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DYNAMIC FLOW STRESS RESPONSE OF ALUMINIUM TO SUDDEN REDUCTION IN STRAIN RATE AT VERY HIGH STRAIN RATES

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RESUME :

L'objectif du travail est d'évaluer les effets de la vitesse de déformation instantanée et l'état structural correspondant à l'histoire de la vitesse de déformation pendant un écoulement dynamique. Pour cela ont été conduits des essais dans lesquels la vitesse de déformation est rapidement abaissée pendant la déformation plastique d'un aluminium polycristallin, dans une gamme 8000 - 20000/s. Un nouvel appareil a été conçu afin d'obtenir une brusque réduction de la vitesse de déformation. Les résultats montrent que la vitesse de déformation instantanée joue un rôle plus important que l'état structural dû à l'histoire de la vitesse de déformation.

Abstract - In order to evaluate the effects of the instantaneous strain rate and the structural state reflecting the strain rate history upon the dynamic flow stress, the tests in which the strain rate is suddenly decreased during the dynamic plastic deformation are conducted for high purity polycrystalline aluminium in a strain rate range from about 8000 to 20000 /s. To obtain a sufficiently steep reduction in the strain rate a new apparatus is devised. The results indicate that the instantaneous strain rate plays a more important role than the strain rate history for the dynamic flow stress in such a very high strain rate range in which the steep increase in the strain rate sensitivity of the flow stress is observed.

1.- Introduction

It has been reported by many investigators, as reviewed also so many times (for example, by Campbell /1/, Lindholm /2/ and Harding /3,4/), that the strain rate sensitivity of the flow stress ($d\sigma/d\log\dot{\varepsilon}$) increases steeply above a critical strain rate of about 5000 /s. In most cases, especially in FCC metals, below the critical strain rate the flow stress increases linearly with logarithm of the strain rate while above the critical strain rate it increases linearly with the strain rate itself. For this phenomenon an interpretation very attractive for the dislocation theory was given by Ferguson, Kumar and Dorn /5/ and has been supported by many investigators; that is, the above mentioned transition in the strain rate sensitivity is due to the transition in the dominant rate-controlling mechanism of the dislocation motion from the thermally assisted cutting of the point obstacles to the viscous phonon drag. However, questions have been also raised not only for this interpretation but also for experimental results themselves at such high strain rates /6/.

On the other hand, it has been also widely recognised that the dynamic flow stress of metallic materials at a given strain depends upon both the instantaneous strain rate and the structural state of the materials reflecting the strain rate history. Recently, an important interpretation for the above mentioned steep rise of the strain rate sensitivity has been presented on the basis of the role of the strain rate history by Follansbee, Kocks and Regazzoni /7/. They measured the *threshold stress* (quasi-static yield stress at 0 K) after imposing a certain amount of dynamic pre-deformation and showed that the dynamic flow stress can be closely correlated with the threshold stress after the dynamic pre-deformation at the same strain rate. Further, Follansbee and Kocks /8/ pointed out that the dynamic flow stress at the state having the same threshold stress depends upon the instantaneous strain rate very little and the steep increase in the strain rate sensitivity at very high strain rates is not observed. Their conclusion was that the drastic increase in the strain rate sensitivity of the flow stress is not due to the viscous drag against dislocation motion which depends upon the instantaneous strain rate but due to the internal structure evolution which reflects the strain rate history.

At this stage, it seems important to confirm the relative importance between the instantaneous strain rate and the strain rate history in the dynamic flow stress. In order to evaluate the effect of the strain rate history, the tests in which the strain rate is suddenly increased or decreased have been made for various materials using the various test techniques. Those works have been reviewed also many times, Campbell /1/, Duffy /9,10/ and Harding /3,4/. In this type of experiments, the strain rate change has been made from quasi-static to dynamic, dynamic to quasi-static, or dynamic to dynamic, and the deformation mode has been mostly torsion or compression. In those tests, the strain rate has been limited below about 2000 /s. However, in order to clarify the roles of the instantaneous strain rate and strain rate history in the above mentioned steep rise of the strain rate sensitivity, the strain rate change test at very high strain rates, at least above 10000 /s, is required. In the present work, using a newly devised apparatus, measurements were made for high purity polycrystalline aluminium at strain rates up to above 20000 /s. Experimental techniques and results are presented together with discussions.

2.- Experimental Method

For the strain rate change tests in such a very high strain rate range, a very steep change in the strain rate is required for the loading system and also a high time resolution capability for the measuring system. As the first step, the authors tried tests using a miniature split Hopkinson pressure bar apparatus of a compression type with a stepped impact bar. But, owing to the dispersion of the elastic wave in the incident and transmitter bars, satisfactory results were not obtained. Although for the dispersion in the transmitter bar correction can be made mathematically by using the dispersion characteristic of the bar, but the dispersion in the incident bar makes it impossible to realise a sufficiently sharp change in the strain rate, which is necessary for the separation of the flow stress change caused by the change in the instantaneous strain rate from the flow stress change due to the *fade-out* of the effect of the strain rate history /11/. In the present work, a new apparatus shown in Fig.1 has been devised. In this apparatus, the projectile hits the specimen directly and then the velocity of the specimen side end of the projectile is decreased sharply by the collision with the decelerator. The initial velocity of the projectile just before hitting the specimen is determined by measuring the time interval between signals from two sets of the light source and sensor systems which detect the passing through of the projectile. The strain at which the strain rate reduction occurs is set by adjusting the amount of projection of the end of the specimen from that of the decelerator with a micrometer screw. The flow stress is measured with two semiconductor strain gauges attached to the

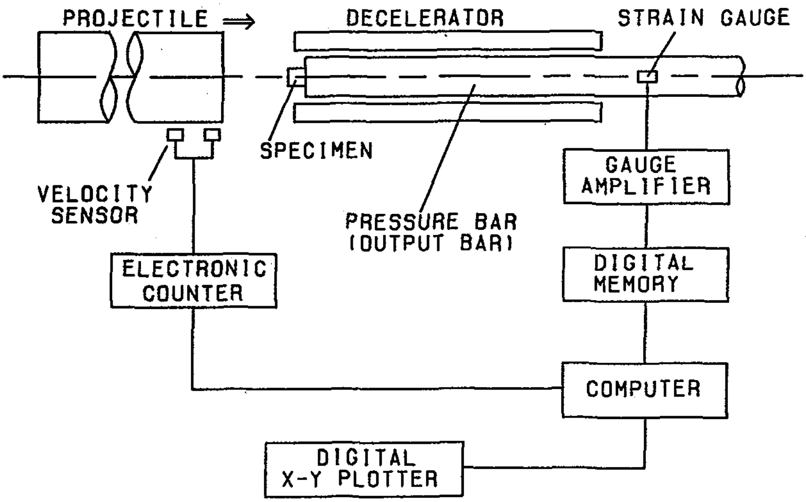


Fig. 1.- Schematic diagram of the devised apparatus for strain rate reduction tests.

pressure bar in symmetry to cancel out the effect of bending. The signal from the strain gauges is amplified with a wide band amplifier and stored in a high speed digital memory. The data are then transmitted to a computer, processed and directly plotted in the form of the true flow stress vs strain with a digital X-Y plotter.

Using the one dimensional bar wave approximation the instantaneous strain rate of the specimen is obtained in the following forms:

(a) before the strain rate reduction

$$\dot{\varepsilon} = (1/L)[V_0 - (2A\sigma/a_1c_1\rho_1) - (2A\sigma/a_3c_3\rho_3)] \tag{1}$$

(b) after the strain rate reduction

$$\dot{\varepsilon} = (1/L)[\{V_0 - (2A\sigma/a_1c_1\rho_1)\}/\{1 + (a_2c_2\rho_2/a_1c_1\rho_1)\} - (2A\sigma/a_3c_3\rho_3)] \tag{2}$$

where V_0 is the initial velocity of the projectile; ρ, c and a are the density, bar wave velocity and cross sectional area, respectively; subscripts 1, 2 and 3 mean the projectile, decelerator and pressure bar, respectively; A, L 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.

Both the projectile and decelerator were made of Ti-6Al-4V alloy and their diameters were 10 mm. The inner diameter of the decelerator was 5.5 mm. The pressure bar was made of maraging steel, and its diameter was 4 mm. Although, in order to reduce the effect of the elastic wave dispersion, use of a thinner pressure bar is required, the adopted diameter was practically the lowest limit for attaching the strain gages. The density and the bar wave velocity of Ti-6Al-4V alloy are 4.42 g/cm^3 and 5060 m/s, respectively. Those of maraging steel are 8.02 g/cm^3 and 4767 m/s. The length and diameter of the specimen were both 2 mm. The above combination gives the strain rate reduction by about 41 % of the strain rate before reduction. The true stress was calculated assuming the deformation of the specimen to be uniform.

3.- Results and Discussion

Measurements were made for 5N purity polycrystalline aluminium. In order to obtain a fully recrystallised state, specimens machined at a cold drawn state were annealed at 500 ℃ for 3 hr in a vacuum. The average grain diameter was about 0.2 mm. Firstly, in order to compare with the results of the strain rate reduction tests, constant strain rate measurements of the flow stress at strain rates from about 4000 to 25000 /s were made for the same aluminium specimens using the same apparatus as used in the strain rate reduction tests. The results are shown in Fig.2. At the strain rates above about 5000 /s the flow stress increases linearly with strain rate. This means that the strain rate sensitivity of the flow stress defined by ($d\sigma/d\log\dot{\varepsilon}$) shows the typical increase seen in the very high strain rate range. For each strain rate reduction test, in order to analyse its result, measurements of two constant strain rate stress-strain curves at strain rates respectively corresponding to before and after the strain rate reduction are required. In order to avoid this troublesome work, in the present work, an empirical formula is derived from the experimental results shown in Fig.2. Using this equation the constant strain rate curves for given strain rates can be predicted. The empirical expression of $\sigma(\varepsilon, \dot{\varepsilon})$ for the strains from 0.05 to 0.30 and for the strain rates from 5000 to 25000 /s is given in a form

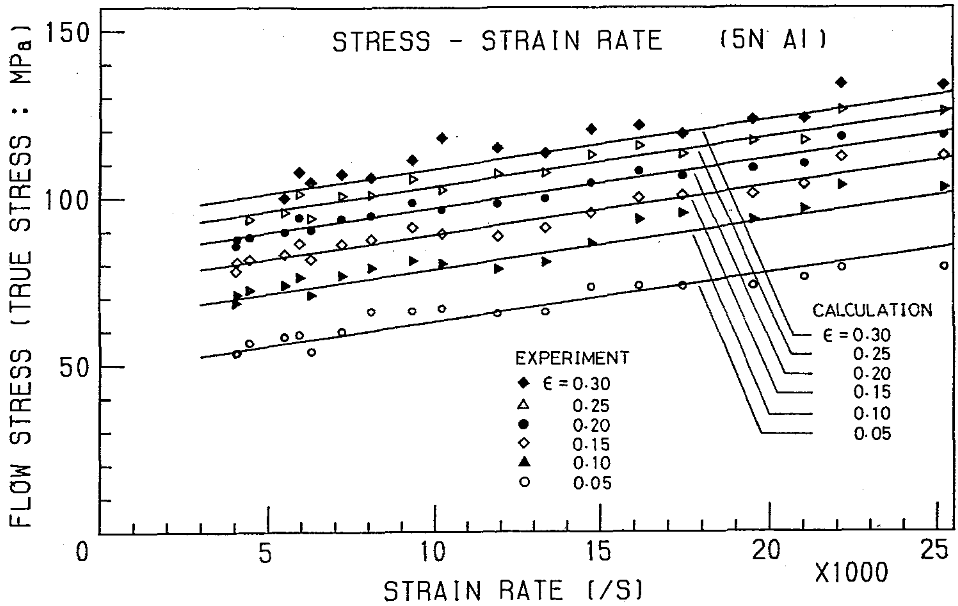


Fig.2.- Results of the constant strain rate tests.
Solid lines are calculated using Eq.(3).

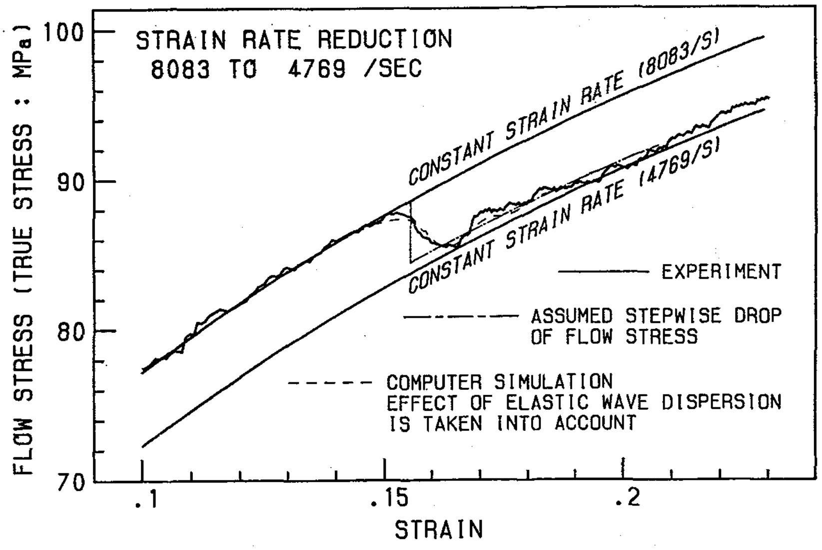
$$\sigma(\varepsilon, \dot{\varepsilon}) = [\sigma_0(\varepsilon) + \alpha \dot{\varepsilon}], \qquad (3)$$

where $\sigma_0(\varepsilon) = 5.35 + 217\varepsilon^{1/2} - 100\varepsilon$ (MPa),

and $\alpha = 1.47 \times 10^{-3}$ (MPa s).

The solid lines in Fig.2 are drawn using the above formula.
The strain rate reduction tests were made from the strain rates ranging from about 8000 to 20000 /s. The strain at which the reduction of the strain rate was imposed was about 0.16. Typical results are shown in Fig.3. In these figures enlarged true stress-strain curves around the rate reduction point are shown. Further, for comparison, the constant strain rate curves at the strain rates corresponding respectively to before and after the strain rate reduction, which are predicted by Eq.(3), are also plotted. With the reduction of the strain rate the flow stress falls to the value near to the constant strain rate curve at the strain rate after the reduction. As seen in Fig.2, the experimental flow stress shows a scatter of the order of a few percent, and, accordingly, in the plotting of Fig.3 type, the portion of the stress-strain curve of the strain rate reduction test before the rate reduction does not fall exactly on the corresponding constant strain rate curve predicted by Eq.(3), and usually a small gap remains. This is inconvenient to analyse the results of the rate reduction tests by comparing with the results of the constant rate tests. In the present work, since the curves predicted by Eq.(3) are based upon a number of tests, the above mentioned gap is canceled out by multiplying the data of the rate reduction test by an appropriate factor. The necessary values of the factors were between 0.97 and 1.03. If it is considered that the strain rate reduction test is a kind of differential test, it should be allowable to apply an appropriate factor very near to unity.

As is seen in Fig.3, the flow stress falls a little gradually compared with the steepness of the strain rate reduction expected to be attained in the devised apparatus of Fig.1. This is not likely due to the *fade-out time* of the memory of the strain rate history but likely due to the dispersion of the elastic wave in the pressure bar for the stress measurement. In fact, by assuming a stepwise fall of the flow stress and taking account of the dispersion effect in the



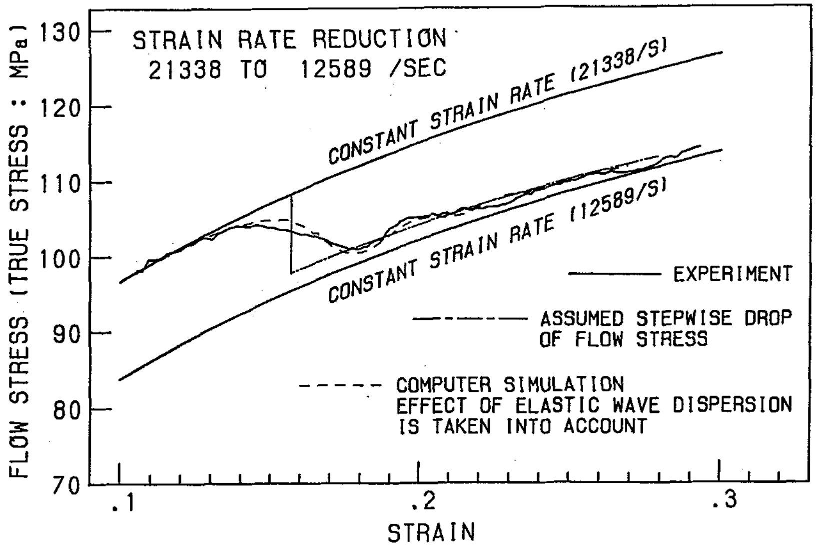


Fig.3.- Examples of the flow stress response to a sudden reduction in the strain rate. For comparison, the response predicted by a computer simulation, in which the wave dispersion in the pressure bar is taken into account, is also shown.

pressure bar, computer simulation predicts the broken curves shown in Fig.3, which shows a good agreement with the experimental response of the flow stress. The dispersion response of the pressure bar to a unit step input used in the above simulation was an experimental one obtained by impacting upon the end of the pressure bar with a bar of the same material and diameter. As shown in Fig.4, the experimental dispersion characteristic is very similar to the theoretical one given in terms of Airy's integral /12/ in the dispersed shape of the wave front, which determine the gradient of the stress fall, although, in the subsequent oscillatory part, it has a smaller amplitude and a little lower frequency. From the above analysis, it may be concluded that the flow stress fall occurs very steeply with the steep decrease in the strain rate. This seems to imply that the flow stress fall is not of structural state origin which should take a time for *fade-out* of the memory of the strain rate history but of instantaneous strain rate origin. The results of the measurements of the flow stress fall caused by the strain rate reduction are summarised in Fig.5. The amount of the reduction of the strain rate was about 41 percent. The ratio of the flow stress fall $(\Delta\sigma)_f$ to the flow stress difference between two constant strain rate curves at the strain rates before and after the rate reduction, $(\Delta\sigma)_d$, are shown in Fig.6. The values of the ratio are about 0.75 to 0.80.

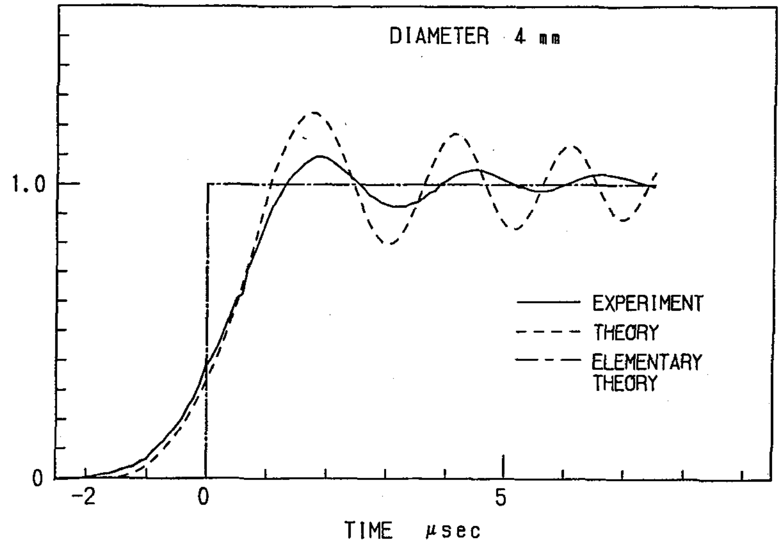


Fig.4.- Experimental and theoretical responses of the wave dispersion in the maraging steel pressure bar to a unit step input: distance from the bar end to strain gauge = 153 mm, Poisson's ratio = 0.3, the other conditions are given in the text.

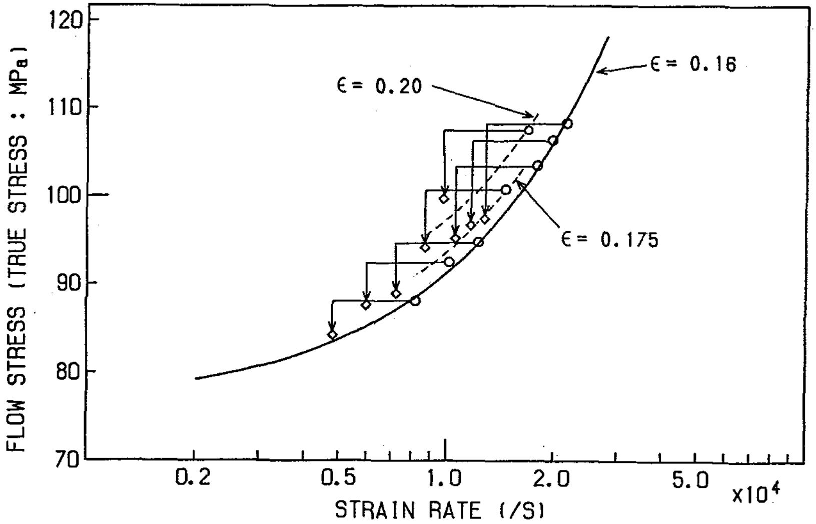


Fig.5.- Flow stress fall caused by the strain rate reduction. The strain at which the strain rate is suddenly reduced is about 0.16 except being indicated in the figure.

The remaining small part, 0.25 to 0.20, can be attributed to the difference in the structural state caused by the difference in the strain rate history. This implies that in the strain rate sensitivity of the flow stress at very high strain rates the instantaneous strain rate plays more important role than the structure evolution reflecting the strain rate history. Although it must be noted that the above conclusion is drawn from the measurements for fully recrystallised polycrystalline aluminium having rather coarse grains, it differs largely from the conclusion drawn from the threshold stress measurements for copper /7,8/.

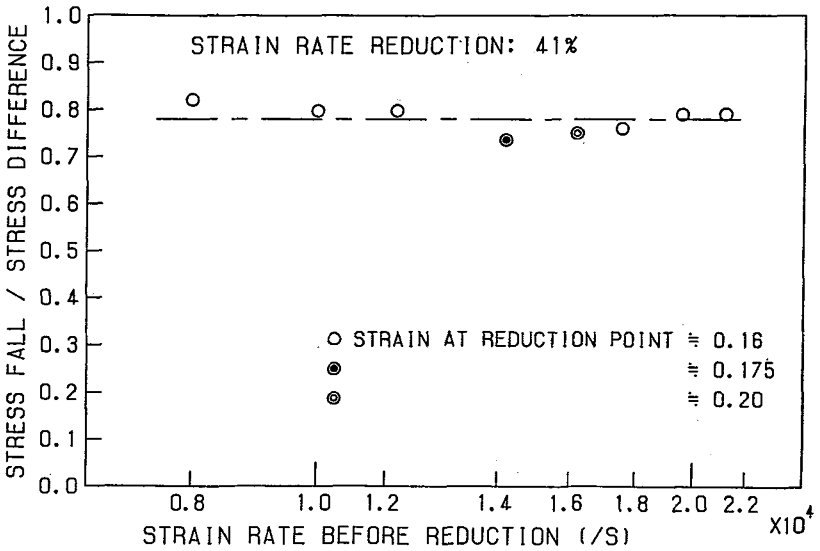


Fig.6.- Ratio of the flow stress fall $(\Delta\sigma)_f$ to the flow stress difference between two constant strain rate curves corresponding to before and after the strain rate reduction, $(\Delta\sigma)_d$.

4.- Conclusions and Acknowledgement

The strain rate reduction tests were conducted for high purity polycrystalline aluminium at strain rates up to about 20000 /s. A new apparatus was devised by which a sharp reduction in strain rate can be obtained. It is concluded that, for the flow stress at very high strain rates, the instantaneous strain rate plays more important role than the structural state of the materials reflecting the strain rate history.

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