On the Unusual Columnar Zone near the Bottom of a Large Ingot

By Akira SUZUKI,** Takayasu NIIMI,** Hiroyuki NAGATA,** Shigeaki TANAKA,** Yoshihiro IWATA*** and Isamu BESSHO***

Synopsis

Unusual zones with columnar structure were observed near the bottom of the 100 t ingot. Metallographic examination of the unusual zones has shown that the growth direction of one zone differs from those of other zones. This means that unusual zones originally solidify elsewhere and finally settle in the sedimental zone.

As it has previously been proposed that the top surface of the ingot is the place where the unusual zones originally solidify, the existence of the frozen top crust was checked at the hot top of a 120 t ingot. Some of the top crust could be picked up in the relatively early stage of solidification of the ingot and their structure was also columnar.

A small scale experiment using Al-0.2%Cu alloy proved that the top crust formed by putting a chill block on the top surface of the ingot sank to near the bottom of the ingot.

I. Introduction

Ingot macrostructures consist of one or more of the three zones: “chill zone”, “columnar zone” and central “equiaxed zone”. The formation process of these zones has been made almost clear by recent studies. However, the structures of which formation process cannot be fully explained yet, has often been observed in practical steel ingots. One of some examples is the unusual zone with columnar structure observed in the bottom region of large steel ingots and it has recently attracted special interest in connection with the origin of the relatively large inclusions.\(^1\)\(^\text{-}^6\) The unusual zone dealt with in this paper is the zone which is observed as a banded structure in the sedimental zone in the bottom region of a steel ingot and has the similar columnar dendritic structure to that of usual columnar zones.

The aim of the present work is to elucidate the formation mechanism of the zone through the metallographic investigation of the zone in practical steel ingot and small scale experiment on Al alloy ingots.

II. Investigation of the Unusual Zone

1. The Structure of the Unusual Zone Observed in the Bottom Region of 100 t Steel Ingot

The vacuum cast 100 t Ni-Mo steel ingot was cut in the bottom part and a test block weighing 5.3 t was metallographically examined on a longitudinal section along the center axis of the ingot. The ingot was cast in vacuum of 3 to 7 mmHg at 1580°C. The chemical composition (ladle analysis) of the ingot is shown in Table 1.

Photographs 1 and 2 show the sulfur print and the macrostructure on the longitudinal section of the test block, respectively. The macrostructure of the bottom region of the ingot consists of columnar zone near the ingot surface and of sedimental zone inside the ingot as shown in Photo. 2. And unusual zones with similar columnar structure to usual columnar zone are observed in the sedimental zone and are from 30 to 60 mm in thickness.

The areas A and B in Photo. 2 are shown in more detail in Photo. 3. As it appeared in Photo. 3 that the growth direction of the dendrites in the area A was opposite to that of the dendrites in the area B, a metallographic examination was performed on the sections perpendicular to the columnar dendrites. Photographs 4 and 5 show dendritic structure on the longitudinal and transverse sections in the areas A and B, respectively. To deduce the growth direction of the dendrites in the two areas, there is no need to measure the primary dendrite arm spacing but it can be clearly seen from Photos. 4 and 5 that the dendrites in the area A have grown upwards whereas those in the area B have grown downwards.

The above results are interpreted as follows. The similarity of the structure between the unusual zone and the columnar zone implies that the unusual zone must have solidified by unidirectional removal of the

---


** Steel Casting and Forging Div., Kobe Steel, Ltd., Wakinohama-cho, Fukiai-ku, Kobe 651.

*** Central Research Laboratory, Kobe Steel, Ltd., Wakinohama-cho, Fukiai-ku, Kobe 651.
It has often been observed that the top liquid solidified as the columnar crystals after almost all the equiaxed crystals settled in the bottom region of the ingot. However, the unusual zones in the sedimental zone as shown in Photo. 2 could not solidify as a columnar structure in the sedimental zone. If the unusual zones solidified in the sedimental zone, they should grow upward because of downward direction of the heat flow in the bottom region of the ingot. However, Photo. 5 shows that the dendrites in the unusual zone B have grown downward. This suggests that the unusual zone did not solidify in the sedimental zone but settled down there from some other place in the ingot. And the secondary dendrite arm spacing of the unusual zones was in the range of 400 to 700 μm, which was much larger than that of the columnar zone near the ingot surface, 200 to 400 μm. This shows that the unusual zone was held in a solid–liquid coexisting state for a longer period than the columnar zone was, and also is supported by considerably coarsened dendrites in Photos. 4 and 5. As proposed by Comon and Bastien, it seems most reasonable to think that the unusual zone originally solidifies at the top surface of the ingot and settles in the bottom region. And it is likely that it rolls over while sinking in the molten steel of the ingot.

The settling time of the unusual zones can be estimated by the equation, $D = k \sqrt{t}$, where $D$ is the thickness of solidified layer (mm) at a solidification time $t$ (min), and $k$ is the constant. However, it is difficult to estimate when the solidification started at the bottom of the ingot, because the shoe was partially melted by poured steel and solidified again as it can be seen in Photos. 1 and 2. This uncertainty may be especially important for the estimation of the settling time since the unusual zones exist comparatively near the bottom surface of the ingot. Since the unusual zone is about 120 mm above the welded interface of the ingot bottom with the shoe, assuming $k$ is 20 mm·min$^{-1/2}$, the solidification time at the area B in Photo. 2 is calculated to be 36 min. Though 36 min is slightly longer than 33 min of the pouring time for this ingot, it seems to be somewhat earlier for the settling time of the unusual zone. This may result from the assumption that the solidification begins simultaneously with the pouring of the ingot.
2. The Structure of the Top Crust of 120 t Steel Ingot

In order to confirm the formation of the top crust in the early stage of the solidification of ingots, a 120 t carbon steel ingot was cast in the similar way to the above-mentioned 100 t ingot and a part of the solidification layer at the top surface was picked up and investigated metallographically. The molten steel was cast in vacuum at 1585°C after tap-degassing, and a part of the top crust was picked up about 25 min after the breaking of vacuum. The chemical composition (ladle analysis) of the heat is shown in Table 1.

The thickness of the collected solidification layer was from 20 to 25 mm. Its structure on the longitudinal section was columnar dendritic as shown in
Photo. 6 and the secondary arm spacing was in the range of 150 to 200 μm. As it is clear that this layer grew downward, the structure was examined on two sections perpendicular to the primary dendrite arms. As expected, the primary dendrite arm spacing on the upper section was much smaller than that on the lower section (Photo. 6).

From these results, it seems to be the most probable that the top crust is partially remelted by addition of exothermic powder and that some fragments of the crust settle and become the unusual zone in the bottom region of the ingot.

III. Experimental Reproduction of the Unusual Zone by Small Ingot

In order to elucidate whether the unusual zone was formed by the above-mentioned mechanism, the following experiment was carried out by using small Al-alloy ingots. Figure 1 shows the steel mold used. Al-0.2% Cu alloy was made from 99.99% pure Al and Al-50% Cu master alloy. 3.5 kg of alloy was melted in an alumina crucible and degassed with flux and then poured at 720°C into the steel mold preheated at 150°C. 720°C was selected as the pouring temperature which made macrostructures completely columnar as shown in Photo. 7. A steel chill block (70 mm × 50 mm) was gently put on the ingot surface immediately after the pouring. The solidified and cooled ingot was cut longitudinally and was investigated on the macrostructure. Photograph 8 shows the macrostructure and the microstructure of the bottom and the top regions of the ingot. As shown in Photo. 8, the coarse dendritic structure was observed in the bottom region and “top crust” of the ingot, and was different from the cellular substructure in most of the rest of the ingot. The dendrite found in the bottom part of the ingot could not solidify at the observed place because of its coarse dendritic morphology but must have been formed by settling of a part of the dendrite layer at the top surface of the ingot which had formed by contacting with the chill block, and the remaining dendrite layer at the top surface is clearly shown in Photo. 8(b).

To demonstrate the settling phenomenon of the dendrite layer, the similar experiment to Photo. 8 was made with some modification by using the steel mold where 40 mesh stainless steel gauze barrier was placed horizontally at 35 mm high from the bottom of the ingot. Photographs 9 and 10 show the macro-
structure of the ingot and the microstructure above the gauze of the central part of the ingot, respectively. The dendrite layer similar to Photo. 8(c) is seen above the gauze in Photo. 10, and it can be seen that the dendrite layer has come from the top surface of the ingot. It is proved that the dendrite layer in the bottom region of the ingot was formed by disrupting and settling of the dendrite layer which originally solidified at the top surface.

IV. Discussion

From the metallographic investigations and the small scale experiments, the formation mechanism of the unusual zones has been elucidated, but furthermore a few points concerning the formation mechanism is considered hereinafter.

The first point is how the top crust is formed in a large-sized ingot. Bogdanova and Maslova\(^1\) found

---

Photo. 7. Macro-structures of Al-0.2\% Cu alloy ingots poured at (a) 720\(^\circ\) C, (b) 680\(^\circ\) C and (c) 670\(^\circ\) C

Photo. 8. Macro-structure of Al-0.2\% Cu ingot chilled the top surface by the steel block (a), Micro-structure of “Top Crust” (b), and Micro-structure of the bottom part of ingot showing unusual “Columnar Zone” (c)
that the formation of the unusual zone in the bottom region of ingots was dependent on the kinds of exothermic powder put on the top surface, though the top crust was not mentioned. Recently, Nemoto et al.\textsuperscript{5}) presumed that the exothermic powder developed the solidification layer at the top surface of ingots. The similar phenomenon is expected in the large-sized ingot examined in the present work, and it is also probable that the solidification layer is developed from the oxide layer on the top surface which is formed upon breaking of vacuum after the completion of pouring.

The second point is why the top crust starts sinking to the bottom region of the ingot. As is conjectured from the result of the small scale experiment, it is possible that the solidification layer on the top surface is broken mechanically by depressing a central part owing to the formation of a pipe. In case of the large steel ingot, it can be also pointed out that the solidification layer is remelted partly by exothermic powder and split into a few pieces.

The third point is why the pieces of the top crust do not remelt away while settling down in the molten
steel. One of the reasons is that the molten steel loses superheat for a relatively short time after the completion of pouring and is kept at the liquidus temperature. And the unusual zones exist in the sedimental zone. Hence, it is considered that many sedimental crystals had already existed there when the unusual zone settled. As settling dendrite debris is reported to be stable in the superheated liquid, comparably large unusual zones will remain undissolved in the melt. And the interdendritic melt of dendrites in the unusual zones is considered to have solidified in the similar manner to the intergranular melt of sedimental crystals, and hence the coarsening of these dendrites might have proceeded as shown in Photos. 4 and 5.

V. Conclusion

The formation mechanism of an unusual zone often found in the bottom region of ingots is proposed herein. This mechanism is deduced from the investigation on unusual zones observed in the bottom region of 100 t steel ingot and is proved by small scale experiment using Al-0.2% Cu alloy. The results obtained are as follows.

(1) The unusual zones with the similar structure to the usual columnar zone were found in the sedimental zone of the 100 t ingot.

(2) Deducing the growth directions of the dendrites in the unusual zones from their morphology, the dendrites in each unusual zone have respective growth directions, upward and downward. The secondary dendrite arm spacing is larger than that of the usual columnar zone near the ingot surface.

(3) From the above results, it was assumed that the unusual zones originally solidified at the top surface of the ingot and then settled in the bottom region of the ingot. Then, the formation of the surface solidification layer (the top crust) is confirmed by picking it up at the top surface of 120 t steel ingot and it is shown that the layer had columnar dendritic structure.

(4) The experimental study using Al-0.2% Cu alloy ingots has proved that the formation of the dendrite layer in the bottom region of the ingot is caused by settling the top crust.

From the above results, it can be elucidated that the solidification layer at the top surface of the ingot formed after vacuum casting is remelted partially by exothermic powder and the comparatively large fragments formed by remelting settle down and become the unusual zones in the sedimental zone.

Acknowledgements

Sincere gratitude and appreciation are due to Mr. Jitsuhi Nakanura and Mr. Toshimas Sakamoto of Kobe Steel, Ltd., for carrying out the experiments using Al-0.2% Cu alloy ingots.

REFERENCES

1) N. G. Bogdanova and V. N. Maslova: *Stal in Eng.*, (1963), 646.