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WORK HARDENING AND MECHANICAL EQUATION OF STATE
IN SOME METALS IN MONOTONIC LOADING

MASTER

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G. L. Wire, F. V. Ellis and Che-Yu Li

Department of Materials Science and Engineering
Cornell University
Ithaca, New York 14850

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ABSTRACT

The work hardening coefficients of Type 316 stainless steel niobium, and 1100 aluminum alloy are measured in tensile tests. It is demonstrated experimentally that in the measured stress, plastic strain rate, and temperature range the work hardening coefficient depends only on stress and plastic strain rate. The significance of the experimental results is discussed in terms of the concept of the mechanical equation of state for plastic deformation.

INTRODUCTION

The purpose of this report is to show that the work hardening coefficient of polycrystalline solids depends only on the current values of stress and plastic strain rate.

It is well known that plastic deformation of a polycrystalline solid is path or history dependent. This dependence of a material can be represented incrementally by⁽¹⁾

$$\gamma d\epsilon_p = d \ln \sigma - \nu d \ln \dot{\epsilon}_p \quad (1)$$

where $\gamma = \left. \frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}_p} \right|_{\epsilon_p}$ which measures work hardening and $\nu = \left. \frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}_p} \right|_{\epsilon_p}$ which measures strain rate sensitivity and σ , $\dot{\epsilon}_p$, and ϵ_p are stress, plastic strain rate and plastic strain respectively.

Recent work⁽²⁻⁶⁾ on the mechanical equation of state for plastic deformation has provided a useful approach for the description of plastic deformation. These results show that the parameter ν in Equation 1 depends on the current stress and plastic strain rate only and can be obtained by load relaxation experiments. The parameter γ has not been examined from this viewpoint in the literature. If it also depends only on the current values of stress and plastic strain rate, Equation 1 can then be integrated for any arbitrary path using parameters γ and ν which are history independent. The advantage of this possibility in mechanical design for plastic deformation is obvious.

Experimentally, if the parameter γ depends on stress and plastic strain rate only, the $\log_{10} \sigma$ vs ϵ_p data at a particular plastic strain rate for a given material with varied deformation histories

will form a set of parallel curves. These curves can be translated onto each other along the plastic strain axis. This means that at a given $\log_{10} \sigma$ and $\dot{\epsilon}_p$, they will have the same slope and therefore the same γ , independent of prior history. In this work this possibility will be demonstrated experimentally in a variety of materials to show its general applicability. These metals include Type 316 stainless steel, niobium, and 1100 aluminum alloy.

EXPERIMENTS

The Type 316 Stainless steel is commercial grade and is obtained from Allegheny Ludlum Steel Company in the form of $\frac{1}{4}$ " rods. The gage section of the specimen is 1.50 inches long with a diameter of 0.100 inch. After machining, the specimen is annealed in vacuum for 1 hour at 1100°C and air cooled. The average grain size of the specimen is about 35 μ .

The high purity niobium (99.999%) is electro-deposited niobium obtained from Union Carbide Corporation and is electron beam melted⁽⁴⁾. It is first zone-refined in two passes and swaged from $\frac{1}{2}$ " to 0.2" and subsequently annealed at 1100°C for one hour. The gage section of the specimen is 1.6 inch long with a diameter of 1/10 inch. The grain size is 200 μ .

The 1100 aluminum alloy is commercial grade and is obtained from Peter A. Frasse and Company in the form of 3/8" diameter rods. It is solutionized at 550°C, swaged to 0.2" diameter and annealed at 370°C for five days. The gage section of the specimen is 1.5 inches long with a diameter of 1/10 inch. The grain size is 25 μ .

The stress-plastic strain measurements are carried out in tension at a constant cross-head extension rate using a table model

Instron. The experimental details are essentially similar to those described in reference 3 for load relaxation experiments. Good temperature stability is also required for the present work at low strain-rates.

Following the work of Hart and Lee⁽⁷⁾, the plastic length L of the specimen is given as

$$L = L_0 + X - P/K \quad (2)$$

where L_0 is the initial gage length, P is the load at a given displacement, X is the displacement of the cross-head and K is the combined stiffness constant of the machine and specimen. During the experiment the displacement and the load are obtained from the load-time record and the known constant cross-head speed. The machine constant K depends on the plastic length of the specimen⁽⁷⁾,

$$K^{-1} = C_m + \left(\frac{L}{L_0}\right)^2 \left(\frac{L_0}{A_0 E}\right) \quad (3)$$

where C_m is the machine compliance, E is the Young's modulus of the specimen and A_0 is the initial cross-sectional area of the specimen.

In the present work the modulus E is measured at room temperature to be $(2.9 \pm 0.1) \times 10^7$ psi, $(1.35 \pm 0.05) \times 10^7$ psi and $(0.87 \pm 0.03) \times 10^7$ psi for Type 316 stainless steel, niobium and 1100 aluminum alloy respectively. The machine compliance, C_m , is measured to be $(1.54 \pm 0.03) \times 10^{-5}$ in -lb^{-1} for experiments on Type 316 stainless steel and $(2.49 \pm 0.05) \times 10^{-5}$ in -lb^{-1} for experiments on niobium and 1100 aluminum alloy. This measured machine compliance reflects mainly the compliance of the load cell. The uncertainties in the Young's modulus and the machine compliance will give an uncertainty

of no greater than 4×10^{-4} in the plastic strain.

The plastic strain of the specimen ϵ_p is $\ln \frac{L}{L_0}$ and the plastic strain rate $\dot{\epsilon}_p$ is $\frac{\dot{L}}{L}$. For the purpose of the present work, $\log_{10} \sigma$ vs ϵ_p data at a constant plastic strain rate are required. From Equation 2, since $\dot{P}/K$ is usually much smaller than $\dot{L}$ except at very low plastic strain, a constant cross-head extension rate $\dot{X}$ will give to a good approximation a constant rate of change in the plastic length $\dot{L}$. This point will be discussed further in a later section. But a constant $\dot{L}$ will not correspond to a constant plastic strain rate because the plastic length of the specimen is a variable. At constant $\dot{L}$, using the definition of ϵ_p and $\dot{\epsilon}_p$ we may write

$$d\epsilon_p \Big|_{\dot{L}} = - d \ln \dot{\epsilon}_p \Big|_{\dot{L}} \quad (4)$$

Substituting Equation (4) into Equation (1) yields,

$$\gamma d\epsilon_p \Big|_{\dot{L}} = d \ln \sigma \Big|_{\dot{L}} + \nu d \epsilon_p \Big|_{\dot{L}} \quad (5)$$

The dependence of the parameter ν in the above equation on the stress and plastic strain rate can be determined by load relaxation experiments and are given in references 4, 6 and 8. For the stress and plastic strain rate ranges involved in the present experiments the values of the parameter ν are small and not important. We may conclude therefore that the slope of the $\log_{10} \sigma$ vs ϵ_p curve obtained at a constant cross-head extension rate will give the value of γ with negligible error.

The value of initial gage length L_0 is taken to be its nominal length, because both ends of the gage section are tapered. Relative errors among specimens due to uncertainty in the gage length

are minimized by the use of a template for specimen machining. The maximum error in stress due to uncertainty in the initial specimen cross sectional area is estimated to be of the order of 0.01 in $\log_{10}\sigma$.

RESULTS AND DISCUSSION

A. Stress-Plastic Strain Data

Typical $\log_{10}\sigma$ vs ϵ_p data taken at various plastic strain rates at room temperature and at 200°C for 1100 aluminum alloy are shown in Figures 1, 2, 3a and 3b. The slope of these curves multiplied by 2.303 gives the value of the work hardening parameter γ . It is seen from these figures that the shape the $\log_{10}\sigma$ vs ϵ_p curves of Type 316 stainless steel is not sensitive to strain rate in the measured range while those for niobium and 1100 aluminum alloy show more strain rate dependence. The main purpose of this work is not to test the validity of existing work hardening theories^(9,10). We have examined, however, some of the proposed $\sigma - \epsilon_p$ correlations. The parabolic correlation is found to be not completely satisfactory for the present data. A more general power relation $\sigma = \sigma_0(\epsilon_p + \epsilon_0)^{\kappa}$ seems to be required where the parameters κ , σ_0 and ϵ_0 depend on strain rate.

B. Strain Rate Change Data

In order to demonstrate that the work hardening parameter depends only on stress and plastic strain rate and is independent of prior deformation history, strain rate change experiments are performed. Figures 4, 5, 6a and 6b show typical results of these experiments. The data points shown in Figure 4 represent the $\log_{10}\sigma$ vs ϵ_p data obtained from a stainless steel specimen. During this

run two strain rates are involved. The solid line in Figure 4 represents data obtained from another stainless steel specimen at a strain rate equal to the higher strain rate in the previous run. This solid line has been translated along the plastic strain axis so that the data of the same plastic strain rates overlap. It is clear from Figure 4 that at same $\log_{10}\sigma$ and $\dot{\epsilon}_p$ the work hardening parameter γ measured by the slope of the curve, is the same for two specimens of different deformation history. Similar results are found for niobium and 1100 aluminum alloy (Figures 5, 6a and 6b). In the latter figures the data points represent the results of a run during which the strain rate is lowered for a period of time and then raised to its original value. The solid line represents the data from another specimen obtained at a strain rate equal to the higher strain rate of the previous run. There is always a slight uncertainty of less than 0.015 in the relative values of $\log_{10}\sigma$ between two specimens. In order to ensure that data comparison is made at the same stress level, the solid line is first placed on a $\log_{10}\sigma$ scale such that it will match the initial portion of the data points of the same strain rate of the other specimen. It is then translated along the plastic strain axis to match the last portion of the data points of the other specimen to show the history independent nature of the work hardening parameter. The data of 1100 aluminum alloy shown in Figure 6b are taken at 150°C which corresponds to 0.45 of the absolute melting point of the alloy. It can be concluded that even at elevated temperatures, the work hardening parameter depends only on the current values of stress and plastic strain rate.

The above experimental results also show that the plastic

strain of a material cannot be used to characterize the structural state of the material because the position of $\log_{10} \dot{\epsilon}_p$ vs ϵ_p curve along the plastic strain axis depends on the deformation history of the material.

C. Low Plastic Strain Data and Transient Behavior

At very low plastic strains the measurement of plastic strain and plastic strain rate is ambiguous. From Equation 2 we can calculate a nominal plastic strain and a nominal plastic strain rate. Typical data for stainless steel in this region are plotted in Figure 7. In this region an important contribution to the measured nominal plastic strain rate is the contribution of the transient plastic strain rate discussed by Hart and Solomon⁽²⁾.

It is seen also from Figure 7 that the measured nominal plastic strain rate is not constant. This is because the total strain rate includes the contribution of elastic strain rate which decrease with increasing plastic strain. For nominal plastic strains greater than 0.003 the nominal plastic strain rate approaches a constant value. This observed asymptotic behavior of the plastic strain rate confirms the statement made in the section on experiments that at large plastic strains a constant extension rate $\dot{X}$ will give a constant $\dot{L}$.

The transient plastic strain rate discussed above probably will be important also in the low plastic strain region of the data shown in Figures 1, 2 and 3. In this region the value of the parameter γ is high and the transient effects resulting from the build-up of dislocation pile-up are likely to occur⁽²⁾. The interest of the mechanical equation of state requires precise values of

stress and plastic strain rate. For the work hardening data correlation to be discussed in the later part of the paper, the values of the parameter γ at room temperature are taken from plastic strains greater than 2.6%, 1.6% and 2.8% for Type 316 stainless steel, niobium and 1100 aluminum alloy respectively.

The transient effects occur also in the strain rate change experiments. As the strain rate increases from a lower value to a higher value, the corresponding stress increase will require a larger dislocation pile-up⁽²⁾. The transient effects are clearly present in Nb and 1100 aluminum alloy as shown by the portion of the data in Figures 5, 6a, and 6b obtained after the strain rate increase which do not fit on to the solid line. The contribution of the transient strain rate results in a lower stress compared to the stress given by the solid line at the same strain rate. The data in Figure 6b show a larger stress change and therefore a larger transient region. It should be noted that if the strain rate is lowered during the run, transient effects will also occur resulting in stresses higher than those in the absence of transients.

D. Work Hardening Data Correlation

The results of the present work and those from load relaxation experiments (2-6), have demonstrated that the parameters γ and v in Equation 1 depend only on the current values of stress and plastic strain rate. We can integrate Equation 1 therefore using these history independent parameters to describe a deformation path of interest. For the convenience of the integration, in this section we shall first rewrite Equation 1 using the hardness parameter

y introduced by Hart⁽¹⁾. We shall define a new work hardening parameter Γ in terms of the hardness parameter and establish its dependence on stress, plastic strain rate and the hardness parameter. As mentioned previously we are not particularly interested in the correlations proposed by existing work hardening theories.

The load relaxation experiments show that any pair stress and plastic strain rate belong to a unique constant hardness $\log_{10} \sigma - \log_{10} \dot{\epsilon}_p$ curve. These constant hardness curves belong to a one parameter family of curves with the arbitrary parameter being the hardness parameter y ⁽²⁾ and can be translated along a straight line in a $\log_{10} \sigma - \log_{10} \dot{\epsilon}_p$ plot to overlap each other. It will be convenient to define the hardness parameter utilizing the translation path to characterize the hardness of a material in a $\log_{10} \sigma - \log_{10} \dot{\epsilon}_p$ plot to be the $\log_{10} \sigma$ value of the intersection of the constant hardness (y) curve and a particular translation path with a slope of $\mu \left(\frac{d \ln \sigma}{d \ln \dot{\epsilon}_p} \right)_v$.

Equation 1 may be rewritten in terms of the hardness parameter y as

$$d \ln y = F(d \ln \sigma - v d \ln \dot{\epsilon}_p) \quad (6)$$

where F is an integration factor.

Along the translation path, $\frac{d \ln \sigma}{d \ln \dot{\epsilon}_p} \bigg|_v = \mu$ and $d \ln y = d \ln \sigma$. Substituting these expressions into Equation (6) we solve for F and Equation (6) becomes

$$d \ln y = \frac{\mu}{\mu - v} (d \ln \sigma - v d \ln \dot{\epsilon}_p) \quad (7)$$

For constant plastic strain rate tests,

$$\left. \frac{\partial \ln \gamma}{\partial \epsilon_p} \right|_{\dot{\epsilon}_p} = \left(\frac{\mu}{\mu - \nu} \right) \left. \frac{\partial \ln \sigma}{\partial \epsilon_p} \right|_{\dot{\epsilon}_p} = \left(\frac{\mu}{\mu - \nu} \right) \gamma \quad (8)$$

we define

$$\Gamma = \left. \frac{\partial \ln \gamma}{\partial \epsilon_p} \right|_{\dot{\epsilon}_p}$$

Both the parameters Γ and γ measures the work hardening properties of a material. For the interest of the application of the concept of mechanical equation of state for plastic deformation it will be convenient to use the parameter Γ ⁽⁸⁾.

The values of the parameter γ are obtained from the data shown in Figures 1, 2 and 3 as a function of stress and plastic strain rate. The relative stress uncertainties among different specimens resulting from uncertainties in the cross-sectional area of the specimen are minimized by performing experiments in which work hardening data of several strains rates are obtained from a single specimen. The values of the parameter μ and ν are obtained from references 4, 6 and 8. The values of the parameter Γ are calculated as a function of stress and plastic strain rate using Equation 8. Figures 8, 9 and 10 show the plot of constant Γ line in $\log_{10} \sigma$ and $\log_{10} \dot{\epsilon}_p$ coordinates for Type 316 stainless steel, niobium and 1100 aluminum alloy respectively. In the same figures the constant hardness (γ) $\log_{10} \sigma - \log_{10} \dot{\epsilon}_p$ curves from stress relaxation experiments are also shown. It is seen that the constant Γ lines show a steeper slope compared to that of constant γ lines. The constant γ lines for Type 316 stainless steel for the present specimens are shifted in $\Delta \log_{10} \dot{\epsilon} = 1.05$ compared to those given in reference 6.

Since both the parameters γ and v have been shown to depend on the current values of stress and plastic strain rate, the parameter Γ should have the same property. From the viewpoint of mechanical equation of state, any two of the three variables, σ , $\dot{\epsilon}_p$ and γ specifies the third one. We have therefore more than one method to correlate the work hardening data, because the parameter Γ is defined by any two of the same three parameters. The plot shown in Figures 8, 9 and 10 represents one of the methods of data correlation. In Figures 11, 12 and 13 a different method is shown.*

In Figure 11, 12 and 13 the constant Γ line is plotted in $\log_{10} \gamma - \log_{10} (\frac{\gamma}{\sigma})$ coordinates for Type 316 stainless steel, niobium and 1100 aluminum alloy respectively. The $\log_{10} \gamma$ values for type 316 stainless steel and niobium are the values of $\log_{10} \sigma$ of the intersections between the constant γ lines given in references 4 and 6 and a translation path. The constant γ lines for Type 316 stainless steel for the present specimens are shifted in $\Delta \log_{10} \dot{\epsilon}_p = 1.05$ compared to those given in reference 6. The translation path used in the calculation passes through a point with $\log_{10} \sigma = 4.6$ and 4.0 and $\log_{10} \dot{\epsilon}_p = -4.85$ and -8.0 for Type 316 stainless steel and niobium respectively. For 1100 aluminum alloy it has been found that its constant γ lines can be represented by $\ln(\frac{\sigma}{\dot{\epsilon}}) = (\frac{\dot{\epsilon}}{\sigma})^\lambda$ where $\lambda = 0.11$ and $\ln \gamma = \ln \sigma^*(8)$.

The constant Γ lines in Figures 11, 12 and 13 in the data range shown can be represented approximately by a set of parallel lines which offer potentially a simple method for data correlation. These data suggests that the work hardening parameter is likely

* E. W. Hart participated in the development of this method.

to be a power function of σ and y . The low Γ data points for niobium deviate from this simple trend. The observed deviation may reflect the possibility that these low Γ points are influenced by plastic instability at large plastic strains during tensile tests.

The trend shown in Figures 11, 12 and 13 based on room temperature data can be supported by work hardening data at higher temperatures. For example in Figure 13 the data for the largest value of $\log_{10} \frac{\dot{\sigma}^*}{\sigma}$ are obtained at 250°C and a strain plastic strain rate $\log_{10} \dot{\epsilon}_p = -5.26$ and the other data points are from room temperature tests. It should be noted that the σ and $\dot{\sigma}^*$ values for 250°C data have been corrected to room temperature values by shear modulus G which is temperature dependent such that the value of σ/G is the same⁽⁸⁾. The values of $\log_{10} \sigma$ and $\log_{10} \dot{\sigma}^*$ at 250°C are further corrected for the amount of 0.1 for grain boundary sliding⁽⁸⁾.

The possibility that the work hardening parameter Γ can be specified by the values of σ and y (or $\dot{\sigma}^*$) offers advantages also in data collection. It is shown in reference 8 that 1100 aluminum alloy will deform at $\log_{10} \dot{\epsilon}_p = -13.1$ and $\log_{10} \dot{\epsilon}_p = 5.26$ at room temperature and 250°C respectively at the same hardness ($\dot{\sigma}^*/G$) and the same applied stress (σ/G). To obtain work hardening data at $\log_{10} \dot{\epsilon}_p = -13.1$ will be difficult indeed.

At elevated temperatures the plastic deformation will include the contribution of grain boundary sliding which will cause difficulties in calculating the parameter Γ for the type of correlation discussed above. Essentially we require the values of σ , $\dot{\epsilon}_p$ and $\dot{\sigma}^*$ which represent the grain matrix behavior^(11,12,13). At the

present we do not have sufficient information to specify these values for the 150°C and 200°C work hardening data of 1100 aluminum alloy which we also obtained in the present work. They are therefore not included in Figure 13. A detailed discussion of these difficulties is given in reference 8.

The dependence of the parameter Γ on stress and the hardness parameter y (or $\bar{\sigma}$) can be supported by the data of Frenkel et al. on aluminum alloys⁽¹⁴⁾. They find that creep data obtained at two different temperatures, but at the same stress overlap in a $\log_{10} \dot{\epsilon}$ vs $\log_{10} t \exp(-Q/RT)$ plot where t is time, Q is activation energy and T is temperature. These results suggest that there is no recovery⁽⁸⁾ and at the same stress and temperature compensated strain rate (i.e., at the same hardness) the work hardening properties of the material is the same. This is consistent with the conclusion of the present work that the parameter Γ can be specified by stress and the hardness parameter y (or $\bar{\sigma}$).

At the present most of the work hardening theories involved plastic strain as a variable^(9,10). Since plastic strain is shown by the present work not to be a useful variable for correlating work hardening data, it is difficult to compare the present results with these theories. If the method of data correlation suggested in Figures 11, 12 and 13 is proven to have general applicability it will be useful to explore its theoretical implications.

In summary, the present work has found:

1. Within the measured data range, the work hardening properties in monotonic loading of Type 316 stainless steel, niobium and 1100 aluminum alloy depends only on the current values of stress and plastic strain rate.

2. The work hardening parameter $\Gamma(\frac{d \ln y}{d \epsilon_p} |_{\epsilon_p})$ can be correlated in the form of constant Γ lines in a plot of $\log_{10} y$ (or $\log_{10} \sigma^*$) vs. $\log_{10}(\frac{y}{\sigma})$ (or $\log \sigma^*/\sigma$).

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FIGURE CAPTIONS

- Figure 1 Log_{10} (stress) vs plastic strain data for Type 316 stainless steel at several plastic strain rates at room temperature.
- Figure 2 Log_{10} (stress) vs plastic strain data for niobium at several plastic strain rates at room temperature.
- Figure 3a Log_{10} (stress) vs plastic strain data for 1100 aluminum alloy at several plastic strain rates at room temperature.
- Figure 3b Log_{10} (stress) vs plastic strain data for 1100 aluminum alloy at several plastic strain rates at 200°C .
- Figure 4 Log_{10} (stress) vs plastic strain data at two different strain rates for Type 316 stainless steel. Points are for a specimen deformed at two different strain rates. Solid line is for another specimen deformed at $\dot{\epsilon}_p = 2 \times 10^{-3} \text{ sec}^{-1}$. The solid line has been translated along the strain axis to show that γ is the same for the two specimens at $\dot{\epsilon}_p = 2 \times 10^{-3} \text{ sec}^{-1}$.
- Figure 5 Log_{10} (stress) vs plastic strain data at two different strain rates for niobium. Points are for a specimen deformed at two different strain rates. Solid line is for another specimen deformed at $\dot{\epsilon}_p = 2 \times 10^{-4} \text{ sec}^{-1}$. The solid line has been translated along the strain axis to show that γ is the same for the two specimens at $\dot{\epsilon}_p = 2 \times 10^{-4} \text{ sec}^{-1}$.

- Figure 6a $\log_{10}$ (stress) vs plastic strain data at two different strain rates for 1100 aluminum alloy. Points are for a specimen deformed at two different strain rates. Solid line is for another specimen deformed at $\dot{\epsilon}_p = 2 \times 10^{-4} \text{ sec}^{-1}$. The solid line has been translated along the strain axis to show that γ is the same for the two specimens at $\dot{\epsilon}_p = 2 \times 10^{-4} \text{ sec}^{-1}$.
- Figure 6b $\log_{10}$ (stress) vs plastic strain data at two different strain rates for 1100 aluminum alloy at 150°C . Points are for a specimen deformed at two different strain rates. Solid line is for another specimen deformed at $\dot{\epsilon}_p = 0.5 \times 10^{-3} \text{ sec}^{-1}$. The solid line has been translated along the strain axis to show that γ is the same for the two specimens at $\dot{\epsilon}_p = 0.5 \times 10^{-3} \text{ sec}^{-1}$.
- Figure 7 $\log_{10}$ (stress) and nominal plastic strain rate data vs nominal plastic strain for Type 316 stainless steel at low strains.
- Figure 8 Constant Γ or work hardening parameter points as a function of $\log_{10}$ (stress) and $\log_{10}$ (strain rate) for Type 316 stainless steel. The dotted lines are constant γ or hardness lines⁽⁶⁾.
- Figure 9 Constant Γ or work hardening parameter points as a function of $\log_{10}$ (stress) and $\log_{10}$ (strain rate) for niobium. The dotted lines are constant γ or hardness lines⁽⁴⁾.
- Figure 10 Constant Γ or work hardening parameter points as a function of $\log_{10}$ (stress) and $\log_{10}$ (strain rate)

for 1100 aluminum alloy. The dotted lines are constant $\bar{\sigma}^*$ or hardness lines⁽⁸⁾.

Figure 11 Constant Γ or work hardening parameter points correlated as a function of $\log_{10} \gamma$ and $\log_{10} \gamma/\sigma$ for Type 316 stainless steel where γ is the hardness parameter.

Figure 12 Constant Γ or work hardening parameter points correlated as a function of $\log_{10} \gamma$ and $\log_{10} \gamma/\sigma$ for niobium where γ is the hardness parameter.

Figure 13 Constant Γ or work hardening parameter points correlated as a function of $\log_{10} \bar{\sigma}^*$ and $\log_{10} \bar{\sigma}^*/\sigma$ for 1100 aluminum alloy where $\bar{\sigma}^*$ is the hardness parameter.

Figure 1

Figure 2

Figure 3a

Figure 3b

Figure 4

Figure 5

Figure 6a

Figure 6b

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13