Tensile Properties of Directionally Solidified AZ91 Mg Alloy

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AZ91 Mg alloy consisting of elongated grains was processed by a directional solidification method and mechanical properties of the directionally solidified Mg alloy were compared with those of the non-directionally solidified Mg alloy by tensile tests at room temperature and at 473 K. The directionally solidified Mg alloy exhibited higher strength at 473 K than the non-directionally solidified Mg alloy because grain boundary sliding was suppressed. Also, the directionally solidified alloy exhibited higher strength and larger elongation at room temperature than the non-directionally solidified alloy. Suppression of intergranular fracture was responsible for high ductility for the directionally solidified alloy.

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1. Introduction

In magnesium, the critical resolved shear stresses for the non-basal slips of the prismatic and pyramidal slips are much larger than that for the basal slip at room temperature\textsuperscript{1,2} and hence the non-basal slips are hardly operative at room temperature. Five independent slip systems are necessary for a polycrystalline material to be able to undergo a general homogeneous deformation without producing cracks. However, the number of independent mode for the basal slip is only 2\textsuperscript{3,4} This gives rise to low ductility at room temperature for polycrystalline Mg and its alloys.

Chapman and Wilson\textsuperscript{3} showed that grain refinement leads to improvement of ductility for Mg alloys. Mohri et al.\textsuperscript{5} revealed that the fracture mode is changed from intergranular fracture to intragranular fracture by grain refinement. This suggests that improvement of ductility by grain refinement is related to the change of fracture modes. However, grain refinement causes a large decrease in strength at elevated temperature. Therefore, it is required to attain both high ductility at room temperature and high strength at elevated temperature for Mg alloys. In particular, it is important to enhance the mechanical properties without addition of special elements such as rare earth metals because addition of the special elements has bad effects on recycle ability for Mg alloys.

Recently, it was reported that grain boundary sliding is responsible for a decrease in strength at elevated temperature for Mg alloy.\textsuperscript{6} Grain boundary sliding can be inhibited by control of grain morphology. For example, grain boundary sliding was inhibited for the W based material with elongated grains, resulting in high strength at elevated temperature.\textsuperscript{7} For Mg based materials as well as the W based materials, high strength may be attained at elevated temperature by control of grain morphology. In the present paper, AZ91 Mg alloy consisting of elongated grains is processed by a directional solidification method and mechanical properties of the directionally solidified Mg alloy are compared with those of the non-directionally solidified Mg alloy by tensile tests at room temperature and at 473 K.

2. Experimental Procedure

AZ91 \textit{(Mg–9 mass%Al–0.8 mass%Zn–0.3 mass%Mn)} alloy was melted at 923 K. Directionally solidified AZ91 alloy was processed by rapid cooling at the surface with chills. The aspect ratio of grains after solidification depends on the ratio of the growth rate to the temperature gradient.\textsuperscript{8} In the present investigation, the ratio was 0.4 K s\textsuperscript{–1}. For comparison, a non-directionally solidified AZ91 alloy was processed without chills.

Microstructures are shown in Fig. 1(a) for the directionally solidified alloy and in Fig. 1(b) for the non-directionally solidified alloy, respectively. The directionally solidified alloy consisted of grains which were significantly elongated parallel to the growth axis of solid/liquid interface. From the measurement of the apparent grain size by the intercept method, the grain size was determined by

\[ d = 1.73 \times d^* \]  

where \( d \) is the grain size and \( d^* \) is the apparent grain size by the intercept method. The grain size in a major axis and in a minor axis was 1491 and 176 \( \mu \text{m} \) for the directionally solidified alloy, respectively. On the other hand, the non-directionally solidified alloy showed almost equiaxed grains. The grain size was 523 \( \mu \text{m} \) for the non-directionally solidified alloy.

Tensile specimens with 10 mm in gage length and 4 mm in gage diameter were machined from the ingots. Tensile tests were carried out at room temperature and at 473 K. The initial strain rate was \( 1.7 \times 10^{-3} \text{s}^{-1} \). The fracture surfaces and side surfaces of the deformed specimens were investigated by scanning electron microscope.

3. Results and Discussion

The nominal stress-nominal strain curves at 473 K for the directionally solidified alloy and the non-directionally solidified alloy are shown in Fig. 2. The 0.2% proof stress, ultimate tensile strength and elongation to failure were 136 MPa, 198 MPa and 27.0% for the directionally solidified alloy and 68 MPa, 138 MPa and 24.7% for the non-directionally solidified alloy. The directionally solidified
alloy exhibited 2 times higher 0.2% proof stress and 1.4 times higher tensile strength than the non-directionally solidified alloy. Clearly, the anisotropic grain shape control leads to high strength at elevated temperature.

The side surfaces of the specimens deformed to failure at 473 K are shown in Fig. 3(a) for the directionally solidified AZ91 alloy and in Fig. 3(b) for the non-directionally solidified AZ91 alloy.

Fig. 3 The side surfaces of the specimens deformed to failure at 473 K, (a) the directionally solidified AZ91 alloy and (b) the non-directionally solidified AZ91 alloy.

Fig. 4 Photograph with high magnification of the bumpy surface observed at the side surface of the specimen deformed to failure at 473 K for the non-directionally solidified alloy.

The nominal stress-nominal strain curves at 473 K for the directionally solidified AZ91 alloy and the non-directionally solidified AZ91 alloy are shown in Fig. 2.

Fig. 2 The nominal stress-nominal strain curves at 473 K for the directionally solidified AZ91 alloy and the non-directionally solidified AZ91 alloy.

Fig. 1 Microstructures of (a) the directionally solidified AZ91 alloy and (b) the non-directionally solidified AZ91 alloy.

Fig. 1 Microstructures of (a) the directionally solidified AZ91 alloy and (b) the non-directionally solidified AZ91 alloy.

The side surfaces of the specimens deformed to failure at 473 K are shown in Fig. 3(a) for the directionally solidified alloy and in Fig. 3(b) for the non-directionally solidified alloy, respectively. The surfaces were bumpy for the non-directionally solidified alloy. On the other hand, such bumpy surfaces were not observed for the directionally solidified alloy.

Figure 4 shows a photograph with high magnification of the bumpy surface for the non-directionally solidified alloy. It
can be seen that the bumpy surface for the non-directionally solidified alloy is related to grain boundary sliding. Therefore, it is suggested that the high strength at elevated temperature for the directionally solidified alloy is attributed to suppression of grain boundary sliding because the bumpy surfaces were not observed for the directionally solidified alloy.

The nominal stress-nominal strain curves at room temperature for the directionally solidified alloy and the non-directionally solidified alloy are shown in Fig. 5. The 0.2% proof stress, ultimate tensile strength and elongation to failure were 176 MPa, 290 MPa and 10.4% for the directionally solidified alloy and 111 MPa, 199 MPa and 5.0% for the non-directionally solidified alloy, respectively. It is noted that the directionally solidified alloy exhibited much larger elongation than the non-directionally solidified alloy.

The fractured surfaces of the specimens deformed to failure at room temperature are shown in Fig. 6(a) for the directionally solidified alloy and in Fig. 6(b) for the non-directionally solidified alloy, respectively. The non-directionally solidified alloy exhibited intergranular fracture. However, no intergranular fracture was observed for the directionally solidified alloy. It is well known for ceramics that crack pinning, crack deflection, crack bridging, pullout and so on occur as effects of the anisotropic grain shape on mechanical properties. The fact that intergranular fracture was inhibited for the directionally solidified alloy indicates that the effect of the control of grain morphology for the Mg alloy is inhibition of crack propagation at grain boundaries.

Another important result in Fig. 5 is that the directionally solidified alloy exhibited not only large elongation, but also high strength, compared to the non-directionally solidified alloy. Mechanical properties of Mg alloys at room temperature are strongly affected by the grain size and texture. According to the Hall-Petch equation, the increase in 0.2% proof stress due to grain refinement is given by

\[ \Delta \sigma_y = Kd^{-1/2} \]

where \( \Delta \sigma_y \) is the increase in 0.2% proof stress due to grain refinement, \( K \) is a constant and \( d \) is the grain size. The 0.2% proof stress was 176 MPa for the directionally solidified alloy and 111 MPa for the non-directionally solidified alloy, respectively. The difference in 0.2% proof stress between the directionally solidified alloy and the non-directionally solidified alloy cannot be explained only by the difference in grain size when \( K \) is 210 MPa. Therefore, the high strength for the directionally solidified alloy may be related to the intense texture formation due to directional solidification. However, complicated deformation mechanisms of twinning, kinking and grain boundary shearing occur at room temperature for Mg alloys. Further research is required to understand the origin of high strength for the directionally solidified alloy.

4. Conclusions

AZ91 Mg alloy consisting of elongated grains was processed by a directional solidification method and mechanical properties of the directionally solidified Mg alloy were compared with those of the non-directionally solidified Mg alloy by tensile tests at room temperature and at 473 K. The results are concluded as follows.

(1) The directionally solidified Mg alloy consisted of elongated grains. On the other hand, the non-directionally solidified Mg alloy consisted of equiaxed grains.

(2) The directionally solidified Mg alloy exhibited higher strength at 473 K than the non-directionally solidified
Mg alloy. This is because grain boundary sliding was suppressed by elongated-grained microstructure for the directionally solidified Mg alloy.

(3) The directionally solidified alloy exhibited higher ductility at room temperature than the non-directionally solidified alloy. The non-directionally solidified alloy exhibited intergranular fracture. However, no intergranular fracture was observed for the directionally solidified alloy. Suppression of intergranular fracture is responsible for high ductility for the directionally solidified alloy.

(4) Also, the directionally solidified alloy exhibited higher strength at room temperature than the non-directionally solidified alloy. Namely, the directionally solidified alloy exhibited not only high strength at elevated temperature, but also a good combination of high strength and high ductility at room temperature. This points out the importance of grain morphology control for enhancement of mechanical properties for Mg alloys.

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REFERENCES