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Warm deep drawability of wrought magnesium alloy sheets manufactured by semi-solid roll strip casting

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An experimental investigation was performed into the warm deep drawability of magnesium alloy sheets that were hot-rolled after a semi-solid roll strip casting process. Magnesium alloy AZ31B was used in this experiment to ascertain the effectiveness of semi-solid roll strip casting. The temperature of the molten magnesium, and the roll speeds of the upper and lower rolls were varied to find an appropriate manufacturing condition. Warm rolling and heat treatment conditions were changed to examine which condition would be appropriate for producing wrought magnesium alloys with good formability. Also, microscopic observation of the crystals of the finished products was performed. It has been found that a limiting drawing ratio of 2.4 was possible in a deep drawing process of the cast magnesium alloy sheets that were hot-rolled after a semi-solid roll strip casting process.

1. INTRODUCTION

Due to the requirement of manufacturing technologies to reduce the total product weight, there has been recent growth in the manufacture and application of magnesium products because of their low specific gravity and relatively high strength. Magnesium is 36% lighter per unit volume than aluminum and 78% lighter than iron. When alloyed, magnesium has the highest strength-to-weight ratio of all the structural metals. Moreover, because of the ease of recycling of metallic materials, magnesium has received global attention from the standpoint of environmental preservation. Utilization of magnesium alloys has mainly depended on casting technology, for instance, thixso-forming. However, demands have been raised in automobile and electronics industries to reduce the total product weight[1]. Automobile manufacturers have tried to evaluate the suitability of magnesium alloys to replace steel and aluminum for automotive structural and sheet applications. Some of them have already made magnesium components for practical use. Unfortunately, the major barrier to greatly increased magnesium alloy use in cars is still primarily high manufacturing cost. One of the keys to solving this problem is to develop semi-solid roll strip casting technology to manufacture magnesium sheet alloys economically while maintaining high quality.

The authors, therefore, investigated the effectiveness of twin roll strip casting for magnesium alloys[2-4]. This paper describes the formability of the cast magnesium alloy sheets after being hot-rolled in the deep drawing tests in terms of rolling reduction and forming speeds. Microscopic observation of the crystals of the finished products was performed to investigate effects of the hot rolling and heat treatment on crystal growth in the products.

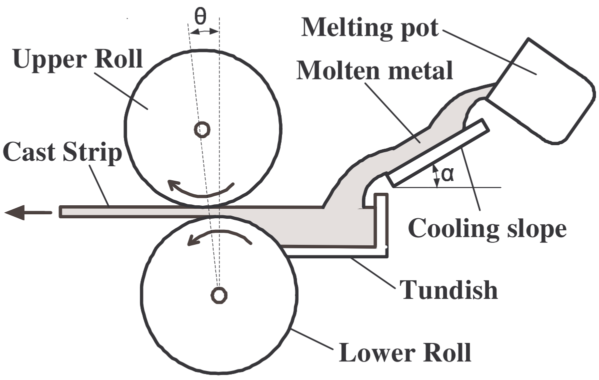

Figure 1. Schematic illustration of semi-solid roll strip casting process.

Table 1
Dimensions of experimental equipments

Rolls	Material	Copper Alloy
	Upper roll	φ 300mm× 100mm
	Lower roll	φ 300mm× 100mm
	Roll speed	10-150m/min
	Inclination angle θ	0-15°
Cooling slope	Material	Mild steel
	Dimension	200mm× 100mm
	Inclination angle α	30°
	Lubricant	BN
Tundish	Material	Insulator
	Volume	$20.0\times 10^5 mm^3$

2. EXPERIMENTAL PROCEDURE

Figure 1 illustrates the twin-roll strip caster for the horizontal casting direction. It includes a source of molten metal that feeds into the space between a pair of counter-rotating, internally cooled rolls. A cooling slope is used to obtain slurries with fine and globular microstructures, which enhance component properties. The principle dimensions of the strip caster and cooling slope are presented in Table1. Illustrated in Table 2 are the experimental conditions to investigate an appropriate manufacturing formation to successfully produce magnesium alloy sheets by twin-roll strip casting. Casting temperatures were changed from 620°C to 630 °C to keep the molten metal in the tundish in a semi-solid state. 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 25 m/min to examine which roll speed is appropriate for solidifying the molten magnesium. The roll gap between the upper and lower rolls was set to 1.9mm to 3.3mm.

Table 2
Experimental conditions.

Casting temperature (°C)	620,625,630
Roll speed (m/min)	5-25
Roll clearance (mm)	1.9-3.3

2.1. Materials and refining processes

The material used in the experiment is AZ31B. The physical properties of the material are listed in Table 3. Magnesium ingots are heated to 650°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 wets the impurities and carries 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 onto the cooling slope to manufacture magnesium strip.

Table 3
Physical properties of AZ31B.

Density ($kg/m^3 \cdot 10^3$)	1.78
Liquidus temperature (°C)	630
Solidus temperature (°C)	575
Specific heat (k/j/kg·°C)	1.04
Thermal conductivity (W/m·°C)	96

2.2. Hot Rolling conditions

Hot rolling process was performed to obtain magnesium alloy sheets with globular and finer microstructures of the crystals. The cast strip sheets were ground to obtain the sheets with 2.5mm, 1.5mm, 1.0mm, 0.5mm thick. In the hot rolling process, the temperature of the cast strip was elevated to 450°C by heaters, and the ground sheet with elevated temperature was rolled. The roll reduction was 50% until the sheet thickness became 0.6mm. Next, the 0.6mm thick sheet was rolled until the sheet thickness became 0.5mm, with the reduction from 50% to 80 %. Finally, the rolled magnesium sheet was annealed at 300°C for 2 hours, and cooled in an electric furnace.

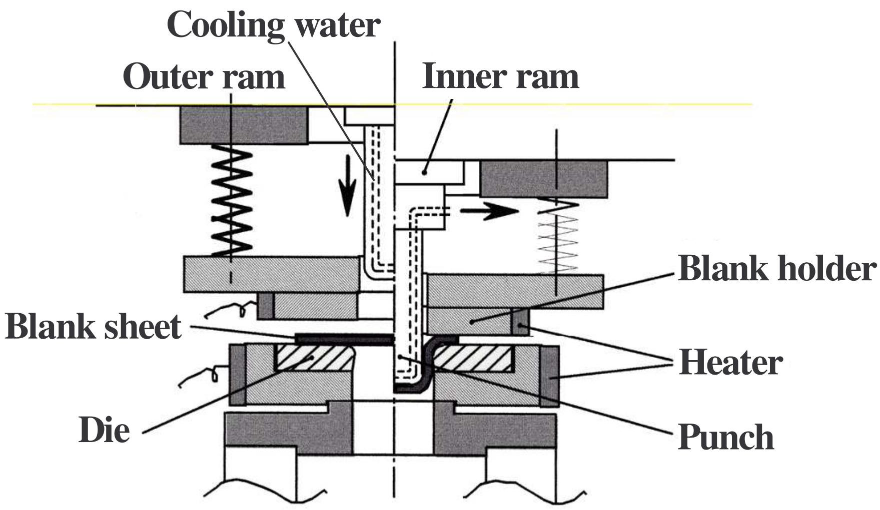

Figure 2. Schematic illustration of deep drawing tool.

2.3. Warm Deep drawing test

Figure 2 schematically illustrates a warm deep-drawing tool. The forming conditions in the test, and dimensions of the deep-drawing tool are described in Table 4. The diameter of the punch is 30mm and is cooled by water flowing through the centre. Molybdenum Disulfide (MoS2) was used as a lubricant in the deep-drawing test. The limiting drawing ratio was investigated by the deep-drawing test at 250°C, in terms of rolling condition. Two drawing speeds, 30mm/s and 2.5 mm/s, were chosen in the deep drawing test.

Table 4
Dimensions of drawing tools and forming conditions.

Radius of punch corner (mm)	2.0
Punch diameter (mm)	28.8
Radius od fie corner (mm)	2.0
Die diameter (mm)	30.0
Blank holding force (kN)	5.00
Drawing speed (mm/s)	2.5, 30
Forming temperature (°C)	250

3. RESULTS AND DISCUSSION

3.1. Relation between drawability and rolling reduction

Figure 3 displays an example of the relation between limiting drawing ratio (LDR) and rolling reduction. The cast magnesium material in Fig. 3 was manufactured at 630°C casting temperature, and 5 m/s roll speed. As observed in Fig. 3, LDR is gradually increased until the reduction reaches 50% in case of relatively high drawing speed (V=30mm/s). The obtained LDR in this case is 1.90. The LDR would not improve and was stable in cases of larger maximum rolling reduction. In case of lower drawing speed (V=2.5mm/s), an LDR of 2.4 is obtained as illustrated in Fig. 4.

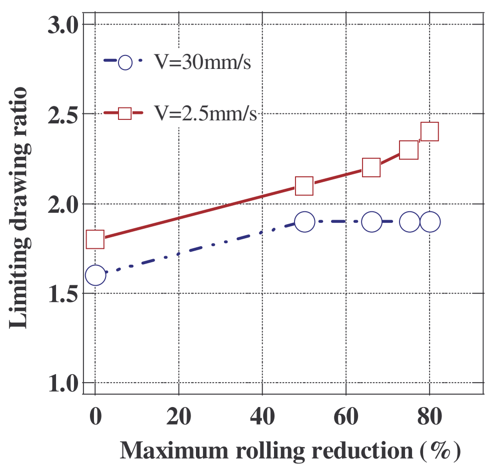

Figure 3. Relation between LDR and rolling reduction.

Figure 4. View of drawn cup (LDR=2.4).

3.2. Microscopic observation of product crystals

Figures 5 (a) and (b) present photographs of the micro-crystals of cast magnesium sheet before hot rolling and after hot rolling. The products depicted in Figs. 5 (a) and (b) were manufactured at a roll speed of 15m/min and a casting temperature of 625°C. It has been found that the mean grain size of the crystals in the products before hot rolling was 30 micrometers. We observed that the grain size of the crystal is less than 10 micrometers as shown in Fig. 5 (b). Although the experimental results obtained suggest a key to reducing the grain size of products made by twin-roll strip casting, more detailed research about the effects of rolling pass on the grain size of the crystals will be required.

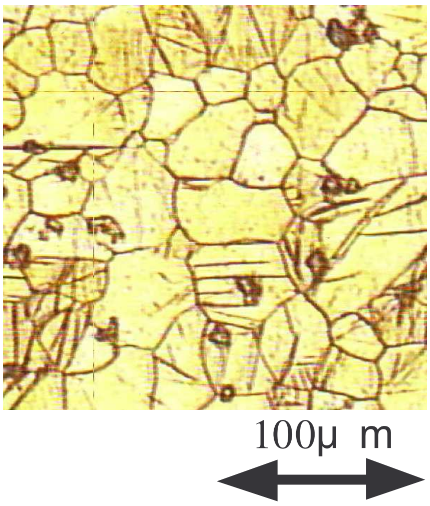

Figure 5 (a).Crystal before hot rolled.

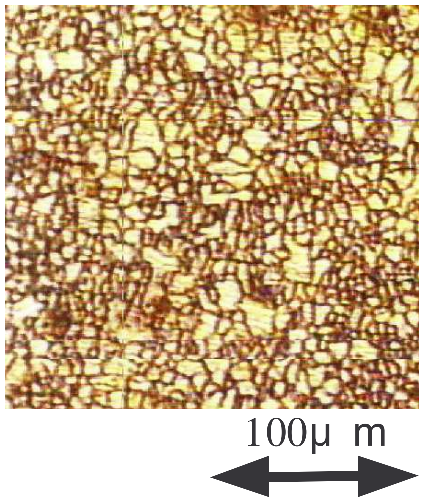

Figure 5 (b). Crystal after hot rolled.

4. CONCLUSIONS

Magnesium alloy AZ31B has been used for twin-roll strip casting. In the present investigation, we examined warm deep drawability of cast magnesium alloy sheets along with microscopic crystals of products. The conclusions obtained are as follows:

1) This experiment clarified that the cast magnesium alloy sheets manufactured by twin-roll strip casting could be drawn with 2.4 of limiting drawing ratio in the case of relatively low drawing speed (2.5 mm/s).
2) It has been found that the grain size of the cast products is 30 micrometers before hot rolling. After hot rolling, the grain size of the cast magnesium alloy sheets can be reduced to 10 micrometers.

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