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ENDOH, Hajime / SAKINO, Kiyotaka

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Evaluation of Flow Stress Drop Caused by Reduction in Strain Rate on Copper at Very High Strain Rates

Hajime ENDOH*, Kiyotaka SAKINO**

Abstract. In the previous work, strain rate change tests were conductedfor high-purity polycrystalline aluminum at very high strain rates. Here we present the results of reduction tests carried outfor copper. The experimental apparatus devised in the previous work is used to attain a sufficiently steep reduction in the strain rate. The flow stress obtained from the reduction tests isanalyzed by means of the deconvolution method. The results indicate that the instantaneous strain rate plays a more important role than the strain rate history for the dynamic flow stress at very high strain rates where a steep increase in the strain rate sensitivity of the flow stress is observed. The above-mentioned results are the same as those found in the previous work.

Key Words : Shock, Strain Rate Sensitivity, Strain Rate History,Differential Method, Deconvolution

1. INTRODUCTION

It has been reported by many investigators, as often pointedout in recent review papers[1], that the strain rate sensitivity of the flow stress $d\sigma/d\log\dot{\varepsilon}$ depends upon both the instantaneous strain rate and the strain rate history. In order to clarify the roles of the instantaneous strain rate and the strain rate history in the dynamic flow stress, differential tests in which strain rate is suddenly increased[2],[3] or decreased[4] have been carried out using a torsional split Hopkinson bar system. In those tests,however, the strain rate was limited to below about 2000/s and few strain rate change tests have been done at very high strain rates above about 5000/s, where the steep increase in $d\sigma/d\log\dot{\varepsilon}$ appears. For this phenomenon, two contrasting interpretations have been given. One[5] ascribes the phenomenon to the transition inthe rate-controlling mechanism of dislocation motion from the thermally assisted cutting of the point obstacles in the lower strain rate range to the viscous drag in the higher strain rate range. This is the interpretation based upon the role of the instantaneous strain rate. The other interpretation[6] ascribes the phenomenon to the internal structure evolution which reflects thestrain rate history. It seems to be very important to confirm therelative importance of the instantaneous strain rate and the strain rate history in the dynamic flow stress, and also to understand the micromechanism of deformation in metallic materials at very high strain rates.

Recently, the authors[7], using a newly devised apparatus with a high time resolution capability, carried out strain rate changetests for high-purity polycrystalline aluminum in strain rate range from about 10000 to 20000/s. The results indicated that theinstantaneous strain rate played a very important role in the dynamic flow stress at high strain rates. However, there are somepublished results which differ remarkably from our results. Follansbee et al.[8] measured "threshold stress" (quasi-static yieldstress at 0 K) after imposing a certain amount of dynamic pre-deformation on the specimen, and they concluded that the flowstress depended little upon the instantaneous strain rate. Furthermore, recently, Tong and Clifton[9] performed a differential test using the pressure-shear impact technique at strain rates of about 100 000/s and they also emphasized that the flow stress depended very little on the instantaneous strain rate. Both the above-mentioned tests were conducted for copper. Accordingly, it is necessary to carry out the strain rate change tests not only for aluminum but also in particular for copper.

Here we describe an investigation in which sudden reduction tests were conducted for high-purity polycrystalline copper using the apparatus devised in the previous work. When the strain rate reduction test is performed for copper which exhibits relatively pronounced work-hardening using a Hopkinson bar system of compression type at high strain rates, it becomes a serious problem that, owing to the effect of the transfer function in themeasurement system, the flow stress drop caused by the sudden reduction in strain rate cannot be obtained correctly. To overcome this problem, therefore, the inverse analysis is appliedto the experimental data. Experimental results and the inverse analysis method for copper are presented together with discussion

2. EXPERIMENTAL METHOD

The experimental apparatus for the strain rate reduction tests shown in Fig. 1 is mainly comprised of a projectile, pressure bar and decelerator, which is the apparatus devised in the previous work.

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* Mechanical Engineering, Graduate school of Engineering
** Department of Mechanical Engineering

In the case of the test for copper the following assemblies were used. Both the projectile and decelerator were made of Ti-6 Al-4 V alloy. Their diameter and length were 13 mm and 100 mm, respectively. The inner diameter of the decelerator was 6 mm. The pressure bar was made of tungsten. Its diameter and length were 4 mm and 300 mm, respectively. The density and the bar wave velocity of Ti-6 Al-4 V alloy are 4.42 g/cm^3 and 5060 m/s, respectively. Those of tungsten are 19.3/cm^3 and 4480 m/s. The above combination gives strain rate reduction by about 44% of strain rate before reduction.

Using the one-dimensional bar wave approximation and considering elastic deformation of the impact bar and output bar caused by the flow stress of the specimen, the instantaneous strain rate of the specimen is obtained in the following form:

(a) before strain rate reduction

$$\dot{\varepsilon}=\frac{1}{l_0}\left(v_0-\frac{a_0\sigma}{A_1c_1\rho_1}-\frac{a_0\sigma}{A_3c_3\rho_3}\right), \qquad (1)$$

(b) after strain rate reduction

$$\dot{\varepsilon}=\frac{1}{l_0}\left(\frac{v_0-(a_0\sigma/A_1c_1\rho_1)}{1+(A_2c_2\rho_2/A_1c_1\rho_1)}-\frac{a_0\sigma}{A_3c_3\rho_3}\right), \qquad (2)$$

where Vo is the initial velocity of the impact bar; ρ , c and A are the density, bar wave velocity and cross-sectional area, respectively; subscripts 1 and 2 correspond to the impact bar and pressure bar, respectively; a_0 , ℓ_0 and σ are the initial cross-sectional area, initial length and instantaneous nominal flow stress of the specimen, respectively. The mass of the specimen is neglected. The true stress is calculated assuming the deformation of the specimen to be uniform.

3. INVERSE ANALYSIS

In general, if a system is linear, the output can be obtained from the input by the following convolution integral:

$$y(t)=\int_0^t g(t-\tau)\cdot x(\tau)d\tau, \qquad (3)$$

where, in the present experiment, y (t) is the output obtained with the strain gauge system, x (t) is the input produced at the end of the the pressure bar and g (t) is the transfer function (impulse response) of this system. Accordingly, the deconvolution integral gives the input x (t) from the output y (t) as

$$x(t)=\int_0^t g^{-1}(t-\tau)\cdot y(\tau)d\tau. \qquad (4)$$

In this work, the above deconvolution was performed numerically. Function x(t), y(t) and g(t) were discretized with a time interval of 0.1 μs, which was equal to the sampling time of the digital memory used for recording the data. Eqs. (3) and (4) were reduced to linear simultaneous algebraic equations. The deconvolution was carried out using Jacobi's iteration method. The iteration was stopped at 5 times, since high frequency noise is amplified by further continuing the iteration. In order to eliminate the high frequency noise in the output data, the output data was smoothed prior to deconvolution by means of the Savitzky-Golay method [10] .

The transfer function g (t) in this system is obtained by differentiating the experimentally determined response to a unit step input. The unit step input was obtained by impacting the pressure bar with an elastic bar of the same material and diameter. The differentiation of the unit step response was obtained by using a smoothing differentiation (discrete points: 7) which eliminated simultaneously the noise contained in S (t) . This transfer function includes not only the effect of the elastic dispersion in the pressure bar but also the response of the strain gauge system. The transfer function dS (t) /dt and the experimental response S (t) are shown in Fig. 1. In the figure L is the distance between the collision end and the gauge position on the pressure bar.

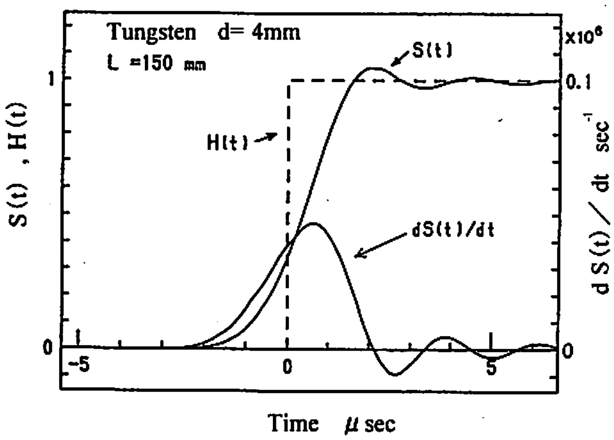


Fig. 1 Experimental response S(t) to unit step input H(t) and transfer function dS(t)/dt.

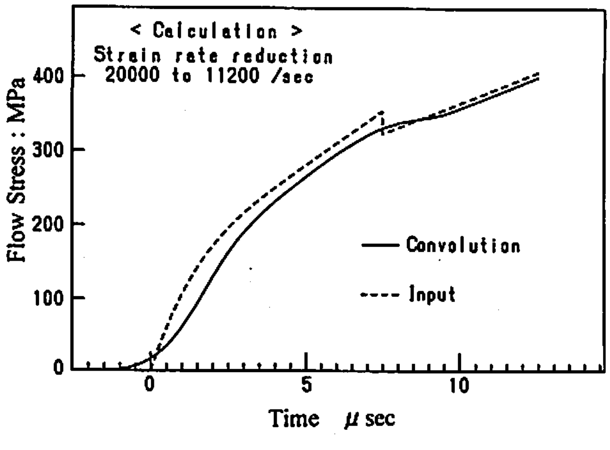


Fig. 2 Result of applying convolution to input estimated from Eq. 5.

4. RESULT AND DISCUSSION

Measurements were made for high-purity polycrystalline copper (OFHC,99.99% purity) . Specimens were machined to 2 mm in both length and diameter from a cold-drawn bar of 3 mm in a diameter. After machining,the specimens were annealed in a vacuum for 3 h at 600 ℃ and furnace cooled, giving a grain size of about 60 μm.

First, for comparison with the results of the strain rate reduction tests, constant-strain-rate measurements of the flow stress at strain rates from about 4000 to 20000/s were performed for the same copper specimens using the same apparatus as used in the strain rate reduction tests. After applying the deconvolution integral to the obtained data, the empirical expression of σ_t for the strain ε and strain rate $\dot{\varepsilon}$ was derived. This expression is given in the form

$$\sigma_t(\varepsilon,\dot{\varepsilon})=\sigma_0(\varepsilon)+\alpha\dot{\varepsilon} \qquad (5)$$

where

$$\sigma_0(\varepsilon)=557\,\varepsilon+262\,\varepsilon^{1/2}+56.5$$

and

$$\alpha=3\times10^{-3}\ \mathrm{MPa\cdot s^{-1}}$$

Before entering into the description of the results of the strain rate reduction tests, the necessity of the application of the deconvolution to the data is demonstrated using a computer simulation and experimental examples.

Figure 2 shows a computer simulation of the strain rate reduction test at strain rates from 20000 to 11200/s. The hypothetical flow stress-time curve was obtained using Eq. (5), assuming a stepwise fall in the flow stress at a strain of 15 % , and shown by a dashed curve in Fig. 2. This curve corresponds to the input produced at the specimen side-end of the pressure bar. The solid curve shown in the figure is obtained by applying the convolution integral to the dashed curve, and corresponds to the output to be obtained as the output of the strain gauge system. As is seen in Fig. 2, there are marked differences between the curves in the shape around the strain rate reduction point and inthe flow stress level. The difference in the flow stress level isparticularly marked in the region before the strain rate reduction where the stress time curve has a steeper gradient. This indicates that it is difficult to obtained the correct flow stress drop directly from the output of the strain gauge system.

The flow stress-time curve obtained by applying the deconvolution to the solid curve of Fig. 2 is shown in Fig. 3 together with the dashed curve of Fig. 2. The dashed and solid curves in Fig. 3 show that, by applying the deconvolution to the output of the system, a satisfactory recovery is attained except the shape in region very near to the strain rate reduction point.

The true-stress strain curves obtained from the solid curvesin Fig. 2 and Fig. 3 are shown in Fig. 4. The dashed curve in Fig.4 is calculated from the solid curve in Fig.2 without deconvolution while the solid curve in Fig. 4 is calculated from the solid curve in Fig. 3, which is obtained by applying the deconvolution. In order to evaluate the amount of the drop in the flow stress, the constant-strain-rate is also shown in Fig. 4. The constant strain curve expressed by a solid curve is obtained by applying the deconvolution, while the dashed curve is obtained without applying the deconvolution. In the case of the solid curves the amount of the flow stress drop $\Delta\sigma_1$ is 26 MPa and equal to the drop of the true stress in the hypothetical input. On the other hand, the true stress drop obtained from the dashed curve, $\Delta\sigma_2$, is clearly small compared with the flow stress drop in the hypothetical input, $\Delta\sigma_1$. Therefore, if we try to measure the dynamic flow stress response to the sudden reduction in the strain rate using a Hopkinson bar system of compression type at high strain rates, it is necessary to apply the deconvolution to the output of the measuring system.

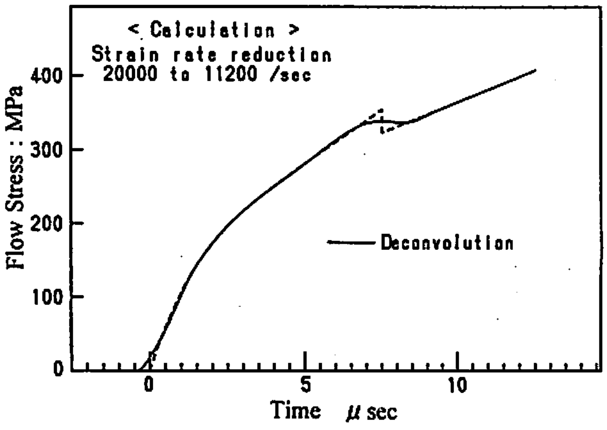


Fig. 3 Result of applying deconvolution to convolution curve shown in Fig. 2.

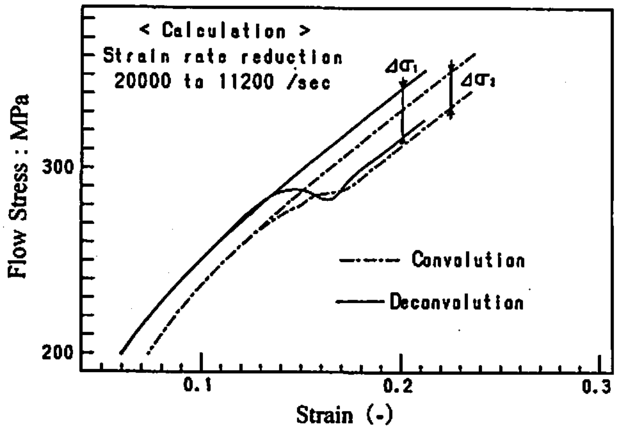
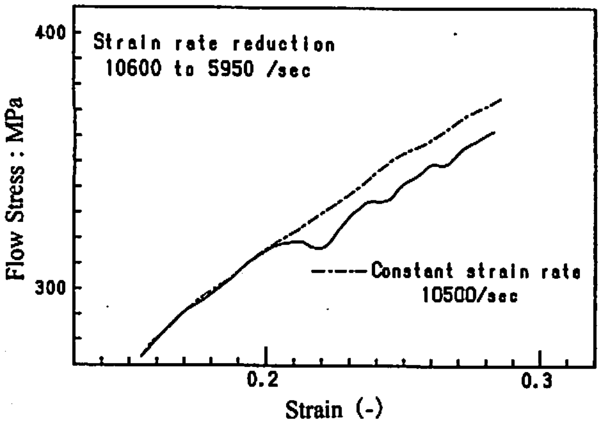
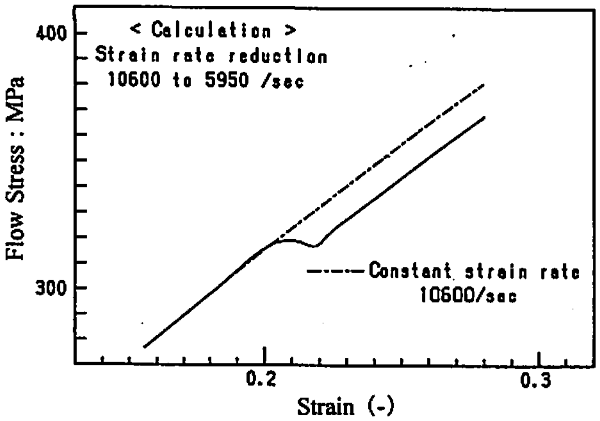


Fig. 4 Comparison of $\Delta\sigma_1$ with $\Delta\sigma_2$. $\Delta\sigma_1$ is the magnitude of flow stress drop obtained from the deconvolution curve of Fig. 3 and $\Delta\sigma_2$ is that obtained from the convolution curve of Fig. 2.

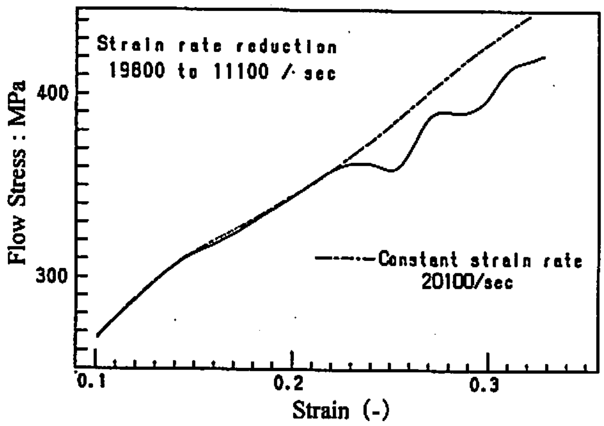


(a) Experiment

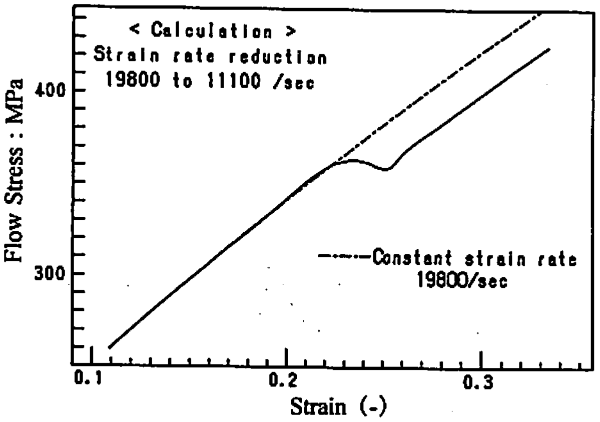


(b) Simulation

Fig. 5 True stress-strain curves for strain rate reduction test at strain rates from 10600 to 5950/s.



(a) Experiment



(b) Simulation

Fig. 6 True stress-strain curves for strain rate reduction test at strain rates from 19800 to 11100/s.

Figures 5 and 6 show the true stress-strain curves for the strain rate reduction tests at strain rates from 10600 to 5950/s and from 19800 to 11100/s, respectively. In each figure (a) and (b) represent the experimental results and computer simulations, respectively. The results of the experiment and computer simulation resemble each other closely in the response of the flow stress to the sudden reduction in the strain rate.

5. CONCLUSION

In order to clarify the roles of the instantaneous strain rate and the strain rate history in the dynamic flow stress at high strain rates above about 10000/s, tests in which the strain rate was suddenly decreased during the dynamic deformation were conducted for high-purity polycrystalline copper. To eliminate the effect of the transfer function of the measurement system from the experimental data, inverse analysis was applied to the output. As a result, it is confirmed that in the strain rate region where the steep increase of $d\sigma / d\log\dot{\varepsilon}$ appears, the instantaneous strain rate plays a more important role than the structural evolution reflecting the strain rate history in the dynamic flow stress. This is the same conclusion as was obtained detailed information on the behavior of the flow stress at for aluminum in the previous work. In order to obtain more the reduction point, a further refined inverse analysis using different approaches is necessary.

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