JMEPEG (2002) 11:71-74

Microstructure Effects on the Forgeability of Zn-22Al Eutectoid Alloy

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(Submitted 11 June 2001)

The forgeability of Zn-22Al eutectoid alloy with two types of microstructure has been studied by using a Gleeble simulation machine. Experimental results showed that the fine-grained Zn-22Al eutectoid alloy possessed excellent forgeability. The flow stress was only 11.5 MPa at 200 °C in a compressive strain rate of 0.006 s^{-1} and then remained constant during the whole forging process. However, the compressive stress-strain curves of lamellar Zn-22Al eutectoid alloy were drastically higher than that of fine-grained Zn-22Al eutectoid alloy tested in the same forging conditions. The stress-softening phenomenon and oscillatory behavior exhibited in these stress-strain curves of lamellar Zn-22Al eutectoid alloy may be attributed to the dynamic recovery (and/or recrystallization) effect at elevated temperatures.

Keywords bulk deformation process, forgeability, Zn-22Al eutectoid alloy

1. Introduction

Forging is an important bulk deformation process, using compressive forces to manufacture complex-shaped components. In the traditional forging process, great force may be necessary to produce the commercial technical alloy deformation even at high temperatures, and the forging equipment is often very heavy. When a material with very fine grain size and duplex structure is forged at the appropriate temperature and a certain strain rate, it exhibits very high elongation under low forming forces. This finding implies that a complex shaped component could be made by using suitable materials and a lighter forming machine. An added benefit is that the die wear could be reduced as well. Tully and Monaghan[1,2] showed that a die cavity for a polymer injection-molding machine could be made by using a fine grain, aluminum bronze alloy by the hobbing process. Somani et al.[3] and Kuboki et al.[4] used the fine-grained titanium alloy to produce the near-net shape components with a forging press.

The Zn-22Al eutectoid alloy is a classic commercial material and has been widely used in automobile and textile industries. By quenching from a temperature above its eutectoid point (275 °C) to room temperature or lower, the single phase will spontaneously decompose into a mixture of zinc-rich and aluminum-rich phases by spinodal transformation.[5] Through such a treatment, the Zn-22Al eutectoid alloy leads to a fine-grained duplex structure. Mohamed et al.[6] reported that the Zn-Al eutectoid alloy with a grain size of 2.5 μm possessed a maximum elongation of 2800% at 200 °C at a tensile strain rate of 1.33×10^{-2} s^{-1}. The grain boundary sliding played an important role in superplastic deformation of the Zn-22Al eutectoid alloy.[7] Moreover, Chokshi and Langdon[8] reported that a large amount of cavities formed during the tensile superplastic deformation of the Zn-22Al alloy has drastically degraded its tensile strength.[8] On the other hand, slowing cooling through the eutectoid leads to a lamellar decomposition product. Because Zn-22Al eutectoid alloy possesses quite different microstructures, its workability should also be dissimilar, or at least to have a markedly different mechanical response at elevated temperatures. In this study, the forgeability of the Zn-22Al eutectoid alloy was evaluated by using Gleeble tests. In addition, the microstructure of this alloy after forging should also be investigated.

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2. Experimental Procedure

The Zn-22Al eutectoid alloy used in this study was prepared by melting pure aluminum and pure zinc (99.9 wt. pct) in an argon atmosphere furnace and then cast into a stainless steel mold. The ingot was homogenized at 375 °C for 22 h and then solution treated at 340 °C for 90 min, ice quenched for 60 min, and then stabilized at 250 °C for 30 min. A mixture of equiaxed zinc-rich (dark areas) and aluminum-rich phases structure was obtained after this heat treatment (Fig. 1a). This alloy possessed a very fine grain size of about 3 μm with a microhardness of 66.4 ± 2.5 Hv. Some ingots were solution treated at 380 °C for 180 min and cooled in a furnace, a typical lamellar eutectoid structure, and an undecomposed matrix coexistence was obtained (Fig. 1b). The interlammellar spacing was about 2-4 μm depending upon the cooling rate.

Upset forge specimens with dimensions of 20 mm diameter × 20 mm length were cut from the material for evaluating the forgeability of Zn-22Al eutectoid alloy. The forging tests were carried out by using a Gleeble 2000 dynamic testing machine. Specimens were tested in air at 150 °C and 200 °C with a compressive strain rate range between 36 and 0.006 s^{-1}. The average heating rate was about 5 °C/s, and the specimens were maintained at the forging temperatures for 3 min before tests. No lubricants between the workpiece and the tools were used during the forging process. A computer recorded the instanta-

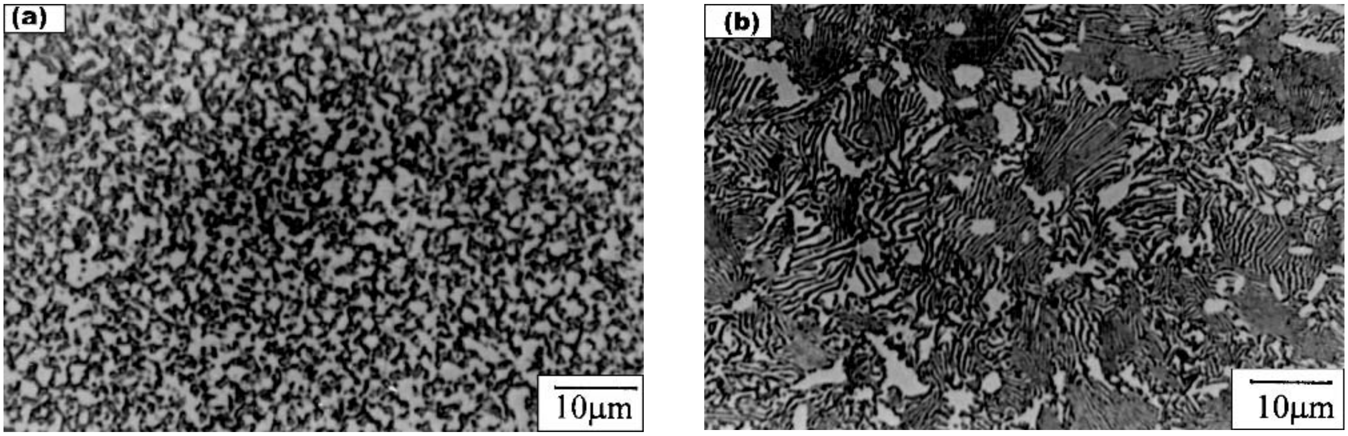

Fig. 1 Microstructure of (a) fine-grained and (b) lamellar Zn-22Al eutectoid alloy

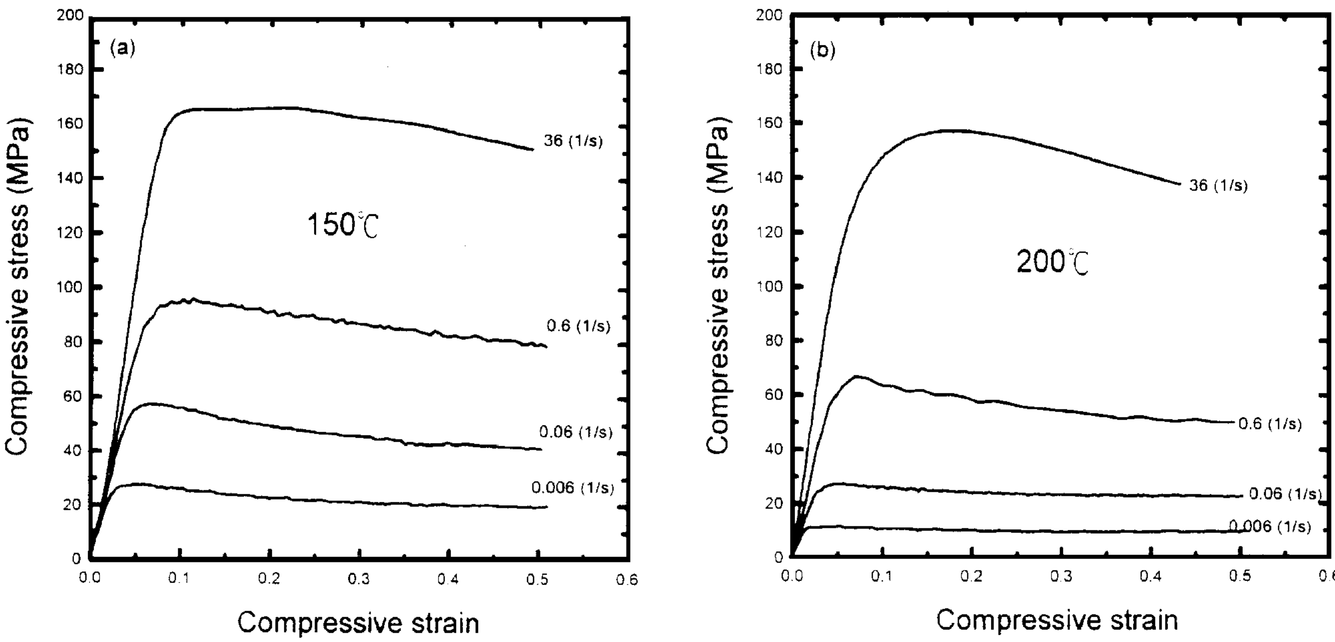

Fig. 2 The σ-ε curves of fine-grained Zn-22Al eutectoid alloy

neous compressive axial heights of specimens and superimposed loads. After forging, the specimens were cooled in air and then cut along the centerline for metallographic analyses by an optical microscope (OM).

3. Results and Discussion

According to the volume constancy ($A_0L_0 = AL$), the compressive strain (ε) and compressive stress (σ) of Zn-22Al eutectoid alloy can be expressed as:

$$\varepsilon = -\ln\frac{L}{L_0}$$

$$\sigma = \frac{FL}{A_0L_0}$$

where F is the superimposed load, A_0 and A are the initial and instantaneous cross-sectional areas, and L_0 and L are the initial and instantaneous longitudinal lengths.

Figure 2 shows the compressive stress-strain curves of the fine-grained Zn-22Al eutectoid alloy tested at forging temperatures in the range from 150 °C to 200 °C as a function of the compressive strain rate. It illustrates that the flow stresses of specimens decreased along with decreasing compressive strain rate. A greater flow stress (>150 MPa) was required for the specimens with a compressive strain rate higher than 36 s^{-1} in this forging temperature range. At the higher strain rate, a drop in flow stress was exhibited after a certain critical strain. However, the stress-strain curves were quite flat through the whole forging process in the forging temperature range from 150 °C to 200 °C in the strain rate <0.006 s^{-1}. The maximum flow stress of the fine-grained Zn-22Al eutectoid alloy with a compressive strain rate of 0.006 s^{-1} at 200 °C was only 11.5 MPa.

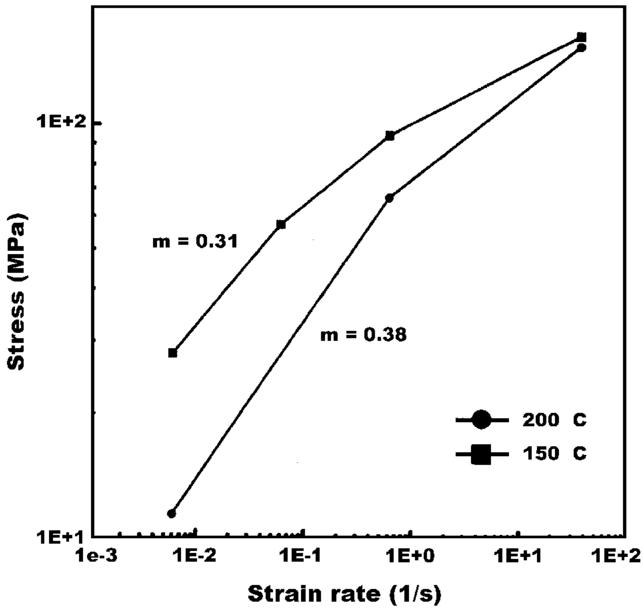

Fig. 3 Compressive instability stresses vs compressive strain rates for fine-grained Zn-22Al eutectoid alloy tested at 150 °C and 200 °C

The compressive instability stresses (σ_i) could be determined by using the 0.002 strain offset method from the compressive σ-ε curves of the fine-grained Zn-22Al eutectoid alloy. The results are plotted on a logarithmic scale in Fig. 3 for the compressive instability stresses as a function of compressive strain rates. The strain-rate sensitivity index ($m = \partial \ln\sigma / \partial \ln\varepsilon$) of the fine-grained Zn-22Al eutectoid alloy in this forging study are ~0.37 at 200 °C under the compressive strain rate range from 0.6 to 0.006 s^{-1} and ~0.31 at 150 °C under the compressive strain rate range from 0.06 to 0.006 s^{-1}, respectively. In general, the superplasticity of the alloy is assumed to occur for values of $m > 0.3$.[7] These results may indicate that the fine-grained Zn-22Al eutectoid alloy possessed superplasticity in the forming conditions.

Because of the frictional forces at ram/specimen interfaces, which retarded the outward flow of material at such interfaces, a barrel appearance of the forged specimens was revealed after tests. No surface cracks were observed in any fine-grained Zn-22Al eutectoid specimens tested in this study even after a very high compressive strain had been achieved. This implies that the fine-grained Zn-22Al eutectoid alloy possesses excellent forgeability. Typical microstructures of the forged Zn-22Al specimens cut along the centerline are shown in Fig. 4. The fine-grained equiaxed structure was maintained during the forging process and no microcracks were observed in the material. These results might be attributed to the diffusion creep and grain boundary sliding (GBS) mechanism, which played important roles for the fine-grained Zn-22Al eutectoid alloy during the forming process under compression stresses.

The compressive stress-strain curves of the Zn-22Al eutectoid alloy with different microstructures tested at forging temperatures in the range from 150 °C to 200 °C with a certain compressive strain rate of 0.006 s^{-1} are shown in Fig. 5. The flow stresses of lamellar Zn-22Al eutectoid alloy were drastically higher than that of fine-grained Zn-22Al eutectoid alloy

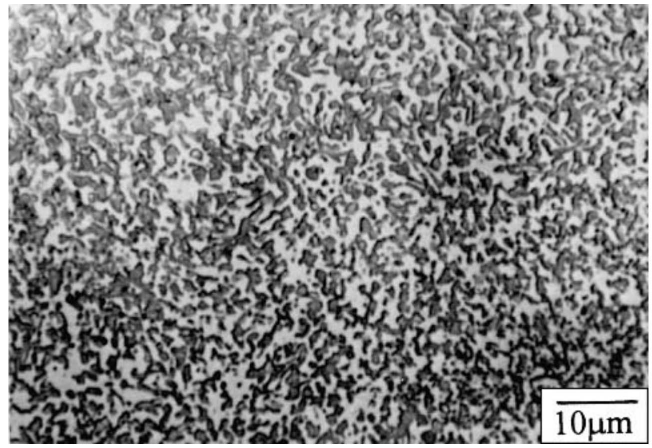

Fig. 4 Photograph of deformed fine-grained Zn-22Al upset specimen

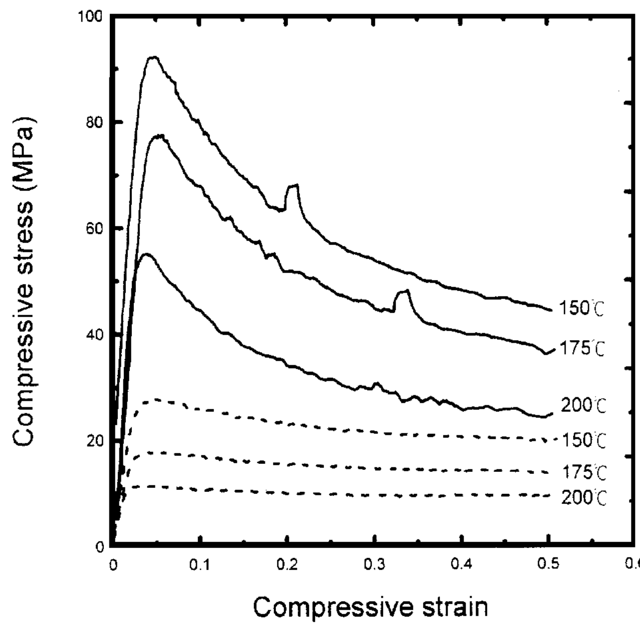

Fig. 5 The σ-ε curves of the Zn-22Al eutectoid alloy with different microstructures tested at various temperatures with a compressive strain rate of 0.006 s^{-1}. (— lamellar Zn-22Al alloy; --- fine-grained Zn-22Al alloy)

tested in the same forming condition. A stress-softening phenomenon exhibited in these stress-strain curves of lamellar Zn-22Al eutectoid alloy after a certain compressive strain. Moreover, the curves were not always smooth but sometimes presented irregularities. A crack was located on the free surface of the lamellar Zn-22Al eutectoid alloy at 45° to the compressive axis in all the tests. Many microcracks appeared on the fracture surface and were found along the lamellar eutectoid cells/undecomposed matrix interface. Final rupture linked the microcracks with the outside surface (Fig. 6a). The present results show that the lamellar Zn-22Al eutectoid alloy did not provide good workability during the forging conditions. After the forging test, the lamellar Zn-22Al eutectoid alloy also consisted of elongated grains structure (Fig. 6b). This implies that the

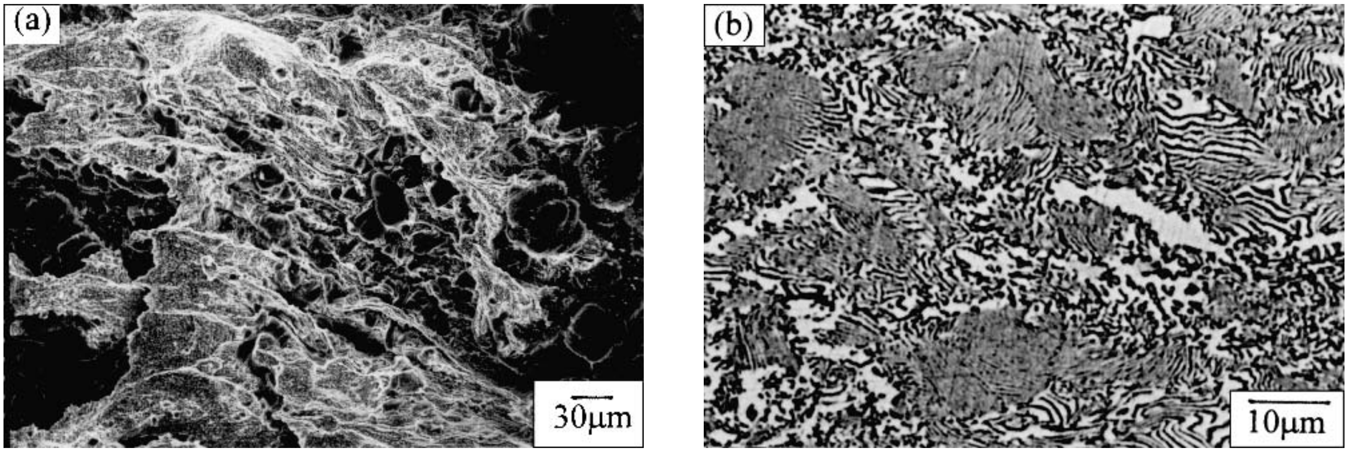

Fig. 6. (a) SEM fracture surface of lamellar Zn-22Al upset sample, (b) Typical microstructure of deformed lamellar Zn-22Al upset specimen

forged lamellar Zn-22Al eutectoid alloy possesses anisotropy. The mechanical properties may be different for different orientations of the test specimen. Because the dislocation motion was the main deformation mechanism of lamellar Zn-22Al eutectoid alloy, in this case, a critical dislocation density was reached at the highest levels in a specific compressive strain, which promoted the dynamic recovery (and/or recrystallization) effect at elevated temperatures. This caused a peak and oscillatory behavior in these compressive stress-strain curves of the lamellar Zn-22Al eutectoid alloy.

4. Conclusion

The fine-grained Zn-22Al eutectoid alloy possessed excellent forgeability at 200 °C with a compressive strain rate of 0.6 s^{-1}. The flow stress was only 11.5 MPa and then remained constant through the whole forging process. No surface cracks were found on these forged fine-grained Zn-22Al specimens, and the mechanical properties of this alloy were preserved after the forging process. However, the flow stress of the lamellar Zn-22Al eutectoid alloy was higher than 157.1 MPa in the same forming conditions. The stress-softening phenomenon and oscillatory behavior exhibited in these stress-strain curves of the lamellar Zn-22Al eutectoid alloy may be attributed to the dynamic recovery (and/or recrystallization) effect at elevated temperatures. A crack was located on the free surface of the lamellar Zn-22Al eutectoid alloy, which indicated that the lamellar Zn-22Al eutectoid alloy did not provide good workability during the forging temperatures between 150 °C and 200 °C with a compressive strain rate range between 36 and 0.006 s^{-1}.

Acknowledgment

The authors acknowledge the financial support of this work from the National Science Council of the Republic of China under grant No. NSC 89-2623-D-216-001.

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