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D. N. Robinson

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ON THE CONCEPT OF A FLOW POTENTIAL AND THE STRESS-STRAIN RELATIONS OF REACTOR SYSTEM METALS

D. N. Robinson

ABSTRACT

Tests are outlined for assessing the applicability of a "flow potential," as introduced by J. R. Rice, in describing the high-temperature mechanical behavior of some reactor system metals. Preliminary uniaxial tests of the type outlined have been conducted on type 304 stainless steel and the results are summarized. Although these results are not sufficient to demonstrate the existence of a flow potential, or more specifically, the stress path independence its existence implies, they are useful in establishing the proper conditions under which definitive multiaxial experiments can be run.

Keywords: Plasticity, creep, constitutive laws, high-temperature, metals, potential theory, stainless steel, ferritic steel

INTRODUCTION

The multiaxial yield surface explorations[1] performed under the High-Temperature Structural Design (HTSD) Program* to date have been conducted at temperatures below the "creep regime." Classical (time-independent) plasticity is a permissible idealization at these temperatures because yield surfaces based on "short" loading times do not differ greatly from those based on "long" times. At temperatures in the creep regime, say 500°C (932°F) and above for many structural alloys, time becomes an essential ingredient; time spent at a given stress level or temperature, for example, may be of great importance. Yield may have to be defined in terms of a specified amount of permanent strain incurred over a specified time.

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*The objective of the High-Temperature Structural Design (HTSD) Program is to develop high-temperature design methods and criteria applicable to Liquid Metal Fast Breeder Reactor (LMFBR) components.

There have been several studies published recently which are concerned with the structure of inelastic stress-strain relations for metals at high temperature, i.e., where time effects dominate. Some of these studies are directed toward specific structural applications and loading histories and are largely ad hoc; others are limited entirely to uniaxial conditions. One study that may well serve as a basis for a rational, multiaxial constitutive theory is that of Rice.[2] Rice takes the viewpoint that plasticity is inherently time-dependent and, in a sense, provides a mathematical framework for the extension of the theory of dislocation dynamics developed by Johnston and Gilman[3,4] to more general stress states and loading paths.

Rice's model consists of an inhomogeneous elastic system, such as a polycrystal, which can undergo macroscopic plastic deformation as a result of internal rearrangement through slip. He alternately considers a continuum model of slip and a discrete dislocation model. Both lead to the same time-dependent, macroscopic structure for the stress-strain relations, in which, at a given history of prior deformation, the inelastic strain rate is derivable from a scalar "flow potential." In other words, Rice shows that, consistent with his model, there exists a potential function:

$$\Omega(\underset{\sim}{\sigma}, \text{history}) \ , \tag{1}$$

which depends on the <u>current</u> state of stress and the <u>past</u> history of deformation. For a fixed history, the inelastic strain rate is given by:

$$\dot{\underset{\sim}{\varepsilon}}^P = \frac{\partial \Omega}{\partial \underset{\sim}{\sigma}} \ . \tag{2}$$

Equation (2) implies <u>path independence</u> in the sense that the integral

$$\int_{\underset{\sim}{\sigma}^A}^{\underset{\sim}{\sigma}^B} \dot{\underset{\sim}{\varepsilon}}^P \cdot d\underset{\sim}{\sigma} \tag{3}$$

is independent of the stress path followed from $\underset{\sim}{\sigma}^A$ to $\underset{\sim}{\sigma}^B$. That is to say,

$$\int_{\underset{\sim}{\sigma}^A}^{\underset{\sim}{\sigma}^B} \dot{\underset{\sim}{\varepsilon}}^P \cdot d\underset{\sim}{\sigma} = \int_{\underset{\sim}{\sigma}^A}^{\underset{\sim}{\sigma}^B} \frac{\partial \Omega}{\partial \underset{\sim}{\sigma}} \cdot d\underset{\sim}{\sigma} = \Omega(\underset{\sim}{\sigma}^B) - \Omega(\underset{\sim}{\sigma}^A) \tag{4}$$

provided, of course, that the "inelastic state" of the material is held constant.

In particular, Eq. (4) gives

$$\Delta\Omega = \oint \dot{\underset{\sim}{\varepsilon}}^P \cdot d\underset{\sim}{\sigma} = 0 \tag{5}$$

over a <u>closed</u> stress path.

Equation (5) provides a good means of examining whether the concept of a flow potential is reasonable for a given material. From a reference stress state one can additionally stress the material over a closed path, recording the inelastic strain rate as each stress point is traversed, and evaluate the integral in Eq. (5). If the stress excursion is done "fast engouth" and/or over a "small enough" path so as to not appreciably change the state of the material,* then <u>path independence</u> as implied by Eq. (2) will be demonstrated by the satisfaction of Eq. (5) over the closed stress loop.

The existence of a "flow potential," in analogy with the yield function in classical plasticity, is a unifying feature which permits a concise, rational formulation of stress-strain relations. Ponter and Leckie[5] have proposed special forms of flow potentials derived by taking a particular creep-recovery model as being locally applicable on the microscale and, using the ideas of Rice, relating this to the macroscale. Using the same approach, a candidate potential function has been suggested by Robinson et al[6] for use with annealed 2 1/4 Cr—1 Mo steel.

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*The same "paradox" exists here as in the exploration of yield surfaces, one must incur some inelastic deformation in order to make the desired measurement (e.g., to locate the yield surface), yet not so much as to appreciably alter the inelastic state of the material.

EXPERIMENTS

An experimental study of path independence, in the above sense, was conducted by Brown[7] on an aluminum alloy at 250°C. Brown's test, however, was uniaxial and cannot be used to demonstrate a general stress path independence. In fact, Eq. (5) is satisfied for any closed uniaxial stress path, regardless of whether Eq. (2) holds, provided only that (i) the inelastic state is not appreciably altered during the test and, (ii) that the inelastic strain-rate is a function of stress. The latter condition is presently taken to be true, so that the uniaxial test can be viewed as a measure of how much the state of the material changes during a test. Moreover, the uniaxial test can provide information on how "fast is fast" and how "small a stress loop is small" in order to maintain a (nearly) constant state.

Brown's test was conducted over a stress range of about 14 MPa (2 ksi) in a period of about 5 sec. Although he reports that the expected path independence is demonstrated, in fact, what is shown is that the state of the material did not change significantly during his relatively rapid stress cycle. A conclusion as to whether Eq. (2) holds, requires at least a biaxial test.

Tests similar to Brown's have recently been conducted at ORNL on type 304 stainless steel.* The tests are uniaxial but are regarded as being preliminary to a more general set of biaxial tests to be performed at a future date.

The results of the ORNL tests are shown in Figs. 1 and 2. The two tests were conducted on the same specimen and, in each case, the stress excursion begins and ends at a reference stress state of 103 MPa (15 ksi). Prior to conducting the present tests, the specimen had been held at a constant tensile stress of 86 MPa (12.5 ksi) for about 3500 hr. This was followed by an additional 250 hr at 103 MPa. The state of the material after the first 3500 hr period at 86 MPa was observed to be

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*Originally, these tests were to have been conducted mainly on 2 1/4 Cr—1 Mo steel. However, it is considered of interest to the HTSD Program to establish whether the inelastic behavior of either or both of these alloys can be adequately described by Rice's theory.

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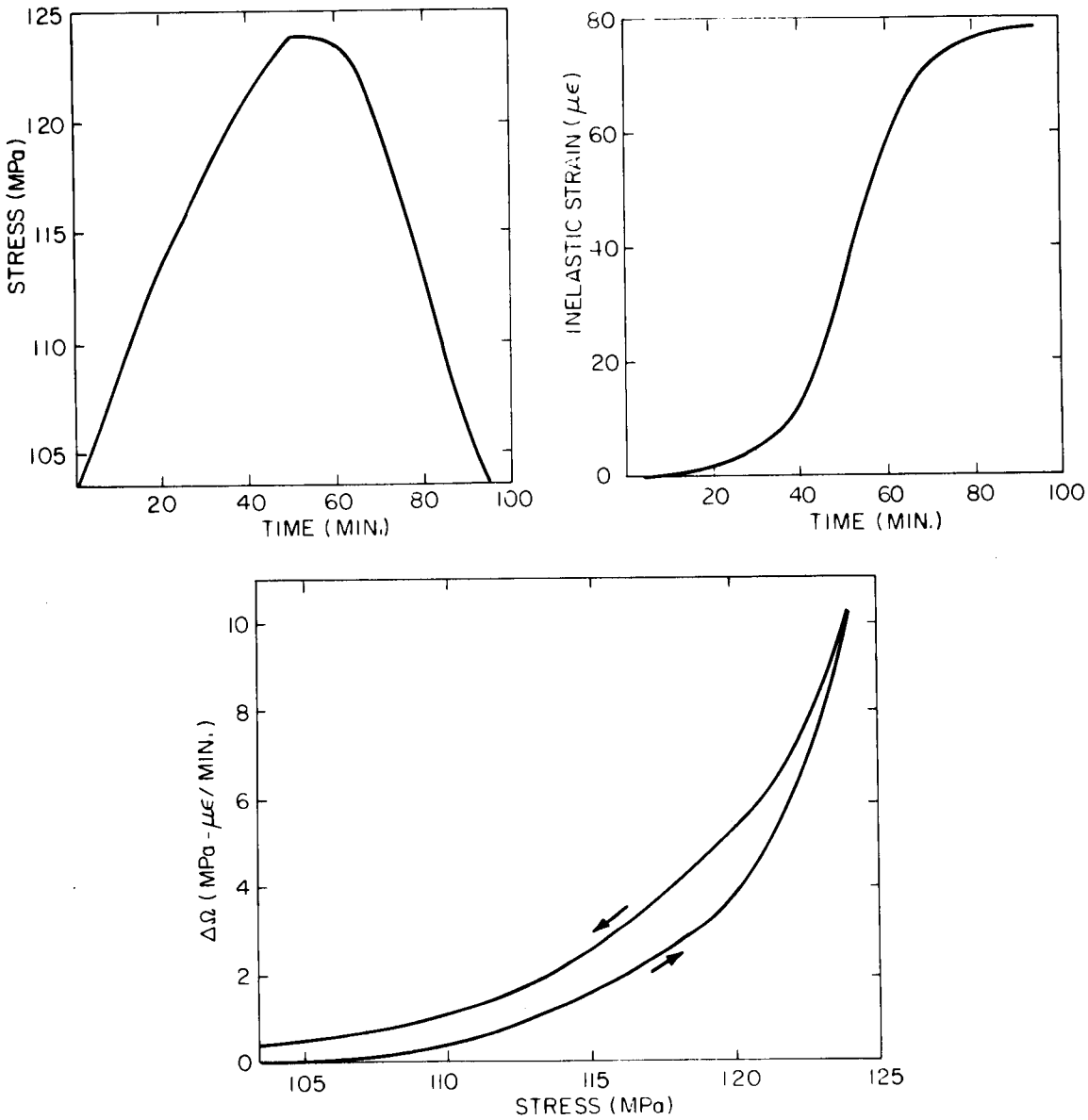

Fig. 1. Stress history, inelastic strain response and change in flow potential corresponding to stress "loop" of 21 MPa (3 ksi) over 95 min.

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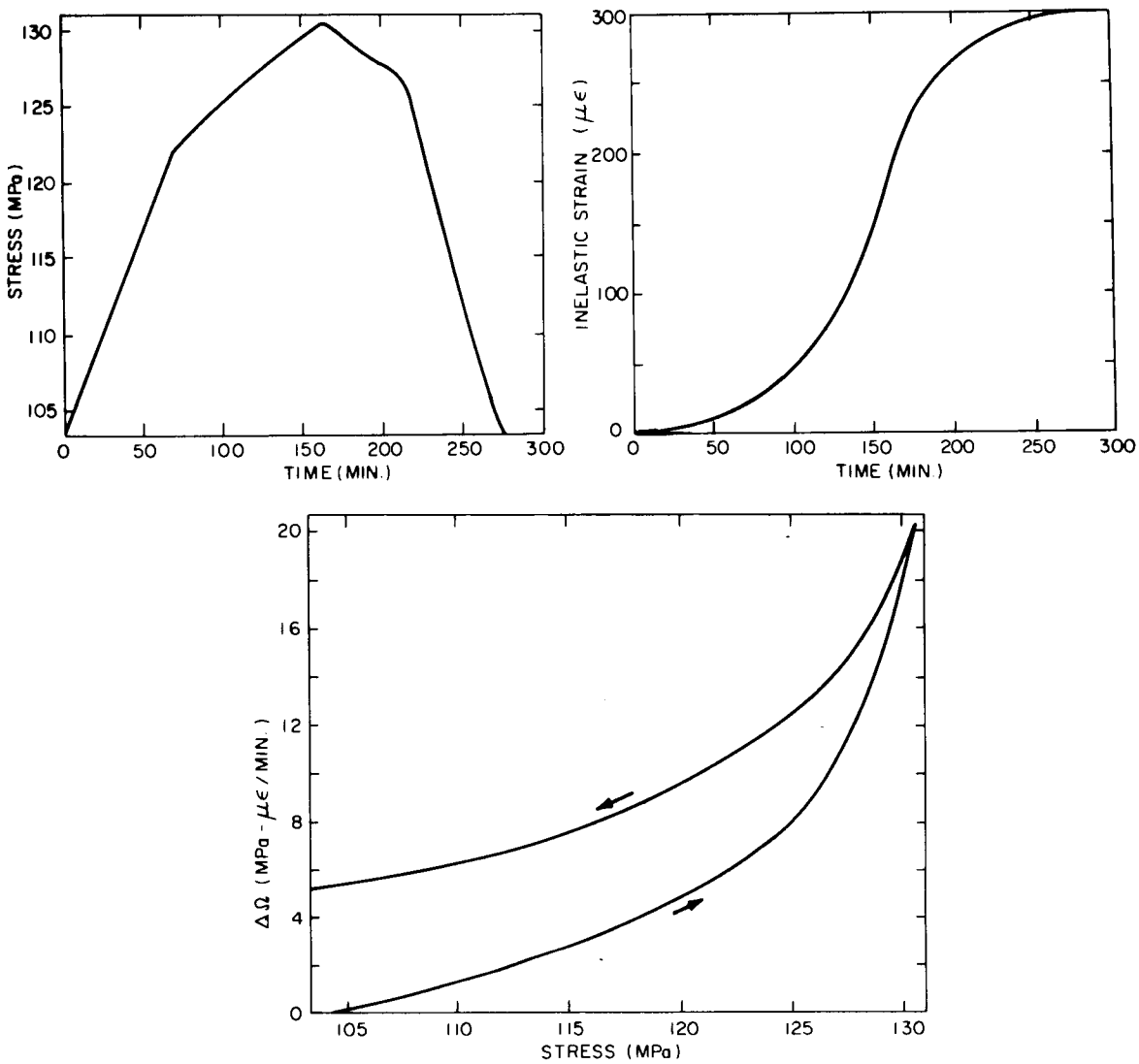

Fig. 2. Stress history, inelastic strain response and changes in flow potential corresponding to stress "loop" of 28 MPa (4 ksi) over 275 min.

relatively "stationary" with a creep rate of approximately 1.5 με/hr. Upon increasing the stress to 103 MPa, additional primary (transient) creep was incurred, with the creep rate diminishing in the additional 250 hr to about 7 με/hr. The present tests were conducted from this "nearly" steady-state condition.

The two uppermost plots in Fig. 1 show the stress history and the inelastic strain response corresponding to the first of the two tests.

The amplitude of the stress excursion, in this case, is about 21 MPa (3 ksi) and the test extends over 95 min. The accumulated inelastic strain is seen to be just short of 80 $\mu\varepsilon$.

Shown in the lower half of Fig. 1 is the change in flow potential $\Delta\Omega$(MPa × $\mu\varepsilon$/min) plotted against stress σ (MPa). $\Delta\Omega$ represents the value of the line integral, Eq. (3), evaluated over the stress loop. Note that the residual $\Delta\Omega$, i.e., the value of $\Delta\Omega$ following the complete stress cycle, is about 3% of the maximum value attained during the test. It may be said that Eq. (5) is "almost" satisfied in this case.

As discussed above, satisfaction of Eq. (5) in a uniaxial test, although necessary, is not sufficient to demonstrate that Eq. (2) holds or equivalently, that the implied path independence exists. The extent to which the $\Delta\Omega$ vs σ curve closes, however, does provide a measure of how much the state of the material has changed during the test.

In the test of Fig. 1, the inelastic state is judged to have remained effectively constant despite the accumulation of some 80 $\mu\varepsilon$ of inelastic strain. This is interpreted as meaning that if a multiaxial test were performed with essentially the same stress amplitude and duration, the state would similarly not change appreciably and, therefore, such a test could be used to assess the validity of Eq. (2). This would, of course, be true only if the reference state of the material is approximately the same in the multiaxial experiment as in the present test. It is expected that the present stress cycle of 95 min duration will be much too "slow" to maintain a constant state in a test conducted from some other initial state of the material,* e.g., from a state at which the response is not so "stationary." In the test described by Brown, for instance, the stress cycle duration is three orders of magnitude smaller than that reported here (5 sec compared to 95 min).

Figure 2 shows the results of the second experiment, performed some 48 hr after that of Fig. 1, and from effectively the same reference

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*Using the terminology of Onat and Fardshisheh,[8] in regions of the "state space" where the $|\tilde{g}|$ is large, the rate of change of the state point will be correspondingly large, and a relatively rapid stress cycle is necessary to maintain a constant state. Where $|\tilde{g}|$ is small, the stress loop can be transversed more slowly, as here, and still maintain a nearly constant state.

state. Here, the stress excursion has an amplitude of about 28 MPa (4 ksi) (103—131 MPa and back) in 275 min. The accumulated inelastic strain in this case, is seen to be close to 300 $\mu\varepsilon$. The $\Delta\Omega$ vs σ curve indicates a much larger residual following the complete stress cycle; the final $\Delta\Omega$ value is nearly 25% of the maximum. This is interpreted as meaning the cycle is "too slow" and that the state of the material changed considerably during the test. A multiaxial stress cycle of roughly the same magnitude and duration would, most likely, also exhibit a significant change of state and, thus, would not be appropriate for assessing stress path independence.

CONCLUSIONS

The test conditions, i.e., stress cycle amplitude and time duration, employed in the experiment of Fig. 1, led to Eq. (5) being "almost" satisfied. Although this is not sufficient to validate Eq. (2), it is taken to imply that similar conditions in a multiaxial test, assuming the test is conducted around the same reference state, would similarly permit constancy of state. Such a multiaxial test would thus be a proper one to test the existence of path-independence as implied by Eq. (2), and hence, to test the validity of Eq. (2) itself. Multiaxial experiments of this type, as well as additional uniaxial tests to be conducted in the neighborhood of other "inelastic states," are planned for this same heat (heat 9T2796) of type 304 stainless steel. A similar experimental program is also being planned for a reference heat of 2 1/4 Cr—1 Mo steel.

The test conditions of the second experiment, Fig. 2, on the other hand, are considered to be not "rapid enough" to maintain the necessary constancy of state, at least around the present reference state.

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