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Feature of flow stress of aluminum sheet used for can during hot compression①

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[Abstract] The flow stress feature of aluminum sheet used for pressure can during plastic deformation at elevated temperature was studied by isothermal compression test using Gleeble 1 500 dynamic materials testing machine. The experimental results show that the steady state deformation is remarkable when the material is deformed in the temperature range of 350 ~ 500 ℃ at strain rates within the range of 10^{-2} ~ $10.0\ s^{-1}$. The material is sensitive to positive strain rate. A hyperbolic sine relationship is found to correlate well the flow stress with the strain rate, and an Arrhenius relationship with the temperature. Semi-empirical constitutive equations of the flow stress are derived from all experimental data for tested material during plastic deformation at elevated temperature by polyelement linear regression analysis.

[Key words] aluminum sheet used for can; high temperature plastic deformation; compression; flow stress

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1 INTRODUCTION

For the purpose of meeting the market needs for various agents packaged with can, the high speed extrusion forming new technology used in aluminum spraying can (or called pressure can) has been imported into our country in the late 1980s. Aluminum piece used for making can was all dependent on importing from abroad before it was successfully developed and put into industrial production by Professor Kang Jixing's research group. At present, the behavior and rule of high temperature deformation and hot working processing parameter of aluminum piece are short of systematical researches. Therefore, the stability of quality and further improvement of properties of the material are restricted, thus influencing the course of the application and spreading of the piece.

In this paper, the flow stress feature of aluminum piece during plastic deformation at elevated temperature is studied by isothermal compression test. Semi-empirical constitutive equations for high-temperature flow stress of the material are established by means of linear regression analysis.

2 EXPERIMENTAL

Commercial aluminum ingots with the purity above 99.85% (mass fraction) were used as the raw materials, the tested aluminum sheet with the composition of Al-0.108Fe-0.031Si-0.019Ti was prepared by melting and purifying in the reverberatory furnace according to the present production technology of aluminum piece made in our country. Solid cylinder compression specimens, with flat grooves in both ends, with the gauge dimension of 10 mm in diameter and 15 mm in height were machined from the 40 mm × 110 mm × 500 mm ingots poured in metal mould. The isothermal compression test at elevated temperature was carried out using Gleeble 1 500 dynamic materials testing machine.

The processing and calculation of the data and regression analysis were carried out with the applying software, MATLAB[1].

3 RESULTS AND DISCUSSION

3.1 Feature of true stress-strain curves

The practically measured true stress-strain curves of tested material during isothermal compressive deformation at elevated temperature for all testing conditions are shown in Fig.1. The curves show the following results.

1) There are two true stress-strain curves during hot compression deformation (i.e dynamic recovery and dynamic recrystallization).

2) There are the remarkable characteristics of the steady-state flow stress in the temperature range of 350 ~ 500 ℃ at strain rates within the range of 10^{-2} ~ $10.0\ s^{-1}$.

3) Under the condition of the same temperature, the true stress increases as the strain rate rises, which

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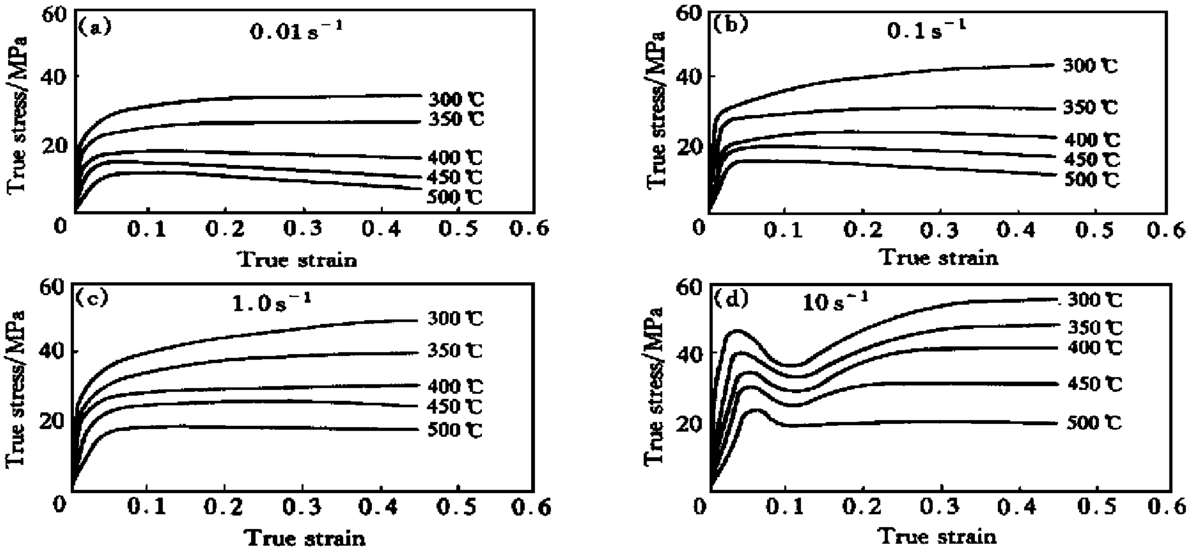

Fig.1 Compressive true stress-strain curves of aluminum sheet at various deformation conditions

implies that the material is sensitive to positive strain rate under the experimental conditions. On the other hand, under the condition of the same strain rate, the true stress decreases as the temperature rises. The mean values of the steady-state stresses modified[2] are listed in Table 1.

Table 1 Mean value of steady-state stress modified during hot deformation for tested material

Strain rate ε/s^{-1}	300 ℃	350 ℃	400 ℃	450 ℃	500 ℃
0.01	32.36	24.50	16.09	12.91	10.90
0.1	39.62	29.66	23.39	17.95	14.04
1.0	47.38	37.12	28.87	23.60	17.08
10.0	52.20	42.01	39.99	28.70	20.32

4) The value of the true strain and true stress corresponding to the onset of the steady-state deformation stage increases with increasing of the strain rate or decreasing of the temperature. Especially at 300 ℃, this value is very larger than that of other temperatures, indicating that at 300 ℃ the working formability of the material is very bad.

(5) When ε is equal to 10.0 s^{-1}, the true stress-strain curves exhibit stress peaks, which reveals that dynamic recrystallization takes place at higher strain rate. It is testified by TEM micrograph of water-quenched specimen (Fig.2).

This result isn't in agreement with the fact that aluminum is a typical dynamic recovery[3~5]. The probable reasons are as follows: high strain rate will lead to increasing of the density of dislocations drastically, and to increasing of the movement rate of dislocations and interfriction between dislocations, thus enlarging the effect of interfriction within the tested material and resulting in higher local rise of deformation temperature. At the same time, the heat caused by the deformation work don't scatter and disappear throughout the deformation body, giving rise to larger heat-insulated effect, thus making the deformation material absorb more deformation energies. These effects above will make the driving force of dynamic recrystallization increases obviously, thus overcoming insufficient driving force of dynamic recrystallization caused by the powerful ability of dynamic recovery of aluminum with high stacking fault energy.

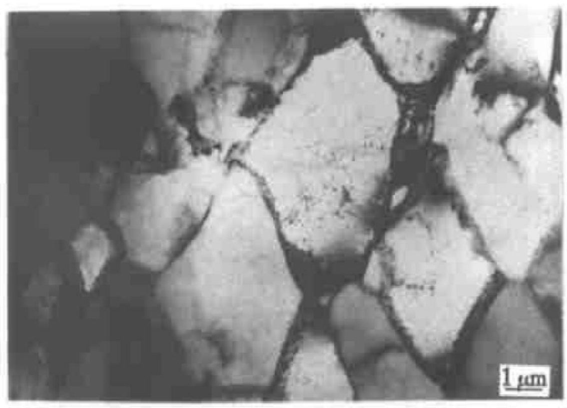

Fig.2 TEM micrograph of water-quenched specimen (ε = 10 s^{-1}, t = 400 ℃)

3.2 Influence of deformation conditions on steady-state flow stress

3.2.1 Influence of strain rate(ε)

The main mathematical expressions have been proposed to describe the relationship between flow stress (σ) and strain rate (ε) for high-temperature steady-state deformation, that is, the simple power relationship, the exponential relationship and the hyperbolic sine relationship[4~10]. Suppose that the relationship between σ and ε of the tested material could satisfy the relationships above, that is

$$\dot{\varepsilon} = A_1 \sigma^{n_1} \quad (1)$$

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma) \quad (2)$$

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^{n} \exp[-Q/RT] \quad (3)$$

where A_1, A_2, A, n_1, β, α, n are experienced constants; $\alpha = \beta/n_1$; R is the gas constant; T is the absolute temperature; Q is the deformation activation energy.

According to data in Table 1, the linear regression analyses are carried out for Eqns.(1), (2) and (3), respectively. The results are shown in Fig.3.

The regression results show that the interrelation between flow stress and strain rate for this material even more satisfies the Arrhenius relationship of the hyperbolic sine form. It implies that the process of plastic deformation at elevated temperature for aluminum sheet also is thermally activated, similar to high-temperature creep of pure aluminum[5~7].

3.2.2 Influence of temperature

Zener-Hollomon parameter (Z) could correlated flow stress to deformation variables as[5~9]

$$\dot{\varepsilon}\exp[Q/RT] = A[\sinh(\alpha\sigma)]^{n} \quad (4)$$

where A is structure factor; n, α is stress exponential, stress-level coefficient, respectively.

If $\dot{\varepsilon}$ is constant, and the value of Q is also constant in the range of experimental temperatures, according to the data in Table 1, the linear regression analysis is carried out for Eqn.(4), the result is shown in Fig.4. The flow stress behavior of aluminum sheet during hot deformation can be described by Z parameter including Arrhenius term, and it also implies that the hot compression of the material is thermally activated.

3.3 Constitutive equations for high-temperature flow stress of tested aluminum sheet

In order to further investigate the inter-dependences of σ, T, ε and $\dot{\varepsilon}$, thus providing the foundation and guide for the calculation of load, and drafting and optimization of the hot working parameters in the course of hot working for aluminum sheet used in can, two forms of constitutive equations[11] are adopted in this paper, i.e.

$$\sigma = a_1 \cdot \varepsilon^{n} \cdot \dot{\varepsilon}^{m} \cdot \exp(-bT) \quad (5)$$

$$\sigma = a_2 \cdot \varepsilon^{n} \cdot \dot{\varepsilon}^{m} \cdot T^{-\gamma} \quad (6)$$

where n and m are the strain-hardening exponent and the strain rate sensitivity coefficient respectively; a_1, a_2, b and γ are all the experienced constants.

Under all experimental conditions, the values of true stresses recorded by the computer of testing machine are modified[2], then, in accordance with the transient stage and the steady-state stage respectively, the corresponding data (σ, T, ε, $\dot{\varepsilon}$) are used in carrying out polyelement linear regression analyses for Eqns.(5) and (6) respectively. The results are as follows:

transient stage

$$\sigma = 1\,384.5\, \varepsilon^{0.198} \cdot \dot{\varepsilon}^{0.094} \cdot \exp(-0.0052\,T) \quad (7)$$

$$\sigma = 2.407 \times 10^{11} \varepsilon^{0.198} \cdot \dot{\varepsilon}^{0.094} \cdot T^{-3.4548} \quad (8)$$

steady-state stage

$$\sigma = 1\,010.8\, \varepsilon^{0.013} \cdot \dot{\varepsilon}^{0.101} \cdot \exp(-0.0053\,T) \quad (9)$$

$$\sigma = 2.688 \times 10^{11} \varepsilon^{0.013} \cdot \dot{\varepsilon}^{0.101} \cdot T^{-3.5297} \quad (10)$$

From equations above one can see that:

1) At the transient stage, the degree of influence of the strain (ε) on the flow stress (σ) is very large. On the other hand, at the steady-state the strain-hardening isn't almost taken on, that is, the degree of influence of the strain (ε) on the flow stress (σ) can be neglected.

2) The value of m at the steady-state stage is larger than that at the transient stage, further indicating that aluminum sheet is a material sensitive to positive strain rate, and the influence of the strain rate ($\dot{\varepsilon}$) on the flow stress (σ) during the steady state deformation is more obvious than that during the transient deformation.

3) The values of γ at two stages are larger than that of other deformation variables, indicating that

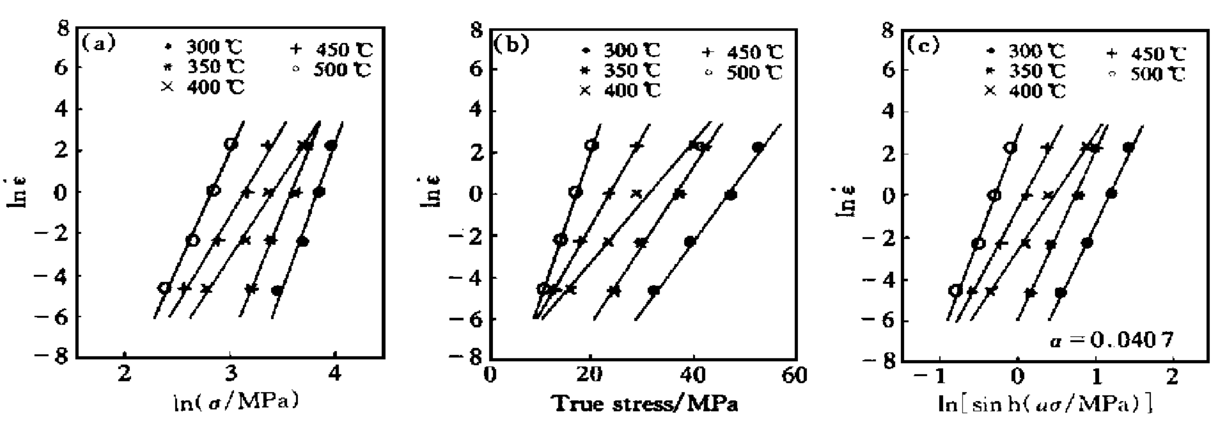

Fig.3 Interdependences of steady-state flow stress (σ) and strain rate ($\dot{\varepsilon}$) of tested aluminum sheet during high temperature deformation

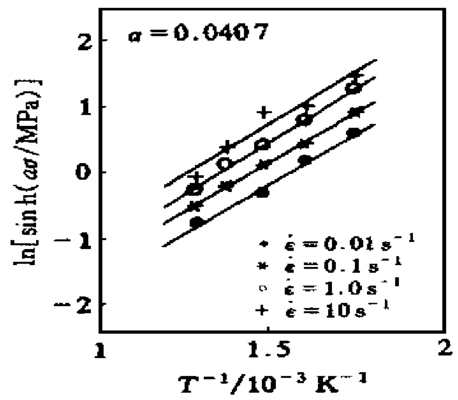

Fig.4 Temperature dependence of flow stress of tested aluminum sheet

the influence of temperature on the flow stress is more remarkable than that of other deformation variables.

4 CONCLUSIONS

1) There is a feature of steady-state flow stress for aluminum sheet used for pressure can during plastic deformation at elevated temperature in the temperature range of 350 ~ 500 ℃ at strain rates with the range of 10^{-2} ~ $10.0\ s^{-1}$. At the same time, when the strain rate exceeds $1.0\ s^{-1}$, the flow stress-strain curves take on the remarkable peak stress.

2) The interdependences of the steady-state flow stress (σ) and strain rate ($\dot{\varepsilon}$) or temperature (T) satisfy a hyperbolic sine relationship or Arrhenius relationship respectively, indicating that the high-temperature plastic deformation of the material is controlled by the thermally-activated process. The material is sensitive to positive strain rate.

3) The semi-empirical equations of the flow stress for this material during hot deformation are derived from experimental data by polyelement linear regression analysis.

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