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Role of Roll Separating Force in High-Speed Twin-Roll Casting of Aluminum Alloys

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Abstract: The role of the roll separating force in the high-speed twin-roll casting of aluminum alloys was examined. In horizontal-type twin-roll casting, as the casting speed increased upon decreasing the roll separating force, the strip texture changed from a shear and rolling texture to a random texture. Direct temperature measurements during high-speed twin-roll casting showed that the roll separating force played a significant role in maintaining a good contact between the strip and the roll surface. This resulted in a high cooling rate around the roll nip and enabled the fabrication of a sound strip with a fine microstructure. Moreover, the high casting speed and lowered roll separating force gave a band structure consisting of fine globular grains in the mid-thickness region of the strip, which could be considered beneficial in the formation of a well-dispersed center segregation.

Keywords: high-speed twin-roll casting; roll separating force; Al-Si alloy; Al-Mg alloy

1. Introduction

In aluminum sheet production, the twin-roll casting (TRC) process has attracted increasing attention due to its economic advantages when compared with conventional direct-chill slab casting and hot rolling processes. Due to the rapid cooling rate of >100 K/s that is employed in the TRC process, the production of 3–10 mm thick strips can be achieved directly from the molten metal. The traditional TRC process was designed to combine the metal casting and hot rolling processes into a single operation, and in general mass production, a horizontal-type (or slightly tilted) caster is typically employed, where the casting speed is optimized to give a range of <2 m/min. However, high-speed twin-roll casting (HSTRC) has recently been developed using a vertical-type caster [1], with the primary aim being to improve the casting speed by rapid cooling rather than through applying the hot rolling effect. Therefore, copper rolls with relatively higher thermal conductivities compared to their steel roll counterparts were employed for this purpose, and the roll separating force (RSF) was reduced to one tenth of the level of the conventional horizontal-type TRC. These conditions allowed the casting speed to be increased to 180 m/min [2].

In the solidification stage of TRC, solid shells begin to grow on the roll surfaces after the molten metal is supplied between two rotating rolls. At a certain point, typically referred to as the “kiss point,” two solidifying shells encounter one another, and joint shells are introduced to the roll gap to produce a single strip. In this process, the RSF is applied to the hot strip when the solidifying shells widen the roll gap. Since the strip is subjected to external stress during solidification, the RSF plays an important role in determining the cast strip microstructure [3].

Thus, the influence of the RSF on the cooling behavior and on the solidification structure of such strips is investigated in this study, and in particular in the high casting speed range. Through microstructural and textural observations, the role of the RSF is clarified, and the mechanism of strip formation is discussed.

2. Materials and Methods

Al-2Si, Al-7Si-0.3Mg, and Al-5Mg (wt%) alloys were melted in an electric furnace, and degassing was conducted using Ar gas for 10 min prior to casting. Lab-scale horizontal- and vertical-type twin-roll casters were used for strip fabrication. The horizontal-type caster consists of two Cu-Cr rolls, which are fixed firmly. Using this caster with minimized lubrication on the roll surface, the casting speed could be increased to 5 m/min. To compare the strip microstructure and texture, the steel roll caster in the mass-production line was also used to fabricate 1250 mm wide strips, which exhibited the typical microstructure of traditional TRC strips. For the vertical-type caster, pure Cu rolls with no lubrication on the roll surface were used to maximize the cooling rate, and one of the rolls was loosely supported by a series of springs. This condition makes it possible to maintain a low RSF at a high-speed casting range. The roll size of both lab-scale casters was 300 mm in diameter, and the rolls were internally cooled by running water during the strip casting process. The strip width fabricated by both casters was 100 mm. A direct temperature measurement technique [4] was adopted to investigate the cooling behavior of the strip during vertical-type HSTRC. A K-type thermocouple (ANBE SMT Co, Yokohama, Japan) was flown directly into the molten pool to measure the temperature from the center line of the upper side of the melt pool to the strip center. The casting speed was 60 m/min, and the RSF was varied from 3 to 60 kN. The temperature change was recorded every 0.5 ms using a data logger (NR600, KEYENCE, Osaka, Japan). For the cast strip, longitudinal cross-sectioned samples were mounted in epoxy resin prior to mechanical polishing. The polished samples were then etched using a 2% solution of Hydrogen fluoride (HF) in distilled water for microstructural observations using an optical microscope. The samples were also anodized at 40 V in a 3.3% solution of HBF_4 in distilled water to reveal their grain structures. The strip textures were observed by electron backscattering diffraction (EBSD) using a TESCAN MIRAII FE-SEM (Brno, Czech Republic) equipped with a Hikari EBSD detector at an accelerating voltage of 20 kV. The EBSD results were analyzed using OIM analysis 7 software provided by TSL, Co., Ltd. An automatic serial sectioning machine (UES Inc., Robo-Met. 3D, Dayton, OH, USA) and 3-D analysis software (FEI, Avizo Fire 7, Hillsboro, OR, USA) were used for three-dimensional characterization of the center segregation [3]. For the as-cast Al-5Mg strips, tensile tests along both the casting direction (CD) and the transverse direction (TD) were conducted using flat tensile specimens with a 25 mm gauge length and 6 mm gauge width. The fracture surfaces were observed using scanning electron microscopy (SEM; JSM-6610LV, JEOL, Tokyo, Japan).

3. Results and Discussion

3.1. Increasing the Casting Speed in the Horizontal-Type TRC Process

To maximize the cooling rate and raise the casting speed in the horizontal-type TRC process, Cu-Cr rolls were used and the castings were conducted in the absence of lubrication on the roll surface. The casting speed was increased to 5 m/min with a decreased RSF. For comparison, strips were also cast at 0.8 m/min using a conventional horizontal caster from a mass production line. Figure 1 shows the inverse pole figure (IPF) maps and pole figures (PFs) of the Al-5Mg strips fabricated at different casting speeds. In the case of the 0.8 m/min condition, the surface region exhibited a shear deformation texture (rot-Cube, {111}//ND), while a typical rolling texture (brass, S, Copper components) was dominant in the central region, thereby indicating that the strip was hot-rolled under high RSF conditions. In contrast, for the 5 m/min condition, the strip exhibited an equiaxed grain structure with an overall random texture. This implies that the rapid solidification structure instead of the hot-rolled grain structure can be obtained at an increased casting speed. It is therefore necessary to consider what role the RSF plays under high casting speeds during the TRC process.

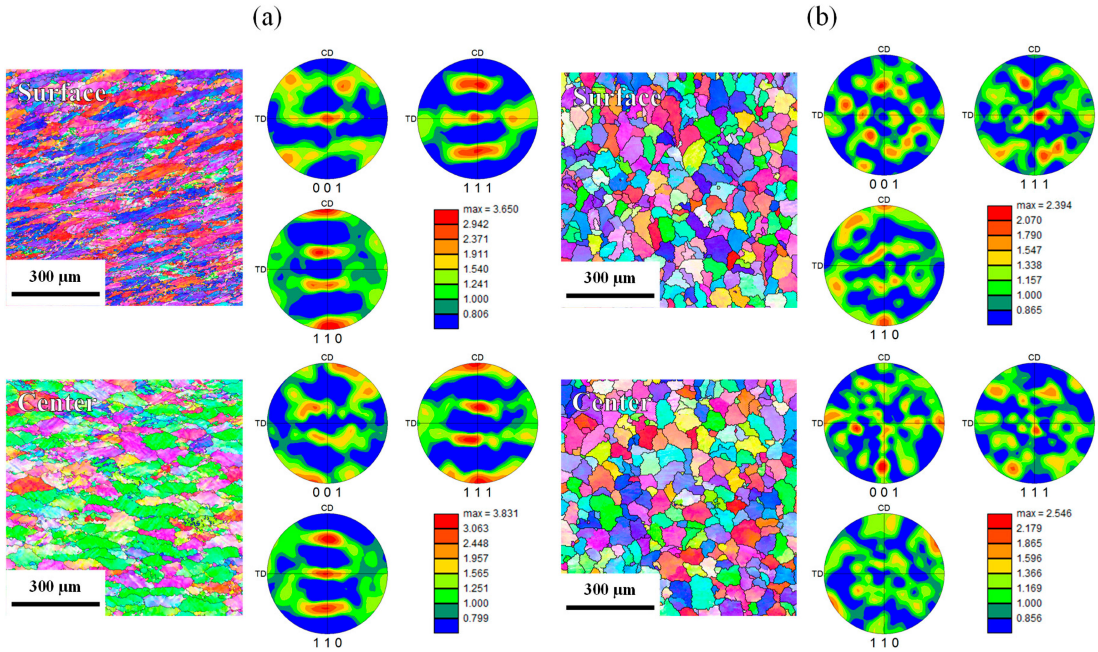

Figure 1. Inverse pole figure (IPF) maps and pole figures (PFs) of twin-roll cast strips fabricated at casting speeds of (**a**) 0.8 m/min, and (**b**) 5 m/min.

3.2. Cooling Behavior of the Strip in HSTRC

Using a vertical-type caster, HSTRC was carried out under various RSF conditions (i.e., 3, 20, and 60 kN) with a casting speed of 60 m/min. The temperature distribution from the center line of the melt pool to the strip center was then investigated using the direct temperature measurement technique. Figure 2 shows the change in temperature in the area of the roll nip. As indicated, the temperature began to decrease significantly at the kiss point where two solidifying shells encountered one another prior to the strip passing through the roll gap. At the roll nip, the cooling rate exhibited its maximum value, and the temperature of the strip center further decreased even after expulsion of the strip from the roll gap, due to the thermal gradient along the thickness direction. This was followed by the air cooling region where the strip temperature remained relatively constant. Using an RSF of 3 kN, the cooling rate at the roll nip was relatively low, resulting in the final strip temperature being equal to the eutectic temperature. As the RSF was increased to 20 kN, the cooling rate increased sharply, although no significant change in the cooling rate was observed upon increasing the RSF further to 60 kN. This result indicates that the contact condition between the strip and the roll surface was enhanced upon increasing the RSF, thereby resulting in the observed increased cooling rate. In the HSTRC process, the cooling behavior of the section from the kiss point to the position of the lowest strip temperature is important, as it determines the final strip temperature. If the cooling rate is decreased, i.e., the contact condition between the strip and the roll surface is poor due to solidification shrinkage, some liquid can remain at the mid-thickness region of the strip. This can cause severe internal cracking or tearing of the strip during the continuous casting process due to the low nature of the high temperature stiffness of aluminum alloys [4,5]. Moreover, if the final strip temperature is higher than or equal to the eutectic temperature, the solidification structure can become coarse under air cooling.

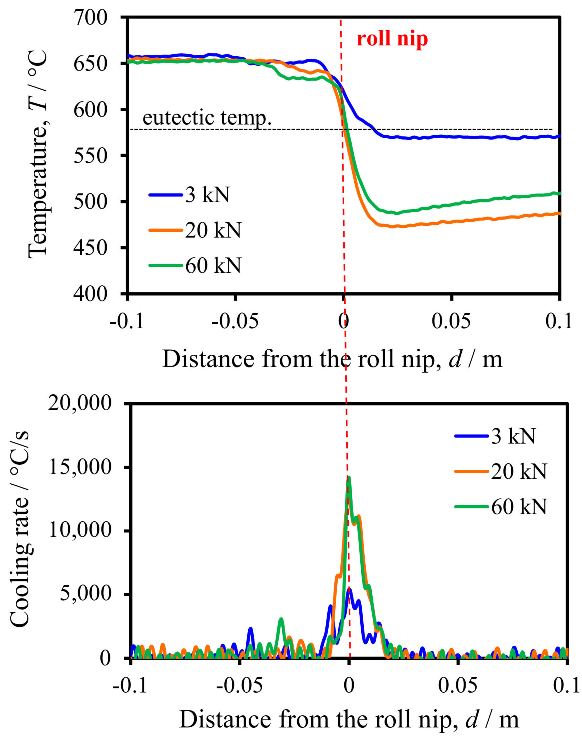

Figure 2. Changes in the (**a**) temperature and (**b**) cooling rate in the mid-thickness region of the strips under various roll separating forces.

Figure 3 shows the microstructures of the Al-7Si-3Mg alloy strips fabricated under RSF conditions of 3 and 20 kN. In the case of the 3 kN condition, relatively coarse plate-like eutectic Si structures were observed, implying that solidification of the strip proceeded under air cooling (i.e., under a low cooling rate) [6]. In contrast, fine dendrite and rod-like eutectic Si was observed in the strip fabricated at 20 kN, indicating that solidification took place during rapid cooling in the area of the roll nip. As such microstructural differences can greatly affect the mechanical properties of the strip [7], the application of an appropriate RSF is therefore critical for the HSTRC fabrication of sound aluminum strips with fine microstructures.

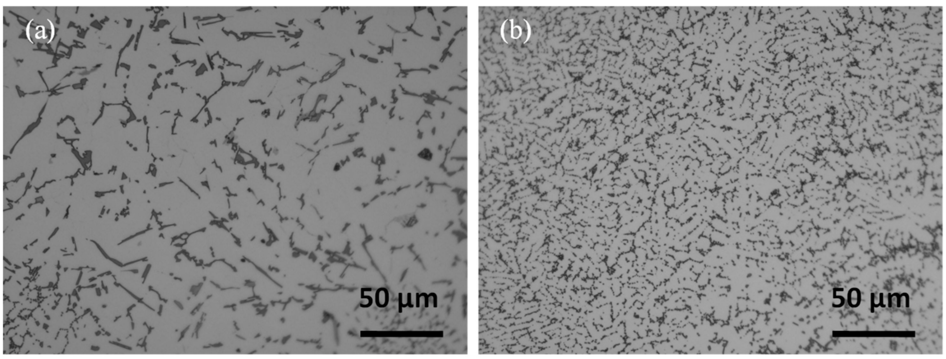

Figure 3. Microstructures of the Al-7Si-0.3Mg alloy strips fabricated using RSF (role separating force) values of (**a**) 3 kN and (**b**) 20 kN.

3.3. Microstructure of the HSTRC Strip

In the HSTRC process, the final solidification region of the strips (generally the mid-thickness region) is greatly affected by the RSF. Especially in the case of aluminum alloys exhibiting a wide range of freezing temperatures, solidification proceeds with the formation of a mushy layer at the growth front of the solidifying shell on the roll surface. Consequently, when two shells encounter one another at the kiss point, the microstructure of the semi-solid mid-thickness region is influenced by the external stress. Thus, Figure 4 shows the macro- and microstructures of the Al-2Si strip fabricated at a casting speed of 60 m/min and an RSF of 20 kN. As shown, an equiaxed grain macrostructure was apparent at the outer shell region, while a band of fine globular grains formed in the mid-thickness region. The formation of this globular grain band is likely related to the compression mode under the different RSF conditions. It is noted that Suery and Flemings conducted a simple compression test on semi-solid dendritic alloys and demonstrated the fragmentation of dendrite arms under a high compression rate [8]. In the HSTRC process, the high casting speed and the RSF conditions caused the active fragmentation of dendrite arms in the semi-solid mushy layer, resulting in the formation of a band structure in the mid-thickness region. This microstructural feature is significant in relation to center segregation control.

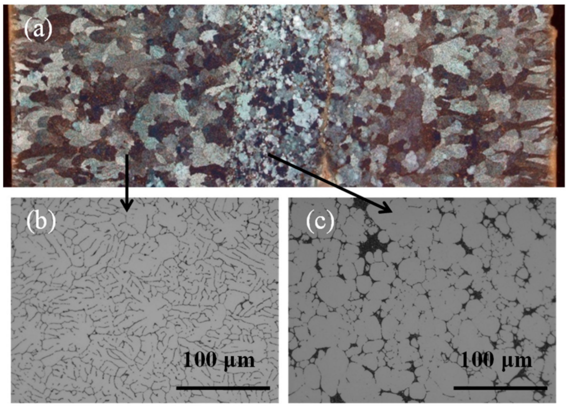

Figure 4. (**a**) Anodized grain structure, and normal etched microstructures of (**b**) the outer shell, and (**c**) the central band region.

3.4. Influence of the Center Segregation Type on the Mechanical Properties of the TRC Strips

In a previous study, it was shown that the center segregation pattern changed with variation in the casting speed [3]. For the horizontal-type TRC of Al-5Mg alloys, typical channel segregation took place under a relatively low casting speed (3 m/min) and a high RSF (Figure 5a). In contrast, the segregation pattern changed to a segregation band consisting of a mixture of an Mg-rich phase and α-Al as casting speed was increased to the high-speed range, i.e., 5 m/min, which is similar to the microstructure shown in Figure 4c (Figure 5b).

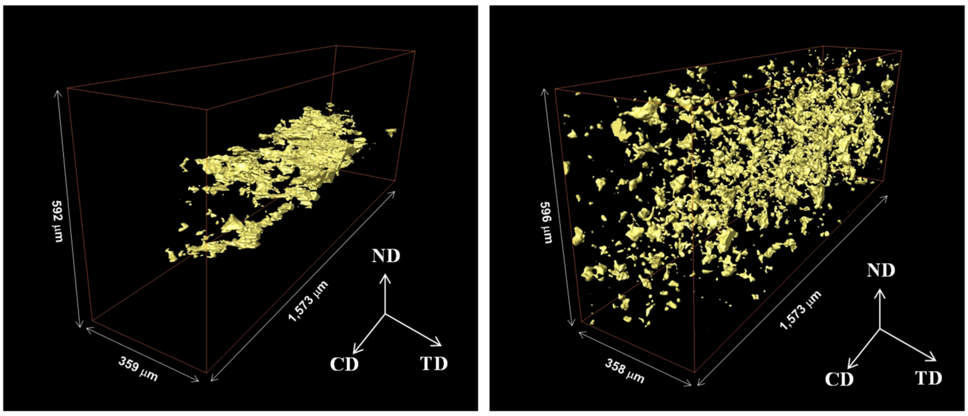

Figure 5. 3D images of center segregation in the strips fabricated at (**a**) 3 m/min, and (**b**) 5 m/min.

To investigate how the center segregation type affects the mechanical properties of the strips, tensile tests were conducted in both the CD and TD. Figure 6 shows the engineering stress-strain curves and SEM images of the resulting fracture surfaces. The SEM images on the right-hand side show the magnified microstructure around the center segregation zones of the left-hand images. The obtained results show that the majority of the outer shell region consisted of dimples, which indicate ductile fracture, whereas the Mg-rich segregation zone revealed cleavages, which suggest brittle fracture. For the 3 m/min conditions, the TD sample exhibited a continuous cleavage along the channel segregation (Figure 4c), causing a premature fracture with a rapid stress drop during the tensile test (Figure 4a). In contrast, the 5 m/min samples showed a region of connected dimples and discrete cleavage in the segregation band, and no drastic premature fracture was observed in both the CD and TD, thereby indicating that formation of this band structure should be beneficial in controlling center segregation in the HSTRC process.

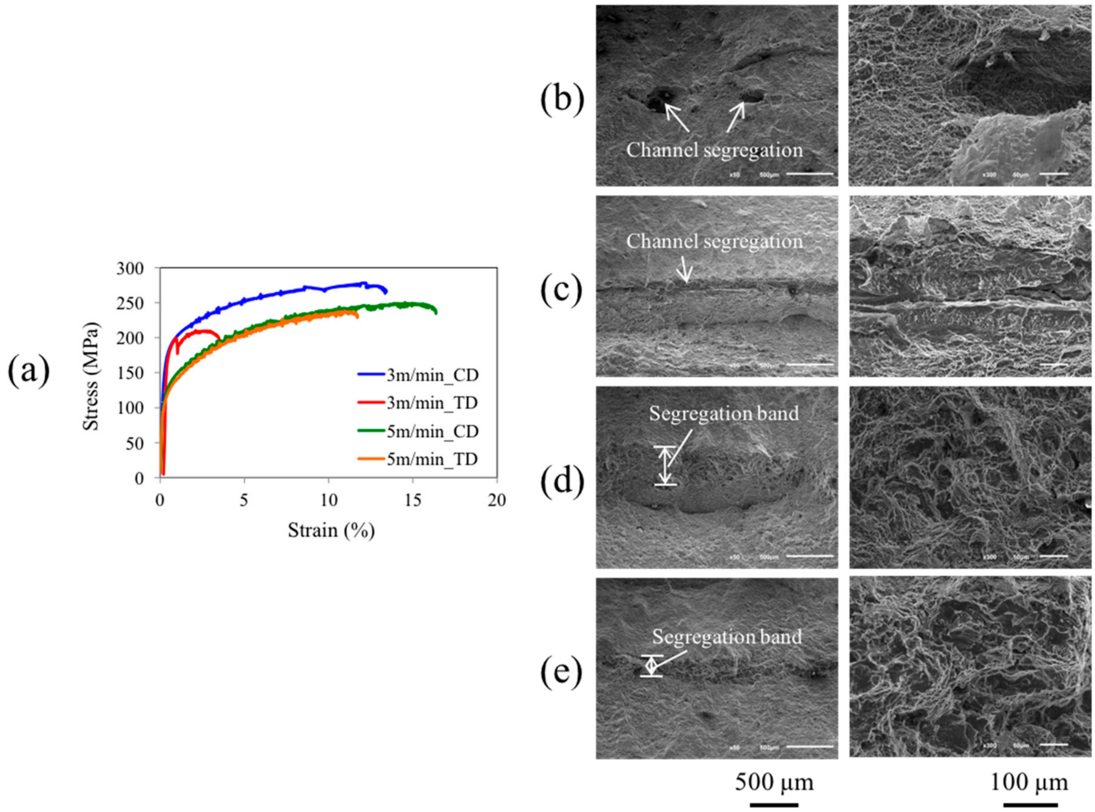

Figure 6. (**a**) Engineering stress-strain curves and SEM images of the fractured surface of the (**b**) 3 m/min, CD, (**c**) 3 m/min, TD, (**d**) 5 m/min, CD, and (**e**) 5 m/min, TD samples.

4. Conclusions

In the traditional twin-roll casting (TRC) process of aluminum alloys, the caster was designed to combine metal casting and hot rolling into a single operation. However, the traditional TRC process is generally operated at low casting speeds (<2 m/min). Thus, to increase the casting speed, the TRC concept was amended from hot rolling to rapid solidification through the application of a minimum roll separating force (RSF). Upon increasing the casting speed with a reduced RSF, it was found that the strip texture changed from a rolling texture to a random texture. In addition, in the case of high-speed TRC (HSTRC), direct temperature measurements indicated that the RSF played an important role in maintaining a good contact between the strip and the roll surface during the casting process. This in turn aided in the fabrication of a sound continuous strip with a fine microstructure. Moreover, the present RSF conditions allowed the formation of a band structure consisting of fine globular grains in the mid-thickness region of the strip, which aids in producing a well-dispersed center segregation pattern. The formation of a segregation band structure was beneficial for the fabrication of a sound strip with no scattering of the mechanical properties.

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Conflicts of Interest: The authors declare no conflict of interest.

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