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ABSTRACT

An anisotropic creep model is formulated for metallic composites with strong fibers and low to moderate fiber volume percent (< 40%). The idealization admits no creep in the local fiber direction and assumes equal creep strength in longitudinal and transverse shear. Identification of the matrix behavior with that of the isotropic limit of the theory permits characterization of the composite through uniaxial creep tests on the matrix material. Constant and step-wise creep tests are required as a data base. The model provides an upper bound on the transverse creep strength of a composite having strong fibers embedded in a particular matrix material. Comparison of the measured transverse strength with the upper bound gives an assessment of the integrity of the composite. Application is made to a Kanthal composite, a model high-temperature composite system. Predictions are made of the creep response of fiber reinforced Kanthal tubes under interior pressure.

INTRODUCTION

Monolithic structural alloys used in high temperature environments (T/Tm > .3 or .4) exhibit complex thermomechanical behavior that is both time and history dependent. The wealth of research activity over the past decade directed toward high temperature structural alloys is testimony to these behavioral complexities and to the need for mathematical representations (constitutive equations) of this behavior in support of component design.

When two metallic alloys are combined to form a composite that is exposed to high temperature, one or both of the constituents may behave inelastically in this same time dependent, hereditary way. Although inelastic response may be suppressed under some special conditions, viz., when a single stress component is aligned directly with strong fibers, high temperature response under general states of stress inevitably involves inelasticity (creep, relaxation, rate sensitive plasticity, etc.) Micromechanics, successful in predicting composite behavior with elastic constituents, has a difficult task of predicting the overall deformation behavior of a composite with its constituents behaving in a time dependent, hereditary way, particularly when an interphase material develops and its properties are also time and history dependent.

An alternative is to consider the composite as a material in its own right, with its own properties that can be measured for the composite as a whole. This amounts to idealizing the composite as a psuedohomogeneous, anisotropic material and applying the principles of continuum mechanics. This is the approach taken in [1,2,3] and more recently in [4,5], dealing with the viscoplastic behavior of unidirectional (one fiber family) metallic composites.

In this paper, we focus on the creep response of metallic composites and specialize some of the results in [5] for the case of very strong fibers and low to moderate fiber volume percent (i.e., less than 40% f.v.p). The former condition limits the deformation along the fiber direction to be essentially elastic. Experiments on a W/Kanthal (~ 35% f.v.p) composite reveal creep rates along and transverse to the fiber direction that are different by several orders of magnitude [6]. The latter condition ensures domination of inelastic response by the matrix and supports an idealization of equal creep strength in transverse and longitudinal shear.

A key feature of the simple theory presented here is that all the properties necessary for characterizing creep of a metallic composite can be determined through uniaxial creep experiments on the matrix material. Once these properties have been established, predictions of creep under variable and multiaxial stress can be made for the composite. The theory is independent of fiber properties requiring only that the fibers are much stronger than the matrix material.

We first formulate the specialized creep theory; then, we outline a procedure for determining the material constants from tests on the matrix material. This procedure is subsequently applied to a Kanthal composite material. Using the constants determined for the Kanthal matrix, predictions of creep response of the Kanthal composite are made under transverse tension and under biaxial stress states corresponding to reinforced thin walled tubes subjected to an interior pressure.

FORMULATION OF THE CREEP THEORY

Earlier work [5] introduced the invariant combination

$$\phi = I_1 + \frac{1}{\eta^2} I_2 + \frac{9}{4(4\omega^2-1)} I_3 \tag{1}$$

in representing the viscoplastic response of a metallic composite idealized as locally transversely isotropic. The invariants I_1, I_2 and I_3 have physical meanings, cf. [5], and are defined as

$$\left.\begin{aligned} I_1 &= J_2 - \hat{I} + \frac{1}{4} I_3 \\ I_2 &= \hat{I} - I_3 \\ I_3 &= I^2 \end{aligned}\right\} \tag{2}$$

in which

$$\left.\begin{aligned} J_2 = \frac{1}{2}\Sigma_{ij}\Sigma_{ji},\ \hat{I} = D_{ij}\Sigma_{jk}\Sigma_{ki},\ I = D_{ij}\Sigma_{ji},\ D_{ij} = d_i d_j \\ \text{and } \Sigma_{ij} = s_{ij} - a_{ij} \end{aligned}\right\} \tag{3}$$

where:

s_{ij} = the components of deviatoric applied stress, a_{ij} = those of the deviatoric internal (back) stress and Σ_{ij} = the components of effective stress. d_i represents a unit vector denoting the local fiber direction (direction of transverse isotropy). η in eq. (1) is the ratio of (creep) strength under longitudinal shear stress K_L to that under transverse shear K_T. i.e.,

$$\eta = \frac{K_L}{K_T} \tag{4}$$

Similarly, ω is the ratio of strength in longitudinal tension Y_L to that in transverse tension Y_T, i.e.

$$\omega = \frac{Y_L}{Y_T} \tag{5}$$

As we wish to consider the case of very strong fibers, we take

$$\omega \to \infty \tag{6}$$

Also, reflecting low to moderate fiber volume percent, we take $K_L = K_T = K$ so that

$$\eta = 1 \tag{7}$$

With eqs. (6) and (7) the invariant ϕ becomes

$$\phi = J_2 - \frac{3}{4} I^2 \tag{8}$$

Guided by [5] we propose a creep representation based on the invariant ϕ and an analogous one defined as

$$\psi = \mathscr{J}_2 - \frac{3}{4} \mathscr{I}^2 \tag{9}$$

where

$$\mathscr{J}_2 = \frac{1}{2} a_{ij} a_{ji} , \qquad \mathscr{I} = D_{ij} a_{ji} \tag{10}$$

A full statement of the proposed (isothermal) theory is as follows

$$F = \frac{4}{\sigma_o^2} \phi \qquad G = \frac{4}{\sigma_o^2} \psi \tag{11}$$

$$\frac{\dot{\epsilon}_{ij}}{\dot{\epsilon}_o} = 2f(F) \frac{\Gamma_{ij}}{\sigma_o \sqrt{F}} \qquad \text{(flow law)} \tag{12}$$

$$\dot{a}_{ij} = h(G) \frac{1}{2} \left[\frac{\dot{\epsilon}_{ij}}{\dot{\epsilon}_o} \right] - r(G) \frac{\Pi_{ij}}{\sigma_o \sqrt{G}} \qquad \text{(evolutionary law)} \tag{13}$$

$$\Gamma_{ij} = \Sigma_{ij} - \frac{1}{2} I(3D_{ij} - \delta_{ij}) \tag{14}$$

$$\Pi_{ij} = a_{ij} - \frac{1}{2} \mathscr{I}(3D_{ij} - \delta_{ij}) \tag{15}$$

The functions and constants to be specified in characterizing a particular material are:

$$f(F),\ h(G),\ r(G),\ \sigma_0 \text{ and } \dot{\epsilon}_0 \tag{16}$$

Under longitudinal stress (fig. 1a) this theory predicts no inelastic strain rate (no creep), i.e., $\dot{\epsilon}_{ij} = \dot{a}_{ij} = 0$.

Under transverse stress (fig. 1b) the theory gives

$$F = \left[\frac{\sigma-\alpha}{\sigma_0}\right]^2,\ G = \left[\frac{\alpha}{\sigma_0}\right]^2 \tag{17}$$

$$\frac{\dot{\epsilon}}{\dot{\epsilon}_0} = f(F) \tag{18}$$

$$\dot{\alpha} = h(G)\left[\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right] - r(G) = h(G)f(F) - r(G) \tag{19}$$

in which $\sigma \equiv \sigma_{22}$ = the transverse applied stress, $\alpha \equiv \alpha_{22}$ = the transverse component of the internal stress and $\dot{\epsilon} \equiv \dot{\epsilon}_{22}$ = the transverse inelastic strain rate.

If, as in earlier work [4, 5], we take

$$f(F) = F^n,\ h(G) = H/G^{\beta} \text{ and } r(G) = RG^{m-\beta} \tag{20}$$

eqs. (18 & 19) become

$$\frac{\dot{\epsilon}}{\dot{\epsilon}_0} = \left[\frac{\sigma-\alpha}{\sigma_0}\right]^{2n} \tag{21}$$

$$\dot{\alpha} = \frac{H'}{\alpha^{2\beta}}\left[\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right] - R'\alpha^{2(m-\beta)} \tag{22}$$

where

$$H' = H\sigma_0^{2\beta} \text{ and } R' = \frac{R}{\sigma_0^{2(m-\beta)}} \tag{23}$$

The material constants are

$$\sigma_0,\ \dot{\epsilon}_0,\ n,\ \beta,\ m,\ R \text{ and } H \tag{24}$$

The constant σ_0 is a reference stress that can be chosen conveniently in the stress range of interest. Note that for $\alpha \approx 0$, i.e., near the virgin state of the material, eq. (21) gives $\dot{\epsilon} = \dot{\epsilon}_0$ for $\sigma = \sigma_0$; thus the constant $\dot{\epsilon}_0$ represents the initial creep rate at the reference stress σ_0.

ISOTROPIC LIMIT

The isotropic limit of eqs. (11) – (15) is found by taking D_{ij} to be an isotropic tensor with $D_{ii} = 1$, i.e., $D_{ij} = \frac{1}{3}\,\delta_{ij}$. Under this limit, there results

$$F = \frac{4}{\sigma_0^2} J_2 , \qquad G = \frac{4}{\sigma_0^2} \mathcal{J}_2 \tag{25}$$

$$\Gamma_{ij} = \Sigma_{ij} , \qquad \Pi_{ij} = a_{ij} \tag{26}$$

Thus, the present creep model reduces to a J_2 *theory* in the isotropic limit. Under uniaxial tension, the governing equations reduce to:

$$\frac{\dot{\epsilon}}{\dot{\epsilon}_0'} = \left[\frac{\sigma-\alpha}{\sigma_0'}\right]^{2n} \tag{27}$$

$$\dot{\alpha} = \frac{\mathcal{H}}{\alpha^{2\beta}}\left[\frac{\dot{\epsilon}}{\dot{\epsilon}_0'}\right] - \mathcal{R}\,\alpha^{2(m-\beta)} \tag{28}$$

in which

$$
\left.
\begin{aligned}
\dot{\epsilon}'_0 &= \frac{2}{\sqrt{3}}\,\dot{\epsilon}_0 \\
\sigma'_0 &= \frac{\sqrt{3}}{2}\,\sigma_0 \\
\mathscr{H} &= \frac{\sqrt{3}}{2}\;\mathrm{H}\;\sigma'^{\,2\beta}_0 \\
\mathscr{R} &= \frac{\sqrt{3}}{2}\;\mathrm{R}/\sigma'^{\,2(m-\beta)}_0
\end{aligned}
\right\} \qquad (29)
$$

We identify the behavior of the matrix material with that corresponding to the isotropic limit and observe that if we experimentally determine the constants σ'_0, $\dot{\epsilon}'_0$, n, β, m, $\mathscr{R}$ and $\mathscr{H}$ in eqs. (27) and (28), i.e., for the matrix, then using eqs. (29) we can find the constants σ_0, $\dot{\epsilon}_0$, n, β, m, R and H in the multiaxial theory for the composite expressed in eqs. (11) – (15) and (20). Thus, we can characterize the multiaxial creep response of the composite knowing the uniaxial creep response of the matrix. As the effect of the fibers amounts essentially to a kinematic constraint, it is the matrix material that controls the inelastic behavior of the composite.

In the following section, we outline a procedure for determining the constants for the matrix material. Following that, we make application of this procedure to Kanthal, a model matrix material of interest for high–temperature applications.

DETERMINATION OF MATERIAL CONSTANTS FOR THE MATRIX

Determination of the (isothermal) material constants σ'_0, $\dot{\epsilon}'_0$, n, β, m, $\mathscr{R}$ and $\mathscr{H}$ from tests on the matrix material requires constant stress creep tests spanning the stress range of interest (fig. 2) and a sequence (at least one) of variable stress tests in the form of step–stress tests (fig. 3). Here, σ'_0 is a reference stress for the matrix material to be selected within the stress range of interest and $\dot{\epsilon}'_0$ is the initial creep rate ($\alpha \approx$ o) under σ'_0 (fig. 2).

We note that the second of eqs. (29), with reference to the flow laws of eq. (21) and eq. (27), indicates that the ratio of the reference stress σ'_0 corresponding to the isotropic limit (identified here with the matrix material) to the reference stress σ_o of the composite under transverse tension is

$$\frac{\sigma_o'}{\sigma_o} = \frac{\sqrt{3}}{2} \tag{30}$$

This result is anticipated in that the isotropic matrix material behaves as a (*von–Mises*) material and with the addition of strong fibers is constrained to deform in transverse tension as a *maximum shear stress* (*Tresca*) material. The creep (or yield) strengths of these classical material idealizations are in the ratio $\sqrt{3}/2$.

Now focusing on a typical step test (fig 3), we identify the creep rates immediately before and after the abrupt change in stress from σ_1 to σ_2 as $\dot{\epsilon}_1$ and $\dot{\epsilon}_2$, respectively. Assuming the stress change is made abruptly enough so that α remains essentially constant during the change, we obtain from eq. 27,

$$\frac{\dot{\epsilon}_2}{\dot{\epsilon}_1} = \frac{\dot{\epsilon}_o'}{\dot{\epsilon}_1}\left[\left[\frac{\dot{\epsilon}_1}{\dot{\epsilon}_o'}\right]^{\frac{1}{2n}} + \frac{\sigma_2-\sigma_1}{\sigma_o'}\right]^{2n} \tag{31}$$

Everything in eq. (31) is obtained from experiments except for the exponent n, therefore we can determine n. If data from several step tests are available, providing several independent expressions like eq. (31), we can find an optimal value of n satisfying these equations, e.g., in a least squares sense. At this stage, the flow law eq. (27) is fully determined as we know σ_o', $\dot{\epsilon}_o'$ and n.

Now we turn to the constant stress creep tests and focus on steady state creep (fig 2). The experimental data provides a steady state creep rate $\dot{\epsilon}_s$ for each stress level σ. The flow law, eq. (27), allows us to determine the steady state value α_s of the internal state variable corresponding to each pair $(\dot{\epsilon}_s, \sigma)$, i.e.,

$$\alpha_s = \sigma - \sigma_o'\left[\frac{\dot{\epsilon}_s}{\dot{\epsilon}_o'}\right]^{\frac{1}{2n}} \tag{32}$$

At steady state $\dot{\alpha} = 0$ and the evolutionary law eq. (28) gives

$$\frac{\dot{\epsilon}_s}{\dot{\epsilon}'_0} = \frac{\mathscr{R}}{\mathscr{H}} \alpha_s^{2m} \tag{33}$$

The only unknowns in eqs. (32) and (33) are m and the ratio $\mathscr{R}/\mathscr{H}$. As before, optimal values of these can be found satisfying several pairs of equations like (32) and (33) resulting from the available test data. We now know σ'_0, $\dot{\epsilon}'_0$, n, m and the ratio $\mathscr{R}/\mathscr{H}$.

Now we focus on the primary creep stage. During early primary creep the first term in eq. (28) dominates and we can write

$$\dot{\alpha} = \frac{\mathscr{H}}{\alpha^{2\beta}} \left[\frac{\dot{\epsilon}}{\dot{\epsilon}'_0} \right] \tag{34}$$

Upon integration of eq. (34) with the initial values $\epsilon = 0$ and $\alpha = 0$ we obtain:

$$\epsilon = \frac{\dot{\epsilon}'_0}{\mathscr{H}(2\beta+1)} \alpha^{2\beta+1} \tag{35}$$

Again, from the flow law, eq. (27)

$$\alpha = \sigma - \sigma'_0 \left[\frac{\dot{\epsilon}}{\dot{\epsilon}'_0} \right]^{\frac{1}{2n}} \tag{36}$$

Now we consider a typical data point P during early primary creep as in fig. 2. At P we know the creep strain ϵ, the creep strain rate $\dot{\epsilon}$, and the stress σ. Thus for a given P the only unknowns in eqs. (35) and (36) are β and $\mathscr{H}$. Again, consideration of a number of data points P during early primary creep yields optimal values of the constants β and $\mathscr{H}$.

This completes the procedure for specifying the material constants σ_0', $\dot{\epsilon}_0'$, n, β, m, $\mathcal{R}$ and $\mathcal{H}$ for the matrix material. As indicated earlier, use of eq. (29) then allows determination of the constants for the composite material, eq. (24). In the next section we present the results of applying this procedure to Kanthal, the matrix material of a Kanthal composite.

DETERMINATION OF THE MATERIAL CONSTANTS FOR KANTHAL

The Kanthal matrix material considered here is of the following composition by weight percentage: 73.2% Fe, 21% Cr, 5.8% Al and 0.04% C. The data base for Kanthal is comprised of a set of constant stress creep tests (fig. 4) and a variable stress test (fig. 5) involving two abrupt stress steps. The data are isothermal at 650 C; this corresponds to $T/T_m \approx .45$ for Kanthal. The constant stress tests are at 10,13,17 and 25 ksi (69,90,117 and 173 MPa) taken over the relatively short time period < 2.2 hr with accumulated creep strain <1%, as seen in fig 4. The short time duration of the creep data exemplifies the cycle duration in some aerospace applications. The creep curves show typical primary creep and the minimum creep rate (the darkened portions of the curves) is identified as steady state for the present purposes.

The step creep test of fig. 5 begins at 13 ksi (90 MPa) with a step to 15.4 ksi (106 MPa) at 2 hr and a second step to 17.9 ksi (124 MPa) at 4 hr; the loading rate is 9000 ksi/hr (62100 MPa/hr). It is assumed that the stress steps are made sufficiently abruptly so that the negligible changes occur in the internal microstructure governing creep behavior (measured phenomenologically by α in eqs. (27) and (28)).

The test data was processed as outlined in the foregoing section. The reference stress σ_0' was chosen as 10 ksi (69 MPa) with $\dot{\epsilon}_0'$ the measured initial creep rate at 10 ksi. Inelastic strain rates were estimated before and after each of the two stress steps of fig. 5 giving two equations, eq. (31), from which an optimal value of the exponent n was obtained. This was accomplished using a Levenberg/Marquardt least squares method.

Steady state (minimum creep rate) data $(\dot{\epsilon}_s, \sigma)$ were obtained from the constant stress creep curves of fig. 4 and used in eqs. (32) and (33). Using the same least squares method indicated above the optimal values of m and $\mathcal{R}/\mathcal{H}$ were obtained.

Primary creep information was based on the three data points on the 10 ksi (reference stress) creep curve indicated in fig. 4. Respective measurements of ϵ, $\dot{\epsilon}$ and σ at these points were used in eqs. (35) and (36) similarly providing optimal values of the constants β and $\mathscr{K}$. This completes the specification of the material constants for the Kanthal matrix.

Values of the material constants for Kanthal and for a composite at 650 ^{O}C are given in Table I (the material constants values are consistent with the units ksi and hr).

Figs. 6 and 7 show correlations of the data of figs. 4 and 5 with calculations using the matrix constants of Table I in eqs. (27) – (29). Equivalently, the calculations could be made using the composite constants of Table I in the multiaxial forms eq. (11) – (15), (20) under the isotropic limit $D_{ij} \rightarrow \frac{1}{3}\delta_{ij}$.

PREDICTIONS OF THE CREEP THEORY

The predictions of this section are made using the composite constants of Table I in eqs. (11) – (15), (20). Fig. 8 compares the creep response of the Kanthal matrix (isotropic limit) at 17 ksi (117 MPa) and 650 C with that predicted for transverse creep of the Kanthal composite, i.e., after the inclusion of strong unidirectional fibers (for example W–fibers) that suppress creep along their direction. As indicated earlier this amounts to a kinematic constraint that forces the matrix material, which would deform inelastically as a J_2 *(von–Mises) material* without fibers, to deform as a *maximum shear stress – Tresca material.* This is reflected in the ratio of reference stresses stated in eq. (30). Note, from eqs. (21),(27) and (29) the ratio of initial creep rates in fig. 8 is

$$\frac{\dot{\epsilon}_{trans}}{\dot{\epsilon}_{matrix}} = \left[\frac{\sqrt{3}}{2} \right]^{2n-1} \tag{37}$$

Here, with n = 3.3 this ratio is approximately 0.45.

The lower curve (transverse creep) in fig. 8 can be interpreted as the creep response of the constrained matrix with no weakening from the introduction of fiber/matrix interfacial imperfections or from the evolution of a weak interphase material through diffusion. In this sense, the lower curve of fig. 8 represents an *upper bound* on the transverse creep strength of the composite. Just as a comparison of creep of the unreinforced matrix with that of the composite along the fiber direction provides a measure of the effectiveness of fiber strengthening, a comparison of matrix creep with that transverse to the fibers (fig. 8) provides a measure of the integrity of the composite. Departure from the prediction of fig. 8 may indicate possible interfacial imperfection or degradation of properties resulting from the introduction of the fibers.

A generic point in a structure composed of a unidirectional (or multidirectional) composite generally experiences stress components in addition to that aligned directly with the fibers; in fact, these adverse stress components (shear, transverse tension, etc.) control the inelastic response (creep) of the structure. This is illustrated by the final predictions shown in fig. 9.

Fig. 9 shows the predicted responses of (closed end) thin walled Kanthal composite tubes subjected to an interior pressure. In one case the tube is axially reinforced (insert A in fig 9) and the other is circumferentially re–inforced (insert C). Each is subjected to an interior pressure p such that $\sigma = \frac{pR}{2t}$ with $\frac{R}{t} >> 1$. The axial stress is $\sigma_z = \sigma$, the circumferential stress is $\sigma_\theta = 2\sigma$ and the radial stress is $\sigma_r \approx 0$.

For the axially reinforced tube (A), the governing eqs. (11) – (15), (20) become

$$\left.\begin{array}{c} \dot{\epsilon}_z^A = 0; \quad \dot{\epsilon}_r^A = -\dot{\epsilon}_\theta^A ; \quad \dfrac{\dot{\epsilon}_\theta^A}{\dot{\epsilon}_o} = \left[\dfrac{\sigma - \alpha}{\sigma_{o/2}} \right]^{2n} \\ \dot{\alpha} = \dfrac{H}{G^\beta} \dfrac{1}{2} \left[\dfrac{\dot{\epsilon}_\theta^A}{\dot{\epsilon}_o} \right] - \dfrac{R}{2} G^{m-\beta} ; \; G = \dfrac{4\alpha^2}{\sigma_o^2} \end{array} \right\} \quad (38)$$

Integration of these equations using the composite constants Table I gives the creep curve labelled $\dot{\epsilon}_\theta^A(t)$ in fig. 9.

The corresponding equations for the circumferentially reinforced tube (C) are

$$\left.\begin{aligned} &\dot{\epsilon}_{\theta}^{C} = 0; \qquad \dot{\epsilon}_{r}^{C} = -\dot{\epsilon}_{z}^{C}; \qquad \frac{\dot{\epsilon}_{z}^{C}}{\dot{\epsilon}_{o}} = \left[\frac{\sigma - \alpha}{\sigma_{o}} \right]^{2n} \\ &\dot{\alpha} = \frac{H}{G^{\beta}} \left[\frac{\dot{\epsilon}_{z}^{C}}{\dot{\epsilon}_{o}} \right] - RG^{m-\beta} \; ; \; G = \frac{\alpha^{2}}{\sigma_{o}^{2}} \end{aligned}\right\} \tag{39}$$

These lead to the curve labelled $\dot{\epsilon}_{z}^{C}(t)$ in fig. 9. Clearly, the creep strength of the circumferentially reinforced Kanthal composite tube is much greater. The ratio of initial creep rates is

$$\frac{\dot{\epsilon}_{\theta}^{A}(0)}{\dot{\epsilon}_{z}^{C}(0)} = 2^{2n} \approx 97, \tag{40}$$

differing by almost two orders of magnitude. This large difference reflects that the transverse stress controls the creep behavior. Transverse tension in the axially reinforced tube (A) is $\sigma_{\theta} = 2\sigma$; that in the circumferentially reinforced tube (C) is $\sigma_{z} = \sigma$. In either case the fibers perform as expected, i.e., ensuring $\dot{\epsilon}_{z}^{A} = 0$ for case (A) and $\dot{\epsilon}_{\theta}^{C} = 0$ for case (C).

SUMMARY AND CONCLUSIONS

An anisotropic creep model is presented for metallic composites having strong fibers and low to moderate fiber volume percent (< 40%). Identification of the matrix behavior with that of the isotropic limit of the theory allows characterization of the composite through creep tests on the matrix alone. This amounts to assuming that the fibers provide a constraint that suppresses creep in their direction and, under transverse tension, forces the J_2 *(von–Mises) matrix material* to deform as a *maximum shear stress (Tresca) material.* The fiber–matrix interface is assumed to be perfect without any weakening through the introduction of fiber/matrix interfacial imperfections or from the diffusion related evolution of a weak interphase material. The prediction of transverse creep under these assumptions (fig. 8) thus provides an *upper bound* on the transverse creep strength of the composite. Comparison of the measured transverse creep response of the composite with that of the matrix as in fig. 8 provides an assessment of the integrity of the composite.

A procedure is prescribed for characterizing the composite using creep tests on the matrix material. The required (isothermal) data base includes constant and step–wise constant creep tests. The procedure is applied to Kanthal composite, a model high–temperature composite material. Creep tests on Kanthal at 650 ^{O}C in the stress range 10–25 ksi (69–173 MPa) comprise the data base from which the material constants are derived.

As an application of the theory, predictions are made of the creep response of thin–walled Kanthal composite tubes (closed ends) subjected to an interior pressure. Longitudinally and circumferentially reinforced tubes are considered. The predictions substantiate that circumferential reinforcement is far more efficient in limiting creep. The applications illustrate that creep is controlled, not by the stress along the fiber direction, but by the transverse component. This stress component is larger by a factor of two in the longitudinally reinforced tube.

When weakening mechanisms arising from imperfect bonding, diffusion or the fiber volume percent becomes significant and the effect of the fibers is not limited just to a kinematic constraint as described earlier, the composite cannot be characterized accurately on matrix testing alone. The composite should then be modeled and tested as a material in its own right as in [4,5]. Then the intrinsic weakening effects and their time and history dependent evolution are appropriately reflected in the experimental results.

REFERENCES

1. Lance, R.H., and Robinson, D.N. (1971)."A maximum shear stress theory of plasticity of fiber reinforced materials." *J. Mech. Phys. Solids*, 19.

2. Spencer, A.J.M. (1972). *Deformations of fibre–reinforced materials.* Clarendon Press, Oxford, England.

3. Spencer, A.J.M (1984). "Constitutive theory for strongly anisotropic solids." *Continuum theory of fibre–reinforced composites*, Springer–Verlag, New York, N.Y.

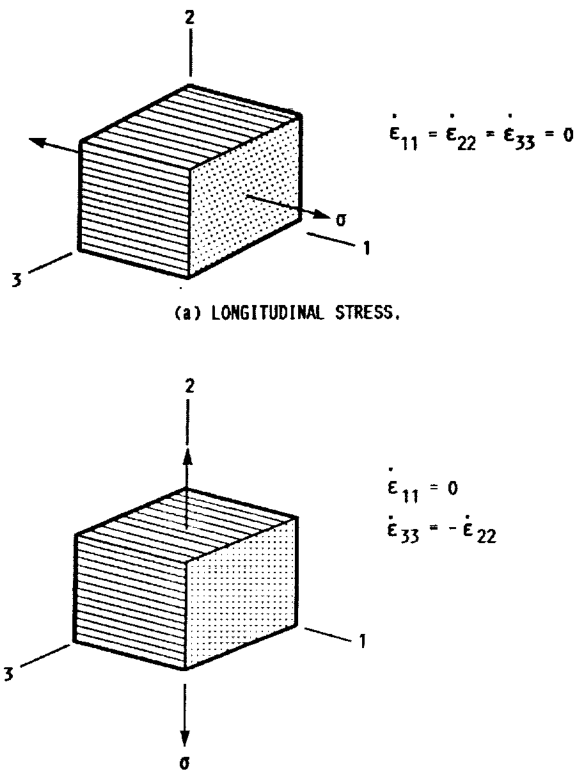
4. Robinson, D.N., Duffy, S.F., and Ellis, J.R. (1987). "A viscoplastic constitutive theory for metal matrix composites at high temperature." *Thermal stress, material deformation and thermo-mechanical fatigue*, H. Sehitoglu and S.Y. Zamrik, eds., ASME/PVP, vol. 123.

5. Robinson, D.N., and Duffy, S.F. (1990). "Continuum deformation theory for high temperature metallic composites." *J. Engr. Mech.*, ASCE, vol. 16, No. 4.

6. Arnold, S.M., and Robinson, D.N. (1989). "Unified viscoplastic behavior of metal matrix composites: theory and experiment ." *1989 HiTemp Review*, NASA CP 10039 (in preparation for publication).

Table I. Material Constants

Matrix	Composite
$\sigma'_0 = 10$	$\sigma_0 = 11.547$
$\dot{\epsilon}'_0 = .00165$	$\dot{\epsilon}_0 = 0.00143$
$n = 3.3$	$n = 3.3$
$\beta = 1.05$	$\beta = 1.05$
$m = 5.78$	$m = 5.78$
$\mathscr{R} = 9.5 \times 10^{-7}$	$R = 3163.68$
$\mathscr{H} = 38.8$	$H = 0.3558$



(a) LONGITUDINAL STRESS.

(b) TRANSVERSE STRESS.

FIGURE 1. - MATERIAL ELEMENTS UNDER STRESS.

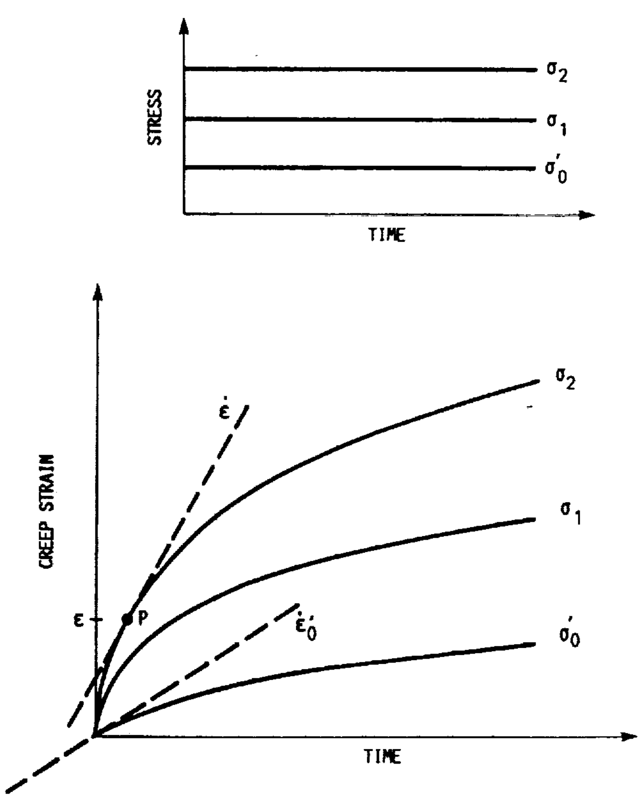


FIGURE 2. - TYPICAL CONSTANT STRESS CREEP CURVES FOR THE MATRIX MATERIAL. σ_0' IS A REFERENCE STRESS AND $\dot{\varepsilon}_0'$ IS THE INITIAL CREEP RATE AT σ_0'. P IS A GENERIC POINT IN EARLY PRIMARY CREEP.

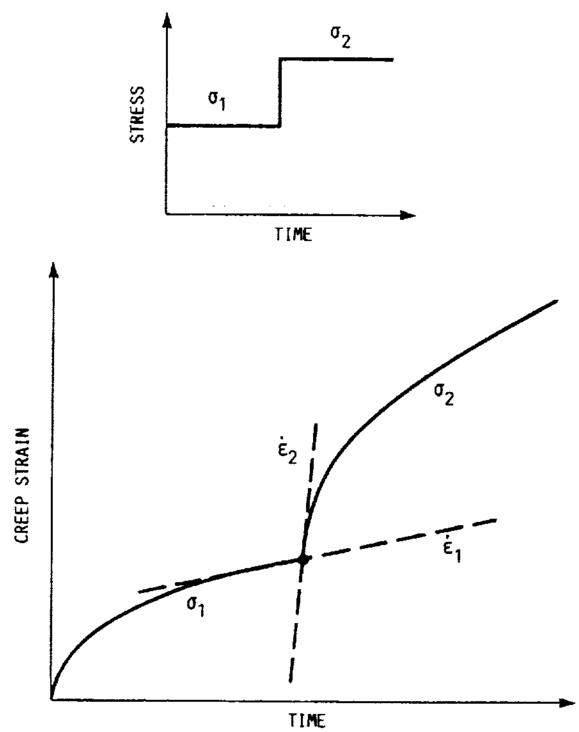


FIGURE 3. - TYPICAL STEP-STRESS CURVE FOR THE MATRIX MATERIAL. $\dot{\varepsilon}_1$ IS THE FINAL CREEP RATE AT σ_1 (BEFORE STEP). $\dot{\varepsilon}_2$ IS THE INITIAL CREEP RATE AT σ_2 (AFTER STEP).

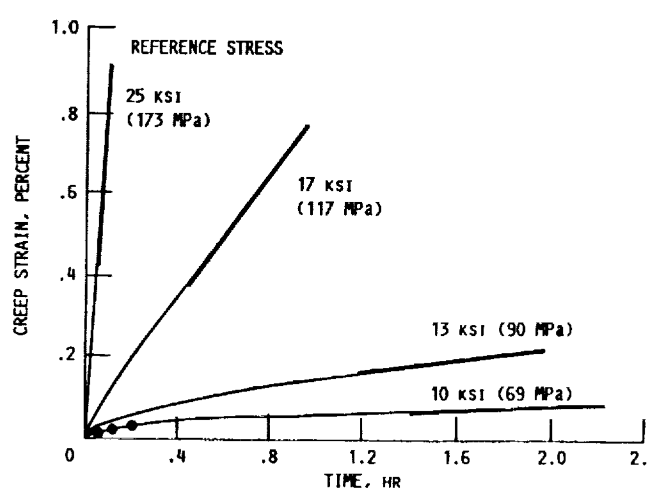


FIGURE 4. - EXPERIMENTAL CREEP CURVES FOR KANTHAL AT 10, 13, 17, AND 25 KSI AT TEMPERATURE 650 °C. MINIMUM CREEP RATES (DARKENED PORTIONS) ARE TAKEN AS STEADY STATE. PRIMARY CREEP INFORMATION IS BASED ON THE THREE POINTS INDICATED ON THE 10 KSI (REFERENCE STRESS) CREEP CURVE.

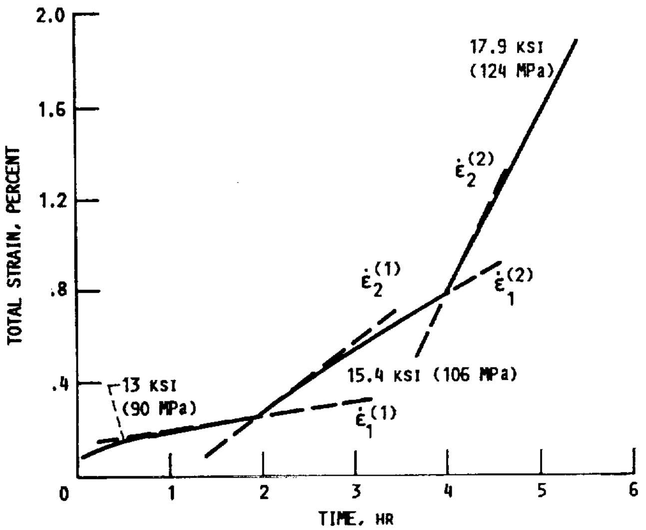


FIGURE 5. - EXPERIMENTAL STEP-STRESS CREEP CURVES FOR KANTHAL AT 13-15.4 KSI (40-106 MPa) AND 15.4-17.9 KSI (106-124 MPa) CREEP RATES ARE IDENTIFIED BEFORE AND AFTER EACH STEP.

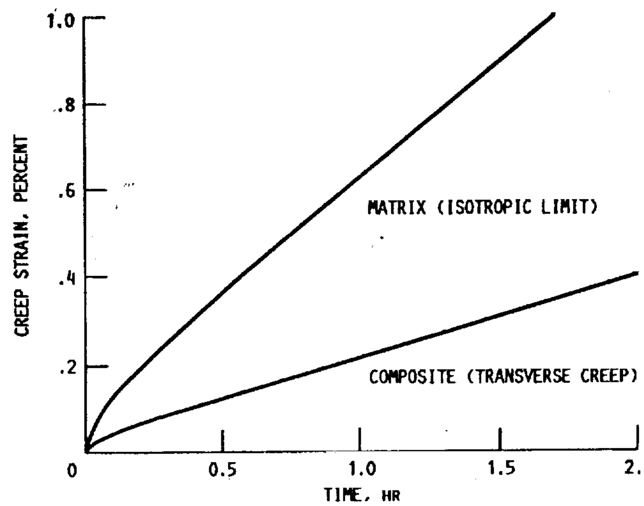


FIGURE 8. - COMPARISON OF PREDICTED MATRIX CREEP AND TRANSVERSE CREEP OF THE COMPOSITE (UPPER BOUND ON TRANSVERSE CREEP STRENGTH) AT 17 KSI (117 MPa) AND 650 °C.

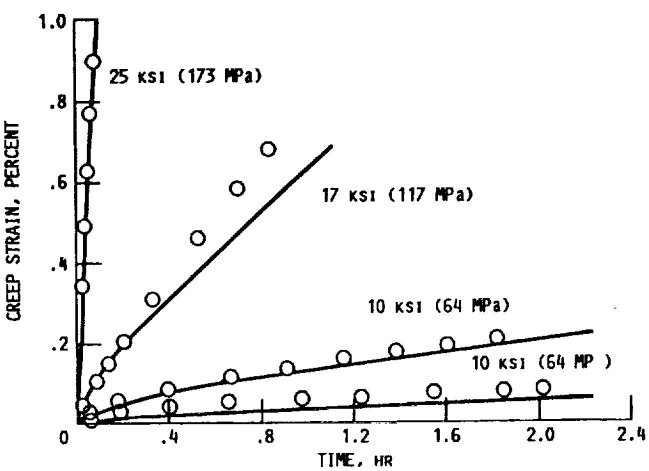


FIGURE 6. - CORRELATIONS OF EXPERIMENTAL (CIRCLES) AND CALCULATED (LINES) CONSTANT STRESS CREEP CURVES. FOR 10, 13, 17, AND 25 KSI (69, 90, 117, AND 173 MPa) AT 650 °C.

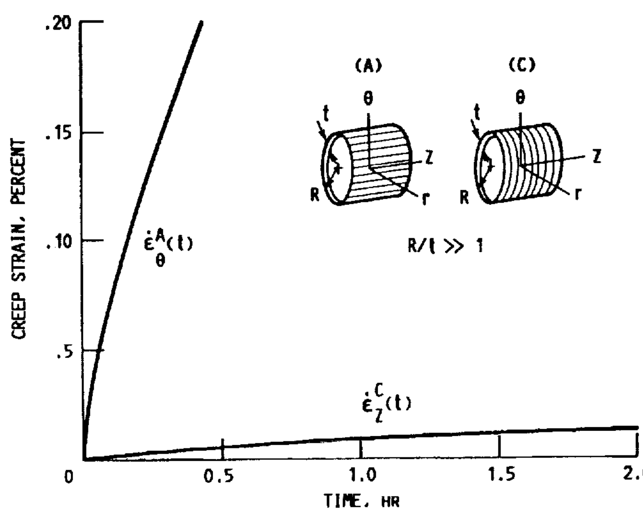


FIGURE 9. - COMPARISON OF PREDICTED CREEP RESPONSES FOR AXIALLY REINFORCED (A) AND CIRCUMFERENTIALLY REINFORCED (C) KANTHAL COMPOSITE TUBES UNDER INTERIOR PRESSURE CORRESPONDING TO σ = PR/2t = 7 KSI (48.3 MPa).

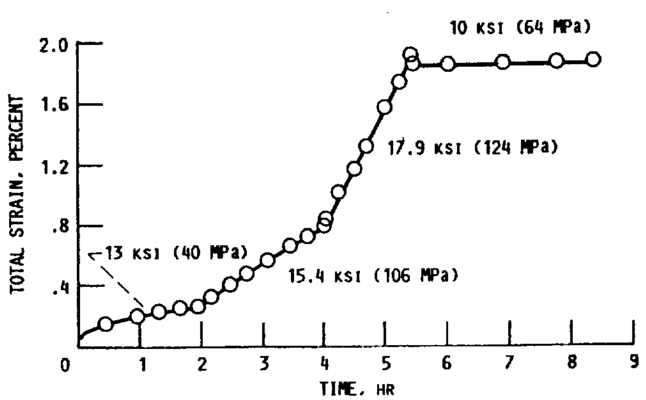


FIGURE 7. - CORRELATIONS OF EXPERIMENTAL (CIRCLES) AND CALCULATED (LINES) STEP-WISE CREEP TESTS AT 13-15.4 KSI (40-106 MPa) AND 15.4-17.9 KSI (106-124 MPa). ALSO SHOWN IS A PREDICTION OF A FINAL STEP 17.9-10 KSI (124-64 MPa) AT 650 °C.

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15. Supplementary Notes

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16. Abstract

An anisotropic creep model is formulated for metallic composites with strong fibers and low to moderate fiber volume percent (<40%). The idealization admits no creep in the local fiber direction and assumes equal creep strength in longitudinal and transverse shear. Identification of the matrix behavior with that of the isotropic limit of the theory permits characterization of the composite through uniaxial creep tests on the matrix material. Constant and step-wise creep tests are required as a data base. The model provides an upper bound on the transverse creep strength of a composite having strong fibers embedded in a particular matrix material. Comparison of the measured transverse strength with the upper bound gives an assessment of the integrity of the composite. Application is made to a Kanthal composite, a model high-temperature composite system. Predictions are made of the creep response of fiber reinforced Kanthal tubes under interior pressure.

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