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Numerical analysis of twin-roll casting to fabricate a laminated sheet from melts

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ABSTRACT

Two types of twin-roll casting process to fabricate a laminated sheet were numerically analyzed in two dimensions. In Type I, which is asymmetric, melts of Mg-AZ31 and aluminum alloy are solidified into a two-layer laminated sheet. In Type II, which is symmetric, these melts are solidified into a three-layer laminated sheet. Assuming the viscosity of a melt and the proportional constant of the flow rule of a Mises material to be equivalent, the rigid-thermoviscoplastic finite-element method was applied to these analyses. As a result, occurrence of buckling and thickening in the clad layer and incomplete solidification in the base layer were predicted as potential problems of the processes. The former was resolved by modifying the separator profile as well as by inducing incomplete solidification in the base layer near the roll exit. The latter was resolved by a subsequent cooling process with pressure rolls, which enhance the bonding strength at an interface and collapse potential voids that would occur during solidification. Details of flow, temperature distribution, solidification, roll torque and roll-separating force were obtained from the analyses.

1. Introduction

Magnesium alloys are expected to be used more aggressively for automotive parts in the future [1]. At present, the poor corrosion resistance is one of drawbacks that hinder the alloys from being used for interior as well as exterior panels. Among various technologies available to improve the corrosion resistance [2–7], cladding or laminating with aluminum alloys by twin-roll casting is known to be efficient without forming oxide films at an interface between layers [8–11]. However, the phenomenon occurring in twin-roll casting is complicated to understand since melt flow, cooling, solidification and plastic deformation take place simultaneously.

Along with various experimental approaches, numerical approaches have attempted to analyze the phenomenon. Beginning with simplified analyses [12], some numerical techniques have advanced to predict vortexes in relation to heterogeneous distributions of microstructures in thickness [13,14]. Assuming the viscosity of a melt and the proportional constant of the flow rule of a Mises material to be equivalent, the rigid-thermoviscoplastic finite-element method was applied to find that only the melt in the vicinity of the nozzle wall was solidified and rolled to a sheet [15]. In addition, roll torque, roll-separating force and contact pressure were predicted by considering plastic deformation after solidification as well as heat transfer in rolls. Later, cladding processes of Mg-AZ31 sheet with various materials were analyzed assuming laminar flows with no vortexes [16]. Recently, two different cladding processes were analyzed comprehensively; Mg-AZ31 sheet was cladded with molten AA3003 in one process while molten Mg-AZ31 was with two sheets of AA1100 in the other [17]. Thinning and fracture were found as potential problems of the processes.

In the present study, two types of vertical twin-roll casting to fabricate a laminated sheet from two different melts were chosen from experimental studies [18–22]. As shown in Fig. 1, they were numerically analyzed in two dimensions to examine validities in process, assuming no variations of velocity and temperature in the direction of roll axis. The light-gray region stands for the base material while the dark-gray region stands for the cladding material; they are Mg-AZ31 and an aluminum alloy, respectively. Type I is an asymmetric process where melts of Mg-AZ31 and an aluminum alloy are solidified into a two-layer laminated sheet. Type II is a symmetric process where these melts are solidified into a three-layer laminated sheet. A separator in a nozzle is to supply the different melts separately into the gap between the rolls. This separator is fixed in space, being different from the scriber or scraper that is movable by a fulcrum in the experimental studies. Also the roll gap is fixed, being different from the roll gap that is flexible through a spring mechanism in the experimental studies.

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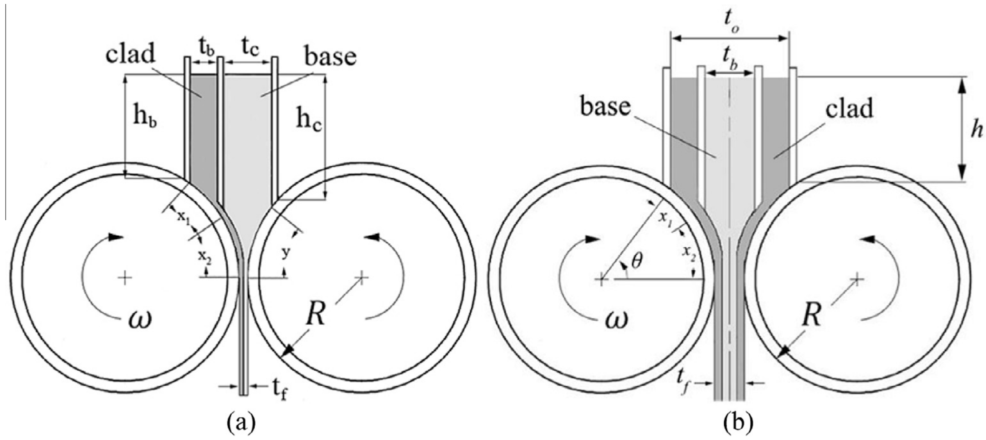

Fig. 1. Twin-roll casting processes to fabricate a laminated sheet: (a) Type I and (b) Type II.

A commercial code DEFORM based on the rigid-thermoviscoplastic finite-element method was utilized for the analyses in the present study.

2. Materials properties and IHTC

Thermal and physical properties of Mg-AZ31 and aluminum alloys are given in Table 1 [9,13–22]. Since an aluminum alloy is higher than Mg-AZ31 in solidus temperature, the former is required to solidify before it is in contact with the latter in the process. Since the liquidus temperature of Mg-AZ31 is only 2 °C higher than the solidus temperature of AA3003 but 39.4 °C higher than that of AA5083, cladding of Mg-AZ31 is expected to be easy with AA3003 but difficult with AA5083 because of a possibility of remelting. Compared to Mg-AZ31, the aluminum alloys are about 50% higher in density and 20–50% higher in thermal conductivity, but about 10% lower in specific heat. AA3003 is about 50–60% higher than AA5083 in thermal conductivity but they are almost the same in specific heat as well as latent heat.

Flow stress curves of AA5083 at various strain rates are presented in Fig. 2 [23–25]. Those of AA3003 and Mg-AZ31 can be found in the previous studies [15,17]. The curves in the solid state were extended to the mushy state according to the experimental findings and further connected to the equivalent points in the liquid state [26–28]. Since cooling rate in twin-roll casting is known to be as high as hundreds of degrees per second, solidification is expected to progress under non-equilibrium conditions. However, effects of the non-equilibrium solidification on the flow stress curves were not taken into account in the present investigation [17].

In most of numerical analyses for twin-roll casting, IHTC (Interface Heat-Transfer Coefficient) at the melt/roll interface was assumed to be a constant in a range of 10–15 kW/m^{2}K or to vary

Table 1
Physical and thermal properties of materials.

Material	Thermal cond. (W/m°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
AA5083	120(<590.6 °C) 60(>638 °C)	2660	900.0	388.5	638/590.6
Mg-AZ31	104–110 (<565 °C) 55 (>630 °C)	1776	1069.8	368.8	630/565

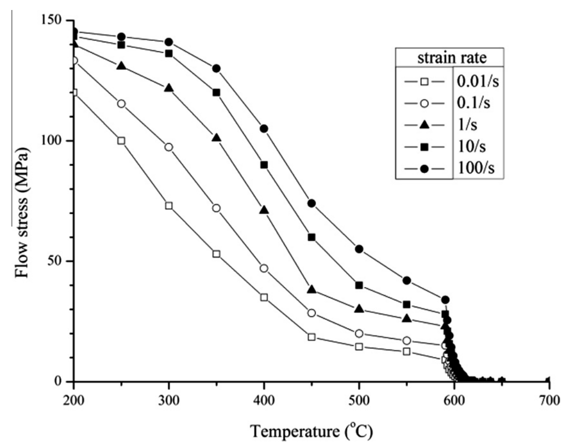

Fig. 2. Flow stress curves of AA5083 at various strain rates (strain = 1).

in a range of 3–30 kW/m^{2}K [12–16]. Recently IHTC at Al/steel interface during twin-roll casting was measured experimentally; it decreases sharply from 50 kW/m^{2}K to 20 kW/m^{2}K in the chilling stage, decreases further to 6 kW/m^{2}K in the solidification shrinkage stage, bounces back to 20 kW/m^{2}K in the compression stage and decreases smoothly in the cooling stage [29]. In the present study, where a CuCoBe alloy was assumed to be used for the roll sleeve [30,31], IHTC at the interface between the roll and the melt of an aluminum alloy was assumed as a function of pressure and temperature. They are shown in Fig. 3(a) and (b) for AA3003 and AA5083, respectively [32,33]. Among the curves, the slope of a curve is lowest for the solidus temperature while highest for the liquidus temperature; it was proportionally adjusted for an intermediate temperature. For a given temperature, IHTC increases with a decreasing rate as pressure increases.

Cooling water was assumed to flow at a speed of 0.5 m/s in the cooling channels that are located at the interface between the roll sleeve and the roll core; it corresponds to the heat convection coefficient of 3 kW/m^{2}K at the surface of a cooling channel. The cooling water was predicted to be heated from 20 °C to 40 °C while flowing in the channels; each channel had a cross section of 9 mm × 9 mm with a length of 500 mm.

3. Finite-element analysis of Type I

As shown in Fig. 1(a), the melt from the left reservoir flows on the left roll and solidifies to be the clad layer as it passes the