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HIGH SPEED D.C. CASTING OF AA-6063 EXTRUSION INGOT

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The purpose of this project is to develop the technique of high speed D.C. casting of aluminium extrusion billets. The project is aimed at improving the productivity of billet casting with respect to the large demand for extruded materials and anticipated increase in labour expenses.

171 mm diameter AA-6063 alloy billets were produced at casting speeds up to 600 mm/min. in a vertical D.C. machine with multi-stage spray rings of cooling water. The main problems encountered in this study were how to prevent cast cracks during casting and structural segregation of alloying elements in the ingot. Sound ingots, free from cast cracks and structural segregations, were obtained by selecting a water cooling system and improving the mould apparatus for molten metal feeding.

Extrusion tests were also made on the cast ingots to investigate the extrudability and qualities of extrusions. Some theoretical considerations were also made for evaluating cast cracking tendencies and structures.

Introduction

Since the late 1960's the demand for extrusion billet, mainly for the use of window frames, has increased steeply in Japan. In order to meet this domestic increase, the production of extrusion ingots has been increased at a considerable rate.

Among these ingots, about 90% of production is of AA-6063 alloy, and this corresponds to about 30% of total sales of primary metal of the smelter. It is expected that the requirement for the production of extrusion billets will still continue at a high level in the future, although the rate of annual increase has now been somewhat reduced.

On the other hand, the recent rate of increase in the labor cost in this country is assumed to be more than 30% per year and it is becoming rather difficult to obtain sufficient manpower.

It is, thus, anticipated that, from the view point of labor productivity, the conventional system of multi-strand semi-continuous casting will be inefficient and be replaced by the full continuous and high speed casting process in the future. The continuous process of billet casting is also expected to greatly improve the labor environment of the cast shop.

The purpose of this paper is, thus, as a first step towards full continuous process, to develop a new technique of high speed casting for fabricating aluminum billets.

Experimental and Equipment

The alloy used throughout the experiments was AA-6063 alloy containing 0.41% Si, 0.52% Mg and 0.2% Fe. Five tons of molten metal were prepared in a holding furnace, and after fluxing, 0.5 kg/ton of Al-5% Ti-1% B grain refiner was added to the melt. Two to four aluminum moulds of 175 mm dia by 80 mm depth and for each strand, a set of 2-8 stage spray rings, each with 6 water nozzles, equipped in the conventional D.C. machine as shown in Figure 1. A conventional type of float connected to the dip tube and basin was set in each of D.C. moulds for molten metal feeding. The amounts of cooling water from the mould and secondary cooling rings were selected and determined according to the casting speed and cooling conditions employed. The ranges of cooling water were 40 to 200 l/min./mould and 5 to 50 l/min./spray ring. The soundness of the cast billet was then examined, in terms of tendency to cast cracking and macro-and microscopic structures. In this case, an ultrasonic inspection machine was used for detecting cast cracks.

In some experiments, the radioactive Al-^{192}Ir and Pb-^{198}Au alloys were added into the molten metal to determine the shape of solidification front of cast material. Solidification time and sump length of the cast samples were, then, calculated. Surface temperature of the ingot during casting was also measured using a special thermo-couple developed for this purpose.

Several ingots were extruded into various sections after the homegenization at 555°C for 2 hours and extrudability of the ingot, surface and mechanical properties, anodized qualities and corrosion characteristics of extruded sections were compared with those from the conventionally cast billets.

Experimental Results and Discussions

High Speed D.C. Casting of 171 mm dia. AA-6063 Alloy in the Range 400 to 1,000 mm/min.

A number of casting experiments were carried out on the equipment shown in Figure 1. In Figure 2, the ratio of the length of cast defects to the total length of cast billet in the steady state was plotted against solidification time at the center of ingot.

The casting speed of these samples were between 400 and 1,000 mm/min. It is apparent from the figure that when solidification time (ts) at the center of ingot was less than 80 seconds, all ingots were cracked regardless of cooling conditions and casting speeds; whereas, if this value stayed between 80 and 100 seconds, several ingots revealed a crack-free and sound structure, the tendency being depended on the cooling condition. In the case of the ingot solidified over 100 seconds, a different type of cast defect was observed in the central region of the billet. This was not cracks but shrinkage pipes due to the lack of molten metal feeding.

As shown in Figure 3, it was found, at the same time, that the central region of the slowly solidified ingot was more seriously etched by the 10% NaOH solution than outer region. The microscopic observation of the deeply etched region revealed that a heavy segregation of coarse eutectic constituents of Al-Fe-Si, Al-Fe and Mg_2Si compounds existed as shown in Figure 4. The trend of the segregation of alloying elements became more serious with increasing solidification time (ts).

Some of the crack-free ingots cast at 400-600mm/min. and control samples cast at 90mm/min. were selected and extruded to examine the qualities of sections.

No appreciable difference in the extrusion pressure, surface characteristics of the sections with and without anodizing treatment and mechanical properties in the F and T_5 tempers was observed among these samples. However, the surface of sections from the billet cast at high speed and solidified rather slowly, often showed defects extended to the extruded direction, which caused a preferential attack by the 10% NaOH solution at 70-80°C. The microscopic observation indicated that these defects were again associated with the segregation of eutectic constituents (Figure 5).

The main problem involved in the high speed D.C. casting was how to eliminate cast cracks and structural segregations from the cast ingot. It is then confirmed from the experiment that the sump length, namely solidification time was one of the most important factors which affects the quality of the cast material.

Thus, it is required to control the solidification time of the center of cast billet in the range 90±10 seconds beyond which the billet suffers from segregations of alloying elements, and below which the material shows cast cracks. This relation may be expressed in the following empirical equation.

$$l = (1.5 \pm 0.17)\ V \qquad (1)$$

where, l; Sump length (cm)
V; Casting speed (cm/sec.)

Considerations on Tendency to Cast Cracking and the Structural Segregation

The thermal stress generated in a thin circular disc with free ends during solidification was calculated from the theory of thermoelasticity. This result indicates that the tendency to cast cracking at the center of solidifying ingot is determined by the ratio of $\Delta\theta_H/\Delta\theta_M$ (1, 2).

For a sound ingot,

$$\Delta\theta_H/\Delta\theta_M < K \qquad (2)$$

where $\Delta\theta_H$ is the cooling rate at the center during solidification and $\Delta\theta_M$, cooling rate of outer region. The value of K depends on the strength of the alloy in the mushy zone, and this was experimentally determined to be 1.1 - 2.0. Namely, in order to prevent cast cracks, the cooling rate of the outer region of ingot should be close to that of the center of ingot when latter area begins to contract during solidification. Bryson (3) proposed a technique called "Delayed Quench" and discussed the tendency of hot cracking by using "Hot Cracking Parameter" (HCP).

$$HCP = \Delta\theta_M - \Delta\theta_H < K' \qquad (3)$$

The outline of this technique is that the ingot should be quenched by major water at the bottom of sump to control this value within a limit described in equation 3.

Computer calculations for the temperature distributions of the 171 mm dia. AA-6063 alloy billet during D.C. casting were also made.

Figure 6 shows these results giving the ideal temperature profile for a sound ingot described above. For the ingot cast at 600 mm/min. the outer shell of the cast ingot is required to keep enough high temperature of above 400°C during sub-mould cooling in order to acquire a steep cooling rate when solidification of the center of ingot commences. If cooling waters from the mould and first 2 or 3 stages of secondary spray rings are too strong, the abrupt temperature decrease at the surface of ingot do not satisfy relations described in equations 2 and 3.

The sump length of such a ingot will consequently be rather short. Thus, the desirable sump length of cast ingot free from cracks is also determined from the theory of cast cracks as given in equation 1.

Al-^{192}Ir and Pb-^{198}Au alloys with different half lives, added at the same time into molten metal during casting at 600^{mm}/min., and autoradiographs of the cast billet were taken 2 and 4 days after casting respectively. Results obtained were shown in Figure 7. The difference in the sump depths in this Figure demonstrates the existence of flowed and stationary regions of molten metal in the sump of cast ingot. The effective rate of solidification and the depth of stationary zone of a sample cast at 600 mm/min. were calculated from the shape of sump obtained by the autoradiographs and plotted against the depth from the surface in the radial direction in Figure 8. The etching characteristics of the ingot by the 10% NaOH solution was also schematically illustrated in Figure 8. It is noted that segregations were serious where the rate of solidification was retarded and became below 1.0mm/sec. The critical rate of solidification for the formation of coarse constituents were empirically measured to be 0.7 to 0.8 mm/sec. by the experiments of uni-directional solidification.

From these results and equation 1, control of the shape and the length of sump by fast and uniform cooling in the sub-mould cooling zone is required to obtain the ideal rate of solidification.

Methods to Produce Sound Ingots at the Casting Speed of 600 mm/min.

Figure 9 shows the improved mould assembly and cooling pattern to obtain sound ingots without cracks and segregations in the high speed casting. This assembly was redesigned from the results of preliminary experiments and theoretical considerations described above. Several stages of spray water rings were equipped to obtain the uniform distribution of pressure water. A special double mould with two separated water chambers was employed. This mould is designed to obtain a strong water circulation in the upper mould and weak water stream on the ingot from the lower mould. These stages of cooling water are devided into 4 zones.

Zone 1: for the shell formation

Zone 2: to control the shape and the length of sump by the weak and uniform water spray

Zone 3: to control cooling rate of outer shell and center region of the ingot at the bottom of sump

Zone 4: to cool the ingot for cutting

Casting experiments of the 171 mm dia. AA-6063 alloy were then continued on the improved equipment at the speed of 600 mm/min.

It is summarized that a number of sound ingots were obtained at the casting speed of 600 mm/min. when the ingot was strongly cooled at the zone 3 in Figure 9, about 850 mm below the mould.

The surface temperature of ingot in the casting direction was measured by means of a peened-in-thermocouple. The results are given in Figure 11, which demonstrates the characteristic profile of the surface temperature of the sound ingot. In this case, the cooling and solidification condition described in equations 1 and 2 were satisfied.

Conclusions

The casting technique to produce 171 mm dia. AA-6063 alloy ingots at the casting speed of 600 mm/min. was established using an improved assembly of mould and secondary cooling zone.

In order to obtain a sound ingot, the sump length of the cast material is required to stay within the range described in equation 1, beyond which the casting suffers from structural segregations.

For preventing cast cracks, the surface temperature of the ingot should be kept at a high enough level and strong cooling is required at the bottom of the sump.

Qualities of extrusions from the ingot cast at the speed of 600 mm/min. were comparable to those from conventional cast ingots.

References

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2. Kubota, M and Kitaoka, S., The 86th Meeting of the Japan Foundryman's Society, Morioka, Japan, October 1974.

3. Bryson, N.B., The Annual Meeting of A.I.M.E., San Francisco, Calif., March, 1972.

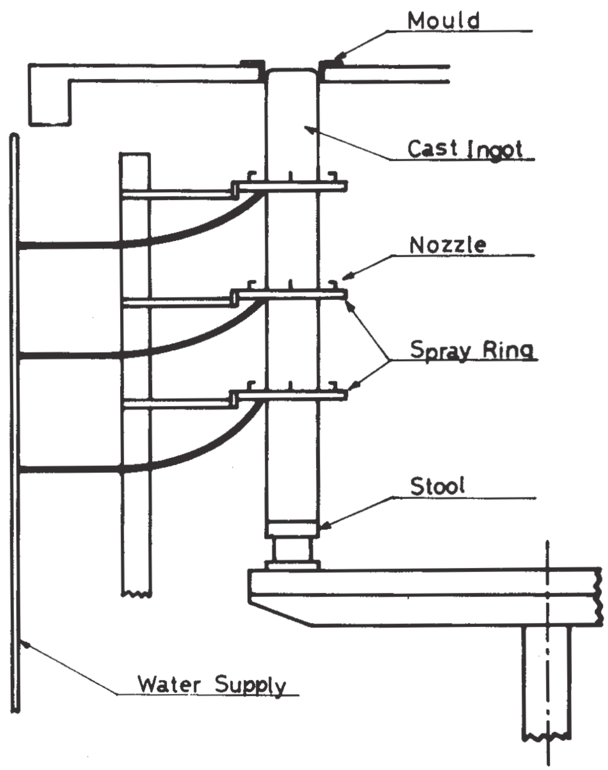

Figure 1. Equipment of high speed D.C. casting.

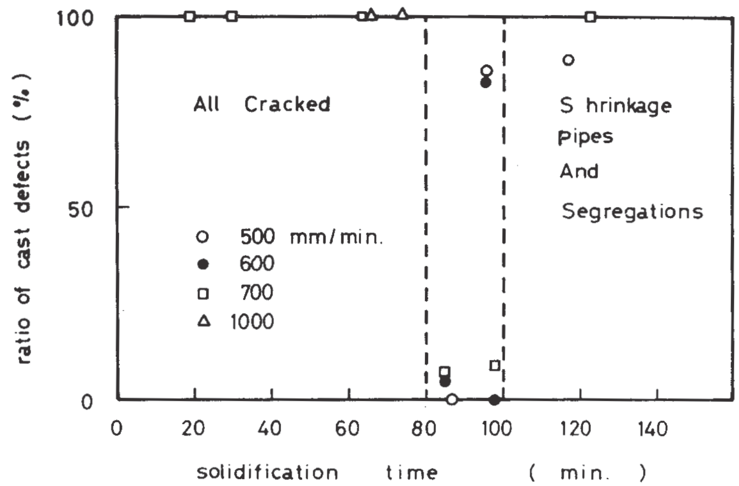

Figure 2. The properties of ingot cast at 500-1,000 mm/min.

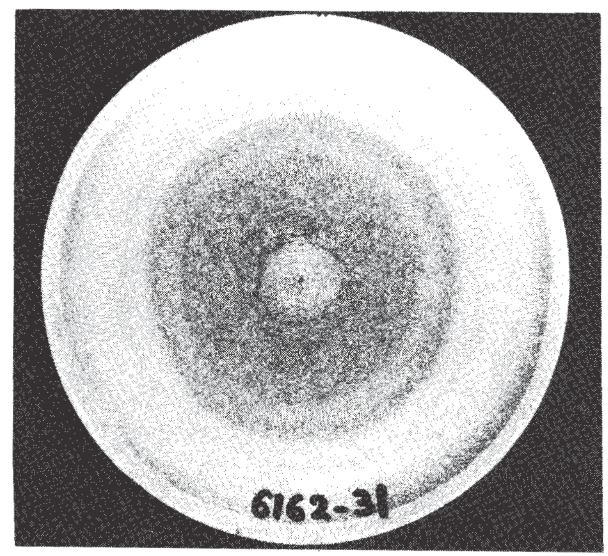

Figure 3. Macrostructure of ingot section with deeply etched region.

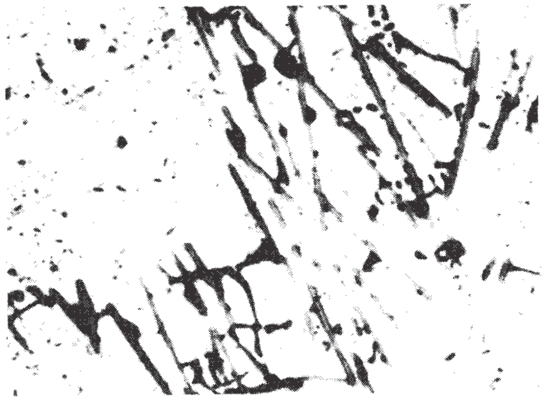

Figure 4. Microstructure of deeply etched region in the ingot shown in Figure 3.

Figure 5. Microstructure of defects in extrusion sections.

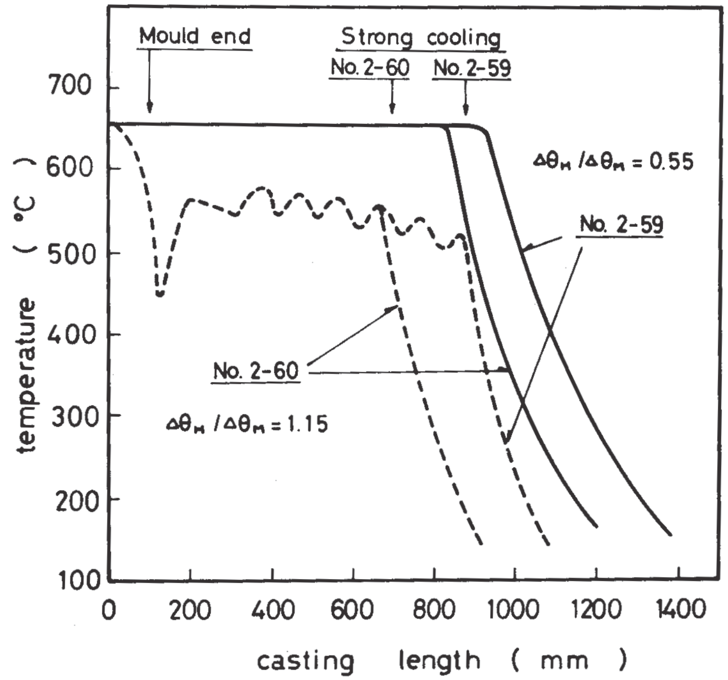

Figure 6. Calculated temperature distribution of ingots cast at 600 mm/min.

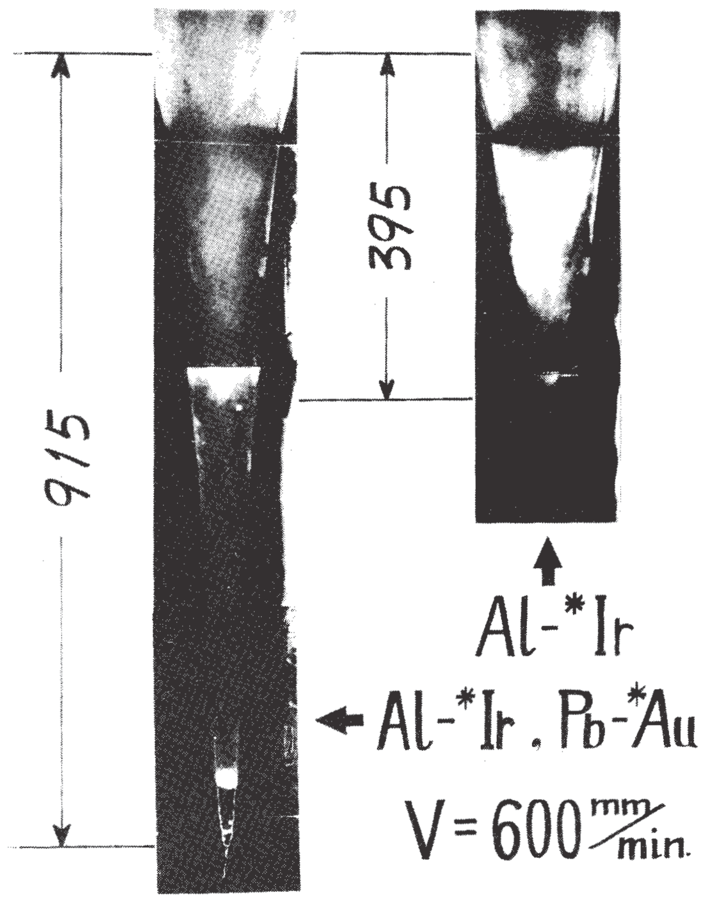

Figure 7. Autoradiographs of sump with Al-*Ir and Pb-*Au tracer alloys.

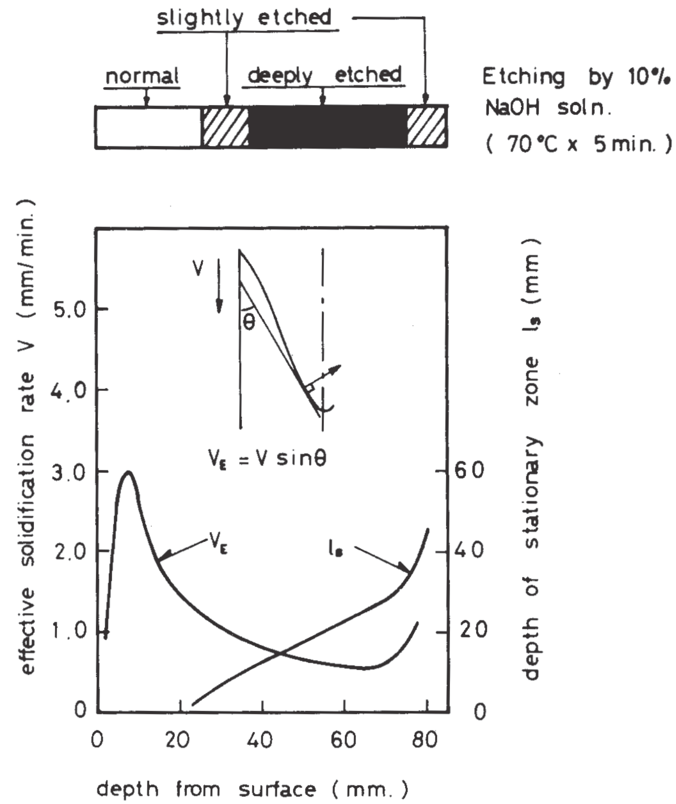

Figure 8. Effect of solidification rate and depth of stationary zone on the etching properties of ingot cast at 600 mm/min.

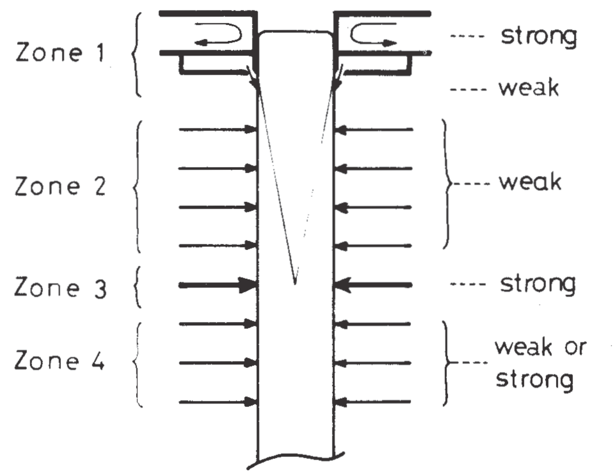

Figure 9. Desirable mould assembly and cooling pattern in a high speed D. C. casting.

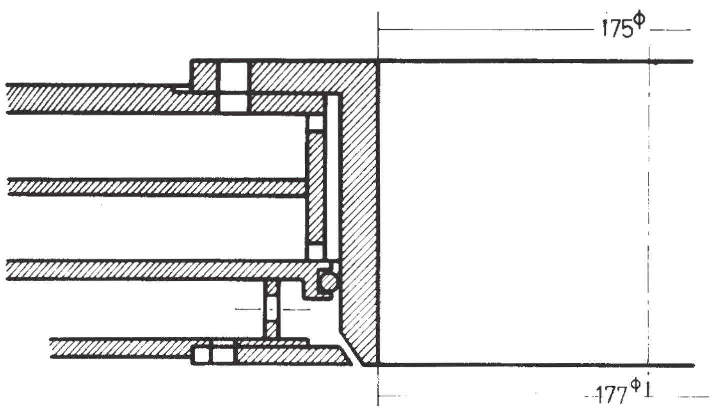

Figure 10. Improved double mould for high speed D.C. casting.

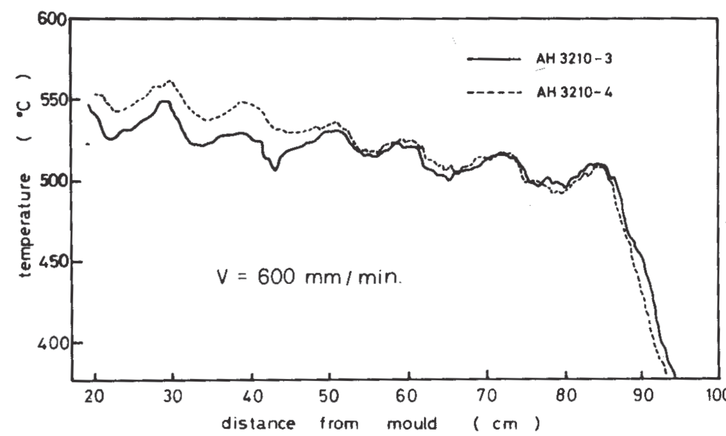

Figure 11. Surface temperature of sound ingots.