On The Possibility of Superplasticity Enhanced by Dynamic Recrystallization

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Abstract

The possibility of superplasticity enhanced by dynamic recrystallization (DRX) in wide temperature range was considered. The classic superplastic material Mg-5.8%Zn-0.65%Zr with initial coarse-grained microstructure was examined. It was shown that the material demonstrates superplasticity in the case when a normalized strain rate of plastic deformation lies below than the power-law breakdown criterion (PLB) ($\varepsilon kT/DGb \approx^{-6}$). At these temperature-strain rate conditions the microstructural evolution during hot plastic deformation could be described in terms of conventional DRX. DRX results in formation of full recrystallized structure with average grain size in range from 1μm to 18μm. Grain boundaries of these grains are rather equilibrium. The magnesium alloy with such structure demonstrates superplastic behavior. At the normalized strain rates lie above 10^{-6} the low temperature DRX occurs. Occurrence of this type of DRX results in formation of submicrocrystalline structure. This structure is granular type with average grain size in range from 0.1μm to 1μm. The main feature of this structure is highly non-equilibrium grain boundaries (NEGBs). These boundaries are sources of internal long-range stress fields. The material with such full recrystallized structure does not demonstrate the superplastic behavior. The possibility of superplastic deformation of ultrafine-grained materials is discussed in terms of the influence of grain boundary structure on mechanisms of superplastic flow.

Introduction

It is known [1-4] that DRX occurrence leads to formation of recrystallized microstructure, enables alloys to deform superplastically. Almost all these investigations were performed at relatively high temperatures. At the same time DRX can lead to formation of full recrystallized structure with grain sizes lying in wide range from 1μm to 20μm [4,6,7]. The certain grain size is stable at temperature such that these grains were formed during plastic deformation. Unfortunately, the superplastic response of a material as a function of dynamically recrystallized grain size was considered very poor. In addition, the influence of recrystallized grain boundary structure on manifestation of superplastic behavior was not taken into account. Although the state of grain boundaries plays an important role in superplastic flow especially in case of submicrometer and nanocrystalline materials. A consideration of influence of grain size and grain boundary structure on superplastic flow in combination is still lacking.

State and structure of recrystallized grain boundaries is determined by operating mechanisms of DRX [6,7]. In turn, a mechanism of strain enhanced recrystallization is in strong relationship with a temperature [7]. Therefore, deformation with different temperatures can result in formation of different types of recrystallized structure. Thus, the purpose of the present work is to investigate the influence of deformation temperature. Consequently, the analysis of effect of recrystallized grain size and structure of recrystallized grain boundaries on occurrence of superplastic deformation in initial coarse grained magnesium alloy has been performed.

Material and Experimental Procedure

The magnesium alloy Mg-5.8%Zn-0.65%Zr used in this study was obtained as a casting. Its initial grain size was 85μm. Specimens ∅ 10 x 12 mm were machined from an ingot. Compression testing was conducted using a Instron testing machine in temperature range from 423 to 723K and at strain rates $\varepsilon=10^{-5}$ - 10^{-1} s^{-1}. All specimens were quenched *in situ* immediately after deformation. To achieve a highly strained state at ambient temperature the specimens of 8 mm diameter and 0.3 mm thick of the alloy were subjected to severe plastic deformation by torsion straining under high pressure (about 7GPa) using a special set of a Bridgeman anvil type. The maximal value of attained logarithmic strain was approximately 7. Tensile samples with the gauge section of 5x1.5x0.2mm were cut from highly strained samples. Tensile samples with the gauge section of 15x5x1.5mm for evaluation of superplastic properties were machined from the blanks of the alloy forged at fixed temperatures 423K, 523K and 723K. Superplastic behavior of different kinds of specimens was examined using the Instron testing machine at the same temperatures in wide range of strain rate.

The metallographic analysis was carried out using a Neophot-32 microscope and an Epiquant automatic structure analyzer. X-ray structural analysis was performed by Williamson-Hall method using a universal diffractometer DRON-4. The thin foils were examined with a JEOL-2000EX TEM utilizing a double-tilt stage.

Experimental results

Table 1 summarizes the values of coefficient of strain rate sensitivity "m" and volume fraction of recrystallized grains V_{rec} in relation to strain in temperature range T=423-723K. It is seen that the coefficient "m" and V_{rec} gradually increases with temperature increase at a fixed strain. Formation of recrystallized structure enables the material to deform superplastically. Notice that at higher temperatures the material makes superplastic (m=0.3) at lower critical strain ε_{cr} and at lower volume fraction of recrystallized grains. For instance, at T=623K and T=723K the critical values of V_{rec} constitute 85% and 50%, respectively.

Table 1. The values of coefficient of strain rate sensitivity "m" and volume fraction of recrystallized grains V_{rec} according strain. Numerator represents the "m" values, and denominator represents the V_{rec} values.

T	strain, ε				
	5%	25%	40%	75%	85%
423K	0.02	0.05	0.07	0.11	-/-
523K	0.12/0	0.15/9	0.2/23	0.25/41	0.34/-
623K	0.16/2	0.2/20	0.24/42	0.31/94	0.37/-
723K	0.20	0.25	0.30	0.38	-/-

In low temperature interval the DRX, leading to formation of a very fine, full recrystallized structure during deformation, does not enable the alloy to deform superplastically. At T=423K the heavily strained alloy with full recrystallized structure does not show superplasticity (m=0.24) at strain rate such that DRX has occurred. The maximum values of coefficient "m" and elongation-to-failure of samples subjected by severe deformation at room temperature do not exceed 0.12 and 4%, respectively.

Figure 1 shows experimental data from the magnesium alloy with different initial recrystallized structure. The recrystallized structures with average grain size of 0.8μm, 2.5μm and 14μm were obtained by deformation at temperatures 423K, 523K and 723K, respectively. These states of the magnesium alloys were tensioned at the same temperatures. A summary of these data is given in Table 2. It is seen that at T=523K and T=723K the material demonstrates superplastic behavior at strain rate at which the recrystallized structures were formed. It should be noted that at T=523K values of the coefficient "m" and total elongation of the alloy are maximum in all examined temperature interval. At T=423K the evidences of superplasticity were observed at strain rate that is much less than the strain rate of prior deformation.

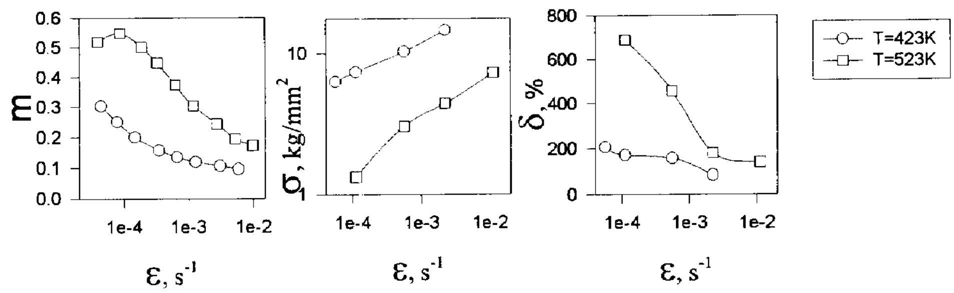

Fig.1. Elongation-to-failure (δ), coefficient "m" and flow stress σ *vs* strain rate.

Table 2. The maximum superplastic properties demonstrated by the Mg-5.8%Zn-0.65%Zr alloy. The temperatures of DRX and evaluation of superplasticity are the same.

T	m	δ	ε
293K	0.12	4%	no effect
423K	0.30	207%	5.6×10^{-5}
523K	0.55	687%	1.1×10^{-4}
723K	0.45	387%	8×10^{-4}

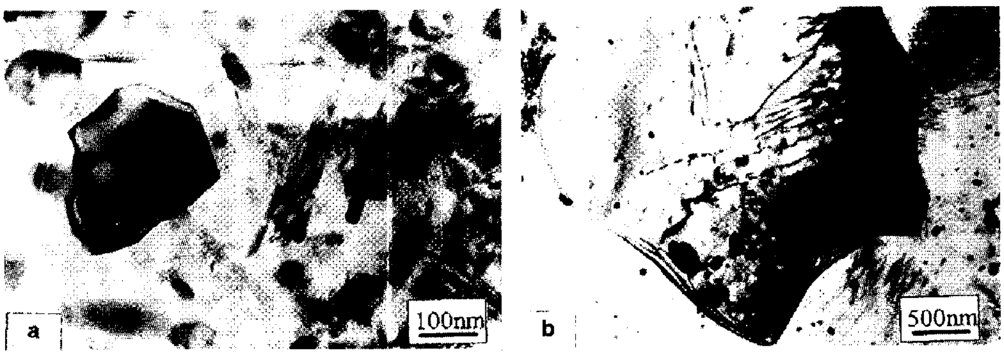

Fig.2. TEM of the magnesium alloy: (a) T=293K, (b) T=523K.

X-ray measurements reveal an increase of internal elastic strain from $\Delta a/a \approx 1.087 \times 10^{-3}$ to $\Delta a/a \approx 1.867 \times 10^{-3}$ with increasing temperature from T=293K to T=423K and following reduction of the strain up to $\Delta a/a \approx 1.027 \times 10^{-3}$ at subsequent temperature increase up to T=523K. At T=723K no internal elastic strain was indicated.

TEM observations show that maximal density of lattice dislocation takes place in recrystallized structure obtained at T=523K ($\rho = 8 \times 10^{8}$ s^{-2}) (fig.2). At T=723K and T=423K the dislocation density is much less in comparison with T=523K. At the same time a specific strain contrast associated with NEGBs in recrystallized structure [8] was observed from the samples deformed at T=423K and especially at ambient temperature. Notice that after severe deformation at room temperature the density of lattice dislocations is minimum.

Discussion

The present results indicate that the capacity of dynamically full recrystallized structure to support superplastic deformation mechanisms depends from temperature. Let us consider the effect of deformation temperature and features of recrystallized structure on the transition of the magnesium alloy into superplastic state during plastic deformation.

The criterion for superplasticity enhanced by DRX

Fig.3 shows a double logarithmic plot of the normalized strain rate εkT/DGb, against normalized stress, σ/G. An examination of Fig.3 leads to significant conclusion. The superplasticity enhanced by DRX can occur only at the normalized strain rates lying below the PLB criterion ($\varepsilon kT/DGb \approx 10^{-6}$). At higher normalized strain rates in interval of exponential creep the material does not show superplasticity. Tension experiments support this conclusion. At T=423K the decrease of strain rate less than that accordingly the PLB criterion ($\varepsilon = 5.6 \times 10^{-5}$ s^{-1}) allows to attain superplasticity (m=0.3, δ=207%). The influence of the temperature increase from T=423K to T=523K on superplastic properties is the same.

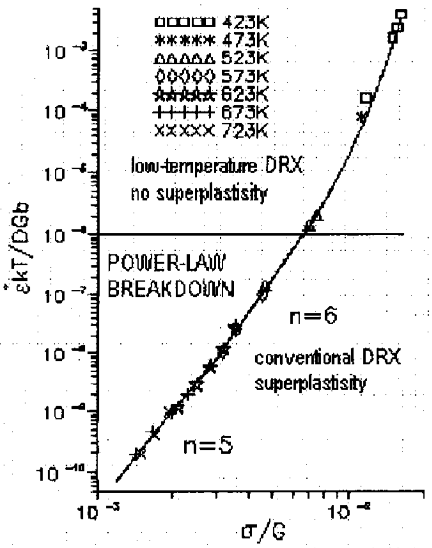

Fig.3. Normalized strain rate *vs* normalized stress.

Analysis of TEM and X-ray data shows that this phenomenon is caused by features of recrystallized grain boundaries. The state and structure of these boundaries is depended on deformation temperature. Occurrence of DRX at the normalized strain rates lying above the PLB criterion results in formation of grains with highly NEGBs. Therefore, it is possible to presume that the possibility of the magnesium alloy with full recrystallized structure to deform superplastically is controlled by the state of the grain boundaries. Let us consider the effect of recrystallized grain boundaries on exhibition of superplasticity by the alloy.

The influence of grain boundary state on the manifestation of superplasticity

At higher temperatures (T=623-723K) DRX leading to evolution of partially recrystallized structure during deformation, enables the alloy to deform superplastically. Boundaries of recrystallized grains are rather equilibrium. The density of grain boundary dislocations (GBDs) is low. The material with full recrystallized structure demonstrates satisfactory superplastic properties. The conventional mechanisms of superplastic deformation are operative [13].

At intermediate temperature T=523K the superplastic properties reach maximum values. It is caused by the fact that fine recrystallized structure is stabilized by precipitation of β - phase (Mg_2Zn_3). In addition, the enhanced density of GBDs was observed. The grain boundaries are non-equilibrium. However, this state of the boundaries is associated only with GBDs. These two factors provide most favorable conditions for superplastic deformation. The grain boundary sliding is dominant mechanism of plastic deformation [13].

In temperature interval T=293-423K low temperature DRX [9] results in formation of specific type of microstructure. This microstructure is adequately described by a model based on the concept of NEGBs containing disordered dislocation networks and junction disclinations which induce long-range stress fields [10]. The material with such structure demonstrates poor superplastic behavior only at T=423K. At ambient temperature the alloy does not show superplasticity in spite of recrystallized grain size reduction by a factor of ten. It is caused by an increase of the power of junction disclination with decreasing temperature. Concurrently, reduction of GBD density takes place [12]. The last component is responsible for strong internal stress fields [12]. As a result, positive temperature dependence of internal elastic strain is observed in temperature interval T=293-423K. Interaction of junction disclination and GBDs affects character of grain boundary sliding. At room temperature the contribution of this deformation mechanism to the total elongation also is significant [11]. However, the material does not demonstrate the superplastic behavior. Probably, the origin of grain sliding along boundaries containing junction disclination is quite different from that at high temperatures along general-type boundaries. Therefore, ultrafine-grained (submicrometer and nanocrystalline) can exhibit superplastic behavior in the case if their boundaries contain small-power junction disclination as in the magnesium alloy recrystallized fully at t=423K.

Thus, not only the size of recrystallized grains but the state of their boundaries as well enables the material to exhibit superplasticity. The PLB criterion is concurrently the criterion for transition of initial coarse-grained materials into superplastic state during plastic deformation. It is caused by the fact that this criterion separates the temperature-strain rate interval for conventional DRX from that for low temperature DRX. The recrystallized structure formed at a normalized strain rate lying below the PLB criterion is characterized by rather equilibrium grain boundaries while in another normalized strain rate interval the formation of recrystallized grains with NEGBs takes place. The DRX, leading to formation of full recrystallized structure, enables the magnesium alloy to deform superplastically in accordance with type of strain induced grain boundaries. In the case than NEGBs of recrystallized grains contain high-power junction disclinations the material does not show superplasticity. The best superplastic properties were demonstrated by the alloy with recrystallized grain boundaries containing only GBDs.

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