PREDICTION OF BUTT CURL DURING EM CASTING OF ALUMINIUM INGOTS

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ABSTRACT

Butt curl is an undesired phenomenon that occurs in the starting phase of the casting of aluminium ingots. To gain the insight necessary to control butt curl, Hoogovens has developed a thermomechanical model that describes how an ingot deforms. In this numerical model, the casting parameters, the cooling conditions, and the alloy's properties determine the temperature changes, the stresses, and the strains inside the ingot. The model also takes into account the interaction between the butt curl and the heat transfer at the butt. Experimentally determined heat transfer coefficients and mechanical properties are included in its input. It is implemented in the finite element package MARC. A comparison with measurements carried out during an actual cast shows that the present thermomechanical model predicts the butt curl accurately enough to gain the insight necessary.

Keywords:
aluminium, electromagnetic casting, thermomechanical model, butt curl, measurements

1. INTRODUCTION

The manufacture of aluminium products starts with the casting of ingots. Ingots are rolled to plate or sheet. Plates and sheets are used for a wide range of products, for example aeroplanes and beverage cans. The most widely used casting technique is direct chill casting. Electromagnetic (EM) casting also found broad application. Both techniques are semi-continuous processes.

EM casting is used in two casting stations of Hoogovens Aluminium in Duffel, Belgium. The essence of this technique is the confinement of the liquid metal by an electromagnetic field (see [2]). Figure 1 shows a cross section of an EM caster at the start of a drop. An inductor, a coil incorporated in the mould, generates this field. There is no physical contact between the metal and the mould. Only the water that cools the ingot's sides touches the cast metal. The ensuing absence of both a primary cooling zone and an air gap results in a very thin shell zone and allows a higher casting speed. These are the advantages of EM casting.

A few problems impede the efficiency of casting. One of them is butt curl. The butt of the ingot deforms during start-up due to non-uniform shrinkage of the solidified material.

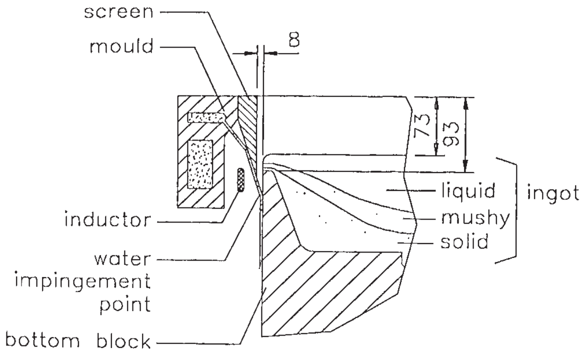

Figure 1. Cross section of mould, emerging ingot, and bottom block in an early stage of casting.

Excessive butt curl may cause instability, bumping of the ingot, or even spills of liquid metal. When significant spills occur, a cast has to be aborted. Reduced cooling can control butt curl. Too weak a cooling, however, may result in a break-out. So fine control of cooling is essential. One way to control the cooling during the start of a cast is to add CO_2 [11]. This method is adopted in the Alusuisse EM casting systems used at Hoogovens Aluminium in Duffel. As soon as the cooling water hits the ingot, CO_2 is stripped from the water. An insulating gas film that consists of water vapour and CO_2 is formed between the ingot and the water film. Thus the cooling can be controlled.

2. MODEL

A dynamic and fully three-dimensional model has been developed to calculate temperatures, stresses, and strains during the starting phase of EM casting of an aluminium ingot. Such a numerical model is called a thermomechanical model. Its thermal part calculates the temperature fields in both the ingot and the bottom block. The model's mechanical part computes the stresses, the strains, and the deformations that the shrinkage of the solidified metal causes. This model is used to gain the insight necessary to control butt curl. One of its features is the coupling between butt curl and the thermal boundary conditions. Because of symmetry, only a quarter of the ingot is simulated. In the model, the mould moves upwards, whereas both the ingot and the bottom block remain in the same position. All elements of the ingot are present in the model from the start, but they are only activated during the passage of the horizontal meniscus, which is linked to the mould. The thermal boundary conditions at the ingot's sides are also connected with it. The model is set up in the finite element package MARC. The model's input consists of :

- the process parameters for the drop;
- the dimensions of the mould, the ingot, and the bottom block;
- the properties of the materials of the ingot and the bottom block; and
- the thermal and mechanical boundary conditions.

The calculated results were obtained with the model simulating the electromagnetic casting of an AA3104 ingot. This can body stock alloy is used as it is representative of the alloys cast with this technique in Duffel. The steady state drop rate was 70 mm/min. The format of this ingot was 520 mm thick by 1640 mm wide. The mould opening was rectangular. The 280 mm high bottom block is made from an aluminium magnesium alloy. The length of the ingot was limited to approximately 1000 mm in the simulation, which gives a complete picture of the start-up. The inlet temperature of the liquid metal was 695 °C. The start temperature of the bottom block is 20 °C.

The properties of the materials of the ingot and the bottom block have mainly been taken from [1] and [3]. The exceptions are the thermal conductivity of solid AA3104, which is based on [9], and thermal expansion coefficient of aluminium, which was taken from [10]. The modified Ludwick equation has been adopted to describe the thermomechanical behaviour of the material. The parameters in this equation depend on the temperature. The application of this equation is widespread [5], [7], and [8]. Delft University measured the parameters for AA3104 in the as-cast condition in the same way as reported in [7]. The mechanical behaviour of the bottom block is discarded in the present model.

Cooling water from the mould hits the ingot or the bottom block in the impingement point (see figure 1). Below this point, water flowing downwards cools them both, whereas above it, radiation and convection to the ambient air cools them. These boundary conditions move upwards together with the mould. The heat transfer coefficient for air cooling equals 250 W/(m^2 K). The surface temperature in the impingement point is approximately 250 °C. Hence nucleate boiling occurs at the top of the falling film. There are many publications on boiling heat transfer, but only Yu [11] provided quantitative information on the effect of CO_2 addition. His data for the case without CO_2 is used to ensure that the effect of CO_2 on the heat transfer may be taken into account easily. The temperature of both the ambient air and the cooling water is 20 °C. Fjær and Jensen [4] reported values for the heat transfer coefficients at the ingot's butt: 1500 W/(m^2 K) if ingot and bottom block are in contact and 400 W/(m^2 K) if there is no contact, i.e. after the formation of a gap. These values have also been used at the bottom block's top. Stagnant air cools the lower end of the bottom block. The pertinent heat transfer coefficient is set to 50 W/(m^2 K).

3. MEASUREMENTS

Measurements have been carried out in the cast house in Duffel to enable a comparison with observations of the real process. The development of butt curl was measured at both ends of an a AA3104 ingot of the size 520 x 1640 mm. Two inductive displacement transducers, which had been installed inside a bottom block, recorded the deformation of the ingot's butt. It is common practice to measure butt curl in this way (see e.g. [6]). The transducers were in the long vertical symmetry plane of the bottom block. The distance from a transducer to the nearest narrow side of the bottom block was approximately 170 mm. Figure 2 shows the vertical displacements that both transducers measured. It also shows the vertical displacement that the thermomechanical model calculated.

Thermocouples measured the temperatures at a few positions in the ingot's butt. Figure 3 shows the measurements of thermocouples whose distances to butt was about 10 mm. They were in the long vertical symmetry plane of the ingot at 150 mm from the centre: one at the left-hand side and one at the right-hand side. The figure also shows the results of the simulation. Figure 4 shows the measurements of thermocouples the whose distances to butt was also about 10 mm.

They were, however, close to the narrow sides of the ingot. For each thermocouple the distance to the nearest narrow side was approximately 170 mm, and the distance to the nearest rolling face was about 130 mm. The figure also shows the results of the calculations.

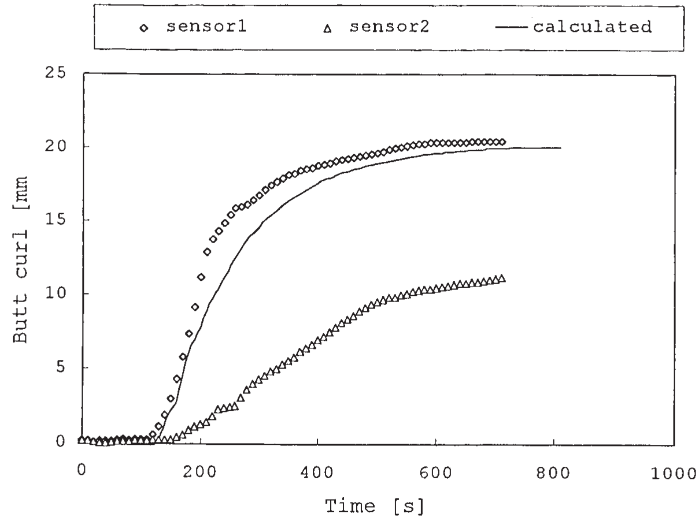

Figure 2. Butt curl: measurements and calculations

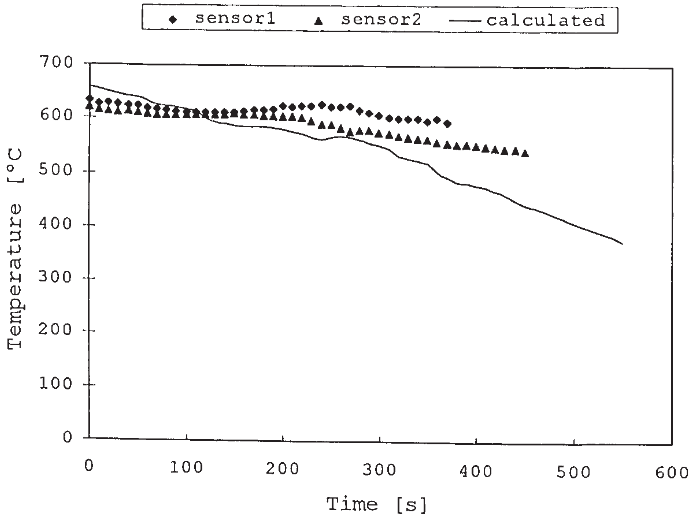

Figure 3. Temperatures in the middle of the ingot's butt: measurements and simulations

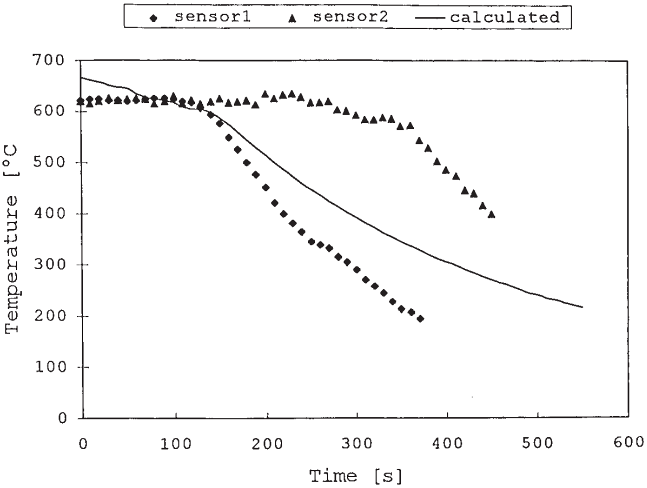

Figure 4. Temperatures at the ends of the ingot's butt: measurements and simulations

4. DISCUSSION

During start up, the cooling water only hits the bottom block. The ensuing indirect extraction of heat from the ingot results in slow solidification of the liquid metal. Hence the butt remains more or less flat. As the bottom block is moving downwards, the impingement point shifts from the bottom block to the ingot. This change causes a sudden increase of the rate of heat extraction from the ingot. The thermal stresses that the thermal shock generates exceed the local yield stresses. This leads to a plastic deformation in the form of convex curved butt: butt curl.

The thermomechanical model supposes that butt curl is a symmetrical phenomenon. The measurements, however, show that the situation is a bit different in the real world. Nevertheless the resemblance between the measurements of sensor 1 and the results of the simulations is sufficient to use the model in practice.

Also the temperature measurements show that butt curl may not be a symmetrical phenomenon. The differences in the figure 3 suggest that the heat transfer coefficient for contact may be less than 1500 W/(m^2 K), whereas the differences in figure 4 suggest that the heat transfer coefficient for no contact may be greater than 400 W/(m^2 K). As they are closer to a rolling face, water cooling may have affected the thermocouples near the butt's end.

5. CONCLUSIONS

The present thermomechanical model predicts the butt curl accurately enough to gain the insight necessary to solve problems, which may occur during the start of a casting. More work on the heat transfer at the ingot's butt is needed to decrease the observed temperature differences.

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