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Modelling of formula for flow stress of a magnesium alloy AZ31 sheet at elevated temperatures

H. Takuda[a], T. Morishita[a], T. Kinoshita[b] and N. Shirakawa[b]

[a]Department of Energy Science and Technology, Kyoto University,
606-8501 Kyoto, Japan, email: takuda@energy.kyoto-u.ac.jp

[b]Metals & Machinery Department, Technology Research Institute of Osaka Prefecture,
Ayumino 2-7-1, 594-1157 Izumi, Japan, email: kinoshita@tri.pref.osaka.jp

Abstract: The flow stress of a magnesium alloy AZ31 sheet is measured at various temperatures, strains and strain rates, and the relationships between them are analysed. A formula for the flow stress is proposed in a simple form with the work-hardening exponent, *n*, the strain rate sensitivity exponent, *m*, and the parameter, *K*. And they are given with functions of temperature.

Keywords: Magnesium alloy, Flow stress, Sheet metal forming

1. INTRODUCTION

The use of magnesium and its alloys has been limited to a narrow range because of the poor formability. However, they have adequate ductility at elevated temperatures between 150 and 300°C. Therefore, the warm forming of magnesium alloys at the temperature range is being investigated from a practical point of view [1-3], and the use of the alloys will bring great improvement in weight reduction. To examine the warm forming processes, the flow stress of material at elevated temperatures is one of the indispensable information. The formula for flow stress is useful to numerically analyse the processes.

For the evaluation of flow stress of a magnesium-based alloy AZ31 sheet in warm forming processes, a formula is derived by analysing the stress-strain curves measured under various temperatures and strain rates in this study.

2. EXPERIMENTAL PROCEDURE

Material used in this study is a commercial magnesium-based alloy AZ31 (Mg-3%Al-1%Zn) B-O sheet with a thickness of 3.0 mm. The microstructure of the sheet is composed of equiaxial grains and the average grain diameter is 25 μm.

For the sheet the uniaxial tension tests were carried out by means of a thermo-mechanical simulator, THERMECMASTOR-Z. The tensile specimens were cut from the sheet in such a way as to be parallel to the rolling direction. The specimens were heated by the coil located at the centre of specimens with high-frequency induction. During the tests the temperatures of the specimens were controlled to within ± 5 °C from 150, 200, 250 and 300 °C. The specimens were elongated with constant crosshead velocities of 0.02, 0.2, 2 and 20 mm s^{-1}.

The strain and the strain rate were derived from the measurement of the displacement of the lines previously described at the surface of the centre part of the specimens.

3. RESULTS AND DISCUSSION

Figure 1 shows the true stress − strain (σ – ε) curves for the four kinds of crosshead velocities. It is found that the elongation increases with temperature, and that the degree of work-hardening increases with decreasing temperature and increasing crosshead velocity, as is usually recognized in the tensile properties of metals at elevated temperatures.

Figure 2 shows the relationships between the stress and the strain for various crosshead velocities at 300 °C in log-log scale. The degree of work-hardening varies depending on the strain range. However, neglecting the low strain range under 0.05 and the high strain range after necking, linear relationships are observed. The similar relationships are obtained for the other temperatures. It is found that the dependence of the stress on the strain can be expressed by the work-hardening exponent, *n*.

Figure 3 shows the relationships between the stress and the strain rate for various strains at 150 °C in log-log scale. The strain rate is given with the average value during each test. The linear relationship is observed for each strain and the inclinations are almost the same, independent of the strain. Also for the other temperatures the similar relationships are observed, and it reveals that the strain rate sensitivity exponent, *m*, can be used.

Therefore, the flow stress is given by the following formula that is commonly used,

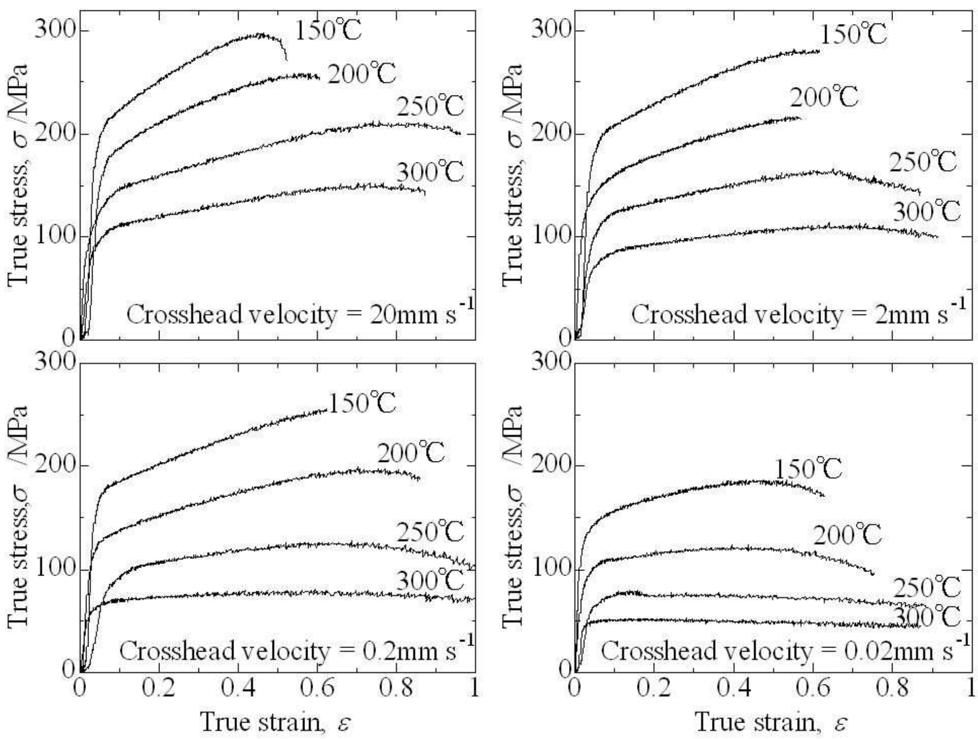

Figure 1. True stress-strain curves obtained from the tension tests

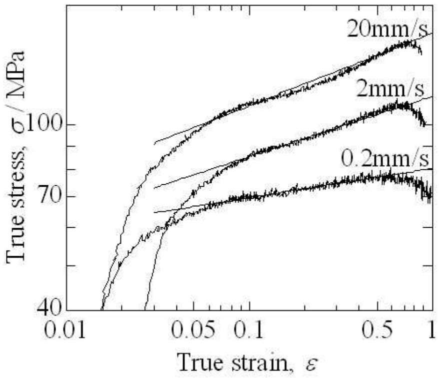

Figure 2. Relationships between stress and strain at 300°C in log-log scale

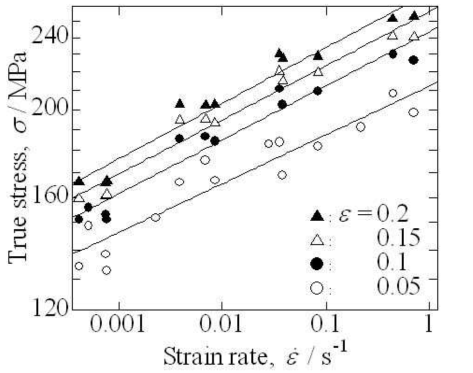

Figure 3. Relationships between stress and strain rate at 150°C in log-log scale

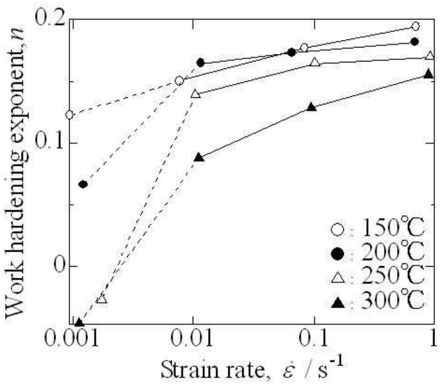

Figure 4. Relationships between work-hardening exponent, *n*, and strain rate

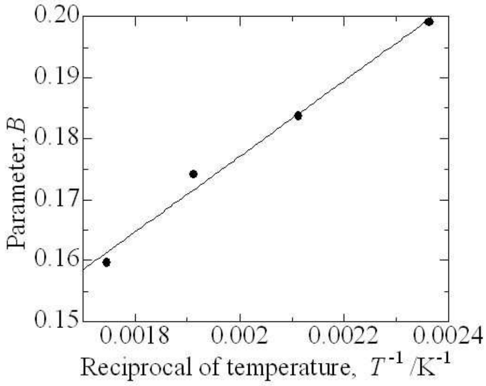

Figure 5. Relationship between parameter *B* and temperature

$$\sigma = K\varepsilon^n \left(\dot{\varepsilon}/\dot{\varepsilon}_0\right)^m \quad \text{[MPa]} \tag{1}$$

where K is the stress coefficient. In order to use the dimensionless strain rate, $\dot{\varepsilon}_0$ is given as to be 1 s $^{-1}$ in this study.

K, n and m-values in the formula are, however, not constant but vary mainly with temperature. Figure 4 shows the relationships between the n-value and the strain rate for various temperatures in semi-log scale. The practical forming processes are performed with higher strain rate. Therefore, let us neglect the data for the lowest strain rate. The range of strain rate is limited between 0.01 and 1 s $^{-1}$ in this study from now on. Then, the linear relationships are observed between the n-value and the logarithmic strain rate, as

$$n = A\log\left(\dot{\varepsilon}/\dot{\varepsilon}_0\right) + B. \tag{2}$$

The parameters A and B correspond to the inclination of the lines in Figure 4 and the n-value at $\dot{\varepsilon}$ = 1 s $^{-1}$, respectively. Because the inclinations for four temperatures are almost the same, the parameter A can be determined to be a constant value,

$$A = 0.016. \tag{3}$$

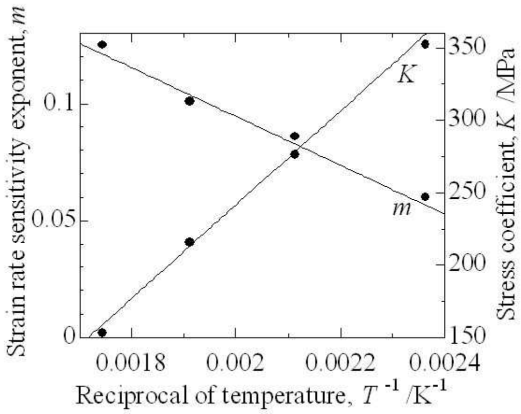

Figure 6. Relationships between values of *m* and *K* and temperature

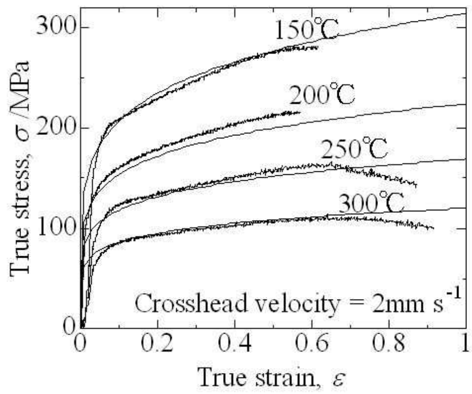

Figure 7. Comparison between calculated and measured flow curves

The parameter *B* depends on the temperature. Figure 5 shows the relationship between the *B*-value and the temperature. The linear relationship is found between the *B*-value and the reciprocal of temperature, and the *B*-value is approximately given by

$$B = 62.0/t + 0.053 \quad (4)$$

where t is the dimensionless temperature transformed by $t = T$ [K] /1 [K].

The linear relationship with the reciprocal of temperature is found also for the *m*-value and the *K*-value, as shown in Figure 6. The values of *m* and *K* are approximately given by

$$m = -105/t + 0.303 \quad (5)$$

$$K = 3.24\times10^5/t - 406 \quad \text{[MPa]}. \quad (6)$$

Now we can calculate the flow stress. Figure 7 shows the stress-strain curves calculated by the present formula, comparing with the measured values. The calculated flow curves agree well with the measured ones quantitatively and qualitatively.

4. CONCLUSION

In this study, the flow curves of the AZ31 magnesium alloy sheet at elevated temperatures were measured and analysed. The formula for flow curves was obtained in a simple form by expressing the flow stress in the function of the strain, the strain rate and the temperature.

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