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High temperature mechanical properties of AlMgZn alloys with copper and zirconium additions

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Abstract: High temperature mechanical properties of AlMgZn alloys grain refined by zirconium were investigated by impression creep and tensile tests. The strain rate sensitivities and activation energies obtained are presented. It has been found that the steady-state impression creep rate is strongly influenced by Cu and Zr addition. The simultaneous addition of Cu and Zr resulted in fine-grained microstructure due to which the material exhibited superplastic properties at high temperatures. Together with the superplastic behaviour the occurrence of a threshold stress has also been observed.

1. Introduction

The mechanical properties of metals are strongly influenced by the alloying elements being either in solution or in precipitates. The effect of alloying additions is also significant in the high temperature region where under certain conditions superplastic behaviour can take place. It was shown earlier that medium to high strength AlZnMg alloys can be made to exhibit superplasticity by the addition of zirconium as a grain refining element [1].

The high temperature creep rate of the metals and alloys can generally be described by the equation:

$$\dot{\epsilon} = A\sigma^{n_a} e^{-\frac{Q_a}{kT}} \quad (1)$$

where A is a material parameter and n_a and Q_a are the apparent stress exponent and the apparent activation enthalpy, respectively [2, 3]. However, it has recently been proved that in some alloys the superplastic deformation is accompanied by the occurrence of threshold stresses modifying both the activation enthalpy and the stress exponent of the process. In this case in equation (1) the stress must be substituted by an effective stress which is the difference between the applied stress and the threshold stress [4-8]. In the case of superplastic materials it is well known that the curve of the $\ln\sigma$ - $\ln\dot{\epsilon}$ plot is sigmoidal and consists of three parts. Superplastic properties are observed at medium strain rates (region II) while at low (region I) and high (region III) strain rates the superplastic behaviour disappears [9-12]. In this paper the effect of Cu and Zr content on the high temperature mechanical properties as well as on the superplastic behaviour of an AlMgZn alloy is discussed.

2. Experimental details

The chemical composition of the alloys investigated is shown in Table I. The alloy samples prepared of 99.99 % purity aluminium were provided by the HUNGALU Engineering and Development Centre, Budapest. After casting the samples were homogenized for 8 hours at 470 °C in air, and hot extruded to sheets of 10x40 mm² cross section. The starting temperature of the hot extrusion was 380 ± 5 °C. For solution treatment the specimens were annealed at 470 °C for 30 min and water-quenched to room temperature. Following this treatment fully recrystallized materials were obtained.

Sample A

Sample B

100 μm

Sample C

Sample D

Fig.1. The microstructure of the alloys investigated

Label	Alloying elements			
	Mg	Zn	Cu	Zr
A	2.0	5.7	-	-
B	2.0	5.7	0.35	-
C	1.9	5.7	1.4	-
D	1.9	5.7	1.4	0.12

Table I Composition of the alloys (concentrations in wt%)

The high temperature mechanical properties were studied mainly by impression creep tests and on the basis of the results obtained from these measurements some complementary measurements were made by tensile testing. The detailed descriptions of the creep tester and the method was published previously [13], as well as in this proceeding [14].

The tensile specimens were cylindrical with gauge length of 24 mm. The test were performed by using an INSTRON type machine operating at a constant crosshead velocity in the range from 0.2 mm/min to

20 mm/min (initial strain rates $\dot{\epsilon}_0$ were $1.33 \cdot 10^{-4}$ to $1.33 \cdot 10^{-2} \text{ sec}^{-1}$).

In addition metallographic pictures were taken to show the microstructure of the samples, and SEM pictures were also taken to help understanding the micromechanisms of the superplastic deformation.

3. Results and discussion

3.1 The Impression Creep test

Fig. 1. shows the microstructure of the samples after quenching. It can be seen that alloys A, B and C with no Zr addition are fully recrystallized and have very similar coarse grained microstructure with about 100 μm mean grain size. On the contrary, there is a fine grained microstructure in alloy D, where the grains are arranged in bands and the average grain size is about 10 μm . The occurrence of this fine grained microstructure can be clearly attributed to the grain refining effect of the zirconium.

Fig. 2. The double logarithmic plot of the p, v data

Fig 2. shows the double logarithmic plot containing the p, v data measured at 673 K with various loads for the four alloys investigated, where p is the pressure immediately below the indenter and v is the steady state velocity of the punch during the impression creep test. The curves for material A and B coincide giving one straight line with $n_a=3.5$ as stress exponent. The line obtained for alloy C is parallel with that previously described but shifted to somewhat higher p values. This means that although the creep rate is lower (the

strength of the material increases due to the higher Cu content) the stress exponent remains unchanged. The curve for alloy D differs significantly from the curves obtained for the other three alloys. Only the central part of it can be approximated by a straight line. This central section of the curve yields a stress exponent $n_a=2.6$. This can be considered as an indication for the superplastic behaviour of alloy D since it is widely accepted that a material can be qualified as superplastic if the strain rate sensitivity, which is the inverse of the stress exponent, is higher than 0.3 [9].

Fig.3. $\ln p$ - $\ln v$ curves for alloy B Fig.4 $\ln p$ - $\ln v$ curves for alloy D

Fig. 3. and Fig. 4. show the $\ln p$ - $\ln v$ functions obtained at various temperatures for alloy B and D. The curves for alloy B are parallel straight lines. (Similar results were measured also for alloys A and C.) The central section of the curves for alloy D - where the deformation can be regarded as superplastic - can also be approximated by straight lines which have practically the same slope. Using these approximations and the cross-cut method an apparent activation enthalpy of 130 kJ/mol has been determined for the deformation process in the case of alloys A, B and C. This value agrees well with that of the bulk diffusion in Al [15]. The activation enthalpy obtained for alloy D is about 170 kJ/mol. The high activation enthalpy determined for the superplastic region of alloy D seems to be contradictory to the theoretical models predicting that grain boundary sliding controls the superplastic deformation. This contradiction can be resolved however, by introducing an effective stress which is the difference between the applied stress and a threshold stress. According

to experimental investigations on superplastic materials the threshold stress exhibits a strong temperature dependence [16, 17]. As a consequence of this temperature dependence the analysis based on the formula (1) results only in an apparent stress exponent and activation enthalpy. By introducing the threshold stress the following expression is obtained instead of equation (1):

$$\dot{\epsilon} = (\sigma - \sigma_0)^n e^{-\frac{Q}{kT}} \quad (2)$$

where σ_0 is the threshold stress, n and Q are the true stress exponent and the true activation enthalpy, respectively. In the case of alloys A, B and C the threshold stress was found to be negligible, so the n and Q values agree with the n_a and Q_a values, but in the case of the alloy D the threshold stress must be taken into account. In a previous work [18] we have introduced a method based on equations (2) for the

determination of the activation enthalpy. By this method the corrected (true) activation enthalpy of alloy D is obtained as 120 kJ/mol.

3.2 The Tensile test

Tensile tests were performed at the temperature and strain rate range where on the basis of the impression measurements the behaviour of alloy D was expected to be superplastic. Fig. 5. shows the stress-strain curves obtained at 788 K with various initial strain rates for the four alloys investigated. It can be seen that in the case of alloys A, B and C at each strain rate the flow stress increases with increasing Cu content, the total elongations, however, remains constant independently of the strain rate and of the Cu content. This is in agreement with the observation that the values of the macroscopic parameters characterizing the creep process (n , Q) are also independent of the amount of Cu additions. In contrast to this, in the case of alloy D the total elongation is strongly changing with strain rate, which is a common feature of superplastic materials [10-12]. While at the lowest strain rate the total elongation is larger than 300 %, at the highest rate the sample elongated only 60 per cent. Fig. 6. shows a sample elongated by 300 per cent. In Fig. 7. the total elongation is shown as a function of the initial strain rate taken at 788 K for alloy D. The data points on the maximum elongation vs. strain rate curve indicates that these measurements were taken in the strain rate regions II and III.

Fig. 8. is a SEM picture taken from the fracture surface of a

Fig. 5. Stress-strain curves for the alloy investigated at a.) low, b.) medium c) high strain rates

sample deformed superplastically in region II. It can be seen that in region II the sample failed along grain boundaries, which confirms that in this region grain boundary sliding yields the major contribution to the deformation.

Fig.6. Sample with total elongation of 300%

Fig. 7. Maximum elongation versus initial strain rate

Fig.8. The fracture surface of a superplastically deformed sample

Conclusions

1. It was shown that the high temperature strength of the AlMgZn alloy studied here is considerably increased by the additions of Cu.

2. In the case of the alloys without Zr the values of the macroscopic parameters (n , Q) characterizing the deformation are independent of the Cu content. From the $Q=130$ kJ/mol and the $n=3.5$ values it can be concluded that in these alloys dislocation creep is the main mechanism of deformation.

3. A strong grain refining effect can be established by adding 0,12% zirconium together with copper, which caused the deformation of the alloy to be superplastic in the temperature range of 400-515 °C at strain rates of $5 \cdot 10^{-6}$ - $2.5 \cdot 10^{-3}$ 1/s.

4. The superplastic processes were accompanied by the occurrence of a strongly temperature dependent threshold stress which led to an exceptionally high value of the apparent activation enthalpy. By taking into account the temperature dependence of the threshold stress a more realistic value of the activation enthalpy has been determined which was close to that of the bulk diffusion of the alloy.

5. The SEM investigation of the fracture surface of superplastically deformed fine grained alloy D samples indicated also that in this case grain boundary sliding is the main mechanism of the superplastic deformation.

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