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MATHEMATICAL MODELING OF THE TWIN ROLL CASTING PROCESS FOR AZ31 MAGNESIUM ALLOY - EFFECT OF SET-BACK DISTANCE

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Abstract

A 2-D coupled thermal-fluid-stress model was developed and used to simulate the twin roll casting (TRC) of an AZ31 magnesium alloy using the commercial software package, ALSIM. The model was used to predict the fluid flow, temperature distribution and mechanical behavior of AZ31 magnesium alloy in the roll bite. An important parameter in controlling the TRC process is the set-back distance; the distance between the nozzle entry to the kissing point of the rolls. There are two approaches to increase the set-back: 1) increasing the entry thickness and 2) decreasing the final strip thickness. In this study the effect of set-back distance and casting speed on the thermo-mechanical behavior of the strip during TRC has been studied. The thermo-mechanical behavior of the strip has a significant effect on the final quality as defect formation depends on such behavior.

Introduction

The interest in magnesium alloys in the automotive industry has been increased in the recent years because of the lightweight properties of these alloys; magnesium is 33% lighter than aluminum and 70% lighter than steel. Currently, most of the magnesium usage in cars is limited to die castings. Additional applications for magnesium alloys sheet is available if reasonable properties and manufacturing costs can be obtained. Conventionally, magnesium alloys used in sheet applications, have been cast using the Direct Chill (DC) casting technology followed by several passes of hot rolling and annealing, where at each pass the reduction is limited to 5-20% with multiple annealing heat treatments in between passes [1]. An alternative process which produces strip from molten metal is twin roll casting (TRC) which incorporates casting and hot rolling in one process and subsequently reduces the costs and energy consumption considerably [2]. This process, known as a near-net-shape manufacturing process, has the capability of producing strips with the thickness of 2-10mm [3, 4]. High cooling rate achieved by this process, in the range of 10^2-10^3°C/s [4], has a significant effect from a metallurgical point of view; increasing the amount of solute in solid solution, enhanced precipitation nucleation within the matrix, a finer distribution of precipitates and a finer grain structure [5].

The need for a quantitative understanding of the process and conditions (e.g. casting speed, set-back distance, strip thickness and casting temperature) that lead to high quality sheet means that it is imperative to develop a knowledge-based process model of the TRC process for magnesium alloys. During the past few years, various models for the TRC process have been developed by considering transport phenomena coupled with solidification effects (Thermal-Fluid models). There were limited attempt to consider mechanical deformation in the model (Thermal-Fluid-Stress models) [6]. In the current study a two dimensional thermal-fluid-stress model has been developed to study the effect of casting speed and set-back distance on the thermal history and stress development during TRC of AZ31 magnesium alloy. A constant heat transfer coefficient (HTC) at the roll/strip interface was chosen based on the validation done by comparing the model results to the measurements done at the Natural Resources Canada government materials laboratory, CANMET located in Hamilton, Ontario.

Model Development

As shown schematically in Figure 1, the twin roll caster at CANMET consists of two water cooled steel rolls with a diameter of 355mm. The speed of the rolls and exit thickness can vary between 1-6m/min and 2-8mm, respectively. The strip width achievable by this caster is 150-250mm. The following assumptions were considered in developing the model [7]:

I. The process is dominated by transport phenomena in two dimensions. In the third dimension (across the width) there is no significant heat transfer or fluid flow as the simulation is done at the mid-width location,

II. The geometry is symmetrical, hence, only the top half is considered in the model,

III. The fluid flow is laminar due to shape of nozzle, and;

IV. Roll deformation is neglected.

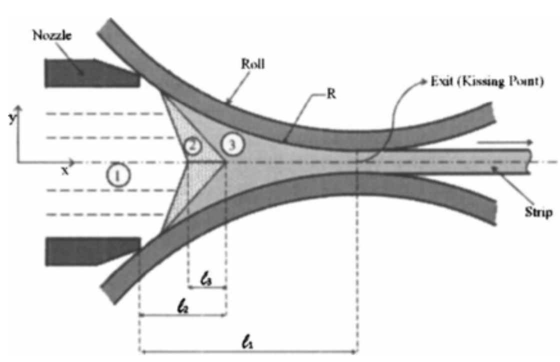

Figure 1- Schematic of the TRC process; region 1 is the liquid metal, region 2 is the mushy zone and region 3 is the solid strip, l_1, l_2 and l_3 are set-back distance, solidification front position and mushy zone depth, respectively [3].

The important physical phenomena which happen during the process and are included in the model are:
I. Heat transfer and fluid flow in the melt sump (liquid metal),
II. Heat transfer, fluid flow and latent heat of fusion release in the mushy zone and deformation in the material once the coherency point is reached,
III. Heat transfer and plastic deformation in the solid phase, and
IV. Heat transfer from the magnesium sheet to the roll surface.

The basis for numerical flow simulation is the conservation laws of mass, momentum and energy [7]. To account for solidification, two important effects of this phenomenon on the fluid flow and heat transfer need to be included; damping fluid flow in the mushy zone and latent heat of fusion. These effects are considered by adding the appropriate source terms to the momentum conservation equation and energy conservation equation, respectively [8].

To model the mechanical deformation occurring during the process, the magnesium alloy is defined as an isotropic elastic-viscoplastic material. The total strain imposed on the material is subdivided into thermal, elastic and viscoplastic components [9] and the constitutive equation shown in Equation 1 models the plastic behavior of material below the coherency temperature [9].

$$\sigma = K(T).(\dot{\varepsilon}_P + \dot{\varepsilon}_{Po})^{m(T)}(\varepsilon_P + \varepsilon_{Po})^{n(T)} \quad (1)$$

where σ is the stress in MPa, $\dot{\varepsilon}_P$ the strain rate in s^{-1}, ε_P the strain, K strength coefficient, n the strain hardening exponent and m the strain rate sensitivity exponent. $\dot{\varepsilon}_{Po}$ and ε_{Po} are small numerical constants needed to ensure that at a plastic strain of zero, the yield stress of the material is correct. For AZ31 a coherency temperature of 595°C (0.9 f_s) was assumed.

The commercial FE package, ALSIM, was used to develop the model and solve the above-mentioned equations to simulate the TRC process of AZ31 magnesium alloy. The thermo-physical and constitutive material properties were taken from the literature [7, 10]. Appropriate boundary conditions were applied and the HTC was chosen equal to 11kW/m^2°C based on previous work [11]. Table 1 shows the range of casting conditions used in the model. The aim of the present study was first to develop and validate the model for AZ31 TRC and then study the effect of set-back distance and casting speed on the thermal history and stress development in the strip. As illustrated in Figure 1, set-back distance (SB), l_1, is the distance between the nozzle entry and kissing point (least gap between rolls). The SB, is influenced by the roll diameter, entry height and exit thickness (reduction), shown by Equation 2.

$$SB = l_1 = \sqrt{R\Delta h - 0.25\Delta h^2} \quad (2)$$

where R is the roll radius in mm and Δh is the reduction (the difference between entry and exit thickness) in mm.

There are two approaches to increase the SB; increasing the entry height for a constant final thickness and decreasing the final thickness for a constant entry height. The former approach was used in the current study.

Table 1- Casting conditions used in modeling

Casting Temperature (°C)	Entry Height (mm)	Exit Thickness (mm)	Set-Back Distance (mm)	Casting Speed (m/min)
677	12	6	32.5	1.0, 1.7, 2.0 & 2.5
	14		37.5	
	16		41.8	

Results and Discussions

Thermal History of the Strip

Figure 2 shows the model-predicted thermal history of the strip surface in the roll bite region for a set-back distance of 41.8mm. As the molten material enters the roll bite and is in contact with the roll surface, the temperature drops to the liquidus temperature and solidification starts. Continuing along the arc of contact, more heat extracted from the material as it fully solidifies and then heat is extracted in the solid strip.

As expected, as the casting speed increase the overall heat extraction is reduced as these is less contact time between the strip and the roll. Since the mechanical properties of the material are temperature dependent, it could affect the mechanical behavior of the strip which shown later.

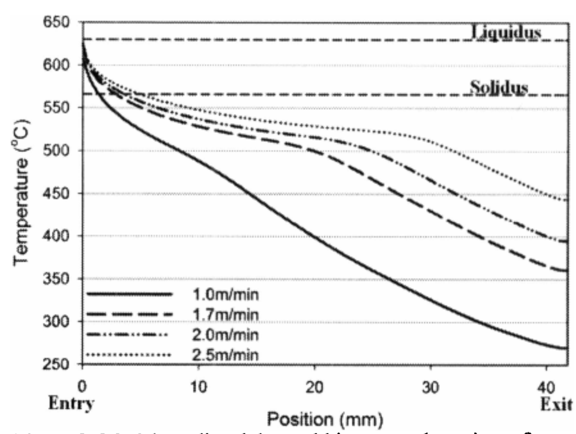

Figure 2- Model-predicted thermal history on the strip surface during TRC for a SB=41.8mm.

Figure 3 illustrates the exit strip temperature for different casting speeds and set-back distances. As expected, the surface temperature increases for higher casting speeds. Moreover, increasing the set-back distance leads to a lower exit strip temperature. This is due to longer arc of contact (strip/roll interface) and more heat transfer from the strip to the roll. The sensitivity of the set-back distance is more pronounced at higher casting speeds; a larger temperature difference is observed by changing the set-back at higher speeds, a maximum of 37°C in the exit temperature for set-back values of 32.5mm and 41.8mm at a casing speed of 1m/min compared to 61°C at a casting speed of 2.5m/min.

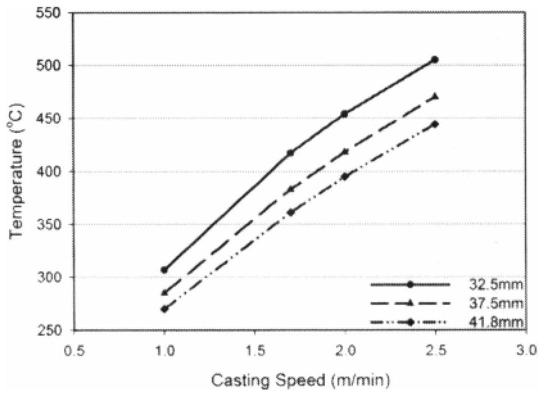

Figure 3- Model predicted effect of casting speed and set-back distance on the strip exit temperature.

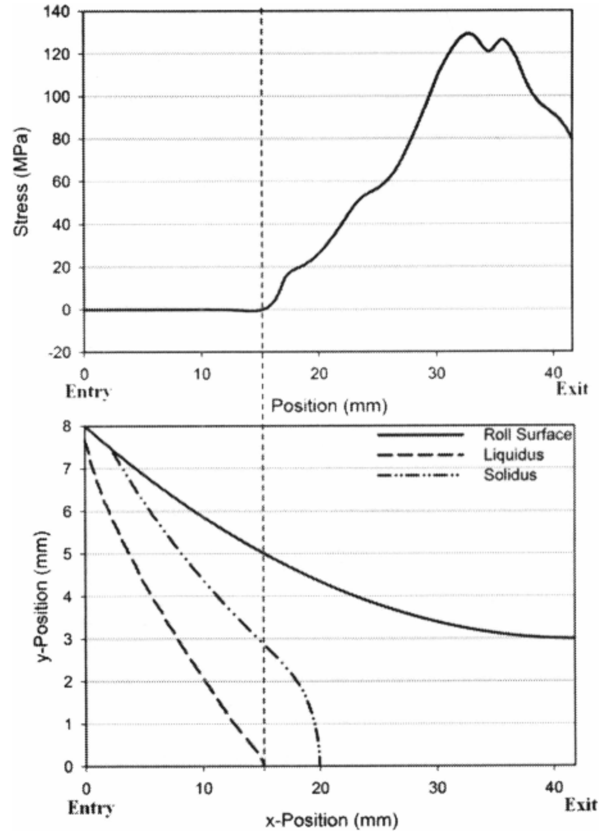

Figure 4- Model-predicted normal stress evolution at the strip surface and contour lines showing liquidus and solidus temperatures during TRC, for SB=41.8mm and casting speed of 1.7m/min.

Mechanical Behavior of the Strip

By using the model developed in the current study, the mechanical behavior during TRC was examined. Figures 4 shows the evolution in normal stress on the strip surface during TRC (roll pressure) in the roll bite for a set-back distance of 41.8mm and casting speed of 1.7m/min in conjunction with the corresponding contour lines in the strip; showing liquidus and solidus temperatures for this case. It can be seen that the roll pressure remains close to zero until almost all the strip has solidified. The zero level of the pressure is due to the inability of the molten material beneath the solidified shell on the roll surface to develop and sustain the stress. The peak in the normal stress is attributed to the friction at the roll/strip interface and the "relative motion" between the strip and roll as well as the amount of deformation the material experiences; rising prior to the neutral point and dropping afterward.

As shown in Figure 5, increasing the casting speed leads to decreasing the pressure peak. Lower casting speed means there is much more time for heat extraction and solidification; so, there would be more solid material in the roll bite and consequently more plastic deformation occurs and the stress develops to a higher values. As shown in the previous part, for lower casting speed the temperature of the strip will be lower and since the mechanical properties of the material is dependent on temperature, the mechanical behavior of the strip will be affected. The material has higher strength at lower temperature; hence, more stress is needed to deform it which leads to higher pressure at lower casting speeds.

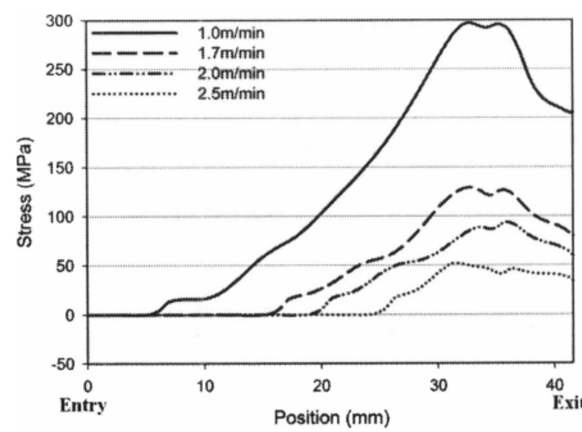

Figure 5- Model-predicted effect of casting speed on the normal stress evolution at the strip surface during TRC, for SB=41.8mm.

Figure 6 shows the effect of set-back on the roll pressure for a casting speed of 1.0m/min on a normalized scale. The procedure of normalizing the x-position (entry to exit) consists of dividing x-position to the value of the set-back distance for each case. Thus, the set-back is scaled to 0 for the entry position to 1 for the exit position, and ranges in this interval. Since for a larger set-back the solidification occurs more quickly in the roll bite and the temperature drops to lower values, hence the peak pressure/stress is greater. The effect of these parameters is similar for roll separating force, as shown in Figure 7. At low casting speeds the process is more sensitive to the set-back distance in terms of roll separating force. At faster casting speeds, less difference in separating force is observed for different set-back distances (794kN difference for set-backs of 32.5 and 41.8mm at 1.0m/min and 125kN at 2.5m/min).

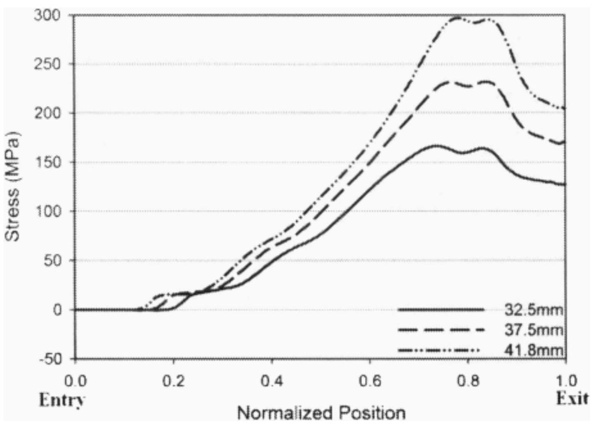

Figure 6- Roll pressure for different set-back distances, the set-back is normalized on the x-axis.

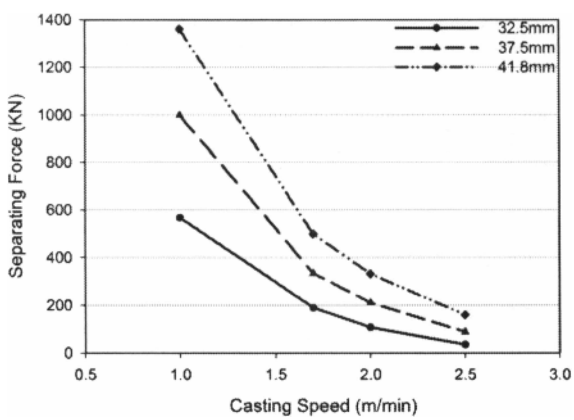

Figure 7- Effect of set-back distance and casting speed on the roll separating force.

Conclusions

1- A 2D thermal-fluid-stress model was successfully developed for twin roll casting of AZ31 magnesium alloy and thermal history and mechanical behavior of the strip was studied.

2- The temperature on the strip surface is affected by both set-back distance and casting speed; lower temperature achieved at lower casting speeds and larger set-backs. Exit strip temperature is more sensitive to set-back distance at higher casting speeds.

3- For larger set-backs and at lower casting speeds, the peak pressure at the roll/strip interface is greater.

4- Roll separating force decreases by increasing the casting speed and also casting by smaller set-back distances. The effect of set-back distance is more pronounced at lower speeds.

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