Strain Rate Dependence of Dynamic Flow Stress of 6061-T6 Aluminum Alloy at Strain Rates ranging from 1×10^3 to $4 \times 10^4 \text{ s}^{-1}$

by

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1 Introduction

It has been reported by many investigators that the strain rate dependence of the flow stress is observed in metallic materials^{1), 2)}. In particular for the case of FCC metals, it is pointed out that the flow stress increases steeply at high strain rates^{3), 4)}. The phenomenon has been due to a transition in a dominant rate controlling mechanism of a dislocation motion from a thermally assisted cutting of point obstacles to a viscous drag in scattering phonons and conduction electrons^{5), 6)}. It is known that there is no effect of the viscous drag of electrons on the dislocation motion at temperatures above a cryogenic. A number of investigations for aluminum alloy 6061-T6 have been carried out, however there is less investigation at high strain rates above 10^3 s^{-1} . Therefore, it is not clear whether the steep increase in the flow stress appears or not at high strain rates and the mechanism is still under active investigation.

Yadav *et al.*⁷⁾ examined the effect of the strain rate on the flow stress for 6061-T6 over a very wide range of strain rate (10^{-4} to 10^5 s^{-1}) using a screw driven testing machine, a split Hopkinson pressure bar and a pressure-shear plate. They indicated the steep increase in the flow stress became explicitly at the strain rate of about $2 \times 10^2 \text{ s}^{-1}$. The above result was different from that presented by Holt *et al.*⁸⁾, indicating the strain rate dependence of the flow stress of 6060-T6 was not observe at strain rate up to 10^3 s^{-1} . Ogawa⁹⁾ performed uniaxial tensile tests on 6061-T6 in the strain rate range from 10^{-4} to $1.5 \times 10^3 \text{ s}^{-1}$ and observed no abrupt increase in the flow stress at higher strain rates. He predicted also that the dynamic flow stress could be represented by the thermal activation flow at the strain rate up to at least 10^3 s^{-1} . The author made strain rate reduction tests for 6061-O¹⁰⁾ and -T6¹¹⁾ at strain rate range above $1 \times 10^4 \text{ s}^{-1}$, and reported the steep increase in the flow stress was observed for 6061-O at strain rate of about $5 \times 10^3 \text{ s}^{-1}$ but for 6061-T6, no distinct increase in the flow stress was observed at strain rate up to $2 \times 10^4 \text{ s}^{-1}$. Using the theoretical equation which could evaluate the effect of the viscous drag in scattering of phonons on the dislocation motion, the author detected

that the increase in the dislocation density shifted the strain rate region in which the flow stress increased steeply to higher strain rate side, and furthermore suggested that there would be a possibility of the steep increase in the flow stress at strain rates above about $2 \times 10^4 \text{ s}^{-1}$ ¹²⁾. In the above experiment, the strain rate reduction tests were made with the specimen of 1.5 mm both in diameter and length, using a output bar of 4 mm in diameter. In the strain rate range beyond $2 \times 10^4 \text{ s}^{-1}$, however it is difficult to obtain a reliable data due to a dispersion of a elastic wave in the output bar.

In this paper, the experimental apparatus composed with the output bar of 2 mm in diameter is devised to reduce the effect of the dispersion of the elastic wave in the bar and strain rate reduction tests are carried out for 6061-T6 using the devised apparatus in the strain rate range from $2 \times 10^4 \text{ s}^{-1}$ to $4 \times 10^4 \text{ s}^{-1}$. Experimental techniques and results are presented together with discussions.

2 Experiment

2.1 Specimen

Measurements are made for aluminum alloy 6061-T6 (commercially available from Daido Corp.). The T-6 treatment designed by manufacturer is a solution treatment for 1 h at 808 K followed by quenching in water, and then aging for 8 h at a temperature of 443 K. Table 1 provides the chemical composition of 6061 aluminum alloy. Specimens are machined to 1.0 mm both in length and diameter, respectively from a cold-drawn bar of 6 mm in diameter.

2.2 Experimental Method

An experimental apparatus employed in this study is briefly mentioned, because the detail of that has already been reported in the previous paper¹⁰⁾. Hopkinson pressure bar system is used for compressive tests in the strain rate range of $2 \times 10^4 \sim 4 \times 10^4 \text{ s}^{-1}$, which is shown schematically in Fig.1. In this apparatus, a projectile hits directly the specimen

Table 1 Chemical composition of 6061 aluminum alloy (mass %).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.60	0.34	0.29	0.05	0.99	0.20	0.04	0.03

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attached on the end of the output bar. The output bar made of tungsten with 2 mm in diameter is employed to prevent the elastic wave dispersion in the output bar, which is strongly developed at high strain rates.

Usually, it is difficult to attach a strain gage on the surface of the bar with a small diameter, however two purity semiconductor strain gages with a gage length of 1 mm and a width of 0.25 mm (SKS-30112: Kyowa Dengyo Corp.) are attached in symmetry to cancel out the effect of bending on the surface of the bar where an electrical insulation coating is applied.

Fig.1 Schematic diagram of apparatus.

In conducting the strain rate reduction tests, the projectile hits the specimen directly and then the velocity of the specimen side end of the projectile is sharply decreased by a collision with a decelerator. The projectile made of Ti alloy being 10 mm in diameter and the decelerator made of Ni alloy being 10 mm and 4.6 mm in outer and inner diameter, respectively. The above combination gives the strain rate reduction by 58.6 % of the strain rate before reduction. An adhesion of grease is utilized for attaching the specimen to the end of the output bar. Using one dimensional bar wave approximation, the strain rate of the specimen is obtained by taking into the deformation of the projectile and output bar caused by the flow stress of the specimen in the following forms:

a) before the strain rate reduction

$$\dot{\epsilon} = \frac{1}{\ell_0} \left(V_1 - \frac{a_0 \sigma_n}{A_1 c_1 \rho_1} - \frac{a_0 \sigma_n}{A_3 c_3 \rho_3} \right) \quad (1)$$

b) after the strain rate reduction

$$\dot{\epsilon} = \frac{1}{\ell_0} \left(\frac{V_1 - (a_0 \sigma_n / A_1 c_1 \rho_1)}{1 + (A_2 c_2 \rho_2 / A_1 c_1 \rho_1)} - \frac{a_0 \sigma_n}{A_3 c_3 \rho_3} \right) \quad (2)$$

where V_1 is a initial velocity of the projectile, ρ , c and A are the bar density, bar wave velocity and cross sectional area of the bar, respectively, subscripts 1, 2 and 3 mean the projectile, decelerator and output bar, respectively, a , ℓ_0 , σ_n , are the initial cross sectional area, initial length and nominal flow stress of the specimen, respectively. The

nominal strain ϵ_n and true flow stress σ_t of the specimen are as follows.

$$\epsilon_n = \int_0^t \dot{\epsilon} dt \quad (3)$$

$$\sigma_t = (1 - \epsilon_n) \quad (4)$$

The term including σ_n is relatively small in magnitude in Eqs.(1) and (2), because the strain rate determined by ignoring these terms is named as the nominal strain rate. The true stress-strain rate curves indicated later is determined from the true stress-nominal strain curves under the assumption that the strain rate does not decrease with increasing strain.

3 Results and Discussion

The results of rate reduction tests conducted at strain rates of 1×10^4 to $2 \times 10^4 \text{ s}^{-1}$ using the output bar of 4 mm in diameter are shown in Figs.2 and 3, respectively.

(a) Nominal flow stress vs. time curves.

(b) True flow stress vs. strain curves.

Fig. 2 Response of flow stress to sudden reduction in strain rate ranging from 1.08×10^4 to $4.47 \times 10^3 \text{ s}^{-1}$ and flow stress at constant strain rate of $1.04 \times 10^4 \text{ s}^{-1}$.

(a) Nominal flow stress vs. time curves.

(b) True flow stress vs. strain curves.

Fig. 3 Response of flow stress to sudden reduction in strain rate ranging from 1.79×10^4 to $7.41 \times 10^3 \text{ s}^{-1}$ and flow stress at constant strain rate of $1.81 \times 10^4 \text{ s}^{-1}$.

Figure 2 shows a response of the flow stress to sudden reduction in strain rate at strain of 0.18 at strain rates from 1.08×10^4 to $4.47 \times 10^3 \text{ s}^{-1}$ and Fig.3 is the reduction test at strain rates from 1.79×10^4 to $7.41 \times 10^3 \text{ s}^{-1}$ at strain of 0.17. Nominal flow stress-time curves are shown in (a) and enlarged true stress-strain curves around the rate reduction point are shown in (b) of each figure. The constant strain rate curve corresponds to the strain rate before the sudden reduction is indicated by broken line in each figure for the purpose of detecting the flow stress drop caused by the sudden reduction in strain rate. No marked difference in the flow stress is observed between both curves after the rate reduction. The flow stress drop (3~5 MPa) is somewhat observed from the result of the reduction test shown in Fig.3, however it cannot be recognized that the flow stress steeply increases. It is also difficult to estimate the flow stress drop accurately because of a periodical oscillation appearing on the flow stress-strain curves in Fig.3. This is due to the effect of

the dispersion of elastic wave in the output bar, which becomes more notable with increasing strain rate.

The results of strain rate reduction tests made in the strain rate range above $2 \times 10^4 \text{ s}^{-1}$ are presented. As was mentioned previously, the output bar with 2 mm in diameter is employed to prevent the elastic wave dispersion, which is strongly developed at high strain rates. In order to suppress the effect of inertia of the specimen as far as possible, the specimens employed are 1 mm both in diameter and length. Figure 4 shows the response of the flow stress to sudden reduction in the strain rate ranging from $2.48 \times 10^4 \text{ s}^{-1}$ to $1.03 \times 10^4 \text{ s}^{-1}$ and Fig.5 is the results of the reduction test in the strain rate ranging from 4.10×10^4 to $1.66 \times 10^4 \text{ s}^{-1}$. As well as in the cases of Figs.2 and 3, the (a) in each figure is nominal flow stress - time curves and the (b) is true flow stress-strain curves which are enlarged in the rate reduction point. The

(a) Nominal flow stress vs. time curves.

(b) True flow stress vs. strain curves.

Fig. 4 Response of flow stress to sudden reduction in strain rate ranging from 2.48×10^4 to $1.03 \times 10^4 \text{ s}^{-1}$ and flow stress at constant strain rate of $2.46 \times 10^4 \text{ s}^{-1}$.

(a) Nominal flow stress vs. time curves.

(b) True flow stress vs. strain curves.

Fig.5 Response of flow stress to sudden reduction in strain rate ranging from 4.10×10^4 to $1.66 \times 10^4 \text{ s}^{-1}$ and flow stress at constant strain rate of $4.16 \times 10^4 \text{ s}^{-1}$.

Fig.6 Flow stress drop obtained from every rate reduction tests at strain rate ranging from 1×10^4 to $4 \times 10^4 \text{ s}^{-1}$.

effect of the elastic wave dispersion is reduced considerably by using output bar with 2 mm in diameter and also a distinct flow stress drop can be observed. In addition, the flow stress drop estimated in Figs. 4 and 5 are about 15 MPa and 22 MPa, respectively.

All results of the rate reduction tests made in the strain rate range from $1 \times 10^4 \text{ s}^{-1}$ to $4 \times 10^4 \text{ s}^{-1}$ are summarized in Fig. 6. The flow stress drop obtained from the each reduction test and strain rates are plotted in the abscissa being on normal scale and the ordinate being on log scale, respectively. It is clear that the flow stress abruptly increases at the strain rate of about $2 \times 10^4 \text{ s}^{-1}$. The flow stress drop obtained from the strain rate reduction test is an instantaneous response to the strain rate itself and the gradient of the flow stress-strain rate curve represents the magnitude of the dependence of the flow stress on the instantaneous strain rate.

From the above results, assuming that the phenomena is caused by the transition in a rate controlling mechanism of the dislocation motion from thermal activation in cutting of each other at relatively low strain rates to the viscous phonon drag at higher strain rates, an analysis is made on the basis of dislocation kinetics.^{13),14)} Usually in FCC metals, as shown schematically in Fig.7 (a), the moving dislocation segments move repeating the thermally assisted cutting of the forest dislocations and the phonon drag controlled jump motion alternately. To simplify the analysis, the unit motion of the dislocation segment is replaced by the motion of distance L of a straight segment, which is shown in Fig.7 (b). L is average distance among the forest dislocations. Suppose that t_t is a waiting time required in cutting a forest dislocation and t_v is the time required in passing the average distance between forest dislocations, the average velocity of moving dislocation is represented as " $L/(t_t + t_v)$ ". Accordingly, the shear strain rate can be given by the following equation:

$$\dot{\gamma} = \rho_d b L / (t_t + t_v) \quad (5)$$

Fig.7 Schematic diagram of dislocation motion: (a) Loop segment model and (b) Straight segment model.

where ρ_d is moving dislocation density and b is Burgers vector. Cutting of forest dislocation is aided by the thermal activation process, the waiting time is as follows:

$$t_t = \nu \exp\{-(E_c - \tau V^*)/kT\} \quad (6)$$

where ν is frequency factor, E_c is activation energy for cutting of dislocation, τ is shear stress (thermal component of shear stress), V^* is activation volume, k is Boltzmann constant, and T is absolute temperature.

As the dislocation motion between forest dislocations is controlled by the viscous drag in scattering phonons, the time required is as follows:

$$t_v = LB/\tau b \quad (7)$$

where B is viscous drag coefficient (damping constant). From Eqs. (6) and (7), Eq. (5) is as follows.

$$\dot{\gamma} = \rho_d b \bar{v}_d = \frac{\rho_d b L}{\nu^{-1} \exp\{-(E - \tau V^*)/kT\} + BL/\tau b} \quad (8)$$

This equation is the relation of stress and strain rate, which can evaluate the transition in the rate controlling mechanism of moving dislocation over the strain rate range from low strain rates to high strain rates. At lower strain rates, or $t_v \ll t_t$, Eq. (8) can be approximated as follows.

$$\dot{\gamma} \approx \frac{\rho_d b L}{\nu^{-1} \exp\{-(E - \tau V^*)/kT\}} \quad (9)$$

This is the thermal activation flow rate-controlled by the thermally assisted cutting of the forest dislocations, in which the flow stress depends linearly upon the logarithm of the strain rate. At very high strain rates, or $t_t \ll t_v$, Eq. (8) can be approximated as follows.

$$\dot{\gamma} \approx \rho_d b^2 \tau / B \quad (10)$$

This is the phonon drag controlled viscous flow in which the flow stress depends linearly upon the strain rate itself. Equation (8) can cover the wide strain rate range including thermal activation flow and the phonon drag controlled flow together with the transition range between them. When comparing quantitatively the calculated with measured flow stress, it is necessary to take into consideration of the effect of athermal components of the flow stress which increases with proceeding deformation. By taking applied stress τ_o and athermal components of the flow stress τ_a , τ required to move the dislocation is $\tau_o - \tau_a$. Equation (8) is used to evaluate the steep rise in the flow stress appearing at the strain rate of

about $2 \times 10^4 \text{ s}^{-1}$ shown in Fig.6. The experimental results are expressed as the relation of the normal stress and strain rate, however the shear stress, shear strain and shear strain rate are used in Eq. (8). Taylor factor employed in converting normal stress to shear stress is 3.07. Unknown quantities in Eq. (8) are L , ρ_d and V^* . Using Eq. (9), activation volume V^* is determined from a gradient of a linear part in σ vs. $\log \dot{\epsilon}$ plot of the experimental flow stress in a relatively low strain rate range where σ is dependent linearly upon $\log \dot{\epsilon}$, and the average dislocation distance L is determined from the relation of " $V^* = Lb^2$ ". The moving dislocation density ρ_d is determined from the strain rate at which the flow stress begins to rise steeply. Athermal stress τ_a is determined from the difference in the flow stress level between the calculated and measured flow stress-strain rate curves. Thus determined values of 6061-T6 are $V^* = 5.49 \times 10^{-27} \text{ m}^3$, $L = 6.71 \times 10^{-8} \text{ m}$, $\rho_d = 2.1 \times 10^{12} \text{ m}^{-2}$ and $\tau_a = 10.4 \text{ MPa}$. Activation energy E_c is $Gb^3/5$ which is proposed by Ashby *et al.*¹⁵⁾. Viscous drag coefficient B is $4.88 \times 10^{-6} \text{ Pa} \cdot \text{s}$ which is measured by Hikata *et al.*¹⁶⁾. The flow stress-strain rate curve determined using above values and Eq. (8) is shown by alternate long and short dash lines in Fig.8. In the calculation, it is assumed that L , ρ_d and τ_a are independent of the strain rate. The marks $\circ$, $\bullet$ and $\blacklozenge$ are measured values in the previous paper¹²⁾, the mark $\diamond$ is the present values measured with small specimens of 1 mm both in diameter and length using the output bar of 2 mm in diameter. The solid line is the flow stress-strain rate curve determined from the results of the strain rate reduction tests shown in Fig.6. In comparison of the calculation and measured, the shape in rise in the flow stress of the calculation is considerably steep compared to the measured one. This seems to be the reason why in Eq. (8), assuming that the intervals between forest dislocations are the constant and the distribution in the length of moving dislocation is neglected. Assuming that the length of moving

Fig.8 Comparison of measured flow stress curve with the predicted one in the strain rate range from about 1×10^3 to $4 \times 10^4 \text{ s}^{-1}$.

Fig.9 Relation of moving dislocation density to steep increase in flow stress at high strain rates for 6061-O, 6061-T6 and 5n Al, respectively.

dislocation loop segments are constant, all of loop segments shift simultaneously to the viscous drag-controlled state, while in the real materials, since the array of forest dislocations should be random and the length of loop segments should have a statistical distribution, because such the simultaneous transition will not occur, the segments shift to the viscous drag region one after another from the longer loop segments as the flow stress becomes high. As a result, the experimental curve seems to be relatively gentle in rising phase of the flow stress compared with the calculated one.

The flow stress-strain rate curves for 6061-T6, 6061-O and 5n Al at high strain rates are together shown in Fig.9. The solid lines are determined from experimental results and the broken lines are calculated by Eq. (8). The experimental results for 6061-O¹⁰⁾ and 5n Al¹⁷⁾ are quoted from strain rate reduction tests presented on the previous papers.

The each level in the flow stress of materials is usually difference attributable to the effect of impurity atoms and precipitations, however the stress level in each curve before the stress increases steeply is conveniently fitted for detecting the strain rate at which the flow stress steeply increases. The strain rate range in which the flow stress increases steeply shifts to the higher strain rate side according to the order of 5n Al, 6061-O and 6061-T6. In calculation using Eq. (8), each value of the activation volume V and viscous drag coefficient B in the three types of materials is the same, however only the dislocation density ρ_d is different in each material. The strain rate at which the steep increase in the flow stress is observed in each material can be evaluated by using suitable values in the dislocation density $\rho_d = 1.5 \times 10^{11} \text{m}^{-2}$, $5.5 \times 10^{11} \text{m}^{-2}$ and $2.1 \times 10^{12} \text{m}^{-2}$ for 5n Al, 6061-O and 6061-T6, respectively. The results obtained in this paper were considerably different in the strain rate at which the flow

Fig.10 Comparison of strain rates in which steep increase in flow stress determined from this experiment with that obtained by Yadav *et al.*

stress increases steeply from those obtained by Yadav *et al.* The above mentioned difference is shown in Fig.10.

The model detects that the moving dislocation density predicted from the results presented by Yadav *et al.* is about $2 \times 10^{10} \text{m}^{-2}$, which is one order in magnitude less than that estimated from the annealed 5n Al. Further, the strain rate at which the flow stress increases steeply depends on the magnitude of the viscous drag coefficient B , and B predicted from the results obtained by Yadav *et al.* is about $5 \times 10^{-4} \text{Pa} \cdot \text{s}$, which differs remarkably from that measured by Hikata *et al.* From the above consideration and the obtained results, it seems reasonable that the steep increase in the flow stress appears at strain rates above 10^4s^{-1} .

4 Conclusions

The constant strain rate and steep reduction in strain rate tests were conducted using the output bar of 2 mm in diameter in the high strain rate range of $2 \times 10^4 \sim 4 \times 10^4 \text{s}^{-1}$ to investigate the steep increase in the flow stress of 6061-T6. The results obtained are as follows.

- (1) The steep increase in the flow stress of 6061-T6 was observed at strain rates of about $2 \times 10^4 \text{s}^{-1}$, which was predicted in the previous paper.
- (2) The increase in the moving dislocation density reduced the average dislocation velocity, thereby causing a movement of the transition region to the higher strain rate side.

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