DESIGNING SHEET INGOT MOULDS TO PRODUCE RECTANGULAR INGOTS OF THE DESIRED THICKNESS AND WIDTH

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Abstract

The design of moulds for casting rectangular sheet ingots has often been based on trial and error. To simplify fabrication, moulds have generally been designed using a series of flats to approximate the real mould contour required to produce a rectangular ingot.

The resulting ingots generally have a gull-winged contour on the rolling face.

This paper will demonstrate that a sinusoidal-type mould contour is required in order to cast perfectly flat sheet ingots.

In addition, an empirical model for calculating mould geometries is described. The model takes into account the alloy, casting speed, ingot width, ingot thickness and the width to thickness ratio when determining mould openings at any point along the mould.

The model has been verified through ingot and mould measurements and is predictive within certain limits.

Introduction

The tendency for sheet ingot dimensional tolerances to become tighter due to scalping and rolling mill demands as well as the adoption of programs aimed at increasing the production recovery in the casting plants, has increased the need for casting equipment to produce precise ingot geometry as well as uniform casting characteristics throughout long production runs.

For many years Alcan Smelters and Chemicals built their own sheet ingot tooling. The mould was fabricated from a shaped extrusion (alloy 6351-T6) which is either bent around a jig and welded together or bent to form a rectangle, welded together and then adjusted to conform to a predetermined template shape. A cross-section of this mould is shown in Figure 1.

The mould section is bolted to a water jacket and the water slot is controlled by the position of the baffle afixed to the underside of the water jacket. The casting face of the mould is unsupported.

The profiles of several production moulds of this type were-measured in detail as well as the shape of the resulting ingots (alloy 3004) in order to evaluate the ability of the mould to produce the required rectangular shape along the length of the ingot1 (butt zone excluded).

Figure 2 shows the result of the mould profile measurements. Figure 3 shows the average profile of the ingots cast in these moulds. One ingot was measured at four locations to determine the stability of the ingot geometry over the cast length. The results are presented in Figure 4.

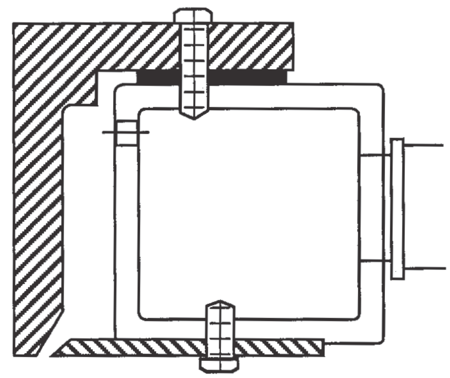

Figure 1: Cross section of mould fabricated from an aluminum extrusion.

It became quite obvious that the moulds being used by Alcan Smelters and Chemicals at that time did not have identical profiles, did not always produce flat ingots of the specified thickness and did not produce a constant ingot profile from end to end of the ingots.

With these facts in hand and with the imminent construction of several new sheet ingot casting centers it was decided to purchase a set of machined moulds from a well known supplier to evaluate the precision of the fabrication as well as their casting performance.

Definition of the Mould Profile

The profile of the moulds to be purchased was defined by Alcan Smelters and Chemicals.

The mould openings were calculated by using the known ingot thickness at any point (Figure 3) to adjust the mould opening at the corresponding point (Figure 2) in order to produce a thickness of 635 mm at that point. The procedure was repeated at 50 mm (2 in.) intervals across the mould width.

The specified mould opening is shown in Figure 5. Measurements of the two as-received moulds confirmed that both met the specification within the error of measurement.

It is worthy to note at this time the sinusoidal nature of the mould opening curve. This same shape was confirmed by measurements that had been made in another branch of the company[2].

Casting Results

Several casts of alloy 3004 were made in these moulds. The ingot profile was flat, slightly below nominal thickness and constant along the ingot length. See Figure 6.

By reducing the casting speed 2 mm per minute the profile was brought onto the nominal value.

Empirical Models

The required mould profile for the previously described case of alloy 3004, dimensions 635 x 1395 mm (25 in. x 55 in.) was defined by measuring existing mould profiles and the resulting ingot profiles for a given casting speed and correcting the mould profile to one that should produce a flat ingot of the required thickness.

This method is perfectly acceptable if one is going to replace a set of existing moulds by a new set. However it is not predictive and cannot cope with requests for thicknesses, widths, alloys and casting speeds that have not been measured.

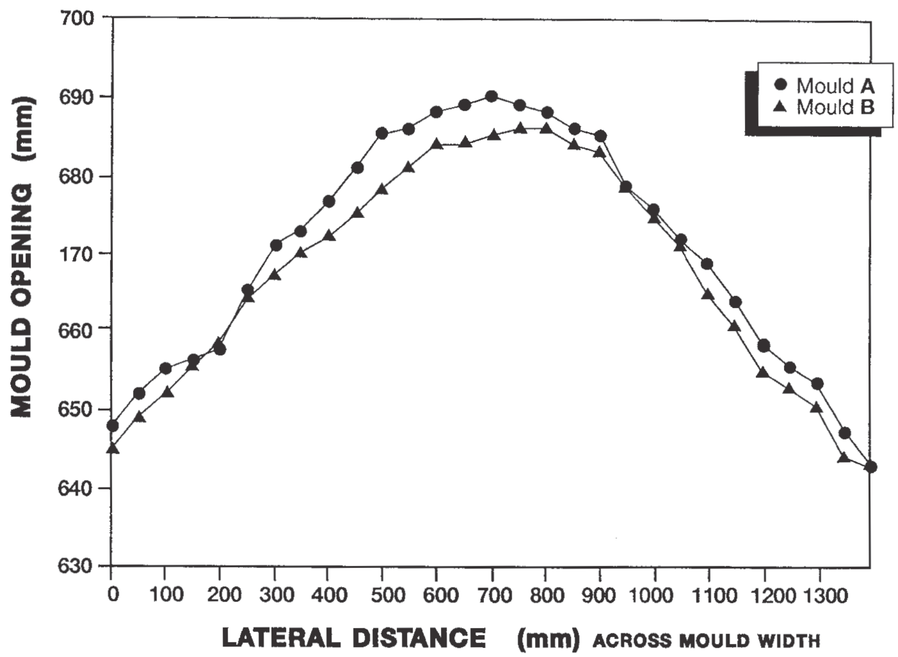

Figure 2: Profile of two moulds used to cast 635 x 1395 mm (25 in. x 55 in.) ingot.

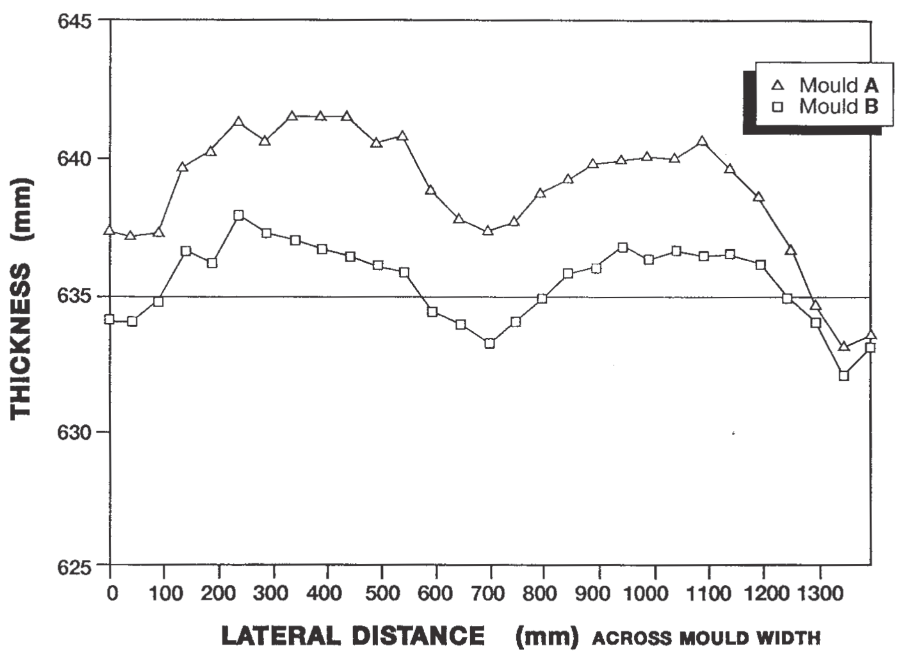

Figure 3: Average ingot profiles cast in 635 x 1395 mm (25 in. x 55 in.) moulds.

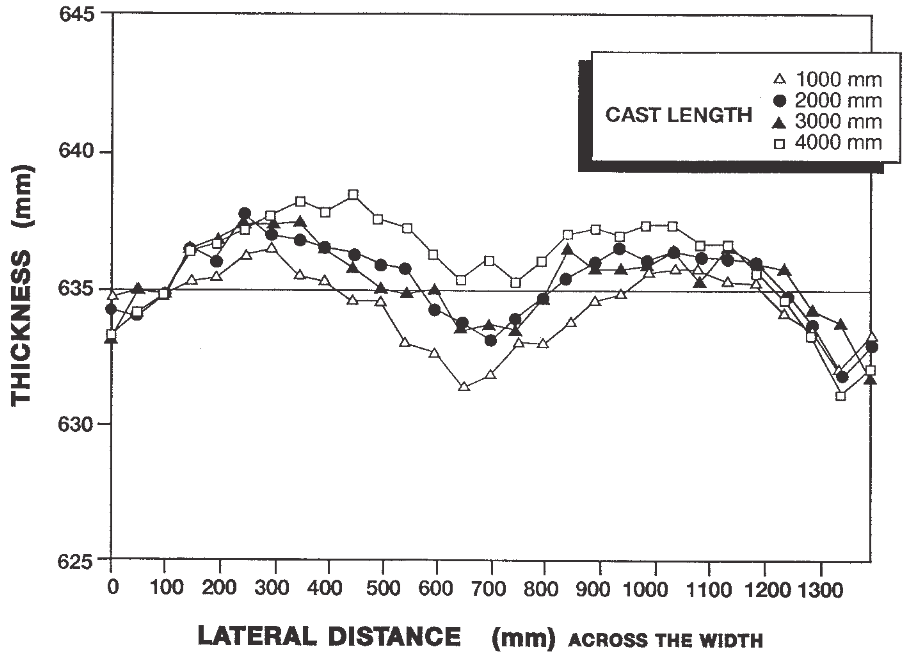

Figure 4: Variation of ingot shape vs cast length for an ingot cast in Mould B (635 x 1395 mm) (25 in. x 55 in.).

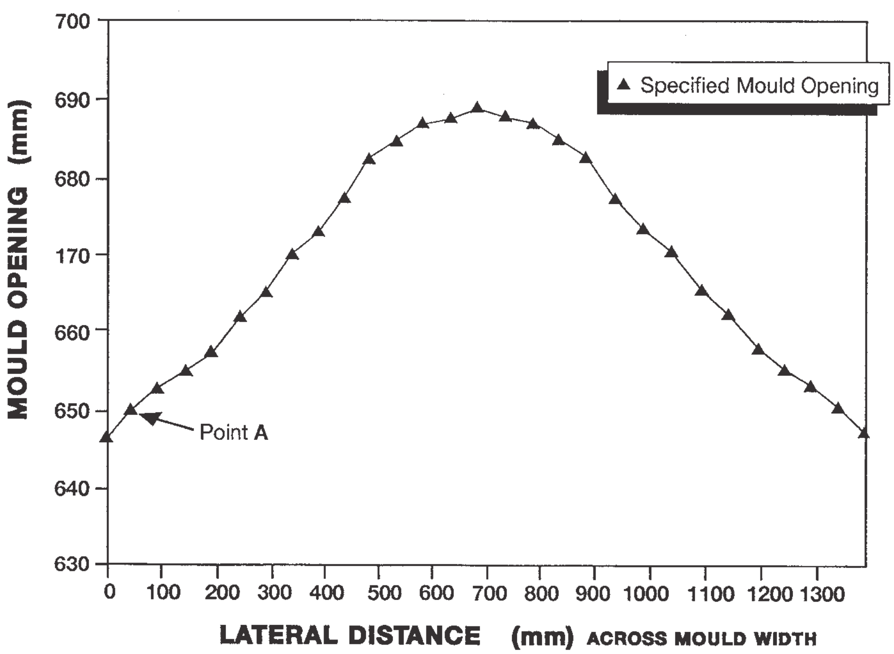

Figure 5: Specified mould opening for machined moulds to produce 635 x 1395 mm ingots (25 in. x 55 in.).

Since the decision had been made to purchase new machined moulds for the new sheet casting facilities there was an urgency to acquire enough data to enable correct mould openings to be specified.

In an effort to define the optimum mould openings for the production of flat ingots of various sizes and alloys a large number of ingots and moulds were measured.

In order to speed up the calculations and treatment of all this data a computer program on Lotus 1-2-3 was developped. This program facilitates the work and gives more flexibility in redefining optimum openings when making slight modifications to the original conditions.

The calculations of the optimum mould opening are based on the following equation3:

$$MO = K_1T + K_2T^2V \qquad (1)$$

Where MO = Mould Opening
T = Final Ingot Thickness
V = Casting Speed
K_1 = Thermal Contraction Constant
K_2 = Pull-in Constant

Results obtained with this method were checked against those obtained with the method originally used and both were found to agree quite well. The original method consisted in adding to or subtracting from the mould opening, the difference between the actual ingot thickness and the nominal ingot thickness.

The drawbacks of the original method are that it cannot easily be used to correct for a change in the casting speed or for a thicker ingot. This is more easily done with the new method.

When using equation (1) to calculate the corrected mould opening, it is necessary to calculate both constants K_1 and K_2.

K_2 will vary across the face of the ingot. It will be at a maximum at the center and will decrease symmetrically towards the ends and should be zero or very close to zero at the extremities. In this formula, MO and T are the actual mould openings and ingot thicknesses measured at regular intervals across the ingot (mould) width. This interval is usually 50 mm.

K_1 is a constant to account for the thermal contraction of the ingot and will be constant across the width of the ingot. It is obtained by measuring the ingot thickness and mould opening at the edge of the ingot where there is no pull-in, hence $K_2 = 0$. Here we have:

$$K_1 = \frac{MO}{T} \qquad (2)$$

For the example mentioned in the introduction, K_1 equals the mould opening (point A, Figure 5) of 650 mm divided by the ingot thickness at that point (point B, Figure 6) of 635 mm. In this case $K_1 = 1.0236$. Points A and B are 50 mm from the ingot edge.

After K_1 is calculated, K_2, the pull-in factor, must be calculated by using formula (1) which has been rearranged to give the following:

$$K_2 = \frac{MO-K_1T}{T^2V} \qquad (3)$$

The next step is to calculate the required mould opening to produce a flat ingot of desired thickness - T, by using equation (1).

The mould opening is calculated at every point across the face of the ingot by using the corresponding K2 value. If new ingots are to be cast at a new speed, this new speed must be inserted in formula (1).

After using this method it has become clear that it is accurately predictive to a limited extent around any set of results that are in the data base. Mould profiles can be safely calculated for sizes of the same alloy group that fall within:

- ± 50 mm thickness
- ± 60-150 mm width depending on aspect ratio
- ± 10 mm/min casting speed of an ingot in the data base.

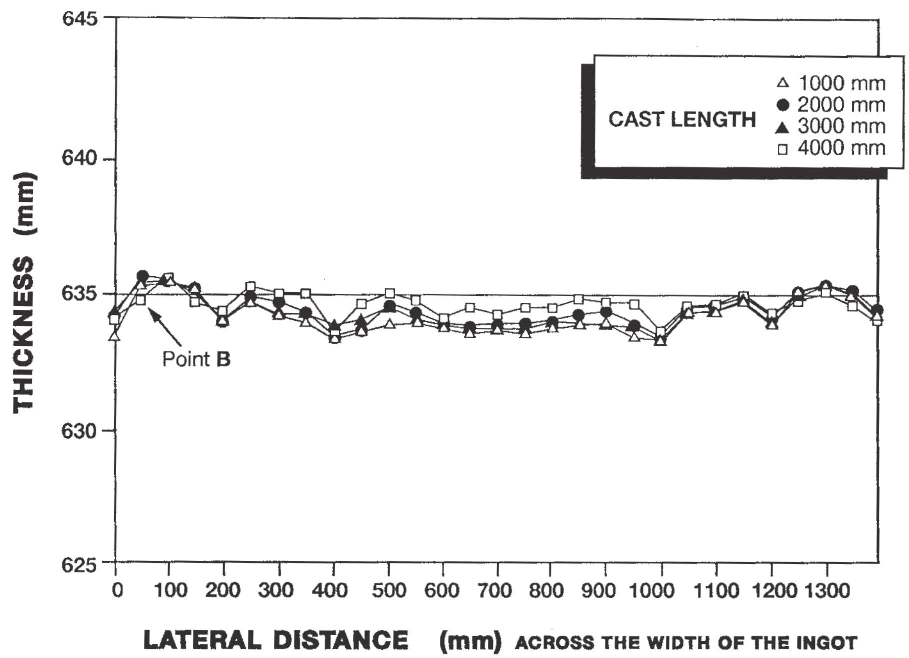

Figure 6: Profiles of an ingot cast (3004) in the machined mould (635 x 1395 mm) (25 in. x 55 in.).

EXAMPLES

Figure 7 shows the mould openings required to produce flat (verified) ingots of various widths of the same alloy (AA 1100) at a casting speed of 102 millimeters per minute. The sinusoidal shape of the curves repeats itselt again and again. For the same alloy, casting speed and ingot thickness, the mould opening increases as the width of the ingot increases. Even with a width to thickness aspect ratio of 3 for the 455 x 1370 mm mould the flat part in the center of the mould is only beginning to show itself.

These openings also produce flat ingots for 3003 alloy but at a casting speed of 93 millimeters per minute. This indicates K2 is alloy dependent.

The eventual flat part or constant mould opening is very apparent in Figure 8 for the alloy 5052 in 455 x 1675 mm size cast at 60 millimeters per minute. The presence of the flat section is due to the aspect ratio of 3.7 and to the slower speed used for this alloy. The mould starts to approximate three straight lines.

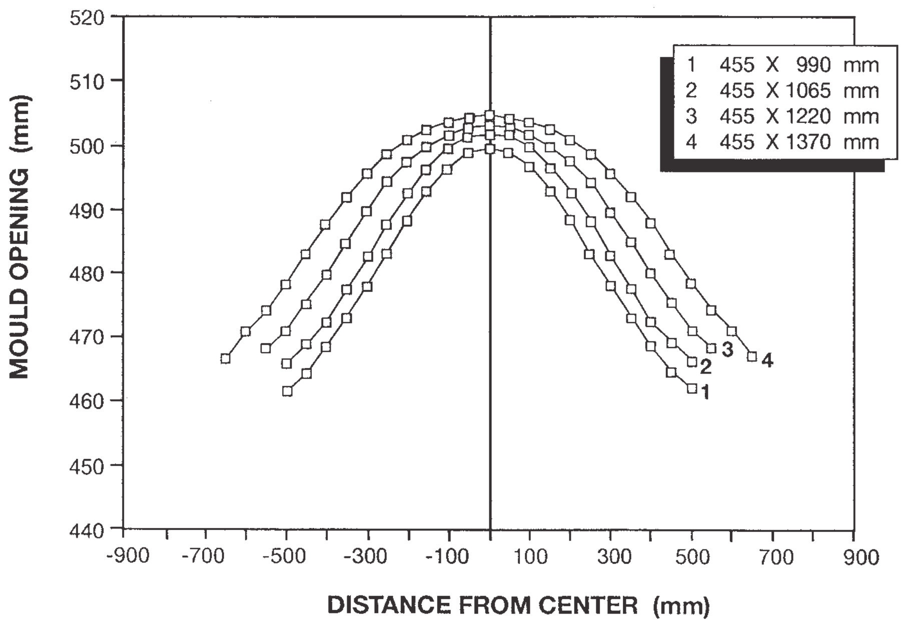

Figure 7: Mould openings to produce flat ingots of 455 mm thickness. Alloy: 1100. Casting speed: 102 mm/min.

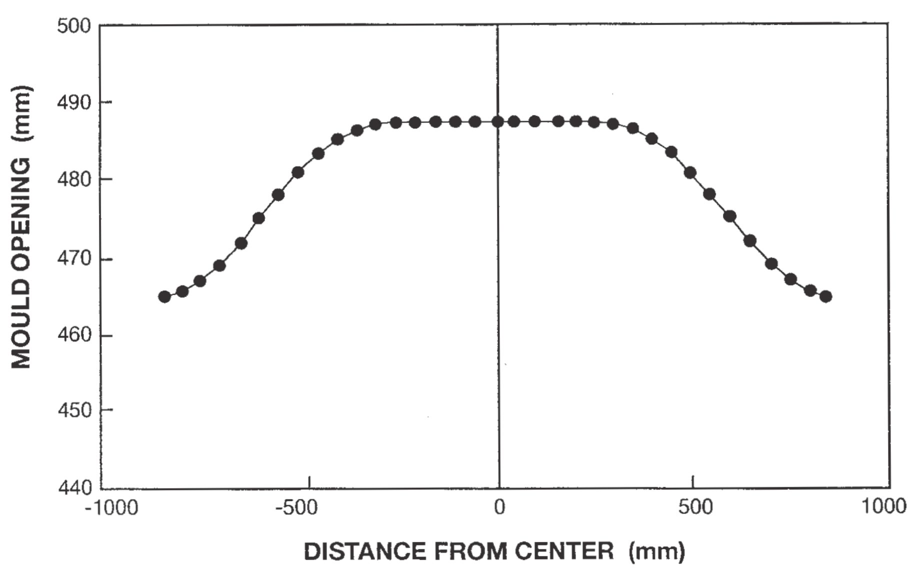

Figure 8: Mould opening to produce a flat ingot of 455 mm thickness. Alloy: 5052. Size: 455 x 1675 mm. Casting speed: 60 mm/min.

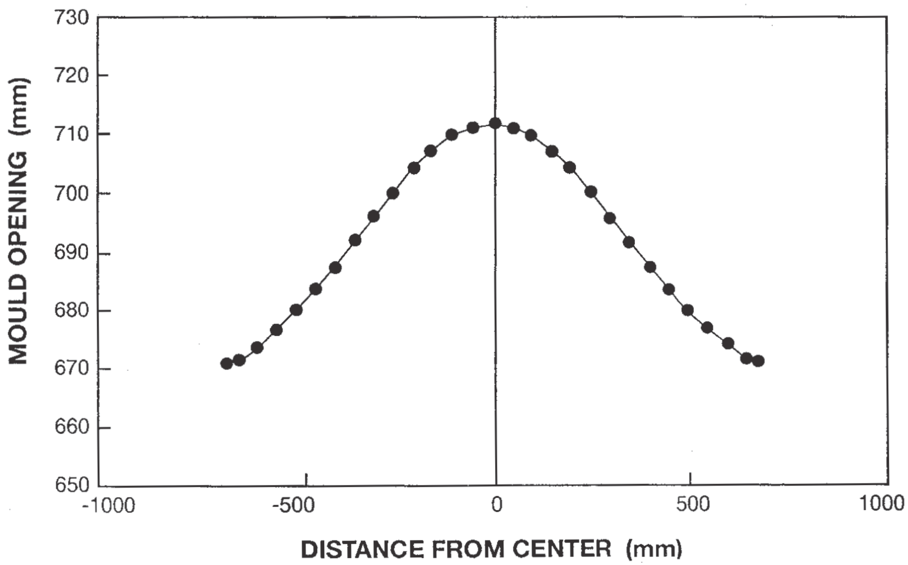

Figure 9: Mould opening to produce a flat ingot of 660 mm thickness. Alloy: 3104. Size: 660 x 1345 mm. Casting speed: 57 mm/min.

Figure 9 shows the opening required to produce a flat ingot of 3104 in 660 mm x 1345 mm size cast at 57 millimeters per minute. The opening starts to approximate two straight lines but retains its sinusoidal shape.

Ingot Width Calculations

While gathering the data for the mould profiles the mould widths and resulting ingot widths were also measured. One could use a constant contraction factor for all widths, alloys and speeds provided the width specification of the ingots is large enough.

It was observed that the percent contraction gradually decreases from about 1.9% at ingot width of 1000 mm to about 1.8% at ingot width of near 2000 mm.

However, for very close control of width, precise shrinkage factors are required. In cases where the same alloy is cast in the same mould the resulting ingot width are not quite the same. For example 5182 cast in a 1675 mm wide mould at the same speed as 3104 will be about 3 to 4 millimeters wider than the 3104 ingot.

Discussion

The mould opening profile required to produce a flat ingot of a given alloy, thickness and width for a given casting speed can vary in shape significantly from approximately two straight lines to a smooth curve to approximately three straight lines.

The sinusoidal shape of the mould opening profile is always present near the outside of the mould and extends at least 1-1 1/2 ingot thickness from the edge of the mould towards the center. This effect is in all probability due to the gradual deepening of the ingot sump that occurs from the ingot edge towards the center.

When the ingot is wide enough the sump flattens out and the mould opening is a constant in that zone.

The simple mathematical model depends on a good data base for accuracy, however, it is predictive within reasonable limits.

A given mould can cast flat ingots of different alloys providing the casting speed is ajusted upwards or downwards. The constant K2 (really the factor K2) is alloy dependent. It is very likely dependent on the thermal conductivity of the alloy in question. K2 would be expected to increase as the thermal conductivity of the alloy decreases. Therefore to produce a flat ingot of thickness, T, in the same mould the casting speed would have to be decreased going from:
1100 → 3003 → 3004 → 5052 → 5182

Obviously if the 1100 is cast at a high speed the speed for casting 5182 in the same mould may still be too high for cracking.
The fact that the percentage ingot width contraction decreases with increasing ingot width indicates that there is some end wall pull-in as well as straight linear contraction. The end wall pull-in has more percentage effect on total width contraction for narrow ingots than it does for wide ingots.

The variation of contraction by alloy could be related to differences in thermal contraction for the alloys and increased (or decreased) resistance to end wall pull-in.

Conclusions

- Rigidly, constructed machined mould can produce very flat ingots over the full ingot length (butt zone excluded) and maintain this ability permanently.

- It is of extreme importance to specify the correct mould contour in order to ensure the mould produces a flat ingot across its full width.

- When moulds are to be replaced it is highly recommended to have measured an old mould and the resulting ingot at the chosen casting speed in order to correct the mould profile (if necessary) to produce a flat ingot.

- The use of a simple mathematical model enables one to calculate new mould profiles for sizes or casting speeds that do not exist or have not been tried.

- The empirical model described in this paper is predictive but has limits.

Future Work

More detailled modelling is being done using finite element techniques that will hopefully enable us to calculate the K2 function across the ingot width for any alloy, dimension and casting speed without relying on an extensive ingot/mould geometry data base.

References

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