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ANALYSIS OF DAMAGE IN MMC COMPONENTS USING AN INTERNAL STATE VARIABLE MODEL

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The need to model the rate dependence and observed creep and plasticity interactions exhibited by materials, particularly at elevated temperatures, has greatly stimulated the development of numerous viscoplastic models. These models, in general, provide a better description of high-temperature time-dependent inelastic behavior of materials.

Owing to their lightweight and enhanced strength, the metal-matrix composite (MMC) materials are attracting considerable attention for high-temperature applications. As a result of concerted and leading efforts in this direction at NASA Lewis, a metal-matrix composite model was developed by Robinson and Duffy (1989). (See figs. 1 and 2.) The concept of damage evolution has recently been included by Robinson (personal communication) in the above model. The evolution of damage is assumed to be governed by a Kachanov-type equation. (See fig. 3.)

The highly nonlinear and mathematically "stiff" nature of the constitutive equations of viscoplastic models renders analytical solutions of problems, in general, intractable. It, therefore, becomes mandatory to develop suitable finite element or other numerical solution technologies to be able to use these models in component design. With this objective in mind, the above viscoplastic damage model was implemented in the finite element code, MARC. Both uniaxial (creep) and multiaxial (an internally pressurized thick-walled cylinder) problems were analyzed using this implementation. Some preliminary results are presented here. These results consider monotonic (constant) loadings. The study of damage accumulation under variable (cyclic) loadings is being undertaken. The results of this study will be presented later.

Figure 4 shows the experimental data (Cooper, 1966) utilized to determine the values of anisotropic parameters that appear in the model.

The creep curves including damage for four fiber orientations are depicted in figure 5. As expected, the minimum creep occurs when load is applied in a direction parallel to the fibers.

The tangential strains at the inner radius of a thick-walled MMC-cylinder for four fiber orientations are plotted in figure 6. The damage is included. The cylinder exhibits the maximum creep resistance when the fibers are oriented in the circumferential direction, perpendicular to the axis of cylinder.

Figure 7 shows the time-to-failure for the thick-walled cylinder for the same fiber orientation angles. As expected, the life of the cylinder can substantially be increased by orientating the fibers in the circumferential direction, perpendicular to the axis of cylinder.

The results, although qualitative, indicate that significant benefits in creep-resistance and service life can be achieved by using MMC materials as structural materials for high-temperature design.

The finite element technology developed herein is proposed to be applied to aerospace structural components subjected to (cyclic) thermomechanical loadings. The results of these analyses will be reported subsequently.

REFERENCES

Robinson, D.N.; and Duffy, S.F. (1989): A Continuum Deformation Theory for Metal-Matrix Composites at High Temperature. Journal of Engineering Mechanics, ASCE (under publication).

Cooper, G.A. (1966): Orientation Effects on Fiber-Reinforced Metals. Journal of Mechanics and Physics of Solids, vol. 14, pp. 103-111.

METAL MATRIX COMPOSITE MODEL INCLUDING DAMAGE

FLOW LAW

$$\dot{\epsilon}_{ij} = \frac{F^n}{2\mu}\Gamma_{ij}$$

WHERE

$$F = \frac{1}{(\psi K_t)^2}\left(I_1 - \xi I_2 - 12\zeta I_3^2\right) - 1$$

$$\Gamma_{ij} = \Sigma_{ij} - \xi\,(d_k d_i \Sigma_{jk} + d_j d_k \Sigma_{ki} - 4 I_3 d_i d_j) - 4\zeta I_3 (3 d_i d_j - \delta_{ij})$$

$$I_1 = \frac{1}{2}\Sigma_{ij}\Sigma_{ij} \qquad I_2 = d_i d_j \Sigma_{jk}\Sigma_{ki} - 4 I_3^2 \qquad I_3 = \frac{1}{2} d_i d_j \Sigma_{ji}$$

$$\xi = \frac{\eta^2 - 1}{\eta^2} \qquad \zeta = \frac{4(\omega^2 - 1)}{4\omega^2 - 1}$$

AND WHERE

d_i = A UNIT VECTOR ALONG THE PREFERRED DIRECTION AT A POINT OF THE MATERIAL

ω AND η = ANISOTROPIC PARAMETERS

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Figure 1

METAL MATRIX COMPOSITE MODEL INCLUDING DAMAGE

EVOLUTION LAW

$$\dot{\alpha}_{ij} = \frac{H}{G^{\beta}} \dot{\epsilon}_{ij} - RG^{m-\beta}\Pi_{ij}$$

WHERE

$$G = \frac{1}{K_t^2}\left[I_1' - \xi I_2' - 12\zeta I_3'^2\right]$$

$$\Pi_{ij} = \alpha_{ij} - \xi\,(d_k d_i \alpha_{jk} + d_j d_k \alpha_{ki} - 4I_3' d_i d_j) - 4\zeta I_3' 3 d_i d_j - \delta_{ij})$$

$$I_1' = \frac{1}{2}\alpha_{ij}\alpha_{ij} \qquad I_2' = d_i d_j \alpha_{jk}\alpha_{ki} - 4I_3'^2 \qquad I_3' = \frac{1}{2} d_i d_j \alpha_{ji}$$

$$\xi = \frac{\eta^2 - 1}{\eta^2} \qquad \zeta = \frac{4(\omega^2 - 1)}{4\omega^2 - 1}$$

AND WHERE
d_i = A UNIT VECTOR ALONG THE PREFERRED DIRECTION AT A POINT OF THE MATERIAL
ω AND η = ANISOTROPIC PARAMETERS

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Figure 2

METAL MATRIX COMPOSITE MODEL INCLUDING DAMAGE

DAMAGE LAW

$$\dot{\psi} = -A\bar{\sigma}^{p}/\psi^{q}$$

$$\bar{\sigma} = \chi\ (N,S)$$

IN WHICH DAMAGE VARIABLE,

$$D = 1 - \psi$$

WHERE

N = MAXIMUM TENSILE STRESS TO THE FIBER DIRECTION
S = MAXIMUM LONGITUDINAL SHEAR STRESS ALONG FIBER DIRECTION

FORM OF FUNCTION χ USED:

$$\bar{\sigma} = \lambda\langle N\rangle + (1 - \lambda)\ S \qquad (0 \le \lambda \le 1)$$

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Figure 3

YIELD STRESS OF TUNGSTEN/COPPER FOR VARIOUS FIBER ORIENTATION ANGLES

ω = 7; EXPERIMENTAL DATA FROM COOPER (1966)

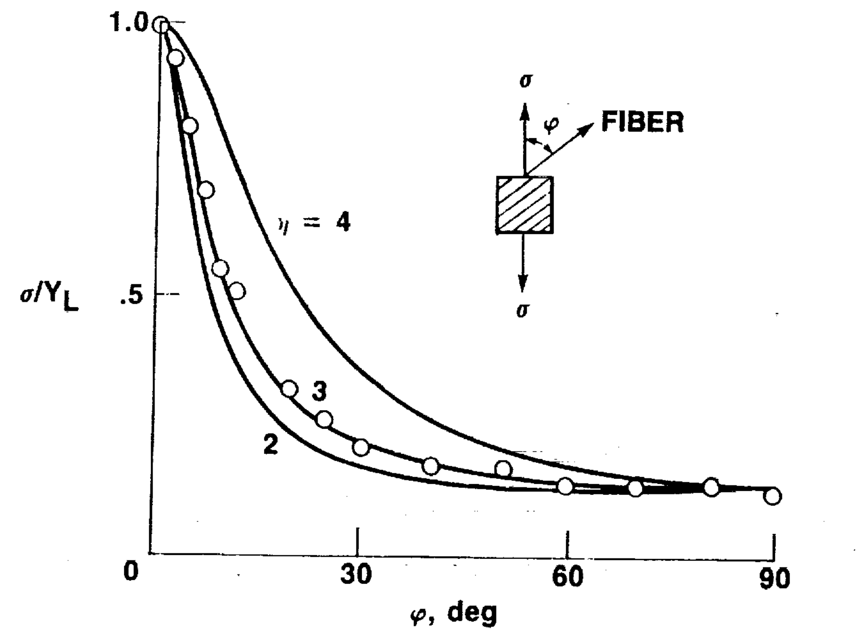

Figure 4

CREEP CURVES INCLUDING DAMAGE

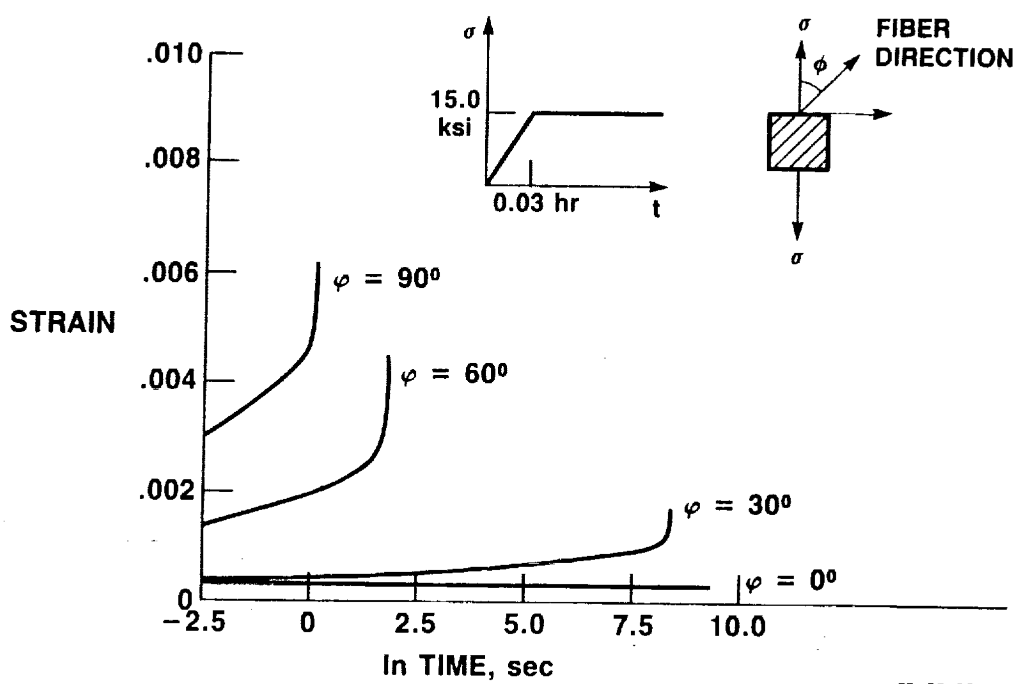

Figure 5

TANGENTIAL STRAIN AT INNER RADIUS OF METAL-MATRIX COMPOSITE CYLINDER (INCLUDING DAMAGE)

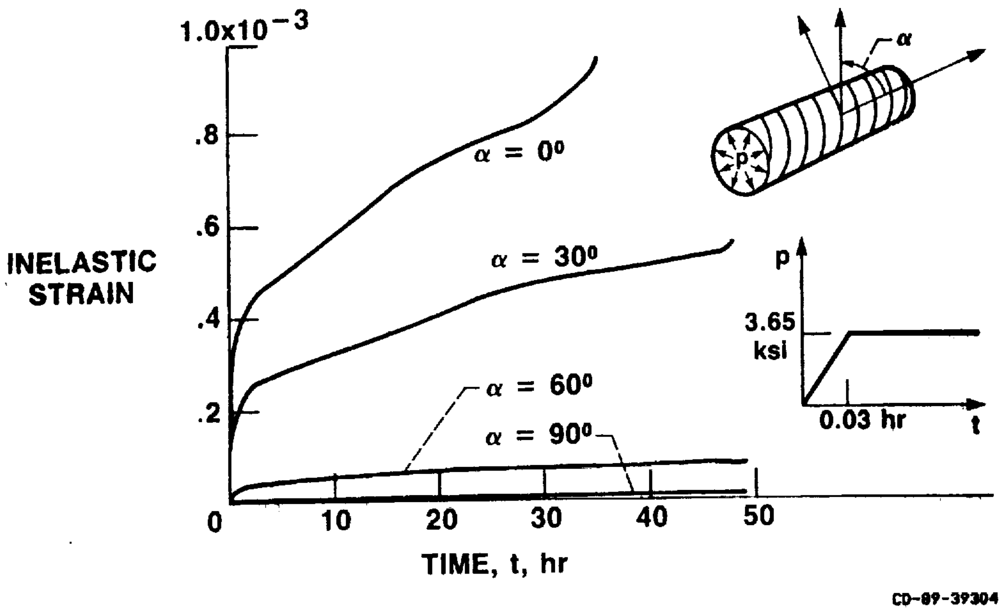

Figure 6

ROBINSON'S METAL-MATRIX COMPOSITE VISCOPLASTIC DAMAGE MODEL

THICK-WALLED CYLINDER

(800 °F, p = 3.65 ksi)

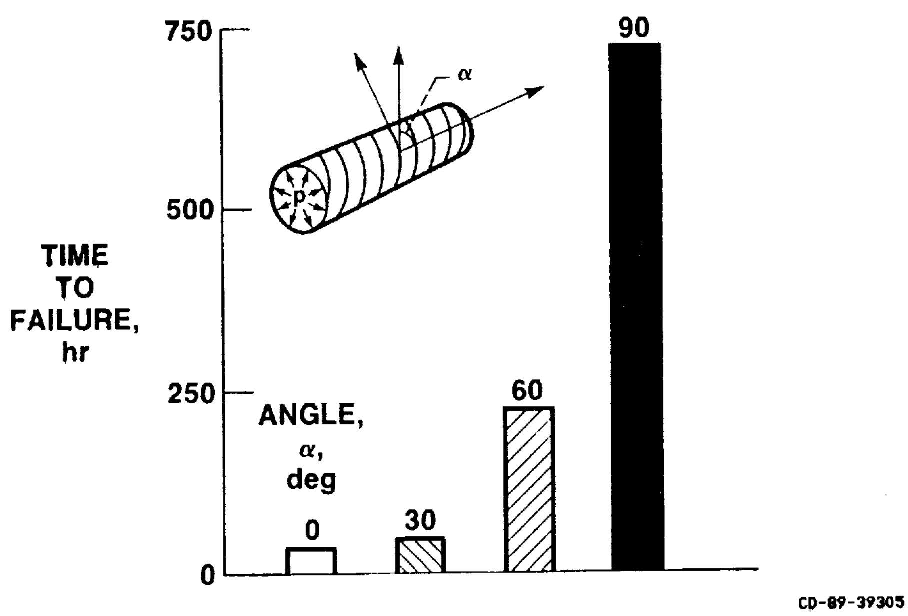

Figure 7