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On Thermomechanical Testing in Support of Constitutive Equation Development for High-Temperature Alloys

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SUMMARY

Three major categories of testing are identified that are necessary to provide support for the development of constitutive equations for high-temperature alloys. These are exploratory, characterization and verification tests. Each category is addressed and specific examples of each are given. Coverage ranges from some general thoughts on testing relative to constitutive equation development to detailed descriptions of specific tests and their interpretation. An extensive, but not exhaustive, set of references is provided concerning pertinent experimental results and their relationship to theoretical development.

The primary objective of this report is twofold: to serve as a guide in formulating a meaningful testing effort in support of constitutive equation development, and to aid in defining the necessary testing equipment and instrumentation for the establishment of a deformation and structures testing laboratory.

INTRODUCTION

Thermomechanical service conditions for aircraft engine hot section components involve temperature levels, thermal transients and mechanical loads severe enough to result in significant inelastic deformation. Structural analysis in support of the design of hot section components - leading to the stress, strain and temperature fields upon which life predictions are ultimately based - therefore depends strongly on accurate mathematical representations (constitutive equations)[a] of the nonlinear creep/plasticity behavior of structural alloys at high temperature. To be generally applicable, constitutive equations must be expressed in multiaxial form and be appropriate for all modes of mechanical and thermal loading expected to be experienced by the hot section components (e.g., cyclic, nonisothermal, nonradial, etc.).

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[a]Here, the meaning of constitutive equations is taken as mathematical descriptions of deformation behavior, i.e., phenomenological relationships between stress, strain, strain-rate, time, temperature, etc. A broader definition, not intended here, could include descriptions of internal damage accumulation as well. Combined deformation/damage modeling is left as a subject of future research.

In recognization of the need to better understand the detailed nature of high-temperature inelastic behavior of structural alloys and to develop accurate constitutive relationships for these alloys, an expansion of the in-house effort in constitutive equation development and the experimental facilities supporting this effort is underway in the Structural Mechanics Branch of the Structures Division at NASA Lewis. Here, some general thoughts on material testing are discussed along with a description of several tests (multiaxial and uniaxial) thought to be critical in the formulation of rationally based constitutive equations. The present report is intended to serve the dual purpose of helping to define the necessary equipment and instrumentation for a deformation laboratory and of acting as a guide in the formulation of a meaningful testing program in support of constitutive equation development.

There are three basic types of experimentation necessary to support the formulation of constitutive equations for high-temperature structural alloys. These are (1) <u>Exploratory</u> tests that guide the development of theory and test the fundamental concepts embedded in the framework of the theory, (2) <u>Characterization</u> tests that fill-in the theoretical framework by providing a data base for determining the specific functional forms and material parameters to represent a particular alloy over a given range of conditions, and (3) <u>Verification</u> tests, often structural in nature, that provide the ultimate test of a constitutive model through comparison of prototypical response data with predictions based on the model. Results from verification tests ideally provide feed back for subsequent developmental efforts. Each type of testing will be separately addressed and specific examples of each given in the following sections.

The experimentation discussed is aimed particularly at high-temperature, high-strength nickel base alloys (e.g., Hastelloy-X, Inconel 718, etc.) and the ranges of temperature, stress, strain-rate, etc. important in aircraft engine design. The ranges of interest are roughly up to 1000° C in temperature, from ±1000 MPa in stress, 10^{-6} to -10^{-2}/min. in strain-rate and less than about 1 or 2 percent total strain.

EXPLORATORY TESTING

Unfortunately, exploratory tests in the above sense are nonexistent in many so-called constitutive equation development programs. In such programs the formulation of constitutive equations reduces to little more than empirical curve fitting. Without the close developmental interaction between experimentalist and theoretician, their eyes trained on both the physical aspects of material behavior and the general class of structural problems ultimately to be dealt with, there results ad hoc constitutive models that cannot be used with confidence, sometimes even just slightly outside the specific conditions addressed by their supporting data base.

Exploratory testing is often largely qualitative. Although a few carefully chosen experiments aimed at verifying key concepts embedded in a theoretical framework are generally sufficient, such experiments are often not easy to define nor are they always easy to conduct.

Test specimens used in exploratory (and characterization) testing must provide a suitable region of homogeneous stress and temperature and be statically determinate so that the stress state is known directly from the measured external loads applied to the specimen. The strain (or strain-rate) state must be independently measurable in the homogeneously stressed region using appropriate extensometry. Only in this way can the causal relationships (constitutive relationships) between force-like variables (e.g., stress) and kinematic variables (e.g., strain) be deduced. In principle, no analysis using (assumed) constitutive equations can be used to analyze test results aimed at establishing constitutive equations.

A particularly glaring deficiency in terms of conceptual or exploratory testing is that regarding multiaxial behavior. The major reason for this has been the lack of extensometry for accurately measuring multiaxial strain at high-temperature. Only through very recent developments in extensometry (ref. 1) has it become possible to do meaningful high-temperature biaxial testing.

Thin-walled tubes under axial force, twist and internal and/or external pressure reflect the current state-of-the-art in specimens for biaxial testing. They are used <u>not</u> because the tube is a prototypical component of aircraft engines or breeder reactors but because they allow known biaxial stress states to be generated that (closely) satisfy the required testing conditions stated above.

The necessity of conducting fundamental multiaxial tests can be best understood in the context of classical plasticity. In that constitutive theory, the concept of a yield surface plays a central role. The existence and description of the yield surface is precisely that which allows a consistent multiaxial statement of plastic flow (flow law) to be written. This is done by making use of the fundamental assumption that the yield surface has the properties of a potential (normality) i.e.,

$$f(\sigma_{ij},\alpha_{ij},T) = K \qquad \text{(yield surface)} \tag{1}$$

$$d\epsilon_{ij}^{p} = \lambda \frac{\partial f}{\partial \sigma_{ij}} \qquad \text{(flow law-expressing normality)} \tag{2}$$

Here, σ_{ij} is the applied stress, α_{ij} and K are tensorial and scalar state variables, respectively, T is the temperature and ϵ_{ij}^{p} is the plastic strain.

An interesting classical (isothermal) example is provided when f in equation (1) is taken as a particular function of the deviatoric stress $S_{ij} = \sigma_{ij} - 1/3\ \sigma_{kk}\delta_{ij}$ alone, i.e.,

$$f = \frac{1}{2} S_{ij}S_{ji} = K \tag{3}$$

Then equation (2) takes the form

$$d\epsilon_{ij}^{p} = \lambda S_{ij} \tag{4}$$

which indicates that each component of the inelastic strain increment is proportional to the corresponding component of the applied deviatoric stress. This remains true regardless of the history of deformation.

Another classical example arises when f is taken as

$$f = \frac{1}{2}(S_{ij} - \alpha_{ij})(S_{ji} - \alpha_{ji}) = K \tag{5}$$

The form of f is just the same as in equation (3) except that the stress dependence is taken in terms of the difference of the applied deviatoric stress and a tensorial (deviatoric) inelastic state variable α_{ij}. In metallurgical terms, α_{ij} is called the <u>internal</u> or <u>back</u> stress. In this case, equation (2) takes the form

$$d\epsilon_{ij}^{p} = \lambda(S_{ij} - \alpha_{ij}) \tag{6}$$

indicating that the components of the current plastic strain increment are proportional to the components of $(S_{ij} - \alpha_{ij})$, and thus depend not on the applied stress S_{ij} alone but also on the inelastic state as reflected through α_{ij}. In other words, here, the <u>direction</u> of the plastic strain response depends on the <u>history</u> of deformation.

In any case, specification of the yield surface equation (1) leads to an associated form of the flow law through equation (2). Multiaxial testing alone provides a quantitative description of f, thus permitting the correct form of the flow law to be deduced.

A wealth of exploratory testing has been done at relatively low temperatures (refs. 2 to 10) in support of the concepts of a yield surface and the normality condition. Much of this work has at least indirectly addressed the distinction between equations (3) and (4) and equations (5) and (6).

At high temperatures, alloys of interest are strongly time-dependent and the concept of a yield surface, in the classical sense, generally breaks down. However, analogous geometrically based concepts can, and have been, postulated for high-temperature time-dependent behavior. One such concept concerns surfaces of constant inelastic strain-rate (SCISR's); they analogously play the same central role in viscoplastic constitutive theories as yield surfaces do in classical plasticity. Using thermodynamic arguments SCISR's can also be shown to have a potential nature and thus, as yield surfaces, constitute the basis of a rational multiaxial theory. Their description in stress space, at a fixed inelastic state, provides guidance for correctly representing multiaxial behavior, both <u>isotropic</u> and <u>anisotropic</u> (ref. 11). This rather fundamental approach to the formulation of a consistent multiaxial theory contrasts with the ad hoc and generally inadequate approach of extending uniaxial constitutive theories for multiaxial conditions by simply placing bars over the pertinent variables and terming them "effective" values.

Tests for the definition and description of SCISR's will now be outlined. Thin-walled tubes of the alloy of interest are subjected to combined isothermal tension-torsion[a] under stress-rate control, i.e., a radial path is traversed in the stress space (σ,τ) at a constant rate (fig. 1). Over each suitable time increment δt the total strain increments ($\delta\varepsilon, \delta\gamma$) are measured using appropriate extensometry, thereby establishing the components of total strain-rate. With knowledge of the elastic moduli this allows computation (through an associated digital computer) of the inelastic strain increments ($\delta_{\varepsilon p}$, $\delta_{\gamma p}$) over δt or, equivalently, the inelastic strain-rates ($\dot{\varepsilon}_p$, $\dot{\gamma}_p$). The magnitude I of the inelastic strain-rate corresponding to each time increment can be thus computed according to

$$I = \sqrt{\frac{1}{2} \dot{\varepsilon}^p_{ij} \dot{\varepsilon}^p_{ji}} = \frac{1}{2} \sqrt{3\dot{\varepsilon}_p^2 + \dot{\gamma}_p^2} \tag{7}$$

When I reaches a preestablished value, say I_1, along the stress path, the specimen is unloaded. A sequence of such probes along various radial stress paths establishes the locus in stress space of points of constant inelastic strain-rate magnitude I_1, (i.e., a SCISR). Similar tests corresponding to other inelastic strain-rate magnitudes define a family of SCISR's. Knowledge of the individual inelastic strain-rate components along each SCISR also allows the applicability of the important normality condition to be assessed. Extensions of these exploratory tests involving measurement of SCISR's following known deformation histories, e.g., periods of prior creep, furnish guidance for modeling hardening and recovery behavior.

Special equipment requirements in SCISR tests include the capability of high-resolution, stable extensometry to supply accurate, low-noise strain signals and an associated digital computer for control, computation and data acquisition. Note that the high-resolution requirement of the extensometry is imposed not because strain levels in the order of, say, tens of microstrain are of particular importance in structural design but because tests as those discussed here are to be conducted at a fixed inelastic state of the material. This can be approximated only by limiting the strains incurred during the test to small values, thus minimizing the disturbance of the current state.

Preliminary SCISR testing was initiated by J. R. Ellis on type 316 stainless steel at approximately 600° C (fig. 2). In that case an MTS tension-torsion test system in conjunction with a PDP8e digital computer were employed.

The same fundamental questions concerning the correctness of multiaxial formulations exist in viscoplastic modelling as in classical plasticity. Forms of viscoplastic flow laws analogous to equations (4) and (6) have been proposed; i.e.,

$$\dot{\varepsilon}^p_{ij} = \lambda S_{ij} \tag{8}$$

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[a]Here, the tests are discussed only for tension-torsion loading of a tube. It is intended that such tests be conducted ultimately under more general biaxial stress states, as might be generated with the inclusion of internal pressure.

and

$$\dot{\epsilon}^{P}_{ij} = \lambda(S_{ij} - \alpha_{ij}) \tag{9}$$

Equation (8) is a form employed by Bodner and Partom (ref. 12) and Stouffer and Bodner (ref. 13) and states that the inelastic strain-rate components are always proportional to corresponding components of applied deviatoric stress or, in other words, the inelastic strain-rate (vector) has the same direction as the deviatoric stress (vector), independently of deformation history. Equation (9), analogous to equation (6), allows the direction of the inelastic strain-rate to depend on prior history through α_{ij}, implying that the material has a memory in this sense. This multiaxial form is the one adopted in most of the unified theories employing the concept of an internal stress (refs. 14 to 19).

In the case of viscoplastic theories based on the well-known Bailey-Orowan concept and thus employing an evolutionary law of the type

$$\dot{\alpha}_{ij} = h\dot{\epsilon}^{P}_{ij} - r\alpha_{ij} \tag{10}$$

it is seen that under steady-state conditions, (i.e., when $\dot{\alpha}_{ij} = 0$) the inelastic strain-rate is given by

$$\dot{\epsilon}^{P}_{ij} = \left(\frac{r}{h}\right)\alpha_{ij} \tag{11}$$

Solving equation (11) for α_{ij} and substituting into equation (9) gives:

$$\dot{\epsilon}^{P}_{ij} = \left[\frac{\lambda}{1 + \lambda(h/r)}\right] S_{ij} = \lambda' S_{ij} \tag{12}$$

which is of the same form as equation (8). Thus, for a Bailey-Orowan material under steady-state conditions, either flow law (eqs. (8) or (9)) is appropriate and leads to the same result. Of course, this is because S_{ij} and α_{ij} are colinear under these conditions. There is also no distinction between equations (8) and (9) if the stress path remains strictly radial, i.e., the stress components are in constant proportion; again this follows from the colinearity of S_{ij} and α_{ij}. However, under conditions other than steady-state or strictly proportional stressing, the flow laws equation (8) and equation (9) are distinct and can lead to very different predictions of response. Equation (9) is the more general form allowing the direction of the inelastic strain-rate to depend on the history of deformation. Experiments related to SCISR tests and bearing on the distinction between the flow laws expressed in equations (8) and (9) were conducted earlier by Blass and Findley (ref. 20) on an aluminum alloy at 250° C. Their results suggest that the flow law defined by equation (8) may be too restrictive to correctly predict the salient features of transient creep response under multiaxial conditions. The Blass-Findley (tension-torsion) experiments show that the components of inelastic strain-rate are not generally proportional to the deviatoric stress during transient creep (except under proportional stress conditions).

The experimental results of Blass and Findley are qualitatively predictable using the model of Robinson (refs. 14 and 19) which incorporates a flow law in the form of equation (9). The restriction to a qualitative comparison is necessary as the model parameters have not been determined for the aluminum alloy used in the experiments. As a first step toward representing the Blass-Findley results in terms of the Robinson model, we consider a pictorial representation of a simple combined tension-torsion creep test (fig. 3) based on that model. The constant tension-shear stress point under which creep occurs is labelled P in the figure. Curves of constant inelastic strain rate (SCISR's) appear as circles in the $\sqrt{3}\tau$ vs. σ space of figure 3 (cf. fig. 2 for supporting experimental evidence). There is an infinite family of circles for any given inelastic state, the state being characterized by the location of the center of the circles. Here, only one circle is drawn corresponding to each inelastic state, that is, only the one that passes through the load point P.

Let us now follow through a simple tension-torsion creep test in which a virgin specimen is abruptly loaded to and held at the stress point P. Initially, the family of circles (SCISR's) is centered at (or near) the origin O. The circle labeled 1 is the one of the family which passes through P. Circle 1 corresponds to a particular magnitude of inelastic strain rate, in this case represented by the longest vector emanating from P[a]. Note that the strain-rate vector is normal to the circle 1 at point P. As the stress is held constant, the material creeps both in a tensile and shear sense, and the inelastic state changes. This is represented by the translation of the center of the family of circles toward the load point P (much like the translation of a yield surface in classical kinematic hardening plasticity). At some later time the circle passing through P is that labeled 2, with its center shifted as shown. This circle corresponds to a lesser strain rate magnitude than the initial value and the current strain-rate vector (normal to the circle 2 at P) is shown as the next shorter vector. The material is hardening, that is, undergoing transient creep.

The circle 3 corresponds to the situation at still a later time, with the strain rate magnitude being smaller yet. This process continues as the stress is held constant until finally steady state is reached and the family of circles no longer translates. Steady state is depicted in figure 3 as the circle labeled 4 with its center at S. The strain rate vector associated with this circle is the shortest one emanating from P representing a steady-state creep rate which, according to this theory, remains constant as long as the stress is not changed.

Thus, both the tensile and shear strain components behave much like the extensional creep strain in a uniaxial test; they both go through a transient creep stage during which the creep strain rate diminishes until finally a steady state is reached. Here, the inelastic state remains constant (no shift of the circles) after steady state is achieved.

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[a]Presently we are not so much concerned with the precise magnitude of the strain rate vector but rather with its direction and size relative to subsequent vectors as creep proceeds. The length of the vectors shown in figure 3 are actually proportional to the strain rate magnitude in a logarithmic sense.

An essential feature of figure 3 is that the predicted direction of the strain-rate vector remains radial throughout the creep test, i.e., the strain-rate components remain in constant ratio and, furthermore, proportional to the components of the applied (deviatoric) stress. This behavior is bourne out by the Blass-Findley test results. However, as pointed out earlier, such behavior can be predicted using a flow law either of the form equation (8) or (9), thus no definitive choice between the two forms can be made on the basis of this test alone.

Now we turn to figure 4. This represents the case of a thin-walled tube that first undergoes a creep period in twist (shear) and then is subjected to the same combined stress state P as was considered in figure 3. Thus, we are conducting the same creep test but now on a material that has a previous loading history.

We interpret the circles and vectors in figure 4 the same way as before. The original (nonvirgin) state in this case is represented by the family of circles centered at O. That circle of the family passing through P is labeled 1. The initial creep strain-rate vector (normal to circle 1 at P) corresponds to the largest vector in figure 4; it differs both in magnitude and direction from the initial strain rate vector of the creep test of figure 3. This initial strain-rate vector is <u>not</u> radial and thus its components are <u>not</u> proportional to the corresponding components of deviatoric stress.

As before, the center of the family of circles translates in time; at some later time the circle passing through P is labeled 2, its center shifted further toward P. The corresponding strain rate vector (nearly in the same direction as before) is now shorter, indicating transient creep. As time passes, the constant strain rate circles (SCISR's) translate to that labeled 3, 4, and finally to that labeled 5, corresponding to steady state conditions. The strain rate vectors corresponding to each of these states sequentially shorten and <u>rotate</u> through the transient creep period. The steady-state condition depicted by circle 5 and centered at S is exactly that of the first creep test (fig. 3) with the same strain rate vector - both in magnitude and direction. Thus, as steady-state conditions are reached, the strain-rate vector becomes radial and its components become proportional to the components of the applied stress.

The material can be characterized as having a <u>fading memory</u>. It remembers what has been done to it in the recent past; but, eventually, that memory fades and the material responds only to the current loading conditions. During the transient creep period, the material responded quite differently to the constant stress when it had been subjected to prior creep in torsion. Once the transient creep period had passed, however, and steady state was reached, both the previously crept material (fig. 4) and the previously undeformed material (fig. 3) responded in the same way to the same loading.

This is precisely the behavior indicated in the Blass-Findley experiments. Under strictly proportional stress or steady state conditions $(\dot{\alpha}_{ij} = 0)$ the inelastic strain rate components are proportional to the components of the applied deviatoric stress S_{ij} and the form of flow law expressed by either equation (8) or equation (9) appears adequate. Under conditions any less restrictive (i.e., transient or non-proportional) only equation (9) appears adequate to represent multiaxial creep response.

Figure 5 shows still another case addressed by the Blass-Findley experiments in which the thin-walled tube was first subjected to axial creep before application of the combined stress P. The predicted results are analogous to those of figure 4 and also show good qualitative agreement with the experimental results.

The SCISR experiments described earlier are capable of providing the information obtained in the Blass-Findley experiments as well as additional information regarding subsequent hardening and recovery. They constitute important exploratory experiments for answering fundamental questions regarding multiaxial aspects of constitutive theories.

Other fundamental questions that arise and need to be answered through experiments of the type described here concern still other aspects of a proper multiaxial generalization of uniaxial models employing the concept of a back or internal stress. For example, consider a uniaxial constitutive model that is expressable as

$$\left.\begin{aligned} \dot{\epsilon} &= f(\sigma - \alpha) \\ \dot{\alpha} &= g(\sigma, \alpha) \end{aligned}\right\} \tag{13}$$

in which σ represents the applied stress and α the back stress. The generalization of equation (13) to a multiaxial form is far from unique. Quite apart from the tensorial properties of the flow law already discussed, two possibilities that can give vastly different multiaxial predictions in structural problems are as follows:

$$\left.\begin{aligned} \dot{\epsilon}_{ij} &= f_{ij}\left(\overline{\sigma_{kl}} - \overline{\alpha_{kl}}\right) \\ \dot{\overline{\alpha}}_{ij} &= g\left(\overline{\sigma_{kl}}, \overline{\alpha_{kl}}\right) \end{aligned}\right\} \tag{14}$$

and

$$\left.\begin{aligned} \dot{\epsilon}_{ij} &= f_{ij}\left(\overline{\sigma_{kl} - \alpha_{kl}}\right) \\ \dot{\alpha}_{ij} &= g_{ij}\left(\sigma_{kl}, \alpha_{kl}\right) \end{aligned}\right\} \tag{15}$$

in which the bars denote the following:

$$\overline{X_{ij}} = \frac{1}{2} X_{ij}X_{ji} \tag{16}$$

i.e. the bar indicates the second principal invariant of the quantity. The first form equation (14) is, in principle, that proposed by Larsson and Storakers (ref. 21) and involves just a single scalar evolutionary equation. The stress dependence in the second form equation (15) is expressed in terms of the difference of each tensorial component and thereby, in general, involves six independent evolutionary equations. As to whether the enormous complexity of the second form over the first must be or can be, tolerated depends on many practical and numerical considerations. Nevertheless, the question as to which form more closely represents real material behavior can only be answered by multiaxial testing, as each form reduces to the same uniaxial model.

One last example of multiaxial exploratory testing will be discussed because of its hybrid nature. Once again, this is an isothermal tension-torsion experiment but now involves stress control in tension with simultaneous strain-control in torsion (or vice versa). In the simplest case the axial stress is held constant while the shear strain is cycled over a fixed range at constant strain-rate. Axial ratcheting results with eventual shakedown depending on the biaxial hardening characteristics of the material. Tests of this type were conducted by Roche et al (ref. 22) on type 316 stainless steel at 600° C for the purpose of investigating the detailed interaction of independent stress components under cyclic ratcheting conditions. Roche's tests also provide information for distinguishing between multiaxial forms such as given in equations (8) or (9).

Apart from the multiaxial aspects of behavior, other important behavioral features can be assessed using far simpler <u>uniaxial</u> exploratory testing. An important example concerns an assessment of the importance of thermal recovery effects. The extent to which recovery plays a role in the temperature range of interest has a direct bearing on the theoretical structure of the constitutive model, particularly the form of the evolutionary law or laws. For example, a Bailey-Orowan form is appropriate only when thermal recovery effects are significant.

Creep tests in which a constant uniaxial stress is interrupted by intermittent periods of unloading (near zero stress) are useful for assessing recovery effects. Varying the duration of the periods of unloading supplies information on the rate of recovery. Figure 6 shows the result of an interrupted creep test on 2-1/4 Cr - 1 Mo steel at 538° C. This alloy exhibits virtually no creep strain recovery in this test but experiences considerable state recovery. It is important that qualitative features such as these be recognized through exploratory testing and reflected in the mathematical framework of the constitutive model. The response indicated in figure 6, for example, can be modeled only through the inclusion of a term in the evolutionary law representing a thermal recovery mechanism.

Another important exploratory testing area that bears directly on the question of separability of time-independent (plasticity) and time-dependent (creep) strains is that concerning the significance of creep/plasticity interaction. This is equivalent to asking whether constitutive models in the <u>unified</u> class need to be adopted in preference to more classical models.

A class of creep/plasticity interaction tests of particular interest are those in which a uniaxial (or pure shear) specimen is first cycled at constant strain rate over a given strain range. Once a reasonably stable hysteretic loop is established, creep or stress relaxation tests are performed from various starting points around the loop. The different starting points, even for those at the same stress (and temperature), correspond to quite different inelastic states and consequently exhibit quite different creep or relaxation behavior. Classical models in which creep and plasticity are treated independently cannot predict such behavior. An example of observed response under these conditions is shown in figure 7.

CHARACTERIZATION TESTING

Characterization tests fill-in the already established constitutive equation framework by supplying the appropriate material constants and parameters for representing the behavior of a specific alloy. Ideally, these tests should be simple to conduct and lend themselves to a routine process for determining the required functional forms and material parameters.

Several relatively standard characterization tests will first be listed after which some less well-known testing in support of unified constitutive models will be discussed. Finally, nonisothermal testing will be briefly described.

There are several conventional tests that are needed to establish a data base and quantify the inelastic behavior of high temperature alloys, these include:

(a) Monotonic tensile tests conducted at various temperatures and constant strain-rates in the range of interest.
(b) Cyclic tests conducted over fixed strain ranges at a variety of strain-rates and temperatures to establish cyclic hardening (or softening) characteristics.
(c) Constant stress (load) creep tests at various stress levels and temperatures to characterize primary and secondary creep behavior.
(d) Stress relaxation tests from several initial stress levels and temperatures.
(e) Variable (multistep) stress and temperature creep tests for quantitative assessments of creep hardening (or softening) characteristics.

Characterization testing in support of unified constitutive models is, of necessity, more comprehensive and demanding than that supporting classical models because, of course, the unified models themselves are more comprehensive. The special testing next described is representative of the general type of testing required for unified representations, however, it is focused mainly on the requirements of the Bailey-Orowan class of equations of which the writers' unified theory (refs. 14 and 19) is a member. For the purpose of discussion, the simplified uniaxial form of the constitutive model will be taken as:

$$\dot{\varepsilon} = f(\sigma - \alpha) \tag{17}$$

$$\dot{\alpha} = h(\alpha)\,\dot{\varepsilon} - r(\alpha) \tag{18}$$

in which the hardening (h) and recovery (r) functions are:

$$h(\alpha) = \frac{H}{\alpha^{\beta}} \tag{19}$$

and

$$r(\alpha) = R\alpha^{m-\beta} \tag{20}$$

Now consider a uniaxial variable strain-rate test in which the specimen is first extended at the constant (total) strain-rate $\dot{e}_1$ (fig. 8). Now suppose that at an instant when the stress and inelastic strain-rate are σ_1 and $\dot{\epsilon}_1$, respectively, the total strain-rate is abruptly changed to the relatively high value $\dot{e}_0$. Subsequently, at values σ_2 and $\dot{\epsilon}_2$ of stress and inelastic strain-rate, the total strain-rate is again abruptly changed to still a third value $\dot{e}_2$. Here, $\dot{e}_0 >> \dot{e}_1$ and $\dot{e}_2$. The rates $\dot{e}_1$ and $\dot{e}_2$ are generally not equal but each is within the range of strain-rates of interest (i.e., approximately 10^{-6} to 10^{-2}/min.). The rate $\dot{e}_0$ is taken to be at least one, or perhaps two, orders of magnitude above the range of interest (i.e., approx. 10^{-1}/min.), high enough so that the behavior under $\dot{e}_0$ is essentially elastic. If this is the case, the state variable α (internal stress) has the same value, say α^*, corresponding to the two measured sets of conditions (σ_1, $\dot{\epsilon}_1$) and (σ_2, $\dot{\epsilon}_2$), and from equation (17) we can write:

$$\sigma_1 - f^{-1}(\dot{\epsilon}_1) = \alpha^* = \sigma_2 - f^{-1}(\dot{\epsilon}_2) \tag{21}$$

Equation (21) provides an expression, involving the function f, that relates the two sets of stress and inelastic strain-rate conditions. Using data in equation (21) from several such tests that span the desired range of stress and strain-rate conditions allows an optimal choice of the function f to be made. Thus, in the context of the model expressed in equations (17) to (20), the strain-rate dependence is completely characterized by variable strain-rate tests, and the flow law, equation (17), is fully specified.

Toward further specification of the model, we next turn to the results of creep tests, in particular, isothermal steady-state creep data in the form $\dot{\epsilon}_s$ vs σ. Now, under conditions of steady state creep, we have $\dot{\alpha} = 0$ in equation (18) and we write:

$$\dot{\epsilon}_s = \frac{r(\alpha_s)}{h(\alpha_s)} \tag{22}$$

in which α_s denotes the steady state value of the state variable corresponding to a given stress. Making use of equations (19) and (20) we can write:

$$\dot{\epsilon}_s = \frac{R}{H} \alpha_s^m \tag{23}$$

As the flow law, equation (17) is known, we can calculate α_s corresponding to a given $\dot{\epsilon}_s$ and σ, thus

$$\alpha_s = \sigma - f^{-1}(\dot{\epsilon}_s) \tag{24}$$

Combining equations (23) and (24) provides an expression relating $\dot{\epsilon}_s$ and σ and involving the pair of unknown constants R/H and m. This expression and the steady-state creep data ($\dot{\epsilon}_s$ vs. σ) can thus be used to obtain optimal values (e.g., in at least squares sense) of R/H and m. This procedure illustrates an interactive process whereby data is first used in determining certain of the unknown functions or parameters; these are then used in a subsequent calculation that, in turn, is employed together with additional experimental data for establishing other parameters, etc.

With f, m and the ratio R/H specified in equations (17) to (20), it remains to determine β and either R or H. One approach is to focus on the recovery characteristics of the material and determine β and R by using results from a series of strain-transient-dip (STD) tests. In these tests a uniaxial specimen is first subjected to constant stress creep at, say σ_0. The stress is then reduced by a specified decrement $\Delta\sigma$ and again held constant. Typical responses to three stress decrements of varying magnitude are shown schematically in figure 9. The immediate response to the abrupt stress reduction is elastic, followed by a relatively small amount of inelastic strain recovery. An apparent hesitation period (longer for larger stress reductions) ensues after which the strain-rate gradually increases, approaching the steady-state value corresponding to the reduced stress. As discussed in reference 14, a reasonable idealization for many metals is to consider f in equation (17) as being zero for negative values of its argument, i.e. for $\sigma - \alpha < 0$. Then, the response following the abrupt stress reduction to $\sigma_0 - \Delta\sigma$ in the STD tests is governed by

$$\dot{\alpha} = - R\alpha^{m-\beta} \tag{25}$$

which can be integrated over a (measured) hesitation period to give

$$\frac{1}{R} \int_{\sigma_0-\Delta\sigma}^{\alpha_0} \frac{d\alpha}{\alpha^{m-\beta}} = \Delta\tau \tag{26}$$

As all quantities in equation (26) are known except the unknown parameters R and β this expression can be used along with test data ($\Delta\sigma,\Delta\tau$) from STD tests to determine optimal values of R and β, which completes the specification of the simple constitutive model expressed in equations (17) to (20).

Traditionally, nonisothermal constitutive theories have been based entirely on isothermal test data collected over a range of temperatures. The inadequacy of this approach relative to classical (time-independent) plasticity theory was recently discussed by Robinson and Swindeman (refs. 23 and 24). Their findings substantiate the intuitively obvious conclusion that a nonisothermal theory must be based on nonisothermal testing. Nonisothermal tests to be used as a basis of thermoplasticity were proposed in reference 23 and the results of some preliminary tests were reported. As tests of this general type may be applicable to a wide class of constitutive models they will be outlined here.

The yield surface in classical thermoplasticity is expressed as equation (1) with the scalar K interpreted geometrically as a measure of the current size of the yield surface. K thus measures isotropic hardening and is usually taken as a function of some measure of accumulated plastic strain (or work) and temperature. That K can be taken as an explicit function of these independent variables implies path independence in the variables and furthermore that all the necessary information concerning K can be obtained from isothermal tests alone. It is shown in reference 23 by the results of simple experiments that K cannot be taken as an explicit function of these variables and, instead, its evolution under an arbitrary deformation and temperature history must be expressed in terms of a path dependent evolutionary law such as:

$$dK = F(P,T)dP + G(P,T)dT \tag{27}$$

in which

$$P = \int \sqrt{d\epsilon_{ij}^{P} d\epsilon_{ji}^{P}} \tag{28}$$

is a measure of accumulated plastic strain and T is the temperature.

The current value of K (i.e., the current size of the yield surface) can be generally determined from equation (27) only if the thermomechanical path is known, i.e., only if

$$P = g(T) \tag{29}$$

is known.

Information for characterizing the function F in equation (27) can be obtained from ordinary isothermal testing, however, nonisothermal tests must be conducted to supply information about G. Such tests are the subject of reference 23 and will be described below.

The function G appears directly in the flow law in classical thermoplasticity, (through imposition of the conditions of normality and consistency), and thus directly governs the predicted plastic strain increment in response to a temperature change. As pointed out in references 23 and 24 considering K as an explicit function of P and T and, consequently, characterizing the hardening behavior solely on the basis of isothermal tests, can lead to large errors in the predicted stress and strain fields in many important nonisothermal structural problems.

The nonisothermal tests in reference 23 are aimed at providing information about the function G(P,T) in equation (27) under conditions of cyclic straining. In these tests a uniaxial specimen is first cyclically strained at constant temperature T_0 over a fixed strain-range and strain-rate, incurring a given amount of accumulated plastic strain P_0 (i.e., as defined in eq. (28)). Cycling is stopped at the tensile peak of the hysteretic loop and the strain held constant while a small, rapid temperature cycle is executed. If the closed temperature cycle involves first a reduction in temperature ΔT followed by an increase, a typical response is shown in figure 10. As the temperature decreases, yielding occurs and the stress increases from point 0 to 1 ($\Delta\sigma_{01}$).

Completing the cycle with a temperature increase to the original temperature T_0 produces an elastic response with an accompanying stress change $\Delta\sigma_{12}$. With $\Delta\sigma_{01}$ and $\Delta\sigma_{12}$ measurable directly from the stress response to the thermal cycle E (Young's modulus) and E_T (the tangent modulus) measurable from the current hysteretic loop, and with the coefficient of thermal expansion α_T known, $G(P_0, T_0)$ can be calculated, i.e., the value of G can be obtained at the current accumulated (cyclic) plastic strain P_0 and the temperature T_0. Conducting tests of this kind over the desired ranges of P and T allows the function $G(P,T)$ to be mapped out in the region of interest. An important assumption here is that the contribution of the first term in equation (27) is negligibly small over the small temperature excursion. Intuitively, this seems to be a reasonable assumption as the hardening (change in K) that occurs in most alloys with accumulated plastic strain is quite gradual. Although significant isotropic hardening may occur over several cycles of mechanical straining, hardening is not pronounced from cycle-to-cycle. Thus, the contribution resulting from the small inelastic strain incurred during the small thermal cycle would be expected to be negligible. This is borne out experimentally for the stainless steels tested in references 23 and 24.

Although the temperature dependence in unified viscoplastic theories is generally formulated quite differently than in classical (time-independent) plasticity, the nonisothermal experiments considered here are nevertheless applicable in characterizing cyclic hardening and thermoplasticity in these models as well. For theories that have a physical basis and the individual terms in the equations have some identification with physical processes (refs. 14 and 19), the complete specification of the temperature dependence can be made with some added confidence.

VERIFICATION TESTING

Verification tests provide an assessment of established constitutive models under conditions that are, ideally, close to prototypical. These tests are necessarily structural in nature, involving inhomogeneous fields of stress, strain and temperature. The stringent restrictions demanded in exploratory and characterization testing regarding homogeneity of stress and temperature and statical determinacy do not carry over to verification testing.

The ultimate assessment of a structural analysis capability, including constitutive relationships, involves a direct comparison of the predicted response of an actual component with experiment. Ideally, from the standpoint of assessing constitutive equations, a detailed comparison of the actual and predicted stress and strain history at critical points in the structure needs to be made. Unfortunately, the actual stress field is <u>never</u> directly measurable for comparison and only very limited information regarding the actual strain field is available, e.g., some strain components at some points on the surface of the structure can be measured. Most often, the only reliable mechanical data obtainable on complex structural components at high temperature are displacements or deflections at some convenient locations. Verification of constitutive theories and structural analysis methods thus often reduces to the comparison of just a few numbers, i.e., measured and predicted deflections at a few points on the structure. This furnishes very little information on which to assess a detailed structural analysis and virtually no information that is useful as feedback for further refinement of a constitutive model.

An alternative approach in verification testing is to test structures such as beams, plates, and simple shells under prototypical conditions of temperature, stress, strain rate, etc. These tests represent the next step up in complexity from the previously described experiments involving homogenous stress and strain fields but, at the same time, are simple enough so that some information concerning the actual stress and strain history can be deduced and compared with predictions of analysis. A wealth of structural testing of this kind has been conducted at Oak Ridge National Laboratory (ORNL) (refs. 25 to 27) and used for assessing structural analysis methods and constitutive models.

Tests on still simpler structures such as frames or trusses retain the essence of structural behavior (e.g., redistribution of stress and strain, shakedown, etc.) while allowing the actual stress and strain fields to be measured and thus compared with those calculated. Experiments on two or three bar structures have been used extensively to approximate the thermomechanical behavior of more realistic structures under complex nonisothermal conditions. The measurement of the detailed stress-strain-temperature history in these tests provides useful information for assessing those aspects of constitutive models that influence critical features of structural response e.g., ratchetting, shakedown, etc.

A series of two-bar tests (ref. 28) conducted on 2-1/4 Cr-1 Mo Steel under a variety of thermal shock conditions will now be described as being representative of this kind of verification testing. In these tests, two uniaxial specimens are tested simultaneously in two servocontrolled electrohydraulic machines which are linked together so that the sum of the loads in both bars is held constant (maintaining equilibrium), while the extension of the two bars is kept the same (maintaining compatibility). Initially, an equal axial stress is applied to both bars. Then, the temperature in bar 1 is ramped downward from the maximum temperature, T_{max}, to a minimum, T_{min}. Subsequently, the temperature in bar 2 is ramped downward while the temperature in bar 1 is kept at T_{min}. After bar 2 reaches the minimum temperature, both bars are heated together to T_{max}. The temperature is then held constant at T_{max} for a prescribed time interval and the sequence is repeated. The response of the two bars roughly simulates the behavior of material elements at the inner and outer radii of a cylinder (pipe) under analogous conditions.

The use of two separate testing apparatus, one under load control - one under strain control, simulates the nonisothermal behavior of a two (or three) bar structure without the virtually impossible task of thermally isolating the two specimens, as would be the case if they were physically part of the same structure. Each specimen has a load cell allowing measurement of the stress and an extensometer measuring strain. This gives a detailed thermomechanical history of each specimen, as well as a record of the mutual interaction of the two regarding time-dependent redistribution of stress and strain.

DISCUSSION AND CONCLUSIONS

Three major categories of testing are identified as being necessary to support the development of constitutive equations for high-temperature alloys. These are <u>exploratory</u>, <u>characterization</u> and <u>verification</u> testing.

Exploratory testing, in the present context, goes hand-in-hand with the formulation of theory and furnishes guidance for its development. In many purported constitutive equation development programs exploratory testing is virtually nonexistent and experimentation is limited to the latter two categories. Without the close developmental interaction between experimentalist and theoretician, through exploratory testing, there results ad hoc constitutive models that cannot be used with confidence outside the specific conditions addressed in the characterization data base. Particularly lacking is reliable exploratory testing under multiaxial and nonisothermal conditions upon which constitutive models can be rationally based.

An important type of high-temperature multiaxial testing concerns the definition of surfaces of constant inelastic strain-rate (SCISR) in stress space. Such tests are the counterparts of tests at lower temperatures that define yield surfaces (surfaces of constant inelastic strain). It is from SCISR tests that the correct framework of a multiaxial viscoplastic theory can be deduced, including the appropriate forms of the flow and evolutionary laws and the subsequent hardening and recovery behavior.

Characterization tests fill-in the already established constitutive equation framework by supplying the appropriate material constants and parameters for representing the behavior of a specific alloy. Ideally, these tests should be simple to conduct and lend themselves to a routine process for determining the required functional forms and material parameters. Several relatively standard characterization tests are identified here as well as some less well-known testing in support of unified constitutive models.

Traditionally, nonisothermal constitutive theories are based entirely on isothermal test data collected over a range of temperatures. The inadequacy of this approach relative to plasticity theory is now known and is discussed here. This substantiates the intuitively obvious conclusion that a nonisothermal theory must be based on nonisothermal testing. Nonisothermal tests to be used as a basis of thermoplasticity are identified and some preliminary results of such tests are reported.

Verification tests provide an assessment of established constitutive models under conditions that are, ideally, prototypical. These tests are generally structural in nature, involving inhomogeneous fields of stress, strain and temperature. The ultimate evaluation of a structural analysis capability, including constitutive relationships, involves a direct comparison of the predicted response of an actual component with experiment. Ideally, from the standpoint of assessing constitutive equations, a detailed comparison of the actual and predicted stress and strain history in the structure is required. Unfortunately, the actual stress field is never directly measurable for comparison and only very limited information regarding the actual strain field is generally available, e.g., some strain components at some points on the surface of the structure. Often, the only reliable mechanical data obtainable on complex structural components at high temperature are displacements or deflections at some convenient locations. Verification of constitutive theories and structural analysis methods thus often reduces to the comparison of just a few numbers, i.e., measured and predicted deflections at a few points on the structure. This furnishes very little information on which to assess a detailed structural analysis and virtually no information that is useful as feedback for further refinement of a constitutive model.

An alternative approach in verification testing is to test simple structures such as beams, plates, shells and bar structures under prototypical conditions of temperature, stress, strain-rate, etc. Tests on frames or trusses retain the essence of structural behavior (e.g., redistribution of stress and strain, shakedown, etc.) while allowing the actual stress and strain fields to be measured and thus compared with those calculated. Experiments on two or three bar structures have been used extensively to approximate the thermomechanical behavior of more realistic structures under complex nonisothermal conditions. The measurement of the detailed stress-strain-temperature history in these tests provides useful information for assessing those aspects of constitutive models that influence critical features of structural response, e.g. ratchetting, shakedown, etc.

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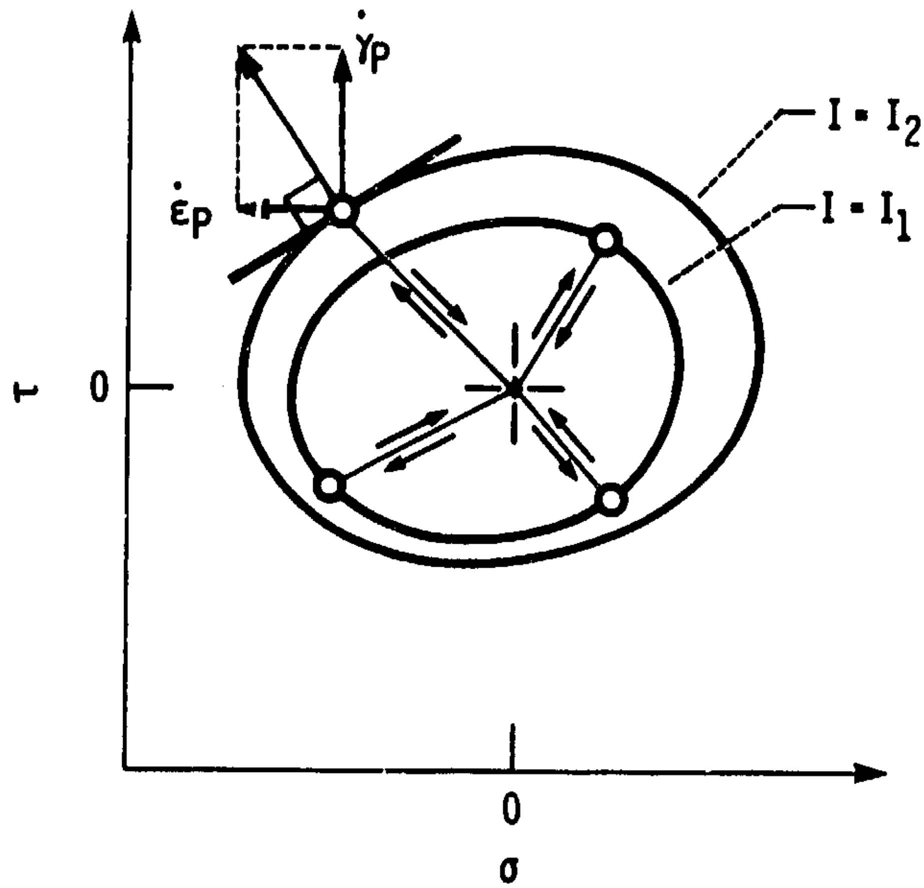

$$\begin{bmatrix} \dot{\varepsilon}_P \\ \dot{\gamma}_P \end{bmatrix} = \begin{bmatrix} \dot{\varepsilon} \\ \dot{\gamma} \end{bmatrix} - \begin{bmatrix} \dot{\sigma}/E \\ \dot{\tau}/G \end{bmatrix}$$

Computed Measured Controlled

Figure 1. - Determination of surfaces of constant inelastic strain rate (SCISR'S).

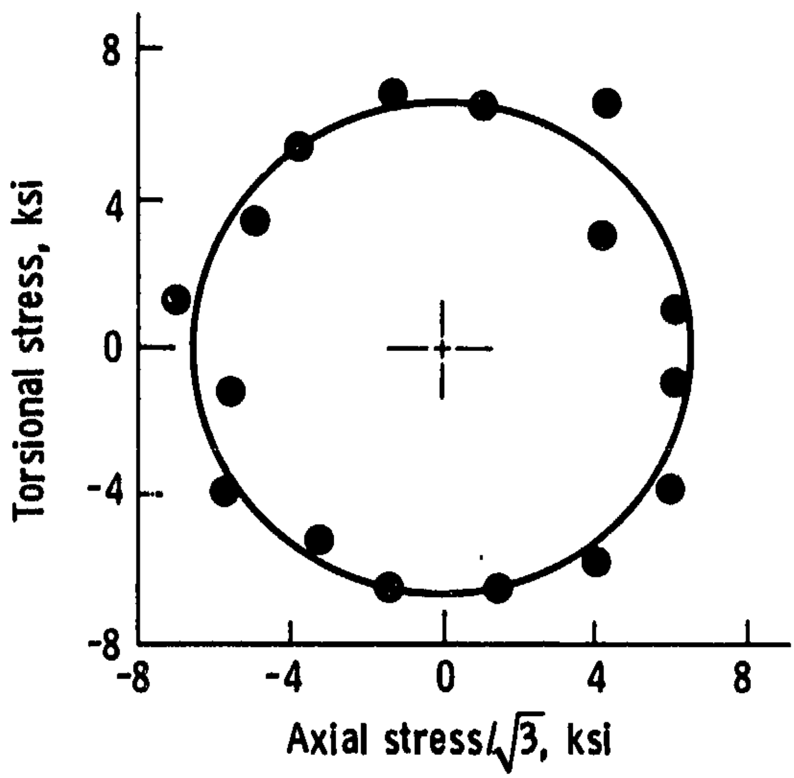

Figure 2. - A SCISR for type 316 SS at 1100° F (593° C).

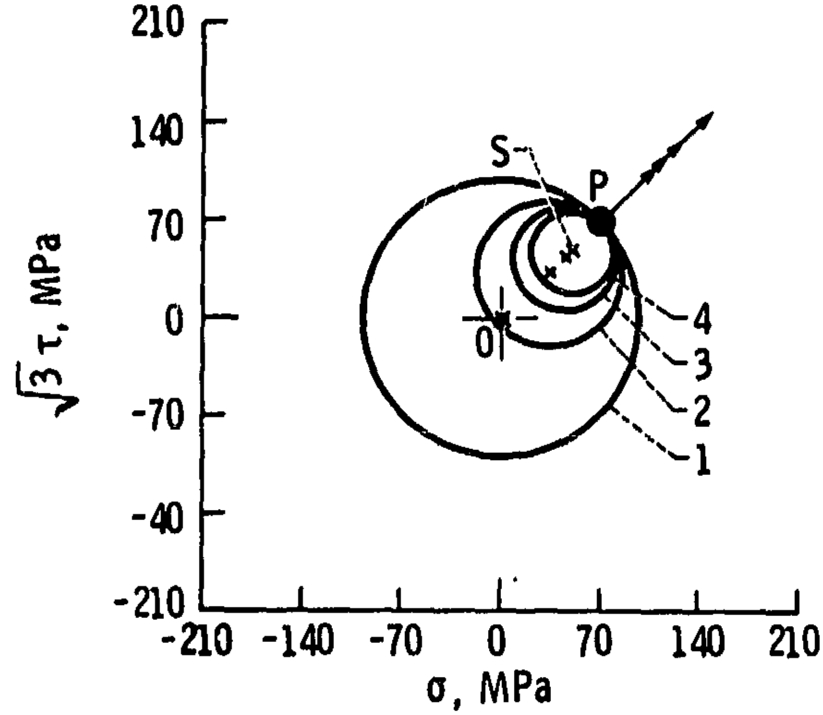

Figure 3. - Prediction of biaxial creep using Robinson's model.

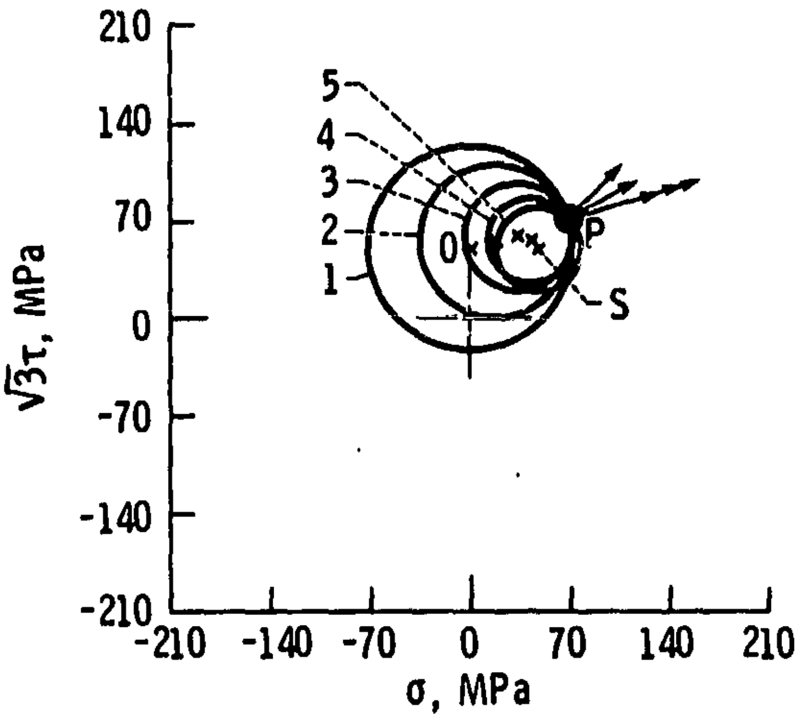

Figure 4. - Prediction of biaxial creep response as in the Blass-Findley experiments using Robinson's model.

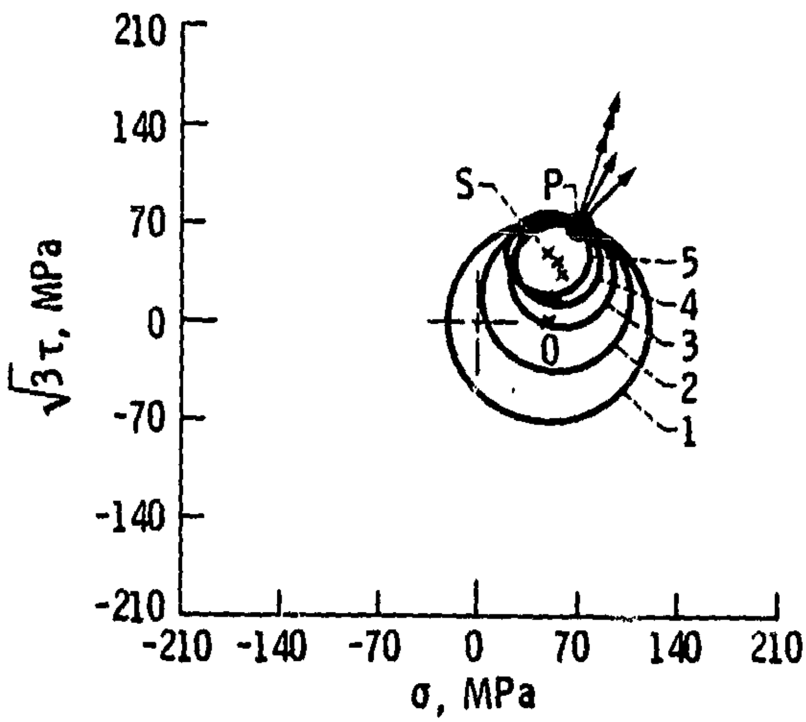

Figure 5. - Prediction of biaxial creep response as in the Blass-Findley experiments using Robinson's model.

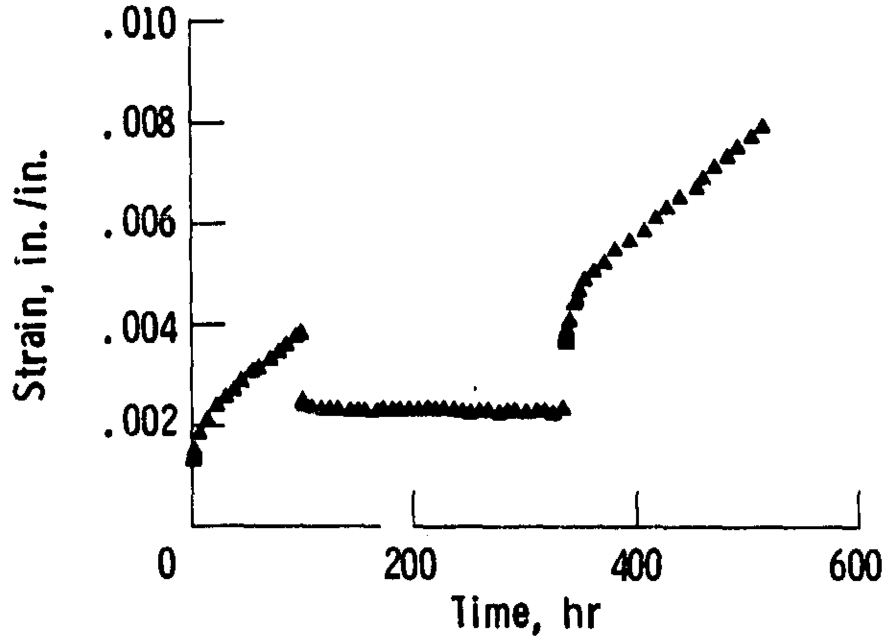

Figure 6. - Strain-time response of $2^1/4$ Cr-1 Mo steel at 1000° F (538° C) to interrupted creep test 100 Mpa - 0 - 100 MPa.

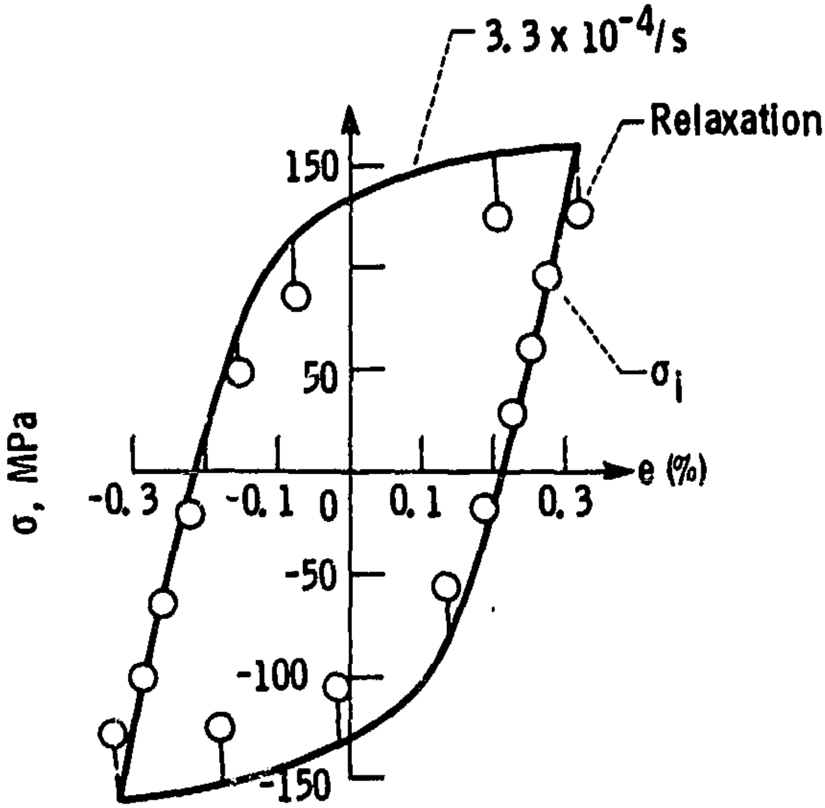

Figure 7. - Stress relaxation in 1 hr from various points around a stable hysteretic loop (3.3×10^{-4}/s) - $2^1/4$Cr-1Mo steel at 1000° F (538° C).

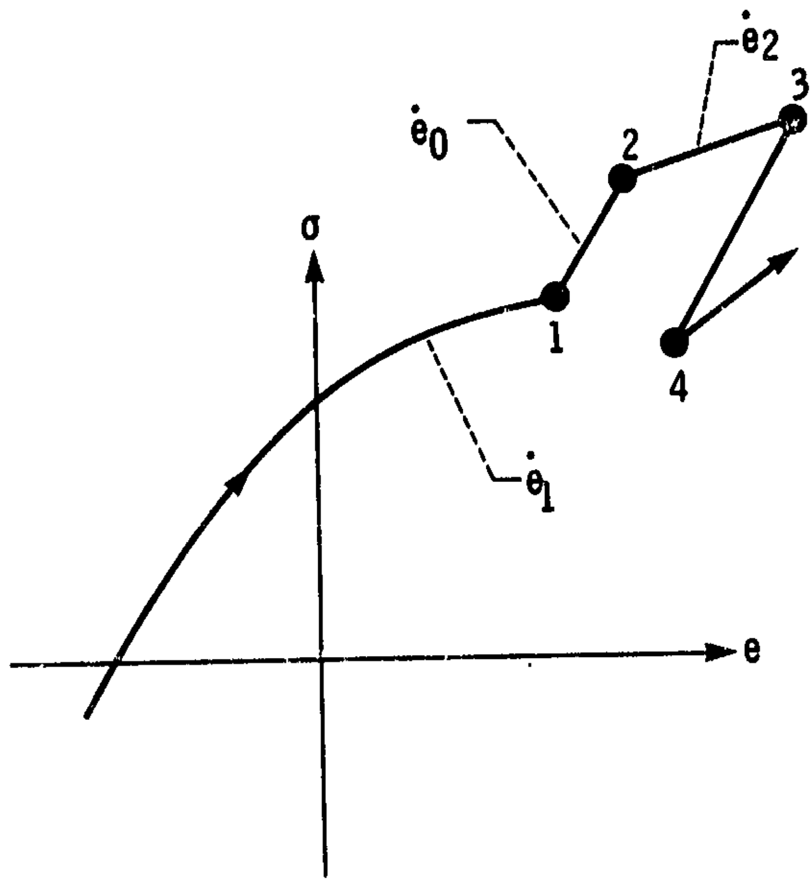

Figure 8. - Schematic representation of rain-rate test. $\dot{e}$ represents total strain-rate.

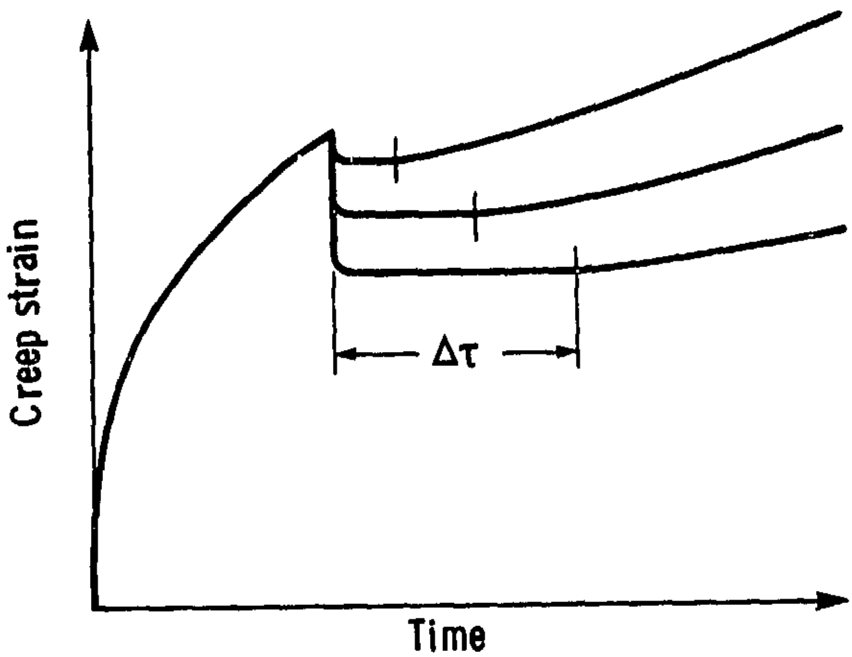

Figure 9. - Schematic representation of strain-time response showing hesitation period $\Delta\tau$ after stress reductions of varying magnitude.

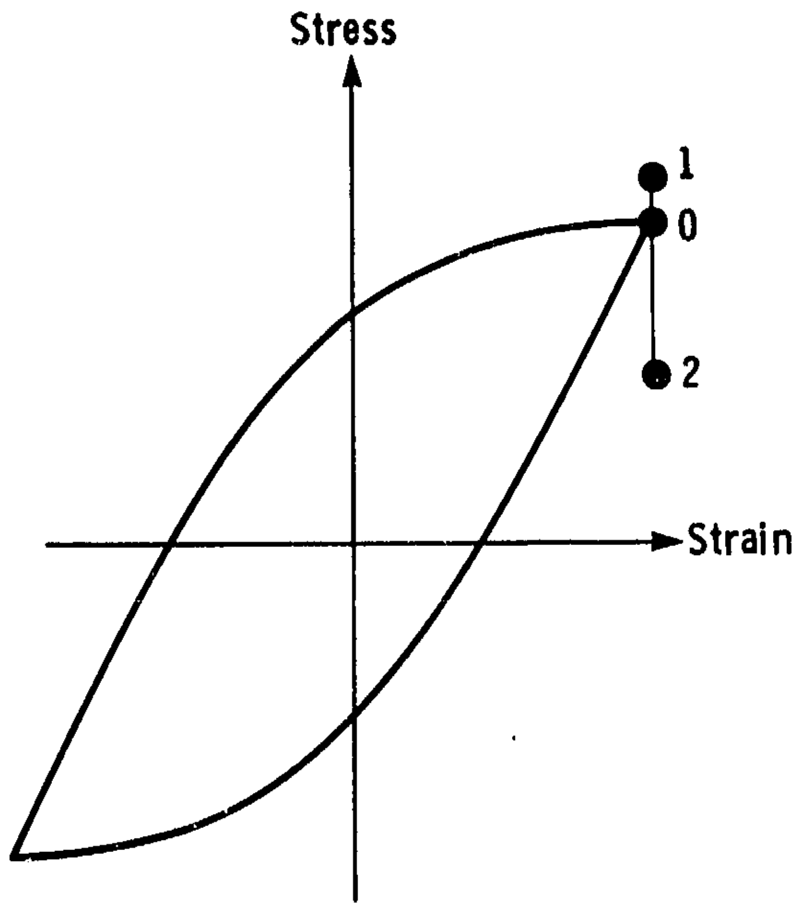

Figure 10. - Typical stress response 0-1-2 to thermal cycle with total strain held constant at tensile tip of hysteretic loop.

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16. Abstract

Three major categories of testing are identified that are necessary to provide support for the development of constitutive equations for high temperature alloys. These are exploratory, characterization and verification tests. Each category is addressed and specific examples of each are given. An extensive, but not exhaustive, set of references is provided concerning pertinent experimental results and their relationships to theoretical development. The primary objective of this report is twofold: to serve as a guide in formulating a meaningful testing effort in support of constitutive equation development, and to aid in defining the necessary testing equipment and instrumentation for the establishment of a deformation and structures testing laboratory.

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