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Superplastic Characteristics of Fine-Grained 7475 Aluminum Alloy

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A 7475-aluminum alloy was subjected to a thermomechanical heat treatment that resulted in a final recrystallized grain size on the order of 10 μm. Tensile specimens of dimensions 10 × 4 × 2.3 mm were machined such that the tensile axis was parallel to the rolling direction. Tensile tests were carried out at high temperatures in the range of 773 to 803 K at different cross-head speeds corresponding to initial strain rates in the range of 10^{-4} to 10^{-2} s^{-1}. Elongations of several hundred percent were observed at strain rates of <10^{-3} s^{-1}. The correlation between flow stress and strain rate suggests that the strain rate sensitivity *m* is close to 0.5 at the lower strain rates. The value of *m* decreases to ≈0.2 at high strain rates. The decrease in *m* suggests a transition in the rate-controlling process from superplastic deformation ($m \approx 0.5$) to dislocation creep ($m \approx 0.2$) with increasing strain rate. The calculated activation energies in the two deformation regions are consistent with the suggested rate-controlling processes.

Keywords activation energy, Al-alloy 7475, hot deformation, superplasticity

1. Introduction

Superplasticity usually describes large tensile elongation without necking in fine-grained alloys, which have a stable microstructure at elevated temperature (Ref 1, 2). The tensile elongation to failure in superplastic materials can be several orders of magnitude. This extraordinary material behavior occurs only within a narrow range of strain rates, and the operational temperature is normally greater than 0.5 T_m, where T_m is the absolute melting point of the material.

Of the many superplastic aluminum alloys that have been developed, the Al-Zn-base 7475 aluminum (Al) alloy is one of the most widely used alloys for commercial superplastic forming. The 7475 Al alloy possesses many interesting characteristics as a structural material, such as low cost, moderate strength, good corrosion resistance, and high formability in conjunction with moderate plasticity (Ref 3-5). The considerable elevated temperature plasticity found in this material was attributed to the grain refinement resulting from recrystallization. Numerous investigations have been conducted to enhance the superplastic properties of the alloy (Ref 5-10). For instance, Smolej et al. (Ref 6) studied the influence of the thermomechanical processing and forming parameters on the superplastic behavior of this alloy. Kaibyshev et al. (Ref 7) examined the effect of the grain refinement taking place during hot working of the as-cast 0.16% Zr-modified 7475 Al alloy. By changing the superplastic parameters, Xinggang et al. (Ref 8, 9) obtained an elongation of about 1700%. However, their thermomechanical treatment and the proposed modifications cannot be easily achieved in industrial manufacturing conditions. Meanwhile, recent progress in low-temperature and/or high strain rate superplasticity, along with the emergence of new techniques for processing ultrafine grain size materials, provide a way to overcome the current limitations of the conventional superplasticity (i.e., high forming temperature and low strain rate). For 7475 Al, there are only a few experimental investigations that have assessed its superplastic behavior.

The objective of the present investigation is to study the superplastic characteristics of fine-grained 7475 Al. Tensile tests were conducted over a wide range of temperatures and initial strain rates. The strain rate sensitivity *m* and the activation energy *Q* were determined for these temperatures and strain rates. The calculated values of *m* and *Q* are usually used to identify the rate-controlling process when compared with the theoretical models of high-temperature deformation.

A constitutive equation for the 7475 Al (Ref 11) was reported that gives the flow stress as a function of the strain and

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Nomenclature

A	Temperature-dependent constant
b	Magnitude of Burgers vector
B	Temperature-independent constant
D	Diffusion coefficient (m^2s^{-1})
D_0	Preexponential factor for diffusion (m^2s^{-1})
G	Shear modulus (MPa)
m	Strain rate sensitivity index
n	Stress exponent (1/m)
p	Grain size exponent
Q	Apparent activation energy ($Jmol^{-1}$)
R	Universal gas constant (8.314 $Jmol^{-1}$ K^{-1})
T	Absolute temperature (K)
ε	true strain
$\dot{\varepsilon}$	true strain rate (s^{-1})
σ	true stress (MPa)
σ_0	Threshold stress (MPa)

Table 1 Chemical composition (wt.%) of 7475 Al

Zn	Mg	Cu	Cr	Si	Mn	Ti	Fe	Al
5.66	2.13	1.68	0.2	0.04	0.01	0.02	0.08	Balance

strain rate at 788 K. The temperature dependence of the flow stress was not considered. Therefore, in the present work a new empirical constitutive equation was developed in the superplastic region that can be used with any numerical technique to model the hot-working processes of this alloy.

2. Material and Experimental Procedures

2.1 Material and Sample Preparation

The fine-grained 7475 Al was supplied in the form of sheets with dimensions 150 × 40 × 2.3 mm. The chemical composition of the alloy is shown in Table 1. These sheets were thermomechanically heat-treated to produce a fine grain size. The grain size of the material was measured using the mean line intercept method in an optical light microscope. The value of the grain size was found to be 12.4 μm.

Test specimens with a gage length of 10 mm and a cross-sectional area of 4 × 2.3 mm were machined from the sheets, such that the tensile axis was parallel to the rolling direction.

2.2 Experimental Procedures

The specimens were tested in tension at 758, 773, 788, and 803 K using a cross-head speed that corresponded to initial strain rates of 10^{-4}, 5×10^{-4}, 10^{-3}, 5×10^{-3}, and 10^{-2} s^{-1}. The tension tests were carried out on an Instron machine, model 1197. A resistance furnace containing three heating zones and controlled by a digital controller was used in all tests. Temperatures were allowed to stabilize for a minimum of 20 min before beginning each test. The load displacement charts were monitored on a strip chart recorder. At each condition of temperature and initial strain rate, more than one test was carried out, and the results confirmed the reproducibility of the experimental data.

3. Results and Discussion

3.1 True Stress-Strain Curves

The true stress-strain curves for different temperatures and initial strain rates are plotted in Fig. 1 to 4. The inspection of these figures reveals that the stress increases with strain until a steady state is reached. The ductility (elongation at fracture) decreases with an increase in the strain rate. It is seen that as the temperature increases at constant strain rate, the strain-hardening rate decreases. Also, there is a region of significant strain hardening before reaching a steady state, especially at high strain rates.

3.2 Stress Dependence of Strain Rate

The relationship between the flow stress σ and the strain rate $\dot{\varepsilon}$ at steady state during high-temperature deformation is governed by Eq 1:

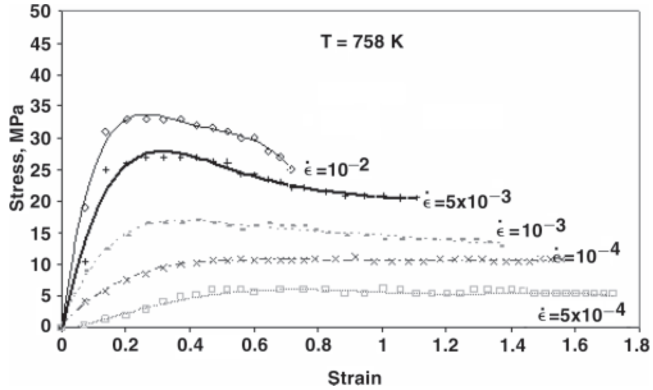

Fig. 1 True stress-strain curves for the 7475 Al alloy at 758 K and five different strain rates

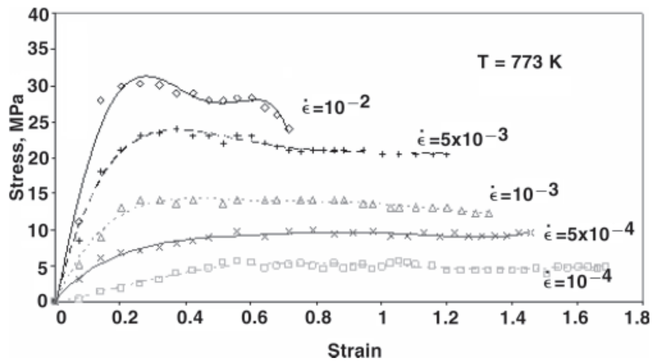

Fig. 2 True stress-strain curves for the 7475 Al alloy at 773 K and five different strain rates

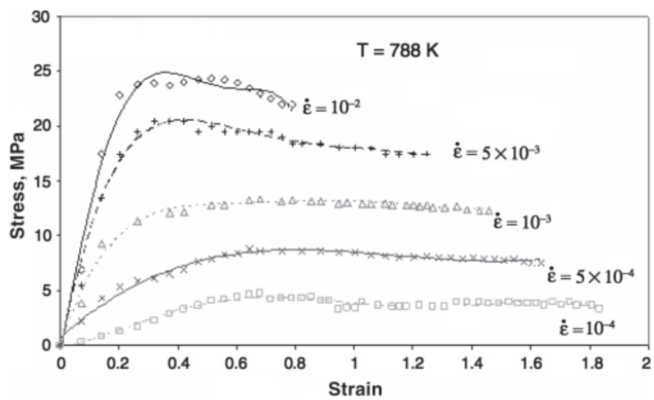

Fig. 3 True stress-strain curves for the 7475 Al alloy at 788 K and five different strain rates

$$\sigma = A\dot{\varepsilon}^{1/n}\exp(Q/nRT) \quad \text{(Eq 1)}$$

To investigate the stress dependence of the strain rate, values for the stress and strain rates at a constant strain (0.45) were plotted on double logarithmic scales, as shown in Fig. 5. The value of the constant strain is chosen so that the steady state is reached at all testing conditions. The data points for each temperature fall on two line segments; therefore, the deformation behavior under the present conditions can be divided into two regions. The strain rate sensitivity *m*, as represented by the slope of each line segment, changes from $m \approx 0.5$ at low strain

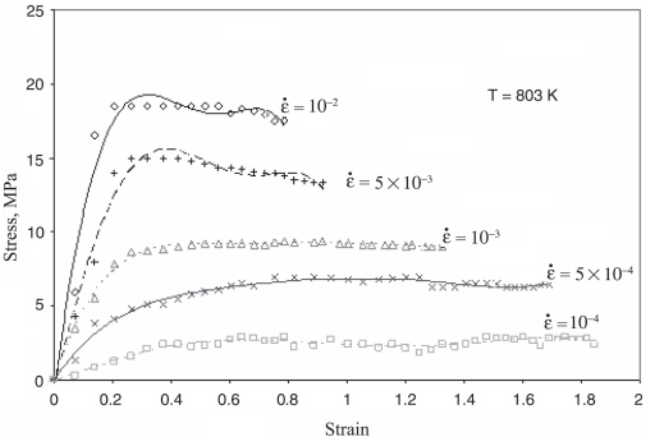

Fig. 4 True stress-strain curves for the 7475 Al alloy at 803 K and five different strain rates

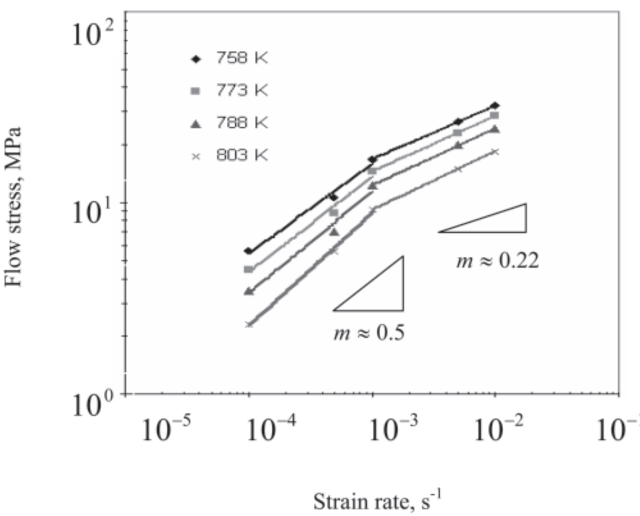

Fig. 5 Stress dependence of the strain rate at $\varepsilon = 0.45$ at various temperatures

rates (superplastic region) to $m \approx 0.22$ at high strain rates (dislocation creep region). The corresponding change in the stress exponent n ($n = 1/m$) is from a value of $n \approx 2$ at low strain rates to $n \approx 4.5$ at high strain rates. It is obvious that the superplastic region lies in the strain rate range of 10^{-4} to 10^{-3} s^{-1}, where the strain rate sensitivity m is in the range of $0.4 \leq m \leq 0.7$. The value of n at high strain rates is similar to that observed in large-grained Al-Zn (Ref 12) of similar composition that was tested at high temperatures.

3.3 Apparent Activation Energy

The apparent activation energy Q is calculated using the following equation (Ref 2):

$$Q = -R\left[\frac{\partial(\ln\dot{\varepsilon})}{\partial\left(\frac{1}{T}\right)}\right]_{\sigma} \qquad \text{(Eq 2)}$$

As stated above, the deformation behavior is divided into two regions. Figure 6 depicts the values of strain rate versus (1000/

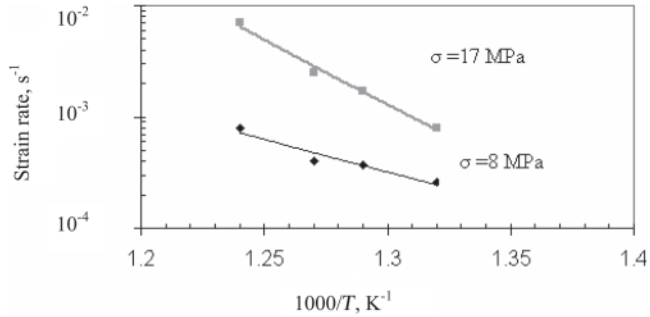

Fig. 6 Temperature dependence of the strain rate under constant stress

T) at constant stress for the two deformation regions. For the superplastic region ($\sigma = 8$ MPa), the value of the apparent activation energy is 126 kJ mol^{-1}, while for the dislocation creep region ($\sigma = 17$ MPa) the calculated value of Q is equal to 168 kJ mol^{-1}. The value of Q in the superplastic region is less than that of self-diffusion in pure aluminum ($Q_{s\text{-}d} = 142$ kJ mol^{-1}) (Ref 13) but is rather similar to the activation for the diffusion of Zn in pure aluminum. The activation energy for the diffusion of Zn in Al-5%Zn was reported to be 30.9 kcal mol^{-1} (corresponding to a value of 129.5 kJ mol^{-1}) (Ref 14). On the other hand, at high strain rates (dislocation creep region), Q is close to that for the self-diffusion of pure aluminum. Under these conditions, the value of n is equal to 4.5, which is similar to that reported for pure aluminum (Ref 15, 16), suggesting that the dislocation climb is the rate-controlling process.

The superplastic deformation mechanism is usually assumed to be controlled by grain boundary sliding. This mechanism has an activation energy $Q_{g.b}$ lower than that of lattice self-diffusion. The dislocation mechanism at high temperatures is diffusion-controlled, so that $Q_{g.b}$ is on the order of 0.6 of the Q observed at high strain rates (Ref 2). The measured $Q_{g.b}$ value is 126 kJ mol^{-1}, which is about 0.75 of the measured value at high strain rates (i.e., the dislocation creep region). This agreement is not unsatisfactory.

3.4 Threshold Stress

To examine the possibility that a threshold stress, σ_0, exists during the superplastic behavior of the present 7475 Al, the data points in this region are plotted as σ versus $\dot{\varepsilon}^m$ ($m = 0.5$) on a double linear scale, as shown in Fig. 7. It is seen that the datum points for each temperature fall on a straight-line segment, the extrapolation of which to zero strain rate passes approximately through the origin, giving a zero value for the threshold stress σ_0.

3.5 Constitutive Equation

The high-temperature deformation behavior of 7475 Al may, in general, arise from the operation of different mechanisms that act either independently or in a sequential manner, where the fastest mechanism controls the deformation behavior for independent processes and the slower mechanism controls the behavior in sequential processes.

The Backofen equation, $\sigma = k\dot{\varepsilon}^m$, was first introduced to describe material behavior in the superplastic region. Several researchers have proposed different constitutive equations corresponding to different situations. A recent article by Xing et

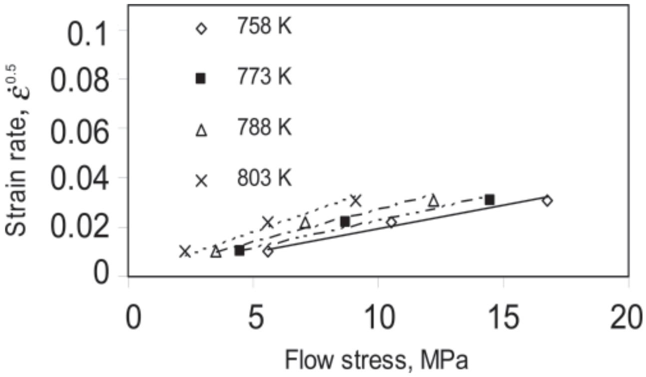

Fig. 7 A linear plot of $\dot{\varepsilon}^{0.5}$ versus flow stress at various temperatures

al. (Ref 17) gives a review of the recent developments of the mechanics of superplasticity and some of its applications. However, the flow behavior of superplastic material is generally described by the Dorn equation in the following form:

$$\dot{\varepsilon} = B\left(\frac{DGb}{kT}\right)\left(\frac{b}{d}\right)^{p}\left(\frac{\sigma - \sigma_0}{G}\right)^{n} \quad \text{(Eq 3)}$$

where D is the diffusion coefficient that controls the deformation process according to:

$$D = D_0 \exp(-Q/RT) \quad \text{(Eq 4)}$$

From Eq 3, any high-temperature deformation process is completely defined by finding the appropriate values for the parameters, B, σ_0, p, n ($n = 1/m$), and Q. Comparison between the experimental values of these parameters and those established for basic deformation mechanisms may lead to the identification of the rate-controlling process.

Equation 3 can be put in the form:

$$B = \left(\frac{\dot{\varepsilon}kT}{DGb}\right)\left(\frac{b}{d}\right)^{-p} \Big/ \left(\frac{\sigma - \sigma_0}{G}\right)^{n} \quad \text{(Eq 5)}$$

The values of the parameters p, n, σ_0, and Q, as determined in the present investigation, are: $p = 2$ (Ref 18, 19); $n = 2$ ($n = 1/m$); $\sigma_0 = 0$; and $Q = 126$ kJmol^{-1}. The value of the shear modulus G in the present temperature range is taken as 22 GPa (Ref 20). Having determined the superplastic parameters, the constant B can be evaluated. Figure 8 shows the relationship between $(\dot{\varepsilon}kT/DGb)(b/d)^{-2}$ and $(\sigma/G)^2$ for the 7475 Al on double logarithmic scales for all temperatures. It is noticed that the relationship can be strictly represented by a straight-line segment having a slope of unity. Using regression analysis, the value for the constant B was calculated as 1.48×10^{10}. As a result, the constitutive equation for the 7475 Al in the superplastic region can be expressed as:

$$\dot{\varepsilon} = 1.48 \times 10^{10}\left(\frac{DGb}{kT}\right)\left(\frac{\sigma - \sigma_0}{G}\right)^{n}\left(\frac{b}{d}\right)^{p} \quad \text{(Eq 6)}$$

It is worth mentioning that the above equation is valid for the temperature range 753 to 803 K, and for strain rates between 10^{-3} and 10^{-4} s^{-1}.

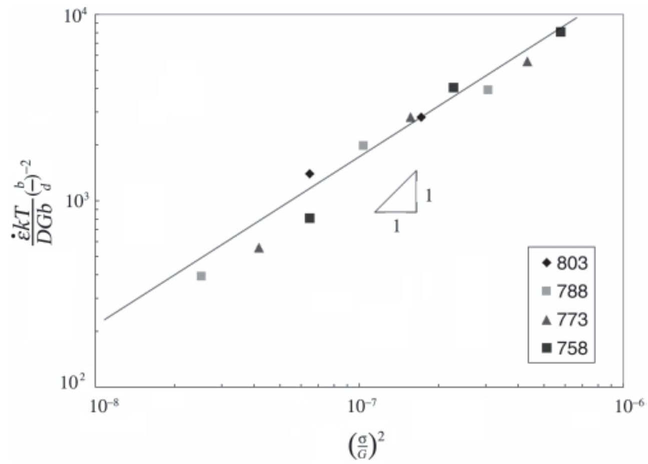

Fig. 8 Relationship between $\left(\frac{\dot{\varepsilon}kT}{DGb}\right)\left(\frac{b}{d}\right)^{-2}$ versus $\left(\frac{\sigma}{G}\right)^{2}$ at different temperatures

4. Conclusions

- Tensile tests were performed on 7475 Al at 753, 773, 788, and 803 K, and at initial strain rates of 10^{-4}, 5×10^{-4}, 10^{-3}, 5×10^{-3}, and 10^{-2} s^{-1}. It was found that at a constant temperature the strain hardening increases as the strain rate increases. It was also found that at a constant strain rate, the flow stress decreases with increasing temperature.
- The deformation behavior under the present experimental conditions is divided into two regions. The high-stress region (dislocation creep), where $m \approx 0.22$, occurs at initial strain rates above 10^{-3} s^{-1}, while the low-stress region (superplastic region), where $m \approx 0.5$, occurs at strain rates below 10^{-3} s^{-1}. The apparent activation energies for the two regions are 168 and 126 kJmol^{-1}, respectively.
- A constitutive equation for the superplastic deformation region was determined that gives the steady-state flow stress as a function of strain rate, strain rate sensitivity, grain size, and temperature.

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