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GRAIN BOUNDARY SLIDING AND STRUCTURE

by

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INTRODUCTION

The work undertaken under this contract is a part of the total effort of this laboratory to develop concepts and methods for the characterization of mechanical properties of polycrystalline solids at elevated temperatures. During the past two years significant progress has been made based on which our approaches and objectives have become more clearly defined. At the present we believe that the concept of mechanical equation of state adopted in this work will have general applicability and it can be developed into a practical tool for characterizing mechanical properties and for mechanical design at elevated temperatures. In the following the approach taken in this work will be introduced briefly.

An arbitrary plastic deformation path of a material can be represented by

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

where ϵ_p , σ , and $\dot{\epsilon}_p$ are plastic strain, stress and plastic strain rate respectively, $\gamma = \left. \frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}_p} \right|_{\epsilon_p}$ and is a work hardening parameter and $v = \left. \frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}_p} \right|_{\epsilon_p}$ and is a rate sensitivity parameter. It is well known that the plastic deformation properties of a solid will be affected by its prior deformation history. The parameters γ and v in equation (1) may therefore be history dependent so that their values will not be easily obtained. This is a part of the reason that the integration of equation (1) has not been widely used to describe plastic deformation along a path of interest for example

in creep.

Hart⁽¹⁾ has proposed recently that based on the concept of mechanical equation of state, the rate sensitivity parameter v will depend only on the current values of stress and plastic strain rate and will be independent of prior deformation history. The existence of mechanical equation of state will also reduce the experimental work required to evaluate this parameter. These possibilities for grain matrix deformation have been confirmed experimentally by Hart and by this laboratory in a variety of materials covering a wide range of deformation parameters (stress, strain rate etc.)⁽²⁻⁶⁾. However at elevated temperatures grain boundary sliding will contribute to plastic strain and plastic strain rate and influence the rate sensitivity parameter. An important objective of the AEC supported work is therefore to test Hart's concept under the condition where the contribution of grain boundary sliding is important. This work is also designed to measure the contribution of grain boundary sliding quantitatively to provide a basis for assessing the damage produced by deformation (intergranular failure) at elevated temperatures⁽⁷⁾.

For the objectives described above we have investigated the deformation behavior of lead and 1100 aluminum alloy by performing stress relaxation experiments. These experiments have been successful. The results of the work on lead are in the form of a paper accepted for publication by Acta Metallurgica. We are in the process of preparing a report for the work on 1100 aluminum alloy. These results will be summarized in the later

part of the progress report.

In equation (1) if both parameters γ and ν depend only on the current values of stress and plastic strain rate, we will be able to integrate equation (1) using these parameters which are history independent to describe plastic deformation along a particular path. This is to say that it will be possible to characterize the dependence of plastic deformation on deformation history by parameters which are history independent and equation (1). The advantage of this possibility in mechanical design for plastic deformation at elevated temperatures is obvious. As described above that the rate sensitivity parameter ν possesses this desirable property and can be evaluated easily using the concept of mechanical equation of state. However the properties of the work hardening parameter γ have not been examined from this viewpoint in the literature. For this purpose we have performed constant extension rate tensile tests on type 316 stainless steel, niobium and on 1100 aluminum alloy to measure the work hardening parameter. Even though the work on work hardening is not included in our proposal we have deviated from our original plan because of its timeliness and its importance. These experiments cover a wide range of deformation parameters and history. The results of the experiments demonstrate that the work hardening parameter γ in these materials also depends only on the current values of stress and plastic strain rate and is history independent. We are preparing a paper on this work and will provide a summary in the progress report.

Based on the progress so far, we believe that the general

validity of the approach taken in this work is established. Considerable work still remains however to develop this approach into a practical tool. In the recent Gordon Conference on "Constitutive Equations for Plasticity" we are invited to present our recent work. As a result of this meeting we are invited also to contribute a paper to a book on the same subject as that of the Gordon Conference.

In the following the results of our recent progress will be summarized.

Grain Boundary Sliding and Mechanical Equation of State in Lead

Stress relaxation experiments are performed on single crystal, bi-crystal and polycrystalline lead specimens. The test temperature is room temperature which corresponds to approximately 0.5 of the absolute melting temperature of lead. At this temperature grain boundary sliding will be significant. During stress relaxation experiments the cross head of the Instron machine is held fixed. Stress relaxation results from converting the elastic strain to the plastic strain of the specimen. The rate of stress relaxation is related to the plastic strain rate of the specimen through a machine constant. The experiment yields $\log \sigma - \log \dot{\epsilon}_p$ curves at various constant structures. The desired structure of the specimen is obtained by preloading the specimen to various plastic strain levels prior to stress relaxation experiments. The slope of these curves gives the rate sensitivity parameter v . The existence of mechanical equation of state can be demonstrated if these constant structure $\log \sigma - \log \dot{\epsilon}_p$ curves belong to a one parameter family of curves. The stress dependence of grain boundary sliding rate is usually smaller than that of grain matrix deformation rate. The existence of grain boundary sliding can be shown when the $\log \sigma - \log \dot{\epsilon}_p$ curves of a polycrystalline specimen exhibit a decreased stress dependence compared to that for the curves of a single crystal specimen. The important findings of this work are listed below

1) The behavior of mechanical equation of state is found in all the specimens tested including those in which grain boundary sliding exists.

2) The contribution of grain boundary sliding is found to increase as the grain size decreases.

3) A series model which includes both the contribution of grain boundary sliding and grain matrix deformation is used to analyze the $\log \sigma - \log \dot{\epsilon}_p$ data. This model allows the determination of the relative extent of grain boundary sliding and grain matrix deformation quantitatively.

4) Grain boundary sliding on the macroscopic scale is found to show non-viscous behavior which is contrary to the assumption usually made in the literature.

5) The stress and strain rate range where grain boundary sliding is observed to be important is consistent with the stress and strain rate range where intergranular failures are found in creep rupture tests.

6) A different mode of plastic deformation is observed which is characterized by irregular flow and low stress dependence. This behavior is interpreted to result from large scale grain boundary migration accompanying grain boundary sliding.

Work Hardening and Mechanical Equation of
State in Type 316 Stainless Steel,
Niobium and 1100 Aluminum Alloy

The purpose of this work is to demonstrate that the work hardening parameter $\gamma \left(\frac{\partial \log \sigma}{\partial \epsilon_p} \right)$ depends only on the current values of stress and strain rate and is history independent. Constant extension rate tensile tests have been performed on polycrystalline type 316 stainless steel, niobium and 1100 aluminum alloy specimens at room temperature. These experiments yield $\log \sigma - \epsilon_p$ curves at constant plastic strain rates with specimens of various prior deformation history. The slope of these curves gives the work hardening parameter γ . If in a $\log \sigma - \epsilon_p$ plot, at the same plastic strain rate the $\log \sigma - \epsilon_p$ curves of two specimens with different prior deformation history can be shifted along the ϵ_p axis to overlap each other, we can conclude that the work hardening parameter γ depends only on the current values of stress and plastic strain rate and is independent of deformation history. A wide range of plastic strain rate and deformation history has been examined. The desired behavior described above is found in all the specimens tested. This behavior will also provide a basis for data correlation and extrapolation and therefore reduce the experimental work required to evaluate the work hardening properties of a material. The work hardening parameter γ for type 316 stainless steel and for niobium at room temperature is found to be not strongly dependent on plastic strain rate. Room temperature corresponds to a higher homologous

temperature for 1100 aluminum alloy. In this material the work hardening parameter γ is more dependent on plastic strain rate.

Mechanical Properties of 1100 Aluminum Alloy at Elevated Temperatures

Stress relaxation experiments and constant extension rate tensile tests have been performed on 1100 aluminum alloy as a function of temperature. The maximum test temperature is 250°C which corresponds approximately to 0.6 of its absolute melting temperature. The experimental results yield data on the rate sensitivity parameter v and the work hardening parameter γ covering a wide range of temperature, stress, plastic strain rate. Detailed data analysis and interpretation are still in progress. Some of the preliminary conclusions are given below:

1) The constant structure $\log \sigma - \log \dot{\epsilon}_p$ curves for all the specimens tested from the stress relaxation experiments show the behavior of mechanical equation of state. In the case where the deformation is controlled only by grain matrix processes these curves can be represented by the expression

$$\ln \left(\frac{\sigma^*}{\sigma} \right) = \left(\frac{\dot{\epsilon}_p^*}{\dot{\epsilon}_p} \right)^\lambda \quad (2)$$

where σ^* is a structural parameter, for a given structure $\frac{\sigma^*}{G}$ (G = modulus) is constant and is independent of temperature; λ is a constant and is temperature and structure independent and $\dot{\epsilon}_p^*$ is a constant and its temperature dependence measures the activation energy for deformation.

2) At higher temperatures the work hardening parameter γ is found to depend also only on the current values of stress

and plastic strain rate.

3) The room temperature constant $\log \sigma - \log \dot{\epsilon}_p$ curves reflect grain matrix deformation and can be represented by equation (2) given above. As the temperature increases to above 75°C, equation (2) is no longer applicable indicating the contribution of grain boundary sliding. At 250°C the $\log \sigma - \log \dot{\epsilon}_p$ can be fitted by equation (2) again. This is consistent with Hart's prediction⁽⁸⁾ that at high temperatures and/or low plastic strain rates grain boundary will offer no resistance and the deformation will be controlled by grain matrix again. This is the first experimental evidence to show definitely that grain boundary sliding is important only in an intermediate temperature and plastic strain rate range.

4) The activation energy for grain matrix deformation is found to change significantly with temperature.

5) The experimental results raise strong questions as to the validity of creep theories which are based on the concept of interplay between work hardening and recovery.

CONCLUSION

The experimental results discussed above support the validity of the general approach outlined in the introduction. Some of the data analysis are still in progress. Attempts will be made also to compare the results obtained with those from creep experiments.

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