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Dynamic softening behaviors of 7075 aluminum alloy

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Abstract: The dynamic softening behaviors during hot deformation of 7075 aluminum alloy were studied by isothermal hot compression tested at temperatures of 250, 300, 350, 400 and 450 ℃ and strain rates of 0.01, 0.1, 1 and 10 s^{-1} on Gleeble1500. The results show that the temperature changes have a significant effect on the dynamic softening rate. It is indicated that the considerable dynamic softening rate associated with dynamic recrystallization leads flow stress value decreasing gradually. A group of coefficients needed by the phenomenological constitutive model containing a softening ratio item were calculated by the multiple linear regression method. The optical microstructures show that the grains of billets compressed become more and more refined with strain rate increasing as well as the degree of dynamic softening and work-hardening higher. The phenomenological constitutive description of 7075 aluminum alloy can accurately describe the relationships among flow stress, temperature, strain rate, strain and dynamic softening, and offer the basic model for plastic forming process simulation.

Key words: 7075 aluminum alloy; flow stress; constitutive model; softening

1 Introduction

Aluminum and its alloys have some advantageous properties that make them an excellent choice for a number of applications. The complex changes in metallurgical structures which occur during multistage hot deformation, such as hot-rolling and hot-forging, results from the balance achieved between work hardening and softening. Utilization of the restoration mechanism during and after processing to provide suitable flow stress requires knowledge of how they respond to each control parameter, including dynamic deformation temperature, strain and strain rate[1]. Usually, the degree of dynamic softening is quantificationally determined by the relative softening or a quasistatic softening technique. Static fractional softening has been determined by three different methods, namely, the offset-stress, back-extrapolation stress and strain-recovery methods[2–5]. However, fundamental knowledge about these is rarely reported for aluminum than that for steel[6–8].

In this study, a phenomenological constitutive model which can accurately describe the relationships among flow stress, temperature, strain and strain rate of the dynamic softening during deformation. A multiple linear regression is helpful to establish the model. A softening item or the softening ratio results in a mutual constitutive description which offers the basic model for plastic forming process simulation. The purpose of this is to gain a fundamental understanding of the dynamic and static softening behaviors during hot deformation of aluminum alloys, so as to carefully control processing variables in tandem hot-rolling and hot-forging of aluminum alloys.

2 Experimental

The chemical compositions of 7075 aluminum alloy used in this study were Zn 5.5%, Mg 2.2%, Cr 2.2%, Cu 1.7%, Si 0.4%, Fe 0.3%, Mn 0.1%, Al 87.6% (mass fraction).

A computer-controlled, servo-hydraulic Gleeble 1500 machine was used for compression testing. It can be programmed to simulate both thermal and mechanical industrial process variables for a wide range of hot-deformation conditions[9]. The specimens were heated to the deformation temperature at heating rate of 1 ℃/s and held at the temperature for 180 s by thermocoupled-feedback-controlled AC current. The homogenized ingot was scalped to diameter 10 mm and height 12 mm with grooves on both sides filled with

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machine oil mingled. Graphite powder was used as lubrication to reduce friction between the anvils and specimen during isothermal hot compression tests at 250, 300, 350, 400 and 450 ℃ and strain rates of 0.01, 0.1, 1 and 10 s^{-1}.

3 Results and discussion

3.1 Stress-strain behavior

The true compressive stress—strain curves of 7075 alloy deformed at different temperatures and strain rates are shown in Fig.1. The flow stress as well as the shape of the flow curves is sensitively dependent on temperature and strain rate[10]. For all of specimens, after initial yielding, the flow stress decreases monotonically with different softening rates. Comparing the curves with one another, it is found that, for a specific strain rate, the flow stress decreases markedly with temperature decreasing. Further, the temperature changes have a significant effect on the dynamic softening rate.

The degree of dynamic softening is considerably smaller during deformation at the higher temperature of 450 ℃. At this temperature, a nearly horizontal line is obtained, which suggests that the rate of thermal softening is balanced by the rate of work- hardening. In contrast, for a fixed temperature, the flow stress generally increases with the strain rate increasing due to the increase of dislocation density and the dislocation multiplication rate. When the flow stress relative to the temperature is compared to the flow stress relative to the strain rate, there is no doubt that the effect of temperature on the flow stress is more pronounced than that of the strain rate on flow stress. Flow softening appears more clearly with the temperature decreasing, especially when the specimen is loaded at a high strain rate.

3.2 Phenomenological constitutive model

In order to understand the plastic behaviour of 7075 aluminum alloy, flow curves obtained in the compression tests are analyzed to determine a material constitutive equation. For this goal, the flow stress value at the curve maximum is correlated to the strain rate and temperature[11–12]. CHENG et al[13] and LIU et al[14] proposed the following equation with a term for the aluminum specific work softening characteristic.

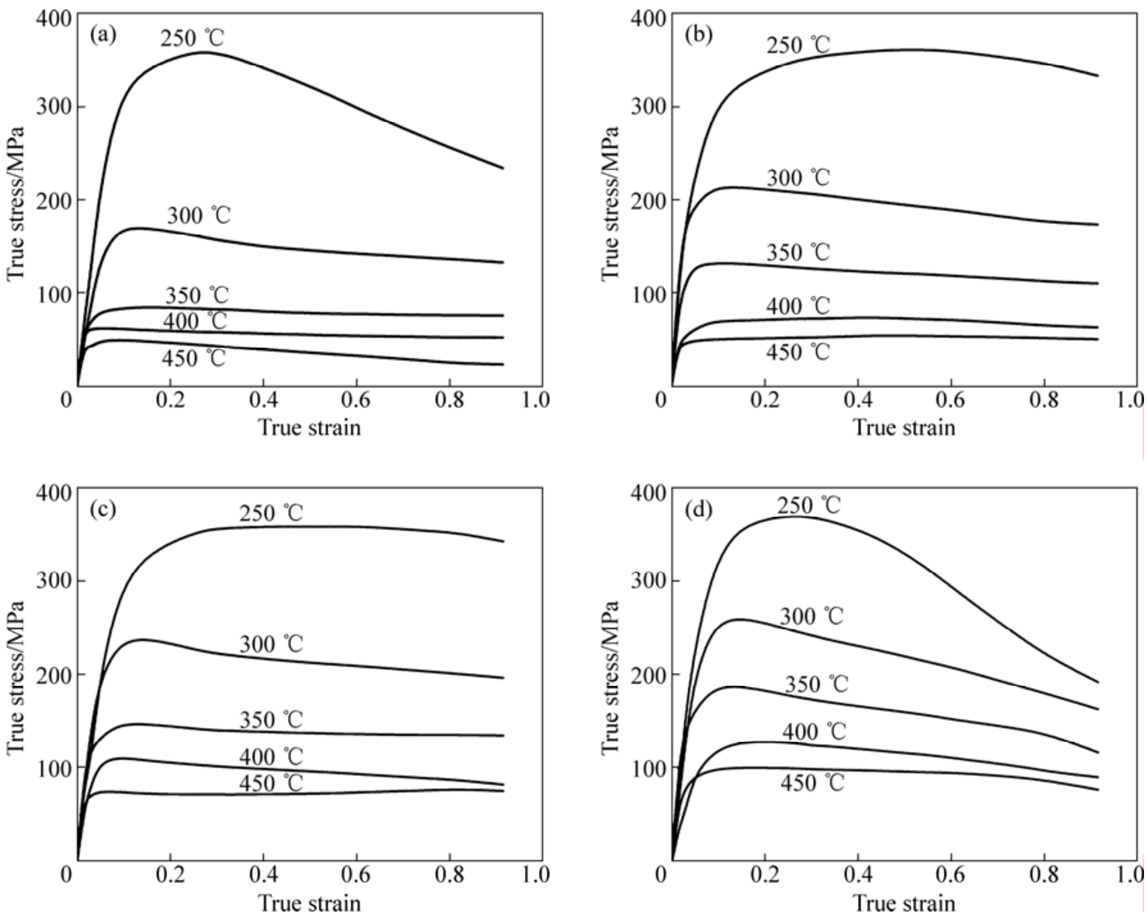

Fig.1 True stress—strain curves by Gleeble 1 500 at different temperatures and strain rates: (a) $\dot{\varepsilon}$=0.01 s^{-1}; (b) $\dot{\varepsilon}$=0.1 s^{-1}; (c) $\dot{\varepsilon}$=1 s^{-1}; (d) $\dot{\varepsilon}$=10 s^{-1};

$$\sigma = C\varepsilon^n \dot{\varepsilon}^m \exp(bT + s\varepsilon) \tag{1}$$

where C is constant; σ is the flow stress; ε is the strain; n is the work-hardening coefficient; $\dot{\varepsilon}$ is the strain rate; m the strain-rate sensitivity index; T is the temperature; s is an exponent for the work softening influence; b is constant.

Although the physical mean of softening items is not clear, it represents the softening ratio of aluminum alloy with the strain increasing. So, in the present study, the softening item is described as s=d(lnσ)/dε.

According to Eq. (1), the following equation can be obtained.

$$\ln\sigma = \ln C + n\ln\varepsilon + m\ln\dot{\varepsilon} + bT + s\varepsilon \tag{2}$$

1) Calculation of m value

It is assumed that the value of ln C+$n$ln ε+bT+$s\varepsilon$ at certain temperature and strain is a constant of K_1. The following formula can be obtained from Eq.(2).

$$\ln\sigma = m\ln\dot{\varepsilon} + K_1 \tag{3}$$

Then, $m = \mathrm{d}(\ln\sigma)/\mathrm{d}(\ln\dot{\varepsilon})$. The linear relationships between ln σ and ln $\dot{\varepsilon}$ are fitted as shown in Fig.2, and the result of m value is obtained as an average value of 0.089 9.

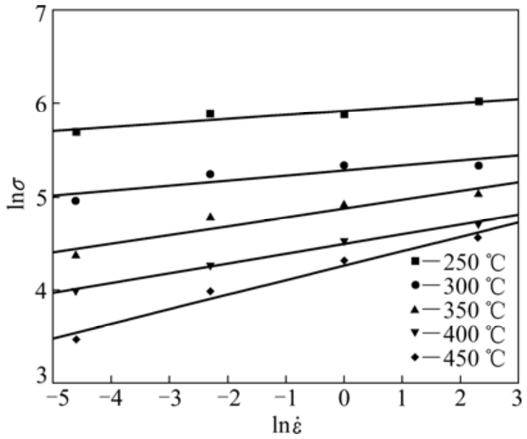

Fig.2 Linear relationship between ln σ and ln $\dot{\varepsilon}$.

2) Calculation of n value

The relationships between true stress and true strain at certain temperature and strain rate are shown in Fig.3. It can be seen from Fig.3 that the values of stress under the uniform deformation stage are almost on the same line, in which the slope is equal to the value of strain hardening exponent. So, the slopes corresponding to the different temperatures and various strain rates can be obtained as shown in Table 1. The mean value of 0.353 5 for these slopes is accepted as n value.

3) Calculation of b value

It is assumed that the value of ln$C$+$n$lnε+ $m$ln $\dot{\varepsilon}$ +$s\varepsilon$ at a condition with certain strain and strain rate is a constant of K_2. The following formula can be obtained from Eq. (2).

$$\ln\sigma = bT + K_2 \tag{4}$$

From Fig.3, a nearly horizontal line of true stress and true strain can be obtained as ln ε varies from −2.0 to 0. Especially, when ln ε=−0.748 7, the ln σ depends on temperature greatly. The linear relationships between ln σ and T at different strain rates are shown in Fig.4. The mean value −0.008 6 of these slopes is accepted as b value.

Table 1 n value at different temperatures and strain rates

t/℃	0.01 s^{-1}	0.1 s^{-1}	1 s^{-1}	10 s^{-1}
250	0.600 3	0.517 5	0.563 2	0.560 2
300	0.486 3	0.357 2	0.511 6	0.626 7
350	0.180 2	0.291 2	0.208 9	0.269 1
400	0.068 6	0.216 0	0.422 4	0.590 4
450	0.120 6	0.089 8	0.154 6	0.235 9

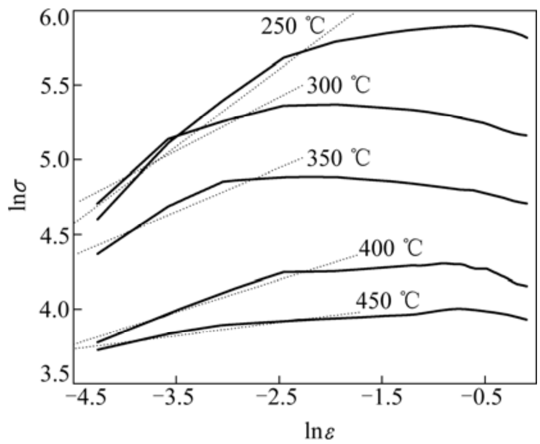

Fig.3 ln σ— ln $\dot{\varepsilon}$ curves at different temperatures and strain rate of 0.1 s^{-1}

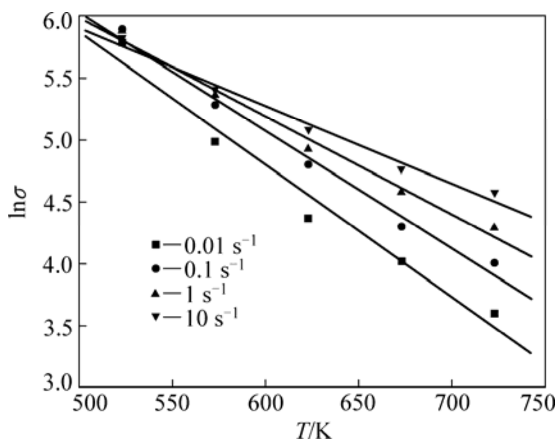

Fig.4 Linear relationship between ln σ and T

4) Calculation of s value

It is assumed that the value of ln$C$+$n$lnε+bT at certain temperature and strain rate is a constant of K_3, then

$$\ln\sigma = n(\ln\varepsilon) + s\varepsilon + K_3 \quad (5)$$

When $\varepsilon = e^{-1}$

$$\ln\sigma_{e^{-1}} = -n + se^{-1} + K_3 \quad (6)$$

When $\varepsilon = e^{-2}$

$$\ln\sigma_{e^{-2}} = -2n + se^{-2} + K_3 \quad (7)$$

So, the following formula can be obtained from Eqs. (6) and (7):

$$s = [\ln(\sigma_{e^{-1}} / \sigma_{e^{-2}}) - n] / (e^{-1} - e^{-2}) \quad (8)$$

According to Eq.(8), the softening exponent at different temperatures and strain rates can be worked out as shown in Table 2. The mean value of −1.1 is accepted as s value.

5) Calculation of C value

So, the C value calculated from Eq. (1) according to the above results is 252 637. Then, the following model can be obtained

$$\sigma = 252637\varepsilon^{0.0899}\dot{\varepsilon}^{0.3535}\exp(-0.0086T - 1.1\varepsilon) \quad (9)$$

Table 2 *s* value at different temperatures and strain rates

t/℃	0.01 s^{-1}	0.1 s^{-1}	1 s^{-1}	10 s^{-1}
250	−1.066 7	−1.054 2	−1.021 1	−1.116 0
300	−1.289 0	−1.277 0	−1.386 9	−1.258 0
350	−1.240 7	−1.216 6	−1.245 4	−1.270 5
400	−1.240 0	−1.095 1	−1.306 2	−1.232 5
450	−1.237 9	−1.155 4	−1.101 7	−1.210 3

3.3 Grain refinement

Fig.5(a) shows the initial microstructure of the casting 7075 ingot. Fig.5(b)−(e) shows the grains of specimens compressed at 250 ℃ and different strain rates. As depicted, the grains of the billet compressed at

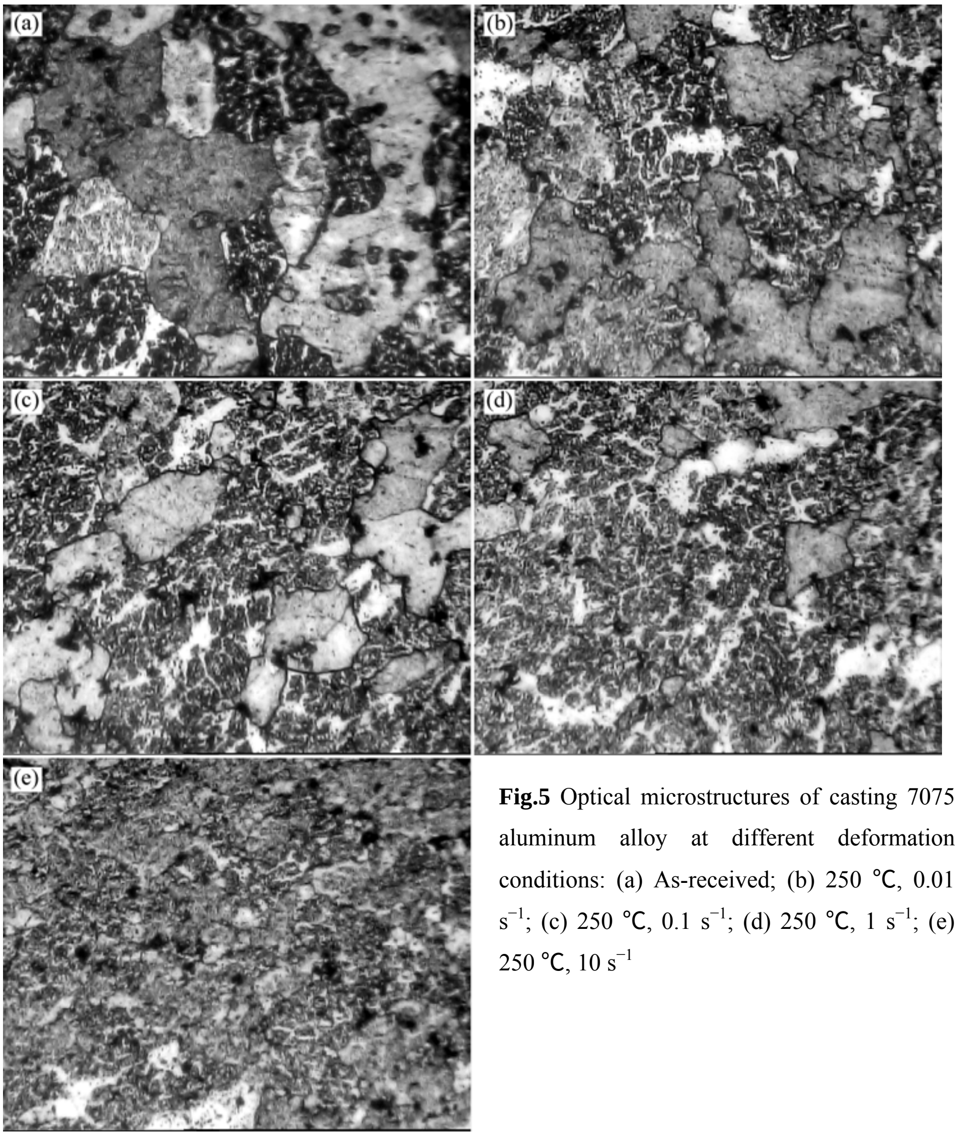

Fig.5 Optical microstructures of casting 7075 aluminum alloy at different deformation conditions: (a) As-received; (b) 250 ℃, 0.01 s^{-1}; (c) 250 ℃, 0.1 s^{-1}; (d) 250 ℃, 1 s^{-1}; (e) 250 ℃, 10 s^{-1}

each strain rate become refined relative to the initial.

Furthermore, the grains of the specimens compressed become more and more refined with the strain rate increasing. This is due to the increasing dynamic recrystallization. But it doesn't mean that the flow stress at higher strain rate is lower. In fact, it is opposite for the reason that the degree of dynamic softening and work-hardening become higher as same as the strain rate higher.

4 Conclusions

1) The true compressive stress—strain curves of 7075 aluminum alloy deformed at different temperatures and strain rates were obtained. The dynamic softening rate sensitively depend on temperature and strain rate depicted.

2) The formula of flow stress for 7075 aluminum alloy during compression tests is constituted through mutual constitutive description model containing softening ratio item.

$$\sigma = 252\ 637\varepsilon^{0.089\ 9}\dot{\varepsilon}^{0.353\ 5}\exp(-0.008\ 6T - 1.1\varepsilon)$$

3) The grains of the billet compressed at each strain rate become refined relative to the initial. The grains of the specimens compressed become more and more refined with the strain rate increasing.

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