Numerical simulations of twin-roll casting for Mg-AZ31 and AA3003 sheets

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Abstract. Sheets of light-weight alloys, such as aluminum alloys and magnesium alloys, are expected to be used more for interior or exterior panels of passenger cars. Among various manufacturing technologies for the sheets, twin-roll casting has been known to be efficient and economical since it can produce sheets from melt directly. However, the phenomenon occurring in the process is so complicated that various numerical techniques have been explored to analyze it. In the present investigation, the rigid-viscoplastic finite-element method was applied to the analysis of a vertical type of twin-roll casting for production of AA3003 and Mg-AZ31 sheets. As a result, details of melt flow, temperature distribution, solidification, plastic deformation, roll torque and roll-separating force were obtained from the analysis.

1. Introduction

TRC (Twin-Roll Casting) is known to be efficient and economical for production of sheets or thin strips of aluminum alloys, magnesium alloys and stainless steels, and also for cladding layers of metal sheets without developing oxide films at interfaces between layers [1-6]. However, the phenomenon occurring in TRC is so complicated that a proper setting of process parameters is not a feasible task. Several numerical approaches have been explored to analyze this phenomenon. Recently, some analysis techniques were able to predict vortex developments in the melt which were related to heterogeneous distributions of microstructures in sheets [7, 8]. The techniques became more sophisticated to find out that, due to the vortices, only the melt in the vicinity of the nozzle wall was solidified and rolled to a sheet [9]. In addition, roll torque and roll-separating force were predicted by considering plastic deformation after solidification in the roll gap. Very recently, several cladding processes by TRC were analyzed where a two- or three-layer laminated sheet was produced from a combination of solid sheets and molten metals, or a combination of different molten metals [10, 11].

In the present study, VTRC (Vertical Twin-Roll Casting) was analyzed by the rigid-viscoplastic finite-element method for AA3003 and Mg-AZ31. The objective of this study was to find out differences between these materials in various aspects of manufacturing, such as melt flow, temperature distribution, solidification, roll-separating force and roll torque. A commercial code DEFORM was utilized for the purpose.

A cross sectional view of a vertical twin-roll casting is illustrated in Figure 1. As the melt flows through the gap between two identical rolls rotating in opposite directions, it cools, solidifies and is finally rolled to a sheet or strip with a specific thickness. As shown in Figure 2, the principle of this technology is to extract heat from the melt through the contact surface with the rolls and also to impose plastic deformation into the solidified sheet. Assuming no variations of flow and temperature in the direction of the roll axis, two-dimensional analyses of the cross section were performed.
The radius of a roll, $R$, was 250 mm, consisting of a Cu alloy sleeve of 25 mm in thickness and a steel core of 225 mm in radius. Cooling water ran in the channels that were machined at the interface between the sleeve and the core. The nozzle thickness, $t_o$, was 10 mm which supplied the melt from a reservoir with the water head, $h_o$, of 200 mm. The roll gap at the roll exit, $t_f$, was 3 mm; the angle of contact between the melt and the rolls, $\theta$, was 9.6° and the vertical length of the contact area, $h_r$, was 41.7 mm.

2. Finite-element modelling

In the present study, a series of finite-element analyses were performed for VTRC of AA3003 and Mg-AZ31. Thermal and physical properties of these materials are presented in Table 1. The amount of heat to extract for cooling from liquidus temperature to solidus temperature was approximated to be 0.398 J/g for AA3003 and 0.439 J/g for Mg-AZ31, or 1.087 J/mm$^3$ for AA3003 and 0.780 J/mm$^3$ for Mg-AZ31 [12]. Since the amount of heat for AA3003 is about 1.4 times that for Mg-AZ31 for the same size of a sheet, a higher productivity in volume is expected for the latter. However, since the thermal conductivity of AA3003 is about two times that of Mg-AZ31, steeper gradients in temperature are expected for the latter during TRC. The latent heat of a melt was taken into account in the analysis by considering it as a supplementary specific heat in the mushy or solid-liquid mixed state.

Flow stresses of these materials in literature [13-17] are presented as curves in Figures 3 and 4. Since those in the mushy state were unavailable, they were derived by proportional divisions from those of the solid state to those of the liquid state. IHTC (Interface Heat-Transfer Coefficient) at the interface between a roll and a melt was assumed as a function of pressure and temperature, as shown in Figures 5 and 6 [10, 11]. The IHTC changes drastically in magnitude at the interface where the melt gradually solidifies as it flows toward the roll exit.

Table 1. Physical and thermal properties of materials

| Material | Thermal cond. (W/m$^2$°C) | Density (kg/m$^3$) | Specific Heat (J/kg°C) | Latent heat (kJ/kg) | Liq./Sol. Temp. (°C) |
|----------|----------------------------|-------------------|------------------------|-------------------|----------------------|
| AA3003   | 193 (<628°C) 96.5 (>655°C) | 2730              | 879.1                  | 373.9             | 655/628              |
| Mg-AZ31  | 104-110 (<565°C) 55 (>630°C) | 1776              | 1069.8                 | 368.8             | 630/565              |
3. Results of the analyses

The initial temperatures of AA3003 and Mg-AZ31 melts were 660°C and 630°C, respectively. Velocity distributions in the AA3003 melt for various roll speeds were obtained, as shown in Figure 7(a). As the roll speed was as low as 0.1 rad/s, no vortexes were observed due to the fact that the melt was solidified in the roll gap. However, as the roll speed increased, vortexes began to appear and increased in size. Flows in the vortexes were slow in speed but those in the vicinity of the rolls were as fast as the roll speed. Temperature distributions for various roll speeds are presented in Figure 7(b). As the roll speed was 0.1 rad/s, the melt was completely solidified. As the roll speed increased to 0.2 rad/s, the melt was solidified only at the roll exit and the majority of the melt remained in the mushy state where vortexes developed. As the roll speed increased to 0.3 rad/s, the melt was solidified only at the surface near the roll exit. Temperature distributions in the melt became to be somewhat proportional along the rolling direction. As the roll speed increased to 0.5 rad/s, the melt cooled less and as a result no solidification appeared.

On the other hand, velocity distributions in Mg-AZ31 are presented in Figure 8(a). As the roll speed was as low as 0.3 rad/s, vortexes appeared in a small scale at the entrance of the roll gap. It was because the melt cooled so much that the viscosity became quite high. As the roll speed increased to 0.4 rad/s, the vortexes increased in size. As the roll speed increased to 0.5 rad/s and further, vortexes
developed fully. Similar to those for AA3003, flows in the vortexes were slow but those in the vicinity of the rolls were as fast as the roll speed. Temperature distributions for various roll speeds are presented in Figure 8(b). As the roll speed was 0.3 rad/s, the melt was solidified near the roll exit and the majority of the melt remained in the mushy state. As the roll speed increased to 0.4 rad/s, solidification was observed only at the roll exit. However, as the roll speed increased to 0.5 rad/s, solidification was observed only at the surface near the roll exit. Temperature distributions in the melt became somewhat proportional along the rolling direction. As the roll speed increased to 0.6 rad/s and further, the melt cooled less and as a result no solidification occurred.

The roll speed is noted to be lower than 0.3 rad/s for AA3003 and 0.6 rad/s for Mg-AZ31 in order for the surface of a sheet to be solidified to avoid rupture during the process. However, if the sheet is required to be rollers to some extent during the process, the speed should be lower than 0.25 rad/s for AA3003 and 0.5 rad/s for Mg-AZ31. As the roll speed is further lowered, more plastic deformation is accumulated into the sheet. Then the strength of the roll materials as well as the stiffness of the roll

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**Figure 7** Predicted distributions for AA3003: (a) velocity and (b) temperature
Figure 8 Predicted distributions for Mg-AZ31: (a) velocity and (b) temperature

Figure 9. Predicted roll-separating forces for various roll speeds

Figure 10. Predicted roll torques for various roll speeds
stand would be critical because they should be able to sustain the large magnitudes of roll pressure and roll-separating force, which is the force acting on the rolls in the horizontal direction.

The roll-separating force and the roll torque were predicted per unit width of the sheet in Figures 9 and 10, respectively. Both of these decreased drastically as the roll speed increased due to a decrease in kinetic energy of vortexes and the viscosity.

4. Conclusions
VTRC was analyzed in two dimensions by the rigid-viscoplastic finite-element method for AA3003 and Mg-AZ31. The rolls were 500 mm in diameter. The melt at the liquidus temperature from a nozzle of 10 mm in thickness flowed through the roll gap and cooled to a sheet of 3 mm in thickness.

From these analyses, the roll speed was found to be lower than 0.3 rad/s for AA3003 and 0.6 rad/s for Mg-AZ31 in order for the surface of the sheet to be solidified at least to avoid rupture during the process. However, if the sheet is required to be rolled to some extent during the process, the speed should be lower than 0.25 rad/s for AA3003 and 0.5 rad/s for Mg-AZ31. As the roll speed is further lowered, more plastic deformation is accumulated into the sheet. The roll-separating force and the roll torque decreased drastically as the roll speed increased due to a decrease in kinetic energy of vortexes and the viscosity, respectively. Since Mg-AZ31 cools faster than AA3003 for the same size of a sheet, a higher productivity in volume is expected for the former.

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References
[1] Haga T and Suzuki S 2003 J. Mater. Process. Technol. 138 366-371
[2] Watari H, Haga T, Koga N and Davey K 2007 J. Mater. Process. Technol. 192-193 300-305
[3] Haga T, Nakamura R, Kumai S and Watari H 2009 Arch. Mater. Sci. Eng. 37 117-124
[4] Nakamura R, Yamabayashi T, Haga T, Kumai S and Watari H 2010 Arch. Mater. Sci. Eng. 41 112-120
[5] Bae J H, Prasada Rao A K, Kim K H and Kim N J 2011 Scripta Mater. 64 836-839
[6] Haga T, Nakamura R, Kumai S, Watari H 2013 Arch. Mater. Sci. Eng. 61 36-44
[7] Zhang X M, Jiang Z Y, Yang L M, Liu X H, Wang G D and Tieu A K 2007 J. Mater. Process. Technol. 187–188 339-343
[8] Zhao H, Li P and He L 2011 J. Mater. Process. Technol. 211 1197-1202
[9] Park J J 2014 Met. Mater. Int. 20 317-322
[10] Park J J 2016 Int. J. Heat Mass Transfer 93 491-499
[11] Park J J 2016 Int. J. Heat Mass Transfer 100 590-599
[12] Park J J 2017 Magnesium Technology 2017 (San Diego, USA: TMS Springer) 79-84
[13] Takuda H, Morishita T, Kinoshita T and Shirakawa N 2005 J. Mater. Process. Technol. 164-165 1258-1262
[14] Tan C, Xu S, Wang L, Chen Z, Wang F and Cai H 2007 Trans. Nonferrous Met. Soc. China 17 41-45
[15] Fatemi-Varzaneh S M, Zarei-Hanzaki A and Haghshenas M 2008 Mater. Sci. Engin. A 497 438-444
[16] Guo W G, Zhang X Q, Su J, Su Y, Zeng Z Y and Shao X J 2011 European J. Mechanics A/Solids 30 54-62
[17] Guo J, Zhao S, Murakami R, Ding R and Fan S 2013 J. Alloys and Compounds 566 62-67