

APPLICATION OF MATHEMATICAL MODELS TO OPTIMIZATION OF CAST START PRACTICE FOR DC CAST EXTRUSION BILLETS

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Abstract

Producers of DC casting billets are interested in reducing scrap caused by hot tearing at the start of casting. This is the subject of large ongoing research programs within the industry. Using a relatively simple thermal model, predictions of pool depth versus cast length are made. Results compare favorably with published pool depth data. We illustrate how a such a model and current know-how could be applied to improve the cast start practice in terms of starting speed and ramp-up or dome height for a given alloy and product diameter in order to reduce cracking tendency. This type of model can be also used to examine the effect of other cast start variables such as dummy design, fill time and hold time.

Introduction

Operators of direct chill casting machines are interested in reducing their production costs. One of the main cost drivers is the scrap rate and one of the more frequent defects generated in DC casting is hot tearing in the center of the billet at the start of the cast. In this paper we illustrate how current know how and relatively simple thermal mathematical modeling might be used to optimize cast start practice to reduce centerline cracks generated at cast start.

Cracking Mechanisms

Hot tearing in DC casting is an area of ongoing research [1], however the main mechanism is generally agreed upon. Hot cracks in DC casting form due to the semi-solid material at the solidification front being subjected to tensile strains generated by thermal contraction of the cooling solid. Different parts of the casting cool at different rates and consequently contract at different rates. The solid at the base of the liquid pool in the center of the ingot is driven to contract after the solid at the surface has already cooled; consequently tension is generated in the mushy material at the base of the liquid pool in the center of the ingot. If the liquid is unable to feed the imposed strain, then crack-shaped voids appear between the grains.

Schneider and Jensen [2,3] examined cracking at the start of extrusion billet casting and proposed the concept of using pool depth as a cracking criterion, i.e. above a critical pool depth cracks would form. This is consistent with recently developed hot cracking theories based around feeding models [4]. As the pool gets deeper it is expected that so too does the width of the mushy zone. Consequently the feeding pressures increase and cracks are more likely to form. Also, the increase in pool depth reflects an increase in strain rate as the differential cooling and contraction rate between the center and the surface of the billet increase. Schneider and Jensen also revealed the phenomenon of

pool depth over-shoot at cast start. If one starts with a constant casting speed the pool depth goes through a maximum before reaching and maintaining a constant steady state value. Flood et al [5] successfully modeled this phenomenon in non-dimensionalized heat flow models and this was also verified experimentally by Grandfield et al [6] (Figure 1). This effect occurs due to the time delay before the cooling effect of the direct chill water spray is felt in the center of the billet while the billet is being lowered.

Control of Cracking at Cast Start

Two types of approach are generally used in the industry to control start cast cracks:

- i) slow start speed and ramp up;
- ii) dummy blocks with a centrally raised section (truncated cone or dome).

With a ramped cast start practice the cast starts at slower speed than the usual run speed so that when the pool depth goes through its maximum it is at a lower level than that which causes cracking. The speed is then increased to the run speed. In the case of the dummy with a centrally raised section, the pool in the center is higher at the start. When the effect of the water cooling has penetrated into the center of the ingot the pool is at a higher position. The difficulty in practice is to know exactly what dummy height or ramp conditions to use for a given alloy and diameter.

Other Factors Affecting Hot Tearing

Casters know well that certain alloys are more crack prone than others. Alloy composition and even variation of minor elements is known to affect hot tearing tendency. For example, copper has been shown to increase cracking in alloy 6060 [7]. Additionally, the grain size and morphology also affect hot tearing. This is the main reason grain refiner is added during DC casting to prevent hot tearing. The role of composition and grain refinement in hot tearing are the subject of ongoing research world wide and within CAST, but are not discussed further in this paper.

If one has an idea of the critical pool depth and can predict pool depth at cast start then some optimization of cast start practice to reduce cracking can take place. In this paper a model and its application to cast start practice are described.

Model Development

The Calcosoft™ software was used to model the start of billet casting. Calcosoft™ is a FEM based heat and fluid flow package tailored for continuous casting applications. Usually a Eulerian frame of reference is used where the solid has a velocity through the domain and steady state casting conditions are simulated [6].

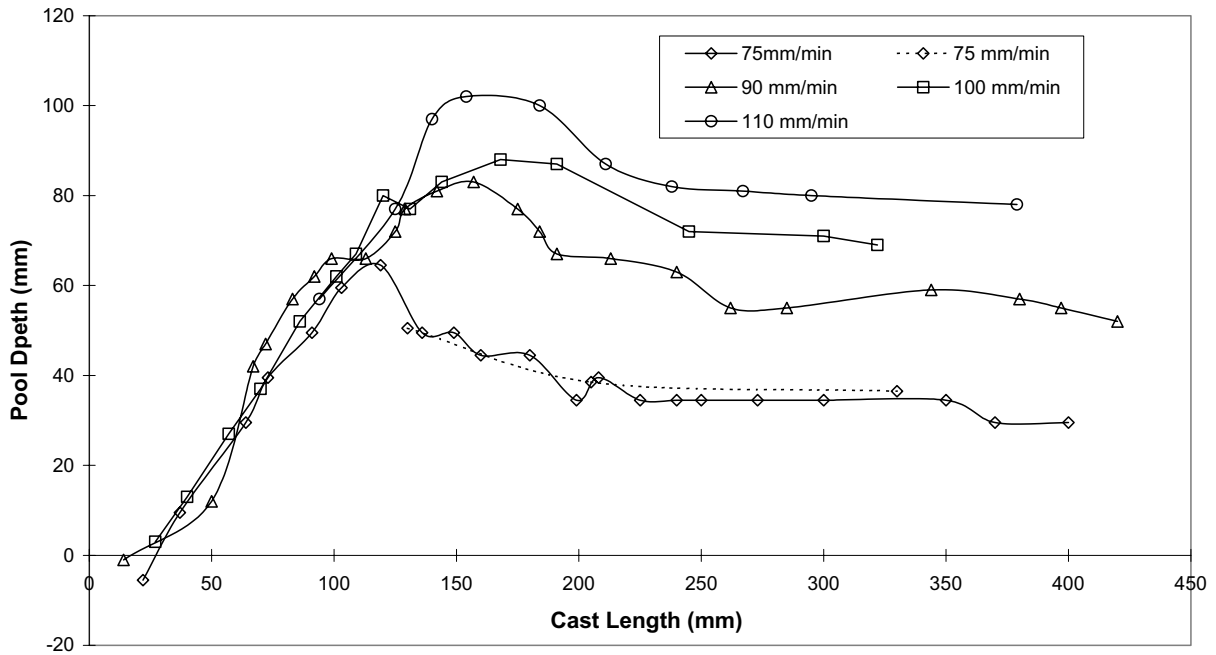


Figure 1 Experimental measurements illustrating the development of measured pool depth as a function of cast speed for 228 mm diameter 6061 alloy billet (from [6]). The depth goes through a maximum before reaching equilibrium.

Cast start represents a modeling challenge due to the fact that the computation domain becomes bigger as the casting grows in length. In order to simulate the start of casting with Calcosoft, a moving boundary condition approach was used where the dummy block is on the bottom of a stack of layers of hot liquid (Figure 2). The influence of fluid flow on the heat transfer and solidification is ignored in this simulation. Rather than the ingot moving down, the mould is moved up by changing the boundary conditions with time. The liquid layers are progressively included in the domain as the cast length increases. This is achieved by adjusting the interface heat transfer coefficient between each layer from a very low value to a very high value. These layers are thus switched from being thermally isolated to being connected to the domain. An axi-symmetric geometry was used.

A 228 mm diameter 6061 alloy billet with a 30 mm mould length, a hold time of 30 seconds, a constant casting speed of 90 mm/min and a flat dummy was simulated to match one of the curves in Figure 1. Any dummy geometry or cast speed condition could be simulated. Alloy property data were taken from references [12, 13] and mould and water spray boundary conditions data used are from Grandfield et al [6]. An initially high value of 1000 W/m²K for the first 10 seconds reducing to 200 W/m²K over 30 seconds was used for the dummy block/billet interface heat transfer coefficient.

Results

Predicted pool depth versus cast length (for 228 mm 6061 alloy billet cast at 90 mm/min with a flat dummy) compares well with the measured values (Figure 3). A peak is observed in the predicted pool depth at around 100 seconds corresponding to the measured peak. After 250 seconds the pool stabilizes to the steady state value. Note that the measured pool depth corresponds to some solid fraction between 0 and 1 where the semi-solid shows sufficient resistance to a steel dip rod (see [14] for more detailed information on pool depth measurement methods in DC casting). A fraction solid of 0.9 gives a good match with the experimental data.

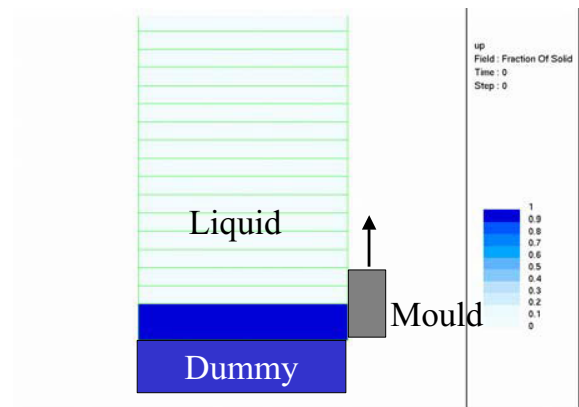


Figure 2 Layout in model with flat dummy.

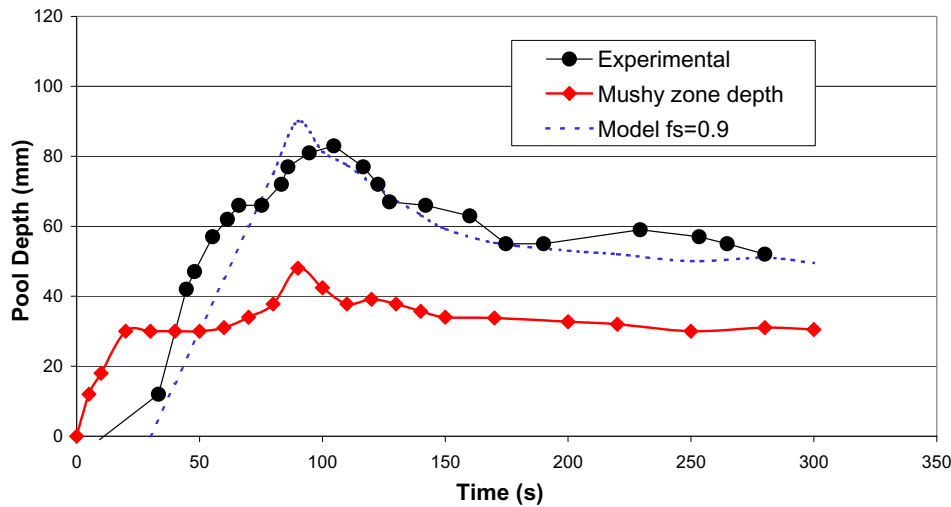


Figure 3 Measured and predicted pool depth for 228 mm 6061 alloy billet cast at 90 mm/min. Hold time 30 seconds. Flat dummy.

Interestingly, the mushy zone depth, which is a key parameter in hot tearing models, is also predicted to go through a maximum. The RDG cracking criteria (Rappaz, Drezet & Gremaud [4]) suggests cracking tendency increases with the square of the mushy zone dimension. This gives one reason why hot tears tend to form at cast start during pool overshoot.

Application

If one knows the critical pool depth at which cracking occurs for a given alloy and diameter then it is a simple matter to do the simulations and predict at what cast start speed this pool depth is exceeded for a given dummy design. This may be done experimentally. One starts casting at low speed and progressively increases speed until cracking occurs and measures the pool depth at that point (see [8,9] for examples of this type of study). However, when producers make many diameters and alloy combinations experimental establishment of critical pool depth becomes untenable. An easier method is needed.

Establishing the critical pool depth

First pass estimates of the critical pool depth can also be made by examining typical cast speed practice across a range of alloys and using Flood et al's non-dimensional number analysis [5]. The maximum speed at which cracking occurs has been found by experience to decrease inversely with diameter for a given alloy. Although it has been known since the 1940s [10] that slower speeds must be used for larger diameter billet it is perhaps not widely appreciated within the industry that the speed at which cracking starts for a given alloy is also found to follow an inverse relationship with size, i.e.

$$V_c = \frac{F}{R} \quad (1)$$

where V_c is cracking casting speed, R is the billet radius and F is a factor which depends on the alloy and grain refinement practice. Non-dimensional number analysis can be used to explain this sensitivity of cracking speed to diameter and also alloy. The normalised pool depth was found in a series of model simulations to be linear with Peclet number and only affected by Biot number in the range of $Bi < 10$ [5] i.e.

$$\Delta_{ss} = (a_1 + b_1 Pe) (c_1 + Bi^{-d_1}) \quad (2)$$

where Δ_{ss} is the normalised steady state pool depth (pool depth divided by radius), a_1, b_1, c_1, d_1 are constants and Pe is the Peclet number

$$Pe = \frac{\rho C_p V R}{k} \quad (3)$$

where ρ is density, C_p specific heat, V casting speed, R billet radius and k thermal conductivity. Bi the Biot number is

$$Bi = \frac{h R}{k} \quad (4)$$

where h is the cooling water heat transfer coefficient.

If we propose a criterion that cracking occurs above some critical pool depth, that equation (1) holds and we ignore the effect of variation in water cooling (as pool depth is only sensitive to changes in Biot number at low Biot numbers not usually used for DC casting corresponding to either low water cooling or small diameters), then the linear relationship between normalised pool depth and Peclet number dictates that there is an inverse relationship between cast speed and diameter for a given alloy (as found in practice). Furthermore, the relationship for different alloys is dictated by the thermal conductivity of the alloy because ρC_p is relatively constant for all alloys i.e. the critical steady state cracking casting speed is

$$V_c = F_1 \left(\frac{k}{R} \right) \quad (5)$$

with F_1 a constant = F/k . Examination of typical plant casting parameters together with room temperature thermal conductivity data from Metals Handbook gives a value of approximately $1.2 \times 10^{-6} \text{ m}^2\text{C}/\text{J}$ for F_1 and a critical pool depth of 75% of billet radius. Thus, one can use a heat flow model (like the one described herein) to establish the casting speed curve for a given fill and hold time, dummy geometry, and water cooling conditions such that the maximum pool depth does not exceed 75% of the billet radius. This provides a "first pass" method of setting cast start conditions.

Note, that there is an implicit assumption in this analysis that the critical pool depth at steady state is the same at startup. However, stress modeling studies indicate this is probably not the case. More sophisticated analysis can also be undertaken using full stress models and RDG type hot tearing models [4,11] which take into account stress conditions at the start, the grain size, dendrite arm spacing and the fraction solid versus temperature curve for the alloy, to establish critical casting speeds and pool depths. However, these models require some critical property data such as the alloy coalescence temperature, which are not yet available.

Ramping cast speed

In the 228 mm example above, the predicted critical pool depth is 85 mm. With alloy 6061 a cast start speed of 90 mm/min was predicted to give a maximum pool depth of 90 mm (Figure 1) with a flat dummy and is therefore predicted to have a good chance of cracking. Simulation of a typical slow start cast speed practice of 75 mm/min ramping up to 90 mm/min (Figure 4) predicts that the pool will not overshoot the critical level, and therefore the chance of cracking is significantly reduced (Figure 7).

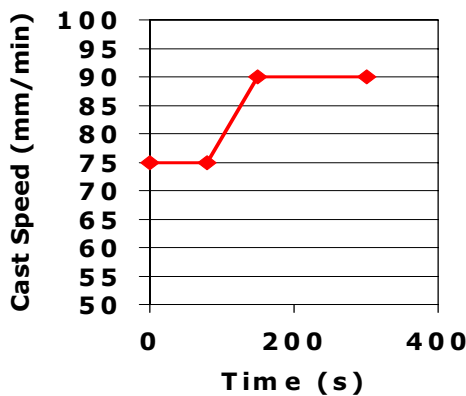


Figure 4 Cast speed as a function of time for ramped practice simulated.

Raised dummy

A dummy with a central area raised 50 mm was simulated (Figure 5). A constant speed of 90 mm/min was simulated. The pool depth is predicted not to overshoot at all (Figure 7) and the likelihood of cracking is greatly reduced. Note that since the critical pool depth is 85 mm the height of the raised area used in this simulation was probably greater than necessary.

Possible new start practice

Note that in the early stages of casting the pool depth is independent of casting speed. This is because the effect of the water spray is not yet felt in the center of the billet. Thus, the choice of cast start speed makes little difference to hot tearing in the center at that time (Figure 1). However, cast speed can affect surface defects such as cold folding and lack of gas-pressurized mode. Thus, one may initially set the speed to optimize these surface defects and then revert to another speed to prevent pool depth overshoot. For example, one might start faster than the run speed in order to control surface defects, then ramp down to a

slow speed to prevent pool depth overshoot and then ramp back up to the run speed. The pool depth for such a start practice is also predicted not to overshoot (Figure 8) indicating it may be a viable practice.

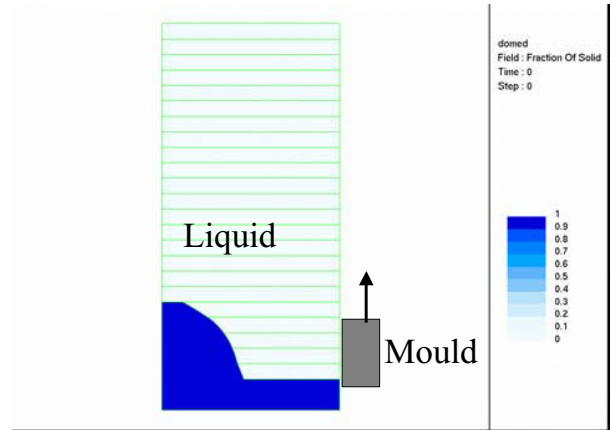


Figure 5 Simulation of a dummy with a centrally raised area.

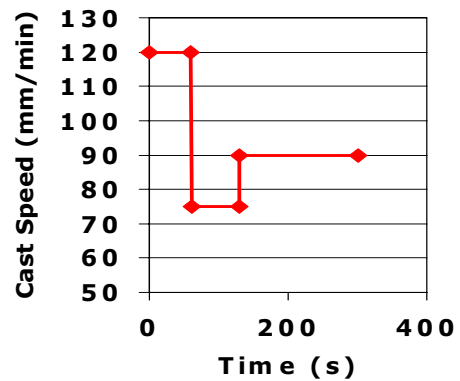


Figure 6 Possible cast start practice involving starting faster than run speed, reducing to a low speed and then ramping to run speed.

Conclusions

In this paper a simple methodology and verified thermal model have been described for optimizing DC cast start practice to minimize crack formation. A broad guideline is to ensure the pool depth does not exceed 75% of the billet radius. The thermal model described allows the casting conditions to be established so that this does not occur.

A possible new cast start practice has been proposed to allow better control of possible surface defects and center-line cracking at cast start.

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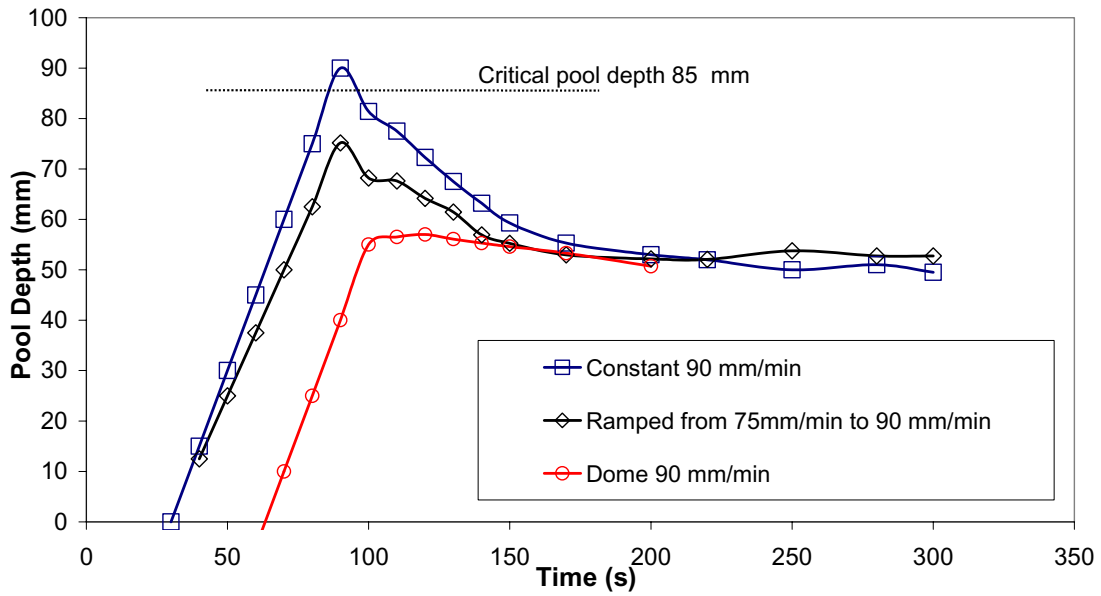


Figure 7 Predicted pool depth for pool depth (fraction solid = 0.9) as a function of cast length for three conditions: a) flat dummy with constant casting speed of 90 mm/min, b) flat dummy slow start speed of 75 mm/min ramping to 90 mm/min and c) constant speed of 90 mm/min with a raised dummy.

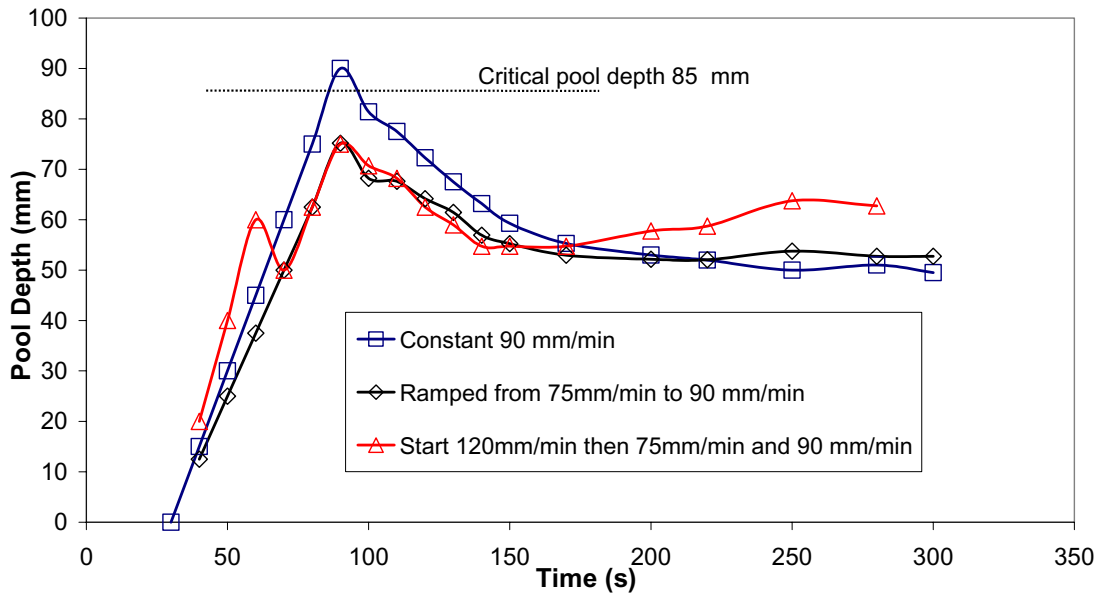


Figure 8 Predicted pool depth (fraction solid = 0.9) as a function of cast length for three conditions: a) constant casting speed of 90 mm/min, b) slow start speed of 75 mm/min ramping to 90 mm/min and c) fast start 120 mm/min, slow interim speed 75mm/min and run speed of 90 mm/min.

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