in the casting with 2670 kg melt remaining is higher than in the casting with 1700 kg remaining melt, but it should be noted that the slices were not taken at exactly the same positions in the two cases.

A clear difference between the castings with the lower amount of melt remaining at the end, table III, compared to the normal castings, table II and figures 3, and 4, is that a low melt level at the end gives a higher amount of inclusions at the end slices, and not in the bottom slices in contrast to the other cases.

Table III. Inclusion distribution in casting with 2670 and 1700 kg remaining melt

Sample position (cm)	#(C)	#(M)	#(S)	#Total	Large size	Remaining melt (kg)
Bottom	71	72	71	214	17	2670
Top	115	98	100	313	17	2670
Bottom	35	19	23	49	4	1700
Top	65	20	23	108	3	1700

<u>Samples from Cast House 2</u>

In cast house 2, as it is described in the introduction, two castings normally are produced from one charge. First casting is done with 40 minutes holding time and about 15000 kg remaining melt after casting and second casting with 35 minutes holding time and about 3000 kg remaining melt. That means that the second casting can be considered as a casting with low melt level at the end of casting. The results in inclusion distributions are shown in figures 5-6.

Figure 5, from the first casting, shows that at the start the number of inclusions is high, then it decreases dramatically (220 cm). A weak increase can than be seen towards the top of billet (end of casting). In addition, it can be stated that inclusions tend to appear in the central zone of the cross-sections. Furthermore, in these samples the number of large inclusions is negligible, except at the slice collected at 440 cm from the bottom.

It can be seen in figure 6, from the second casting, that the number of inclusions at the very bottom of the billet (10 cm) is somewhat increased, then after a reduction at two positions, it is followed by a clear trend of increasing number of inclusion, which continues towards the top of the billet.

It can be observed that at 440 cm from the bottom of the billet a sharp increase in number of inclusions was detected. Furthermore, these inclusions at 440 cm have large and shallow characteristics and were not found with the same frequency in other samples. Moreover, these shallow etching pits looked like agglomerates and were identified as aluminum oxide films by optical microscopy. Figure 7 shows the image of these large etch-pits and corresponding microscopic picture.

Besides the mentioned sample (440 cm), there were also a noticeable number of large size inclusions at the bottom slice (start of solidification).

The trend of inclusion distributions from both castings is illustrated in figure 8, and it shows that the number of inclusions is totally different in each position. It can be stated that close to the bottom of the billet in the first casting, a higher number of inclusions were observed, while in the second casting a strong increase was observed towards the top.

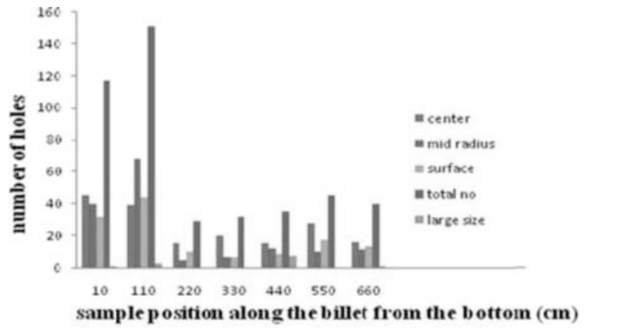


Figure 5. Inclusion distribution in first casting.

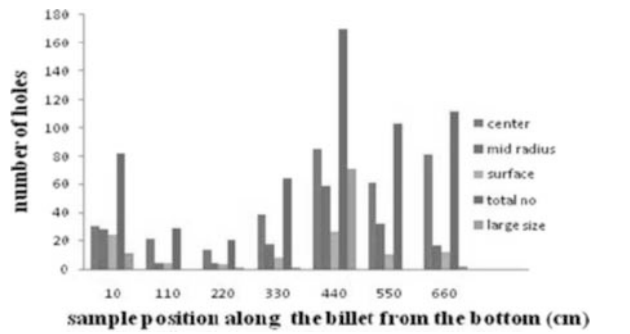
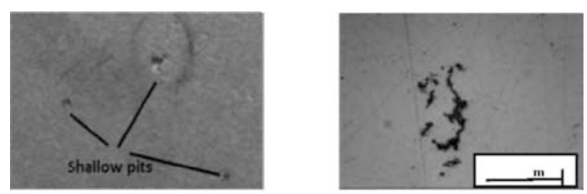


Figure 6. Inclusion distribution in second casting.



(a) (b)

Figure 7. (a) Macro-photo image of shallow voids in sample from 440 cm from the bottom of the billet, (b) Micrograph of oxide film.

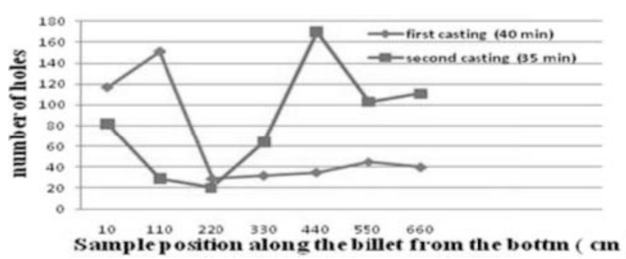


Figure 8. Trends of inclusion distribution along the billets from cast house 2.

Theoretical calculation

As discussed in the introduction, aluminum oxide is known as the most common inclusion in aluminum melts [5]. Therefore, Stokes law is used to predict the settling velocity of oxide particles with different sizes in the furnace during holding time [8].

$$V=2r^2(\rho_1-\rho_2)\,g\,/\,9\mu \quad (1)$$

Where r is particle radius ρ_1 and ρ_2 the densities of particle and liquid, respectively, g is the acceleration due to gravity (9.81 $m.s^{-2}$) and μ is the liquid viscosity. The density of an aluminum melt was assumed to be 2350 $kg.m^{-3}$ [9], and the viscosity 1.037 m.Pa.s [10], (both at 1023 °K [750 °C]). The density of an Al_2O_3 particle was taken to be 3970 $kg.m^{-3}$ [11]. The size of aluminum oxide particle varies from 0.2 to 30 µm[11] in diameter, and therefore the settling rate for five sizes of particles in this range is computed and shown in figure 9.

Figure 9 shows the settling distance of inclusions in the furnace as a function of particle size and time. It is necessary to mention that the depth of the furnace in the center is approximately 700 mm and shorter at the sides in both cast houses. According to the calculation, it can be concluded that inclusions larger than 20 micron reach to the bottom and settle in 30 minutes, but smaller inclusions need more time. Furthermore, the diagram reveals that small inclusions (less than 10 micron) will remain in the melt and will not settle even after long holding times. In addition, the diagram shows that, for inclusions of about 20 µmin size, there are relatively small effects in inclusion settling behavior in the interval from 30 to 60 minutes. It can also be stated that 10 minutes is not sufficient even for large inclusions (25 micron) to settle. It should be noted that these result were obtained without considering the thermal convection in the melt.

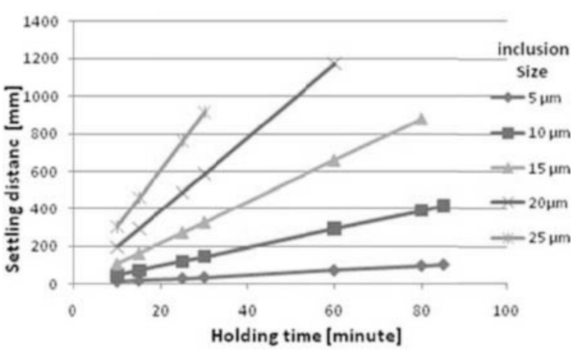


Figure 9. Settling rate of an Al_2O_3 particle in an Al melt at (750 °C).

Discussion

The results from normal amount of melt remaining after casting, i.e. about 5000 kg and more, show that inclusion population decreases from a high amount at the bottom of the billet, i.e. beginning of the casting, towards the center where it levels out. At start a strong turbulence occurs in the melt during filling, and the protective oxide layer is disrupted. This leads to an increase of inclusions at the very start of the casting. Also loose parts in the launder system will follow the first melt and end up in the beginning of the casting. In the case of two consecutive castings, figure 5,6 and 8, it is clear that the first part of first casting hold more inclusions than the second casting, indicating that the first melt "cleans up" the launder system. This part was investigated in more detail in [2], and it was concluded that about 15 cm from the start should be cut away [12].

The trend of decreasing inclusion counts from the start and along the billet, most clearly shown in figure 4 from casting with 10 min holding time, has been discussed in papers where LIMCA has been used [1,6]. The explanation given is that settling is going on in the furnace during casting, thus giving decreasing amount of inclusions coming out of the furnace. In the present investigation this settling effect along the billets only is visible after short holding times when the melt has been stirred a short time before start of casting. According to figure 9, inclusions of sizes 20 to 25 µm settle during the time period corresponding to the start of a casting with a holding time of 10 minutes. At the end of this casting the settlement is probably disturbed and the amount of inclusions increase again giving a high level, seen over the whole billet as a result. 10 minutes holding time is therefore concluded not to be sufficient.

The obtained results from the 30 and 60 minutes holding times indicate similar inclusion distribution along the billets for both castings. Figure 9 illustrates that the difference in settling behavior to a depth of 700 mm for the range of 30 to 60 minutes is relatively small, and actually all inclusions larger than 20 µm should have settled already at 30 minutes. Although this partly explains the findings one have to consider that larger inclusions were found in castings also after long holding times. An explanation can be that some oxide films form bi-films with attached bubbles, and will therefore not follow the settling process and exist also after long holding times [8].

It should also be considered that the settling calculations assume no convection, which is not the case in a holding furnace.

With small amount of remaining melt after casting, in both cast houses, the numbers of inclusions at end of a casting were significantly higher than at the start. This was also shown in [1], using LIMCA measurements, where a sharp increase in inclusion concentration occurred at the end. It is clear that settlements before and during casting can be stirred up at the end. The level of remaining melt that is critical is partly depending on furnace design, but the present results indicate that about 3000 to 4000 kg tend to be the limit.

The analysis of inclusion distribution over the billets cross-sections indicates that inclusions were located mostly at the centre. The tendency of inclusion concentration to the center zone can suggest that fluid flow and solidification front together push the inclusions from the surface of the chill mold to the center of the billet and trap them in the last stage of the solidification [7].

Conclusion

Using a method, that actually reveals the thru positions of inclusions in billets, quantitative data on inclusion incorporation has been obtained.

The amount and distribution of inclusions along billets varies with holding time before casting and remaining melt after casting.

A 10 minutes holding time is too short. Holding times in the range of 30 to 60 minutes give no significant difference in inclusion distribution.

A significant increase in inclusion population towards the end of castings was found in billets with 3000 kg and less of melt remaining after casting.

In billet cross-sections, inclusions mostly were located in the central zone.

Acknowledgements

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