DOI: 10.24425/amm.2020.133700

YOUNG-CHUL SHIN[1,2*], DAE-KWAN JOUNG[1], SEONG-HO HA[1],
HO-JOON CHOI[1], SOONG-KEUN HYUN[2*]

PREDICTION OF HIGH STRAIN RATE FLOW BEHAVIOR OF 7175 ALUMINUM ALLOY BASED ON ARRHENIUS-TYPE CONSTITUTIVE EQUATIONS

The flow behavior of 7175 aluminum alloy was modeled with Arrhenius-type constitutive equations using flow stress curves during a hot compression test. Compression tests were conducted at three different temperatures (250°C, 350°C, and 450°C) and four different strain rates (0.005, 0.05, 0.5, and 5 s^{-1}). A good consistency between measured and set values in the experimental parameters was shown at strain rates of 0.005, 0.05, and 0.5 s^{-1}, while the measured data at 5 s^{-1} showed the temperature rise of the specimen, which was attributable to deformation heat generated by the high strain rate, and a fluctuation in the measured strain rates. To minimize errors in the fundamental data and to overcome the limitations of compression tests at high strain rates, constitutive equations were derived using flow curves at 0.005, 0.05, and 0.5 s^{-1} only. The results indicated that the flow stresses predicted according to the derived constitutive equations were in good agreement with the experimental results not only at strain rates of 0.005, 0.05, and 0.5 s^{-1} but also at 5 s^{-1}. The prediction of the flow behavior at 5 s^{-1} was correctly carried out by inputting the constant strain rate and temperature into the constitutive equation.

Keywords: Aluminum alloy, Hot compression, Arrhenius-type equation, High strain rate flow behavior, Flow stress

1. Introduction

High productivity in plastic working processes is achieved with high processing speeds. Accurate modeling is necessary to describe the flow stress in the high strain rate and temperature range at which a material is deformed when predicting the behavior of a material in warm or hot forming processes with the use of finite element analysis. Several previous studies have examined the internal factors that govern the plastic behavior of a material to examine the flow stress at elevated temperatures, which is affected by the temperature and strain rate. The behavior of various alloys has been predicted through constitutive equations based on variables such as temperature, strain, and strain rate [1-9]. A hot compression test is generally performed using a cylindrical specimen to experimentally examine the flow stress of a material. However, it is challenging to implement a high strain rate over a certain level and maintain the specimen at a constant temperature due to the additional heat generated during high-speed compression. Due to these difficulties, the experimental data for high strain rates should be carefully examined when deriving the constitutive equations. In this study, the flow behavior of 7175 aluminum alloy was modeled using only flow curves while maintaining constant temperatures and strain rates among the compression test results based on an Arrhenius-type constitutive equation suggested by Lin et al [1]. This approach was adopted to minimize errors in the fundamental data caused by temperature increases of the material and fluctuations in the strain rate during high-speed compression. Flow curves at high strain rates were obtained by extrapolation from the constitutive equation, and the approach was subsequently validated.

2. Experimental

Extruded 7175 aluminum alloy was used in this study. Cylindrical specimens were machined with a diameter of 10 mm and a height of 15 mm. Hot compression tests were performed on a Gleeble-3500 thermal-mechanical simulator at three different temperatures (250°C, 350°C, and 450°C) and at four different strain rates (0.005, 0.05, 0.5, and 5 s^{-1}).

Fig. 1 depicts the true stress-strain curves obtained from the hot compression of 7175 aluminum alloy. As can be seen in

1 KOREA INSTITUTE OF INDUSTRIAL TECHNOLOGY (KITECH), INCHEON 21999, REPUBLIC OF KOREA
2 INHA UNIVERSITY, INCHEON 22212, REPUBLIC OF KOREA
* Corresponding authors: ycshin@kitech.re.kr, skhyun@inha.ac.kr

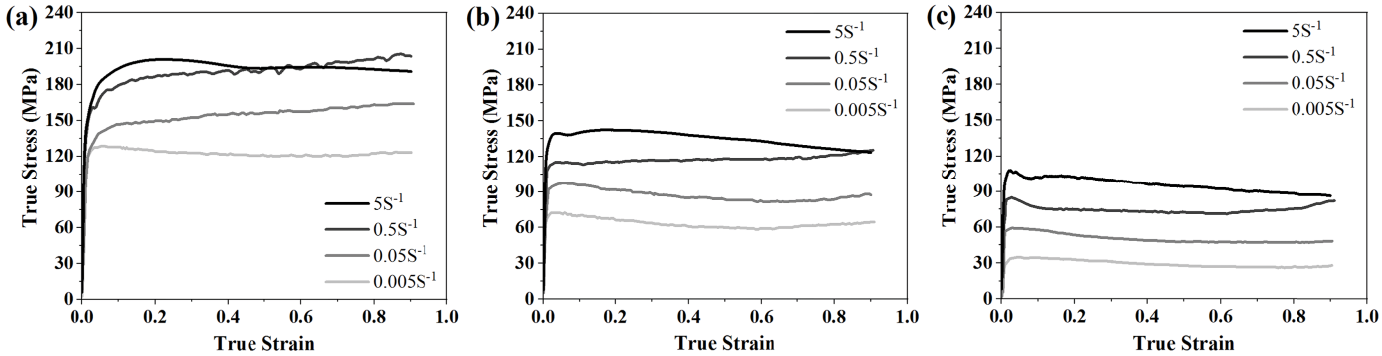

Fig. 1. True stress-strain curves for 7175 aluminum alloy at various temperatures: (a) 250°C, (b) 350°C, and (c) 450°C

Fig. 1(a) and (b), the curves at a strain rate of 5 s^{-1} showed excessive softening that was unlike other strain rates and intersected with those at a strain rate of 0.5 s^{-1}.

Given the abnormal behavior observed at a high strain rate, the temperatures and strain rates measured during the compression test were examined to verify the accuracy of the operating conditions in the hot compression test. Fig. 2 shows the comparison between the measured values and the set conditions in the controller. The compression tester exhibited good consistency, except at a strain rate of 5 s^{-1}. At a strain rate of 5 s^{-1}, the temperature of the specimen increased by 3%-16% during the test. In addition, the strain rate increased and decreased immediately after it reached 5 s^{-1}, indicating that it was inaccurate at such a high strain rate. The variation of the strain rate at 5 s^{-1} is thought to be due to the limit in controllability of the test conditions in the tester. The temperature rise of the specimens was attributable to deformation heat during the plastic working process. Generally, materials at strain rates higher than 1 s^{-1} can be under adiabatic conditions due to a lack of sufficient time to emit the internal heat. Consequently, the specimens increase in temperature, leading to flow stress degradation. Therefore, to express accurate flow curves, the flow stress degradation must be corrected.

3. Constitutive equations of 7175 aluminum alloy

An Arrhenius-type constitutive equation modified by Lin et al. [1] was used to describe the flow stress of 7175 aluminum alloy according to different temperatures and strain rates. Flow stresses only at strain rates of 0.005, 0.05, and 0.5 s^{-1} were em-

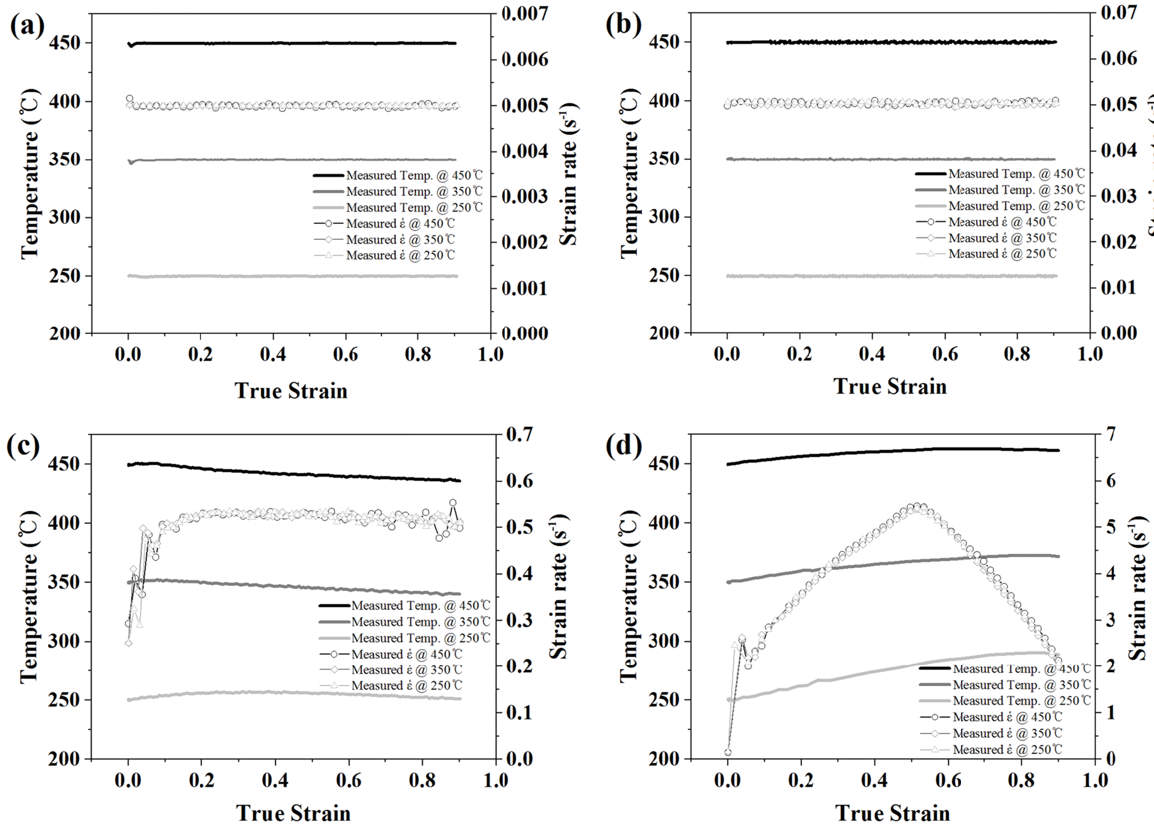

Fig. 2. Measured temperature and strain rate curves during hot compression tests: (a) 0.005 s^{-1}; (b) 0.05 s^{-1}; (c) 0.5 s^{-1}; (d) 5 s^{-1}

ployed except at 5 s^{-1}, which included errors inevitably caused by the temperature rise and fluctuation of the strain rate.

The effects of the temperature and strain rate on the deformation behavior were represented by the Zener-Hollomon parameter in the exponent law-type equation [10-13]. These are mathematically expressed as

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

where R is the universal gas constant (8.314 J mol^{-1} K^{-1}), T is the absolute temperature in K, and Q is the activation energy (kJ mol^{-1}).

Following the developments by Lin et al. [1], the activation energy can be written as

$$Q = Rn \frac{d\left\{\ln\left[\sinh\left(\alpha\sigma\right)\right]\right\}}{d\left(1/T\right)} \tag{2}$$

where A, β, n_1, σ, and n are the materials constants, $\alpha = \beta/n_1$.

Once the materials constants are evaluated, the flow stress at a particular strain can be predicted. Accordingly, the constitutive equation that relates the flow stress and Zener-Hollomon parameter can be written in the following form:

$$\sigma = \frac{1}{\alpha} \ln\left\{\left(\frac{Z}{A}\right)^{\frac{1}{n}} + \left[\left(\frac{Z}{A}\right)^{\frac{2}{n}} + 1\right]^{\frac{1}{2}}\right\} \tag{3}$$

The strain energy and the materials constant are greatly affected by the deformation. A method for formulating a constitutive equation was proposed by Lin et al. [1] based on the assumption that the activation energy and the materials constant are functions of the polynomial equations. Fig. 3 shows the results of the polynomial fitting of the activation energy and the materials constants obtained from the flow curves of 7175 aluminum alloy.

4. Verification of constitutive equation

The flow stress curves determined experimentally and calculated by substituting the materials constants determined in Fig. 3 into Eq. (3) were compared. They exhibited reasonable concordance at strain rates of 0.005, 0.05, and 0.5 s^{-1}. The correlation coefficient R and absolute average error AARE values that were calculated, corresponding to 0.995 and 6.35%, respectively, which showed good accuracy.

Although the flow stress curves determined experimentally at 5 s^{-1} could not be used to derive Eq. (3) due to the aforementioned errors, the flow stress curves at a strain rate of 5 s^{-1} were also calculated by substituting the actual sensed data for temperatures and strain rates shown in Fig. 2 into Eq. (3) in order to examine the applicability of the derived constitutive equation at a strain rate of 5 s^{-1}. The calculated values were compared with the experimental results in Fig. 4. The R and

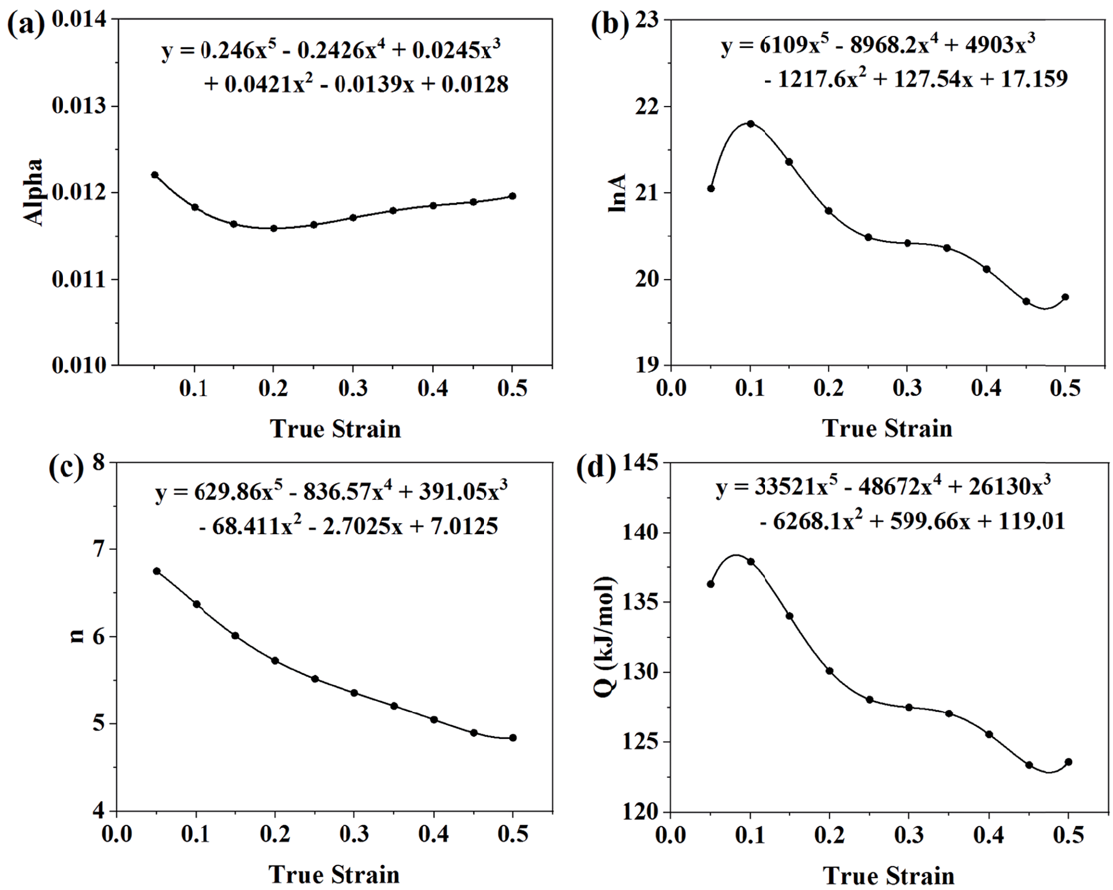

Fig. 3. Variation of (a) alpha, (b) lnA, (c) n, and (d) Q with true strain

AARE values shown in Fig. 4 were 0.989 and 5.35%, respectively, which showed good accuracy. These results indicated that an Arrhenius-type constitutive equation derived based on the experimental data at 0.005, 0.05, and 0.5 s^{-1} was also reliable in its prediction for 5 s^{-1}.

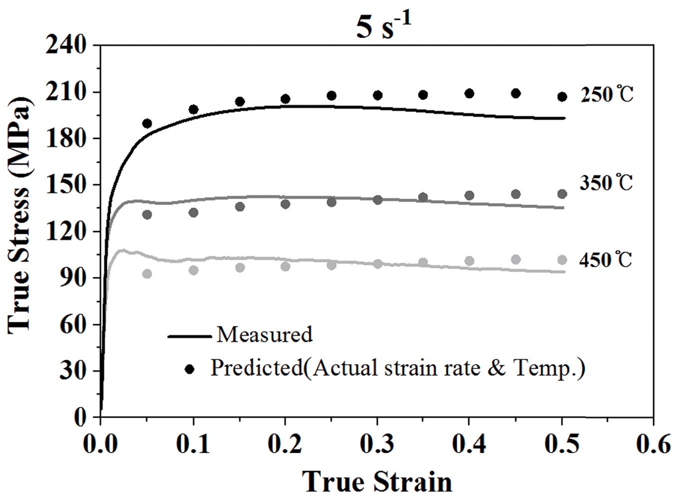

Fig. 4. Comparisons between the predicted (circles) and measured flow stress curves (solid lines) at a strain rate of 5 s^{-1}

Fig. 5 demonstrates a prediction of the normal flow behavior at 5 s^{-1} by inputting a constant strain rate and temperature into Eq. (3). Unlike the measured curves, stress degradation did not occur throughout all the true strain ranges, indicating that the flow curves at such high strain rates could be extrapolated using the derived Arrhenius-type constitutive equation.

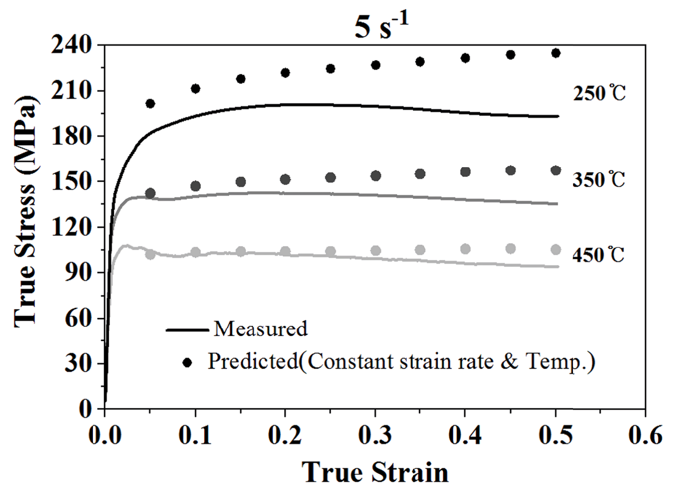

Fig. 5. Predicted normal flow stress curves (circles) at a strain rate of 5 s^{-1} using constant strain rates and temperatures

5. Conclusion

In this study, the flow behavior of 7175 aluminum alloy was modeled with Arrhenius-type constitutive equations using flow stress curves obtained from a hot compression test. The constitutive equations were derived using flow curves at strain rates of 0.005, 0.05, and 0.5 s^{-1} only except a strain rate of 5 s^{-1} to minimize errors in the fundamental data. Because the measured data at 5 s^{-1} showed the temperature rise of the specimen, which was attributable to deformation heat generated by the high strain rate, and a fluctuation in the measured strain rates. As a result, the flow curves that were predicted based on the derived constitutive equations were in good agreement with the experimental results at strain rates of 0.005, 0.05, and 0.5 s^{-1}. In addition, the flow stress curves at a strain rate of 5 s^{-1} calculated using the actual sensed data for temperatures and strain rates also showed good accuracy. These results indicated that an Arrhenius-type constitutive equation derived based on the experimental data at 0.005, 0.05, and 0.5 s^{-1} was also reliable in its prediction for 5 s^{-1}. The prediction of the flow behavior at 5 s^{-1} was finally implemented by inputting the constant strain rate and temperature into the constitutive equation. The results of this study indicate that the experimental data for high strain rates should be carefully examined when being used to derive constitutive equations.

Acknowledgements

This work was supported by the Technology Innovation Program (10073115, Development of Energy-Saving Type Constant-Speed Extrusion System for High Strength Al Alloys) funded By the Ministry of Trade, Industry & Energy (MOTIE, Korea)

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