Improving room temperature formability of twin-roll cast Mg-Al-Zn-Sn alloy by repeated bending

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Abstract. A twin-roll cast Mg-9mass%Al-1 mass%Zn-2mass%Sn alloy was used for the purpose of fabricating for wrought magnesium alloy which can be bent in the room temperature. An appropriate solution annealing time was found in order to reduce beta phase precipitation, which may cause cracking without coarsening of crystal grain size while for improving cold formability of twin-roll cast Mg-9mass%Al-1 mass%Zn-2 mass%Sn alloy. After solution heat treatment of the twin-roll casting of the material, repeated bending by three rolls of the solution heat treated strip was performed in order to examine of bendability of the materials. It has been clarified that repeatedly bending and reverse bending after solution heat treatment were effective for improving formability of the Mg-9mass%Al-1 mass%Zn-2 mass% Sn alloy at room temperature.

Introduction

It has been considered that magnesium (Mg) alloys are attractive materials for manufacturing lightweight products due to their light weight and high specific strength. However, applying practical use of Mg alloys for plastic forming at room temperature is difficult due to its crystal structure [1-3]. The low ductility and poor formability are related to the hexagonal close packed crystal structure of magnesium which cannot provide sufficient slip systems for room temperature deformation. The dominant deformation mechanisms in magnesium and its alloys are basal slip, secondary (prismatic and pyramidal) slip, and twinning [4]. The critical resolved shear stress (CRSS) of has been reported for basal slip is less than 1.0 MPa. In addition, the CRSS of prismatic slip is approximately 40 to 50 MPa in pure Mg [5].

Under the situation of Mg alloys, the possible ratio between bending radius (R/t) and sheet thickness shows 5.0 at room temperature. Many studies have been conducted with the aim of improving formability of wrought magnesium alloy sheet at room temperature. It is reported that adding 0.13 mass% of Ca into Mg-3 mass%Al-1 mass% Zn alloy was effective for tilting the pole of the texture with respect to the sheet thickness direction as well as a repeated bending and reverse bending with a curvature of 15 times sheet thickness. The paper reported that a minimum bending radius R/t of 2.5 in cold V-bending was achieved by applying strain to the rolled material and annealing [6].

However, when the Ca is added to magnesium alloys, there is low corrosion resistance problem due to the effect of adding Ca. Generally, it has been recognized that Sn, Ca, reduces the CRSS of prismatic slip when in adding to magnesium alloys. Ebrahim et al. achieve a 5% cold rolling without formation of a basal texture using a solution-treated Mg-9 mass%Al-1 mass%Zn alloy cast material, applying asymmetrically cold rolling [7]. Also, Mg-Sn based alloys have attracted increasing attention due to the considerable strengthening ability of Mg_2Sn precipitates due to the dynamic range of solubility as a function of temperature [8,9]. It has been reported that the formation of thermally stable Mg_2Sn could precipitates also imparts Mg-Sn based alloys with high thermal stability at elevated temperatures [10,11,12].

In this paper, it has been clarified effectiveness of repeatedly bending and reverse bending after solution heat treatment for improving formability of twin-roll cast Mg-Al-Zn-Sn alloys at room temperature.

Experiment method

Horizontal twin roll caster. The material was cast by a horizontal twin roll caster as shown in Fig.1. The material was rapidly cast by using copper rolls in the Figure 1. The roll diameters were 300 mm, and the roll width was 100 mm. The material of upper and lower rolls was pure copper. A spring was attached to the top of the upper plate at the upper roll, which can give a certain reduction when the strip was go through between the upper and the lower roll. The spring force was varied from 6 kN, 10 kN, 20 kN, in order to examine the effects of roll load to obtain a desired cast strip during twin roll casting.

Material used in twin roll casting experiment. Mg-9mass%Al-1mass%Zn-2mass%Sn alloy (AZT912) was selected to the differential cold speed rolling the experiment after solution treatment. Sn content of the materials was about 2.0% into AZ91 which is one of the popular casting materials in the magnesium alloys. The chemical composition of the Mg-9mass%Al-1mass%Zn-2mass%Sn alloy used in the roll casting experiment is shown in Table 1.

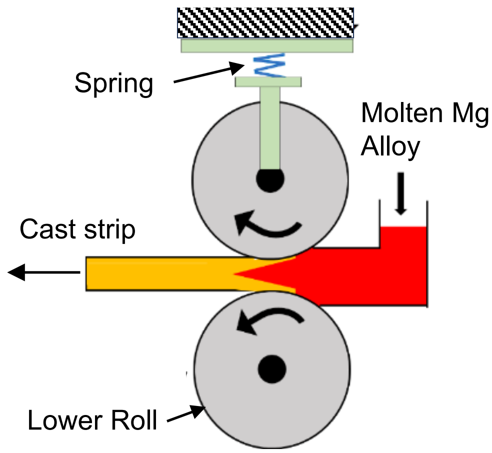

Fig. 1 Schematic illustration of horizontal twin roll caster.

Table 1 Chemical composition of Mg-9mass%Al-1mass%Zn-2mass%Sn alloy.

Mass %									
Al	Zn	Mn	Si	Fe	Cu	Ni	Be	Sn	Mg
8.99	0.72	0.21	0.02	0.001	0.001	0.0006	0.0011	1.86	Bal.

Heat treatment of twin-roll cast strip. In the heat treatment process of the roll cast material, the solution treatment temperature was set to 404°C, and the solution treatment time was varied from to 0.5 h, 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 8 h, and 24 h. After that, a tensile test piece for a tension test was cut from the solution heat-treated strip by a wire electric discharge machine. From the relationship between solution treatment time between the maximum elongation of the tension test, an appropriate heat treatment condition was determined to obtain a desired microstructure while keeping minimizing of the solution treatment time. The selected heat treatment condition of the twin roll cast material was found as shown in Table 2**.**

Table 2 Solution heat treatment conditions of roll cast material.

Temperature [°C]	406
Time [h]	0.5 h, 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 8 h, 24 h
Quenching condition	Hot Water at 60

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Repeatedly rolling and reverse bending process. Two methods of applying pre-strain to the twin-roll cast strips were selected. A differential cold speed rolling experiment to give a pre-strain to the twin-roll cast strips were performed in order to obtain grain refined magnesium alloy in static recrystallization after solution heat treatment as shown in Fig. 2.

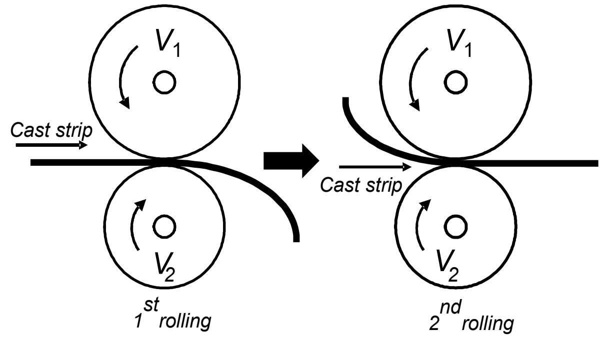

Fig. 2 Repeated bending by differential speed rolling.

Two passes of rolling were performed without lubrication using rolls of 45 mm and 50 mm diameters rolls with a different speed ratio of 1.1. The rolling reduction ratio of the rolls is 4% for the first pass and 6% for the second pass, so that the total rolling reduction ratio become 10%, in order to obtain same curvature of the rolled sheet after the first pass and the second pass. After the second rolling pass, the solution heat treatment of the pre-strained material was carried out under the conditions of 406 °C in 5 hours, and hot water quenching at 60 °C.

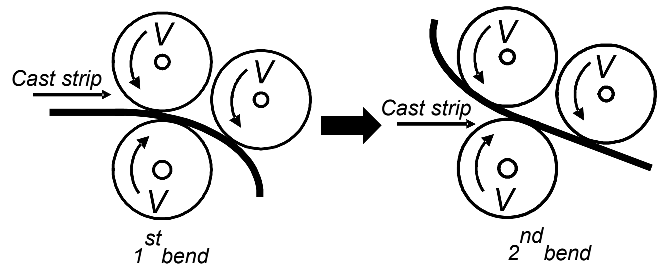

Fig. 3 Repeated bending by using three rolls.

Figure 3 shows how to apply pre-strain with bending and reverse bending using three rolls of 30 mm diameters. In this experiment, bending was repeated under two conditions; one in which the strip curvature was the same as the first and second passes respectively in differential speed rolling in Fig. 2, and the other one in which the strip curvature was fifteen times of the cast strip thickness. After the repeated bending using three rolls, the solution heat treatment of the pre-strained material was carried out under the conditions of 406 °C in 5 hours, and hot water quenching at 60 °C.

V-bending test. A 90-degrees bending test was conducted for solution heat treated cast materials were performed as shown in Fig.4. Table 2 shows the V-bending test conditions.

Table 3 V-bending test conditions.

Punch angle [A_P/deg.]	90
Punch radius [R/mm]	7.2, 6.0, 4.8
Die angle [A_D/deg.]	90
Width of die [W_D/mm]	14
Test piece thickness [t/mm]	1.8±0.05
Test piece width [w/mm]	20
Stroke speed [V/mm・min^{-1}]	1.00

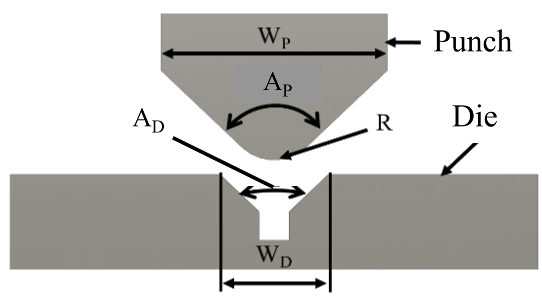

Fig. 4 Punch and die of V-bending test.

Result and Discussion

Microstructure of cast strip. Figure 5 shows strips fabricated with different spring loads. The plate was 2.5 mm thick and 100 mm wide. Cast condition of the strips is shown in Table 4. From the observation of the microstructure of the strips, we can see macroscopic segregation around the center of the thickness of the strip as shown in Fig.6 (a). In Fig.6(a), we can see very fine globular microstructure in the middle of the strip thickness as roll cast materials.

Table 4 Twin-roll casting conditions.

Roll gap [mm]	2.43
Initial load [kN]	21.0
Roll contacting length [mm]	50
Temperature of molten Mg at roll contact [°C]	596
Roll velocity [m/min]	36

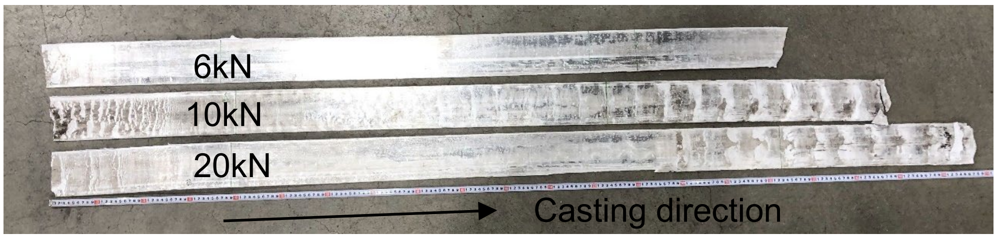

Fig. 5 Twin- roll cast AZT912.

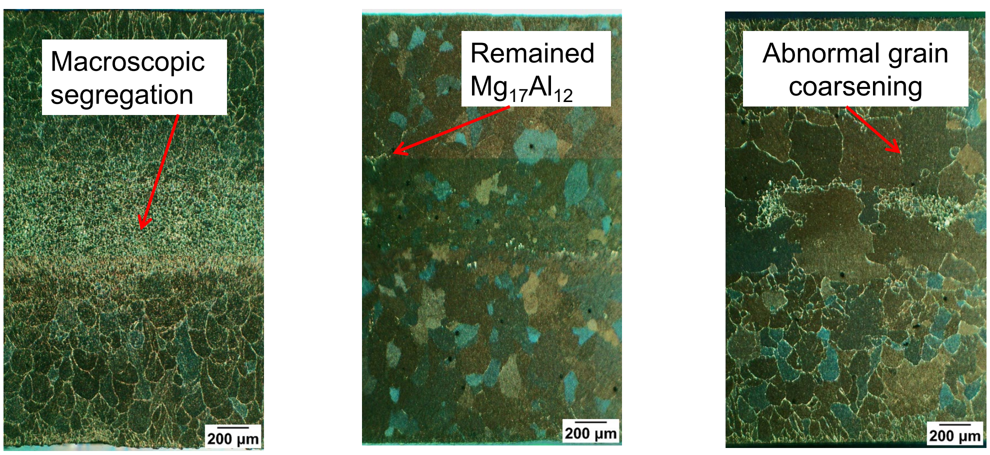

Fig. 6 Microstructure of twin- roll cast AZT912.
((a) Microstructure of as cast strip (b) 406 °C, 1 h heat treatment (c) 406 °C, 8 h heat treatment)

Microstructure after solution heat treatment. Microscopic observation of cast strips after heat treatment were indicated as Figs. 6 (b) and 6 (c). An abnormal grain growth was confirmed at the central part in the plate thickness direction when the solution treatment time was eight hours or more in Fig6 (c). In addition, no grain growth was observed except for the central part at any solution treatment time. In the case of 4h solution time, we could not see any beta phase in the material. It can be seen that in the case of one hour solution heat treatment time, we can see very small remained beta phases $Mg_{17}Al_{12}$. It can be concluded that four hour and more is an acceptable solution heat treatment time after twin roll casting process.

Effect of differential speed rolling on microstructure. Figure 7 shows a cold rolled strip with a curvature (15 times of strip thickness) after differential cold speed rolling. After two passes of rolling, annealing was performed along with heating strain correction under the conditions of holding temperature 404 °C, holding time one hours, and hot water quenching at 60 °C. The obtained mean grain size was about 22 μm in the central part of the strip and about 54 μm in the surface part as shown in Fig. 8. Microscopic observation of the strip after annealing revealed fine microstructure as shown in Fig.8 especially around the surface area of the strip which was about 100 μm in the case of as cast strip.

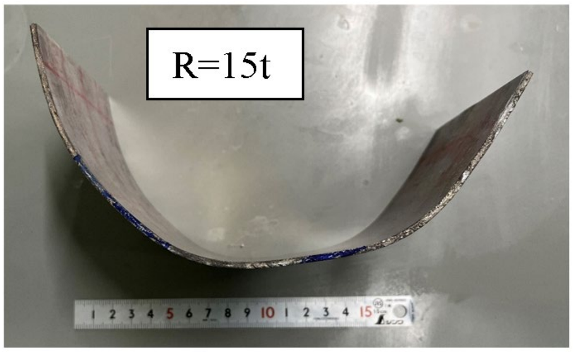

Fig. 7 Rolled strip by differential speed rolling.

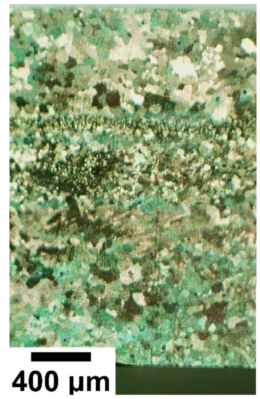

Fig. 8 Microstructure of annealed strip after differential speed rolling.

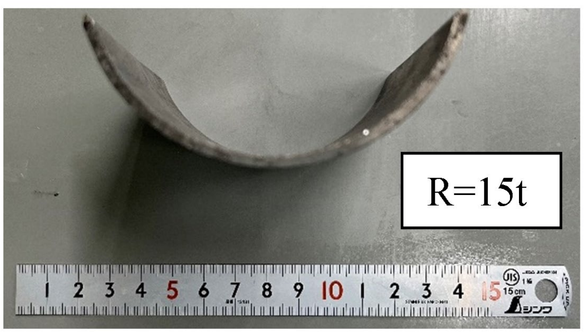

Fig. 9 Bent strip by three rolls.

Fig. 10 Microstructure of annealed strip after bending by three rolls.

Effect of bending and reverse bending on microstructure. Figure 9 shows a bent strip with a curvature (15 times of strip thickness) after bending by three rolls. After second bending, annealing was performed along with heating strain correction under the conditions of holding temperature 404 °C, holding time one hours, and hot water quenching at 60 °C.

The obtained mean grain size was about 28 μm in the central part of the strip and about 108 μm in the surface part as shown in Fig. 10. The microstructure of the bent strips by three rolls was almost the same as that of the twin-roll as cast material, and grain refinement was not observed. We could not confirm the effect of the difference in the curvature of the bent strips on the microstructure with comparing a curvature of cast strips (R=21t) and a curvature (R=15t).

Estimation of bendability at room temperature by V-bending. A V-bending test was conducted to investigate bendability at room temperature. One of the V-bending test result in the case of R=7.2 (R/t=4) is shown in Table 5. Bendability at room temperature was evaluated as the minimum bending radius value in the V-bending test. The minimum bending radius is the one of the important parameters of V-bending. Generally, the smallest bending radius that can be bent without cracking is considered as limiting bending ratio of R/t. It is well known that commercial wrought magnesium alloys, such as AZ31 and AM 60 has a limiting value of R/t, about 4 to 5, which is a large value compared to zero to 0.5 for aluminum alloy A5052, or zero to 2 for cold rolled steel.

Table 5 V-bending test results depending on processes (R=7.2).

Materials	AZT912								AM31-O		AM60-O	
Process	As cast		Differential speed rolling		Bending and reverse bending （R=21t）		Bending and reverse bending （R=15t）		Rolling		Rolling	
Bent direction/ degrees	0	90	0	90	0	90	0	90	0	90	0	90
Cracks	AAB	ABB	ABB	ABB	AAA	AAB	AAA	AAA	CCC	AAC	CCC	BCC
Springback/ degrees	10.9	10.9	19.8	15.6	15.5	14.2	13.6	13.1	—	15.5	—	—

It is assumed that the minimum bending radius will be reduced by performing the grain refinement process on the twin roll cast materials. The minimum bending radius of the bent material was examined using a V-bending test as indicated condition in Table 3. In the V-bending test in Table 5, the test pieces were classified into three crack ratings. Namely, A shows a case where there is no cracking, B indicates a case where a crack occurs on the inside or outside of the bending, and C shows a case where the test piece was completely separated in two pieces after V-bending. In the comparison with commercial wrought magnesium alloys, AZ31-O (t=1.2) and AM60-O (t=2.4) were tested for the V-bending test. The test piece was subjected to V-bending in two directions: 0° to the rolling direction, and 90° to the rolling direction, as shown in Table 5. Magnitude of the springback angles of test pieces after bending were also measured. As a result of the V-bending test, it was found that the AZT912 sheet plate manufactured by twin-roll casting was not completely separated, and all test pieces in the three-roll cyclic bending test at a curvature of 15 times the plate thickness did not show cracks.

Regarding the amount of springback, it is thought that the amount of springback decreases as the minimum bending radius decreases, except for the twin-roll as cast material. It was considered that the reason why the amount of springback in the twin-roll cast material was smaller than in other conditions was due to the occurrence of very small cracks that could not difficult to be identified with naked eyes in the as cast twin-roll cast materials. Figure 11 show a result in the case that the bending radius was 4.8 mm (R/t=2.7).

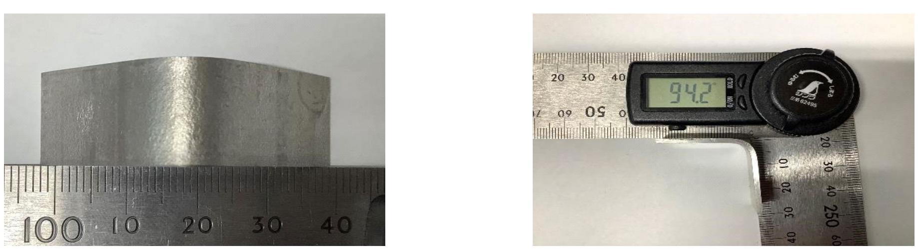

Fig. 11 Surface of bent test pieces and springback (R/t=2.7).
((a)Surface condition of bent strip. (b) Measuring of springback.)

As shown in Fig.11, the AZT912 alloy by twin-roll casting and after bending and reverse-bending, shows the minimum bending radius, 2.7t. Also, the obtained magnitude of the spring back angle is 4.2 degrees. It is suggested that the magnesium alloy obtained by solution heat treatment after twin roll casting is effective to improve the bendability at room temperature, and it could be possible that the minimum bending radius R was the 2.7 times of the sheet thickness t in this experiment conditions.

Summary

A twin-roll cast Mg-9mass%Al-1 mass%Zn-2mass%Sn alloy was cast by using a horizontal twin roll caster to fabricate wrought magnesium alloy, which can be bent at room temperature. An appropriate heat treatment condition was clarified. By adopting a V-bending test, it has been suggested that a bending and reverse-bending process was effective for improving formability of twin-roll cast magnesium alloy AZT912 at room temperature, comparing to different speed cold rolling.

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