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Rheological behavior and constitutive equations of 7075 aluminum alloy sheet at elevated temperatures

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Rheological behavior and constitutive equations of 7075 aluminum alloy sheet at elevated temperatures

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Abstract. In order to investigate the rheological behavior of 7075 aluminum alloy sheet at elevated temperatures and used in numerical simulation, hot tensile tests by Gleeble 3500 were conducted.at temperatures of 350°C /400 °C/ 450°C and strain velocity of 0.01 s^{-1}/0.1 s^{-1}/1 s^{-1}. In this paper, the rheological behavior of 7075 aluminium alloy sheet at high temperature is studied, and two constitutive equations are used to describe the rheological behavior of the material. The results show that the deformation temperature has a significant effect on flow stress .During the whole process of tensile deformation, both work hardening and dynamic recovery affect the flow stress. The Cobb-Simonds constitutive equation has good predictive ability.

1. Introduction

Under the developmenttrend of energy conservation, environmental protection and lightweight, aluminum alloys, such as the 6XXX and 7XXX series, more and more widely used in automobile industry [1]. So hot stamping of heat-treatable aluminum alloy sheet was developed by Lin et al. [2]. In this technology, the sheets are formed at high temperatures, Therefore, it is necessary to understand the rheological behavior of aluminium alloy sheets,and the rheological behavior is often characterized through constitutive equations. In addition, the constitutive equations can be used in numerical simulations.

The flow behavior of aluminium alloy at high temperature is usually described by constitutive equation [3-7], but most of them are complicated and need many experiments to obtain the parameters in the constitutive equations. In this work, the rheological behavior of 7075 aluminum alloy sheet at elevated temperatures was studied and two constitutive equations were used to describe the material rheological behavior. It will help to obtain more accurate numerical simulation results.

2. Experimental

The material used in this experiment is 7075-T6 aluminum alloy, and the main composition(shown in Table 1) of the material were detected by optical emission spectroscopy with PDA-7000.

Table 1 Main chemical compositions of 7075-T6 aluminum alloy [wt. %]

Chemical elements	Mg	Zn	Mn	Cu	Fe	Cr	Si	Al
Contents	3.161	5.895	0.1778	1.63	0.1309	0.2113	0.03	Remain

The hot tensile tests was performed with a Gleeble 3500 thermo-mechanical simulator .The shape and dimensions of the specimen are shown in Fig.1. The tensile direction was along the rolling direction of the sheet. Experimental process is shown in Fig. 2. Firstly, The experimental samples were heated to 480 C by 2 C/s heating speed, and the solid solution heat treatment was completed by standing for 10 minutes.The samples were cooled by 20°C / s cooling rate to 450, 400 or 350°C for 10 seconds. Finally, the samples were stretched to fracture on a tensile testing machine at rates of 0.01, 0.1 or $1s^{-1}$, and then quenched immediately to20°C.

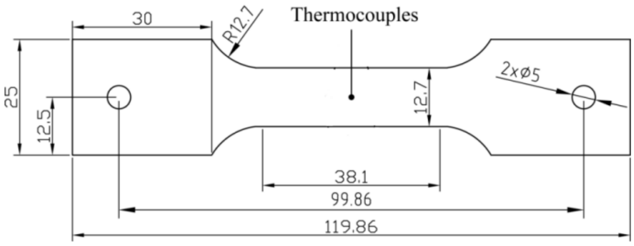

Figure.1 Experimental pattern size (unit: mm)

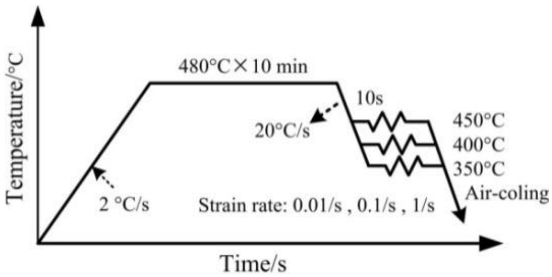

Figure.2 Experimental process

3. Results and discussions

3.1. High temperature true stress-true strain curves

The true stress-true strain curves of 7075-T6 aluminium alloy are obtained by modifying the tensile tests at different deformation temperatures and strain rates. The curves are shown in Fig. 3. It can be seen that the deformation temperature has significant influence on the rheological stress. When the strain rate was constant, the rheological stress decreased with the increasing of the temperature, meaning the deformation resistance of the material decreased. When the strain rate is 0.01/s, the maximum stress decreases with the increase of temperature. When the temperature rises from 350 to 450 degrees C, the maximum stress decreases from 76 MPa to 36 MPa; when the strain rate is 0.1/s, the maximum stress decreases from 112 MPa to 56 MPa; when the strain rate is 1/s, the maximum stress decreases from 148 MPa to 86 MPa. At a certain deformation temperature, the rheological stress was higher when the strain rate was larger.

During the whole process of tensile deformation, the work hardening and dynamic recovery both affected the rheological stress. The hardening behavior was dominated when the deformation temperature was low and strain rate was larger. Conversely, the dynamic recovery was dominated. In addition, the strain rate had more significant effects on work hardening. In the stable stage, the work hardening and dynamic recovery reached a balanced state, where the rheological stress remained constant or had a very low growth level

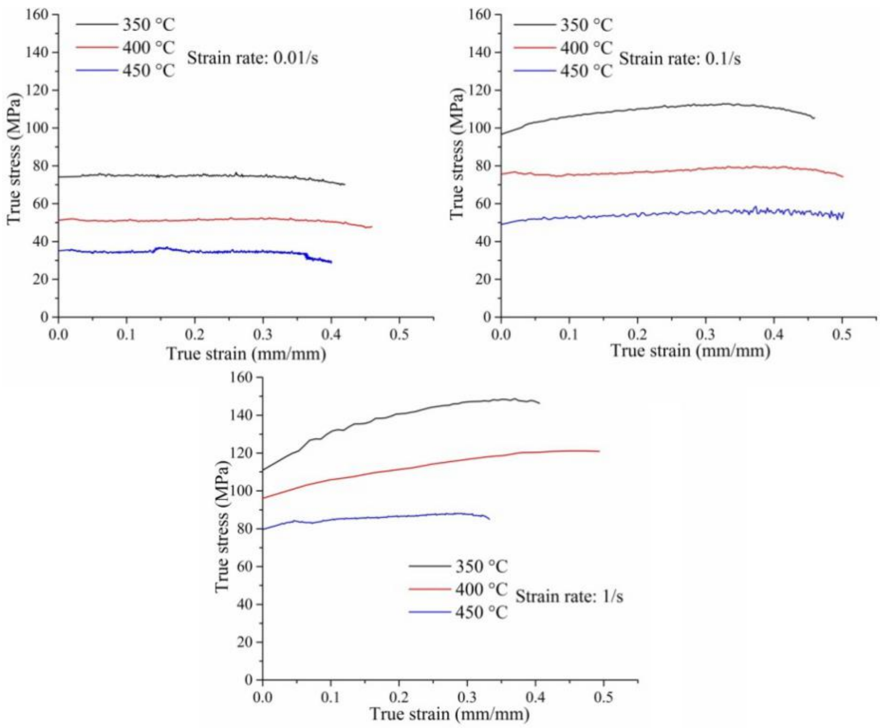

Figure.3 true stress-strain curves of 7075-T6 at different strain rates and deformation temperatures

3.2. Constitutive equations

3.2.1 Modified Arrhenius Constitutive Equation. Equation (1) exists:

$$A\left[\sinh\left(\alpha\sigma\right)^{n}\right]=\dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \tag{1}$$

And the strain correction type Arrhenius constitutive equation can be described as Equation (2):

$$\sigma=\frac{1}{\alpha}\operatorname{arcsin\,h}\left[\exp\left(\frac{\ln\dot{\varepsilon}-\ln A+Q/RT}{n}\right)\right] \tag{2}$$

Where σ is the rheological stress (MPa).The coefficients were strain-dependent. The calculation of the coefficients are complicated and the details could be referred to [8, 9]. Finally, five-order polynomial coefficients as follows:

$$\beta=0.10960-0.33296\varepsilon+0.83044\varepsilon^{2}+3.53166\varepsilon^{3}-21.55873\varepsilon^{4}+28.08671\varepsilon^{5} \tag{3}$$

$$\alpha=0.01363-0.01282\varepsilon+0.13949\varepsilon^{2}-0.82430\varepsilon^{3}+2.17074\varepsilon^{4}-2.03913\varepsilon^{5} \tag{4}$$

$$n=5.99473-13.41233\varepsilon-18.96346\varepsilon^{2}+602.21199\varepsilon^{3}-2309.26215\varepsilon^{4}+2644.68803\varepsilon^{5} \tag{5}$$

$$Q=1.65633E5-1.86576E5\varepsilon+6.41486E5\varepsilon^{2}-1.47315E6\varepsilon^{3}+3.65965E6\varepsilon^{4}-6.24898E6\varepsilon^{5} \tag{6}$$

$$\ln A=26.63659-34.43410\varepsilon+136.41445\varepsilon^{2}-440.70914\varepsilon^{3}+1223.78242\varepsilon^{4}-1734.80649\varepsilon^{5} \tag{7}$$

3.2.2 Cowper-Symonds constitutive equation. Cowper-Symonds model is applied to the numerical simulation of metal hot forming [10]. The model is shown in Formula (8).

$$\sigma = \left(\sigma_0 + B\varepsilon_{\mathrm{pl}}^{n}\right)\left[1+\left(\dot{\varepsilon}/C\right)^{1/P}\right] \tag{8}$$

Obviously, temperature is not included in the model, and all parameters are temperature dependent. The calculation of the coefficients was done by nonlinear fitting and their values are shown in Table 2.

Table 2 The coefficients for the Cowper–Symonds model

Temp. (°C)	Strain rate (s^{-1})	σ_0	B	n	C	P
350	0.01	73.14224	-56.45747	3.14724	4.81385	1.73491
	0.1	93.00339	20.49347	0.22160	9.42187	1.06849
	1	102.96086	62.04358	0.45263	400.20220	1.96971
400	0.01	49.29278	-168.05881	5.19868	6.51623	2.10864
	0.1	74.06259	6.32787	0.50339	18.95898	0.25746
	1	95.60275	41.27818	0.59100	145.28447	0.66189
450	0.01	30.61806	-11460.51113	8.40095	122.90826	4.78718
	0.1	47.62507	9.50168	0.27319	1.57220	0.54140
	1	78.80804	13.18400	0.36961	7.07776	0.34637

3.2.3 Prediction capability of the two constitutive equations. In this paper, two constitutive equations are used, so it is necessary to evaluate their predictive ability of flow stress, mainly through statistical methods. The results are shown in Figure 4 The Cowper-Symonds constitutive equation can not only predict the flow stress in the whole strain range, but also has better predictive ability than the Arrhenius constitutive equation based on strain correction. The predictive deviation of the modified Arrhenius constitutive equation is larger when it approaches the maximum strain.The values of the statistical parameters are shown in Table 3. The AARE and RMSE values of the revised Arrhenius constitutive equation are higher, R values are lower and the structure is complex, so the solving process is cumbersome, and the corresponding subroutines need to be written to be used in numerical simulation. Generally speaking, the Cowper-Symonds constitutive equation has better prediction ability, and the solving process is simple, and it can be more convenient to apply in numerical simulation.

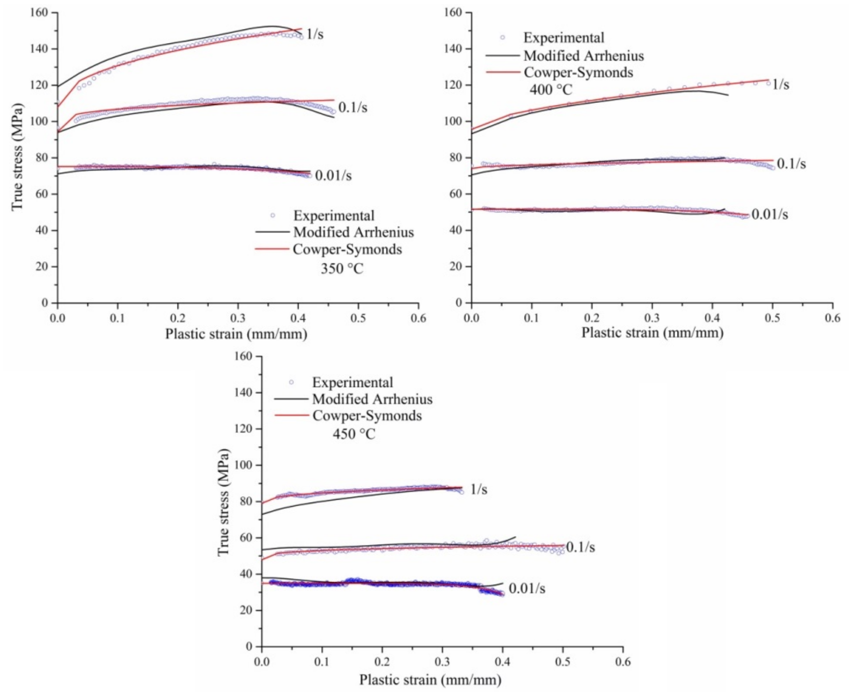

Figure. 4 comparison of predicted and experimental values of two constitutive equations

Table 3 The statistical parameters of the prediction capability of the two constitutive equations

Constitutive model	R	AARE	RMSE
Arrhenius based on strain correction	0.9976	3.17%	2.0317
Cowper–Symonds	0.9995	1.25%	0.8821

4. Conclusions

4.1. Deformation temperature has a significant effect on flow stress. When the strain rate is constant, the flow stress decreases with the increase of temperature. When the strain rate is 1/s, the maximum stress decreases from 148 MPa to 86 MPa, and at a certain deformation temperature, the larger the strain rate, the greater the flow stress.

4.2. During the whole process of tensile deformation, the work hardening and dynamic recovery both affected the rheological stress. The hardening behavior was dominated when the deformation temperature was low and strain rate was larger. Conversely, the dynamic recovery was dominated.

4.3. Both constitutive equations have good prediction capability. But the Cowper-Symonds constitutive equation has better prediction capability, and the solution process is simple and can be applied to numerical simulation more conveniently.

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