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Effects of production parameters on characteristics of magnesium alloy sheets manufactured by twin-roll casting

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Manufacturing and processing

ABSTRACT

Purpose: : The purpose of the work is to establish a manufacturing process and technology to facilitate the economical manufacture of high-quality magnesium sheet alloys.
Design/methodology/approach: Magnesium alloy AZ31B was used to investigate the appropriate manufacturing conditions for use in twin-roll strip casting. Temperatures of the molten materials and roll speeds were varied to find the appropriate manufacturing conditions. The effects of manufacturing conditions on possible forming were clarified in terms of roll speeds and roll gaps between upper and lower rolls.
Findings: In the hot-rolling process, a temperature exceeding 200°C was chosen to keep cast products from cracking. An appropriate annealing temperature was effective for homogenizing the microstructure of the rolled cast sheets after the strip casting process. The grain size of the manufactured wrought magnesium alloys sheet was less than 10 micrometers. The obtained magnesium alloy sheet exhibited an equivalent limiting drawing ratio in a warm-drawing test.
Research limitations/implications: AZ31 were used to investigate the appropriate manufacturing conditions for use in twin-roll strip casting. Casting temperatures were varied from 630°C to 670°C to find the best casting conditions. Roll casting speeds were varied from 5m/min to 30 m/min in order to examine which roll speed was appropriate for solidifying the molten magnesium.
Practical implications: It was found that the cast magnesium sheet manufactured by roll strip casting could be used for plastic forming if the appropriate magnesium sheets were produced after the roll casting process.
Originality/value: This paper showed the effectiveness of twin roll casting for magnesium alloys by a horizontal roll caster.
Keywords: Manufacturing and processing; Casting; Plastic forming; Magnesium alloy; Twin-roll caster

1. Introduction

Magnesium alloys are expected to play an important role as next-generation materials, with the potential to help lighten total product weight when magnesium products are used to replace aluminum and mild steel products. The specific density of magnesium alloy is 2/3 that of aluminum and 1/4 that of iron. When alloyed, magnesium has the highest strength-to-weight ratio of all structural metals. Moreover, magnesium has received global attention from the standpoint of environmental preservation because of the ease of recycling metallic materials. The utilization of magnesium alloys has depended mainly on casting technology (e.g., thixo-forming) because of their less workable characteristics due to the crystal structure of the hexagonal close-packed lattice. Recently, demands have arisen in the automotive and electronics industries to reduce the total product weight [1-4].Unfortunately, high manufacturing costs continue to be a major barrier to greatly increased magnesium alloy use. A key to solving this problem is the development of roll strip casting technology to manufacture magnesium sheet alloys economically while maintaining high quality [5-9]. Park et.al. [10] investigated microstructure and mechanical properties of cast AZ31B magnesium alloys by strip casting and suggested possibilities of the development of new wrought magnesium alloysheet by twin roll casting.

The authors also investigated the effectiveness of twin roll casting for magnesium and aluminium alloys by a horizontal roll caster [11-30]. This paper describes the forming characteristics of the cast magnesium alloy sheets after being hot-rolled in a warm deep drawing test and establishes the appropriate manufacturing conditions for producing high-quality strip using a purpose-built strip-casting mill. The influences of such process parameters as materials of roll, casting temperature, and roll speed are ascertained. A warm deep drawing test of the cast magnesium sheets after being hot rolled was performed to demonstrate the formability of the magnesium alloy sheets produced by a roll strip casting process. The microstructure of the manufactured wrought alloy sheets was microscopically observed to investigate the effects of the hot-rolling and heat-treatment conditions on crystal growth in the cast products.

2. Experimental procedure

2.1. Horizontal Twin roll caster and experimental conditions

Figure 1 illustrates the horizontal twin roll strip casting process used in the experiment. It includes a source of molten metal that feeds into the space between a pair of counter-rotating, internally cooled rolls. The principle dimensions of the horizontal twin roll caster are presented in Table 1. The inclination angle of the mill in Fig. 1 was set to zero degrees. The L_c in the Fig. 1 indicates the contact length between rolls and molten metal. Illustrated in Table 2 are the experimental conditions to investigate appropriate manufacturing conditions to successfully produce magnesium alloy sheets by twin roll strip casting.

Casting temperatures were varied from 630°C to 670 °C to find the best casting condition as shown in Table 2. Temperatures of the molten magnesium in the melting pot and tundish were measured by thermo-couples.

Roll casting speeds were varied from 5 m/min to 30 m/min to examine which roll speed is appropriate for solidifying the molten magnesium. The roll gap between the upper and lowerrolls was determined by simple calculation results based on a basic solidification theory. The determined gaps were from 2.0mm to 3.6 mm. Any shielding gases were not used in the experiment.

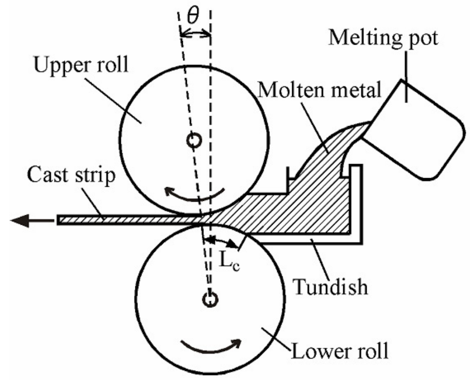

Fig. 1. Schematic illustration of horizontal twin roll casting

Table 1.
Dimensions of roll caster and tundish

Rolls	
Materials	Copper, Copper alloy
Upper roll (mm)	Φ300*150
Lower roll (mm)	Φ300*150
Roll speed (m/min)	0-150m/min (Max.)
Inclination angle (deg)	0
Tundish	
Material	Insulator, mild steel
Roll contacting length (mm)	50

Table 2.
Experimental conditions

Temperatures (°C)	630, 650, 670
Roll speeds (m/min)	5, 10, 15, 20, 25, 30
Roll clearance (mm)	2.0-3.6
Shield gas	No shielding

Table 3.
Material properties of AZ31B magnesium alloy

Density ($kg/m^3 \cdot 10^3$)	1.78
Liquidus temperature (°C)	630
Solidus temperature (°C)	575
Specific heat (J/kg· °C)	1040
Thermalconductivity (W/m·°C)	96
Latent heat (kJ/kg)	373

2.2. Material and its refining process

The material used in the experiment was AZ31B. The physical properties of the material are listed in Table 3. Magnesium ingots were heated to 680°C in a melting pot with an electric furnace. In the magnesium melting process, magnesium oxide and other suspended nonmetallic matter were removed with flux that preferentially wet the impurities and carried them to the bottom as sludge. After the refining process, the molten magnesium metal in the melting pot was carried to the strip caster and poured into the tundish to manufacture magnesium strip.

2.3. Concept of twin-roll caster

Historically, it is well known that Pechiney has been dedicated to developing twin roll casting of aluminum technology and products for more than 40 years. A key difference between twin roll casting and DC casting is the solidification rate of the metal. In the case of DC casting the solidification rate is limited to 1 to 50°C/s, however it reaches 1000°C in the case of aluminum strip casting. It gives very fine microstructures in the cast products. Also, the twin roll casting of aluminum is the only process that combines both solidification and rolling in a single step. Normally, for instance, about 10% or 20 % reduction is given to the cast sheet during the strip casting process. To investigate the effects of the rolling reduction during casting process on the properties of the cast sheet, it is important to know the exact reduction in strip casting process. In the experiment, relations between quality of the cast product and thickness of the cast sheets, rolling load, reduction of the produced products are examined from the viewpoints of possibilities of practical use of the proposed process.

2.4. Hot-rolling process after twin roll casting

The hot-rolling process was performed to obtain wrought magnesium alloy sheets with globular and fine microstructures to be used for plastic forming. The cast strip sheets were milled to obtain sheets with 2.0mm thickness to remove oxide film. The cast strip was heated and rolled in the hot-rolling process. Rolling temperatures were varied from 200°C to 300°C. The milled sheet was rolled by several rolling pass schedules until the sheet became 0.8mm thick. Next, the 0.8mm-thick sheet was rolled again until the sheet became 0.5mm thick. Finally, the rolled magnesium sheet was annealed at 350°C for two hours, and cooled in an electric furnace. A 5 m/min roll speed was chosen in hot-rolling process, even though the reduction was less than 10%. Cracks were seen during the hot-rolling process when rolling temperature was less than 200°C, even though the reduction was less than 10%. A temperature over 200°C was chosen to keep the cast products from cracking.

2.5. Predicting method of cast magnesium sheet's thickness

A simple solidification theory by the following equation has been used for predicting the cast sheet's thicknesses.

$$\frac{d}{2} = \sqrt{\frac{\lambda(T_f - T_r)t}{2\rho H_f}} \tag{1}$$

where d is thickness of cast sheet, λ is thermal conductivity of material, T_f is liquidus temperature, T_r is temperature of mould (roll)surfaces, ρ is density, H_f is latent heat of material. The solidification time t in the equation (1) can be calculated by the contacting length L_c in Fig. 1. and roll speed V. The equation (1) is well known as the solution by Stefan problem. The assumptions in equation (1) are as follows;

(a) no thermal registance at the casting roll interfaces;
(b) teere is a linear temperature gradient in the solidification portion of the casting.

3. Results and discussion

3.1. Stiffness of twin - roll caster

Figure 2 illustrates the typical relation between roll gap and rolling load obtained by load cells attached to the mill. The result presented in Fig. 2 is the case of a mill fitted with copper rolls. The horizontal axis reveals the differences between initial roll gaps and the obtained sheet thickness. It expresses pure deflection of the mill during the strip-casting process. The circles in the figure represent results for an initial roll gap of 2.0mm, the squares for an initial roll gap of 2.8mm, and the triangles for an initial roll gap of 3.6mm. From Fig. 2, the spring constant of the mill was approximated as 10009 (N/mm).

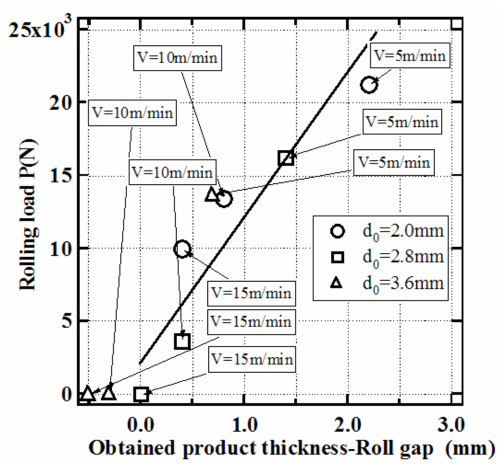

Fig. 2. Relation between roll loads and gap of rolls

3.2. Thickness of cast sheets

Thicknesses of cast sheets were measured to investigate the casting phenomenon of magnesium alloy in the twin roll casting process. The sheet thicknesses of three forming directions were measured. Figure 3 presents an example of results for a copper roll caster. The circles indicate results for the case that roll rolling loads are zero. It is seen that sheet thickness gradually decreases as roll speed increases. The solid in the Fig. 2 line represents a theoretical sheet thickness obtained by simple 1-D solidification modeling by equation (1) when T_r is supposed to be equals to 230 dgrees centigrade. The dotted line shows the case that T_r is supposed to be equals to 130 dgrees centigrade. The difference of the sheet thiknesses due to different T_r was aproximately 11% in this case. It has been also found that the sheet thicknesses couls be well predicted in the case of T_r=230 dgrees centigrade.

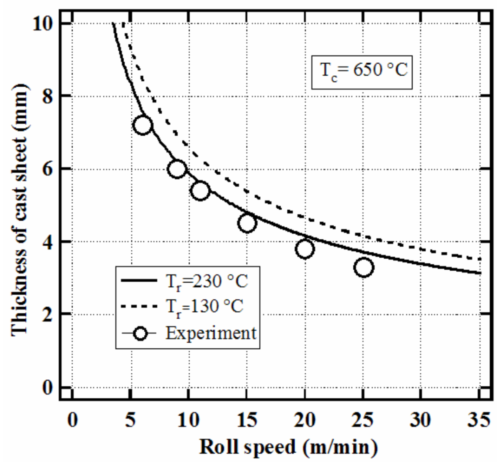

Fig. 3. Relation between roll speeds andrhicknesses of cast sheets

3.3. Surface conditions of cast products and shape defects

Figure 4 presents a photograph of the surface condition of cast products manufactured by a roll caster with copper rolls.

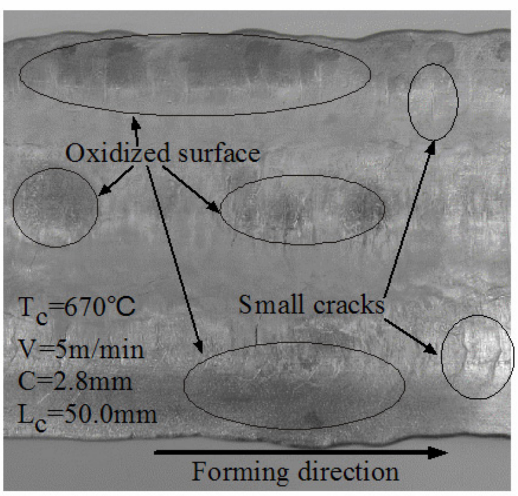

Fig. 4. Surface condition of cast strip (T_c=670°C, V=5m/min, d_0=2.0mm, L_c=50mm)

The product shown in Fig. 4 was manufactured at a roll speed of 5m/min and a casting temperature of 670°C. Magnesium oxide is created on the surface of the cast sheet due to reaction with oxygen in the air when no cover gas is used in the manufacturing process. However, the surface of the cast sheet in Fig. 4 did not react much with oxygen in the air, even though no cover gas was used for shielding the cast magnesium in the strip casting. On the surface of the cast sheets were small cracks that were difficult to identify with the naked eye.

3.4. Microstructure of hot rolled cast sheet

Figures 5(a), 5(b), 6(a), and 6(b) present photographs of the microstructures of hot rolled sheets after the roll strip casting process using a copper-alloy caster. The sheet depicted in Fig. 5(a) was hot rolled at 200°C, and no annealing process was used. In Fig. 5(b), the cast sheet was annealed at 350°C for two hours after hot rolling at 200°C. The sheet in Fig. 6(a) was hot rolled at 300°C without annealing. The photo in Fig. 6(b) was annealed at 350°C for two hours after hot rolling at 300°C. We can see that the crystals were well homogenized with an appropriate annealing process, although the grain sizes of the crystals became larger by recrystallization.

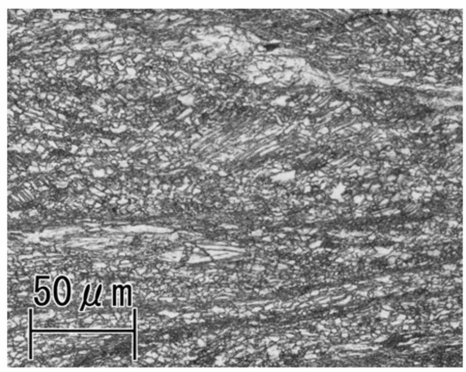

Fig. 5 (a). Microstructure of cast sheet hot rolled at 200°C (without annealing)

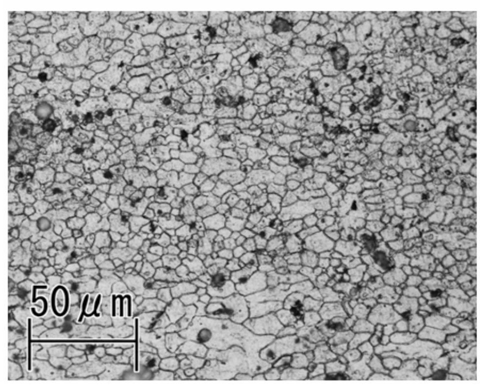

Fig. 5 (b). Microstructure of cast sheet hot rolled at 200°C (with annealing)

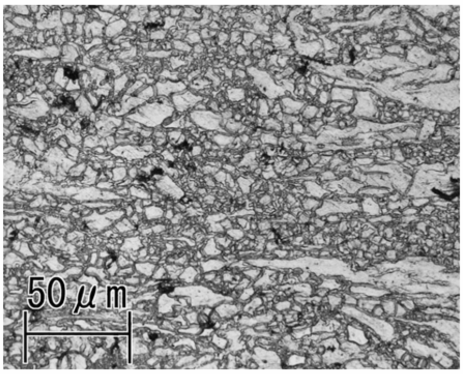

Fig. 6 (a). Microstructure of cast sheet hot rolled at 200°C (without annealing)

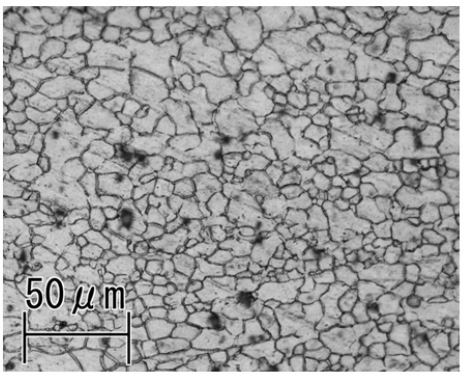

Fig. 6 (b). Microstructure of cast sheet hot rolled at 300°C (with annealing)

3.5. Plastic formability of obtained wrought magnesium alloy sheet

After the cast magnesium sheets were hot rolled, a warm deep-drawing test was performed to examine the forming characteristics of the magnesium alloy sheets produced by twin roll strip casting. The forming conditions in the test, and dimensions of the deep-drawing tool are described in Table 4. The diameter of the punch is 28.8mm and is cooled by water flowing through inner of the punch. A lubricant solution was used. The limiting drawing ratio was investigated by a deep-drawing test at 250°C. A drawing speed of 30mm/s was chosen in the test. A limiting drawing ratio of 2.6 was obtained in the warm deep-drawing test, as indicated in Fig. 7. The result presented in Fig. 7 suggests that the wrought magnesium alloy sheets that were hot rolled after the strip casting process had plastic formability equivalent to that of the wrought magnesium alloy sheets manufactured by the conventional DC casting process.

Table 4.
Dimensions of deep drawing tool and forming conditions

Punch diameter D_p (mm)	28.8
Radius of punch R_p (mm)	3.0
Die diameter D_d (mm)	30.0
Radius of die R_d (mm)	2.0
Drawing speed V_d (mm/s)	30
Blank holding force (kN)	5.0
Forming temperature T_f (°C)	250

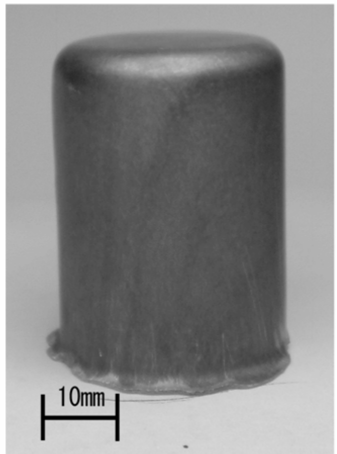

Fig. 7. Cup drawn in a warm deep drawing test (DR=2.6, hot rolled at 250°C, with annealing)

4. Conclusions

AZ31B magnesium alloy was cast by using a horizontal twin roll caster. The obtained cast sheets were hot rolled, and a warm deep drawing test was performed to demonstrate the effectiveness of twin roll strip casting of magnesium alloys. The following conclusions were obtained.

(1) In the hot-rolling process, a temperature exceeding 200°C was chosen to keep cast products from cracking.
(2) A simple solidification theory of Stefan problem was effective for predicting the cast sheet's thicknesses.
(3) An appropriate annealing temperature was effective for homogenizing the microstructure of the rolled cast sheets after the strip casting process.
(4) The grain size of the manufactured wrought magnesium alloys sheet was less than 10 micrometers. The obtained magnesium alloy sheet exhibited an equivalent limiting drawing ratio in a warm-drawing test.

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