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A MODEL FOR THE BIAXIAL POST-YIELD BEHAVIOR OF EXTRUDED POWDER ALUMINUM AT ELEVATED TEMPERATURE (U)

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DISCLAIMER

A MODEL FOR THE BIAXIAL POST-YIELD BEHAVIOR OF EXTRUDED POWDER ALUMINUM AT ELEVATED TEMPERATURE

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ABSTRACT

A model has been developed which describes the post-yield behavior of extruded powder aluminum tested biaxially in tension and torsion at elevated temperature. Plots of shear stress versus shear strain for the powder aluminum loaded in simple torsion show that the shear stress increases linearly to the yield point, then remains relatively constant in a pure plastic type of behavior. For the tension-torsion tests, there is an initial linear region up to the yield point followed by a fairly linear decrease in shear stress. A similar linear decrease in axial stress with increasing axial strain is observed in uniaxial tension tests. The model for post-yield behavior of extruded powder aluminum gives a quantified description of the macroscopic material behavior in terms of changes in the laminar powder aluminum structure.

INTRODUCTION

The structure of extruded powder aluminum is a consequence of the structure of aluminum powder particles and the extrusion process. Aluminum powder particles, each coated with a thin layer of aluminum oxide, are compacted to form a billet and then extruded into a rod. During the extrusion, the particles become greatly elongated, forming a laminar structure consisting of ligaments or laminae of aluminum separated by stringers of aluminum oxide. The presence of aluminum oxide is the major factor which causes the behavior of the extruded powder aluminum to differ so greatly from the behavior of the 1100 aluminum.

During extrusion, the material experiences tensile, compressive, and shear loadings [1,2]. The combination of tensile and shear deformation particularly effect the quality of the extruded rod. Therefore, a better understanding of the effects of tensile and shear deformation on powder aluminum should provide information that will aid in the design of improved extrusion dies.

The biaxial model presented is an extension of an earlier model developed for simple tension [3]. It is intended to provide a description of post-yield behavior which includes macroscopic stress-strain data and also considers the microscopic behavior of the laminar powder aluminum structure.

EXPERIMENTAL PROCEDURES

Test specimens were machined from extruded powder aluminum and from 1100 aluminum rod. The specimens are tubes with a length of approximately 76 mm, a gage length of approximately 50 mm, and inner and outer radii of approximately 4 mm and 6.4 mm in the gage region. The axis along which the tensile load is applied corresponds with the extrusion axis. Torque is also applied along this axis in the biaxial tests. The specimens were tested in pure torsion, simple tension, and combined tension-torsion using a testing system which has been described in detail previously [4]. Tests were conducted at 425° C, the extrusion temperature of the powder aluminum. The tested specimens were sectioned, mounted, polished and etched for microscopic examination [5]. Quantitative stereology is then used to determine the relative volume of separation regions in the tested material [6]. The significance of the separation regions will be discussed in detail in the description of the model.

RESULTS

Figures 1 and 2 show average shear stress vs average shear strain for extruded powder aluminum and 1100 aluminum tested in pure torsion and in simultaneous tension and torsion [7]. The average shear stress, τ_{avg}, is defined as:

$$\tau_{avg} = \frac{T\, r_{avg}}{J} \tag{1}$$

where

T = applied torque
r_{avg} = average radius of the cross-section at each instant
J = polar moment of area of the cross-section

and

$$J = \frac{\pi}{2}\left(r_o^4 - r_i^4\right) \tag{2}$$

Average shear strain, γ_{avg}, is defined as:

$$\gamma_{avg} = \frac{\phi \, r_{avg}}{L} \qquad (3)$$

where

ϕ = angle of twist
L = specimen length at each instant

Average shear stress in the post-yield region is greater in the powder aluminum specimens. Another significant difference in behavior is the relatively linear decrease in average shear stress with shear strain as the seen in the biaxial powder aluminum curves. The rate of decrease increases with increasing axial strain. This effect is not observed in the 1100 aluminum specimens where, in contrast, the average shear strain stayed relatively constant or increased with increasing average shear strain.

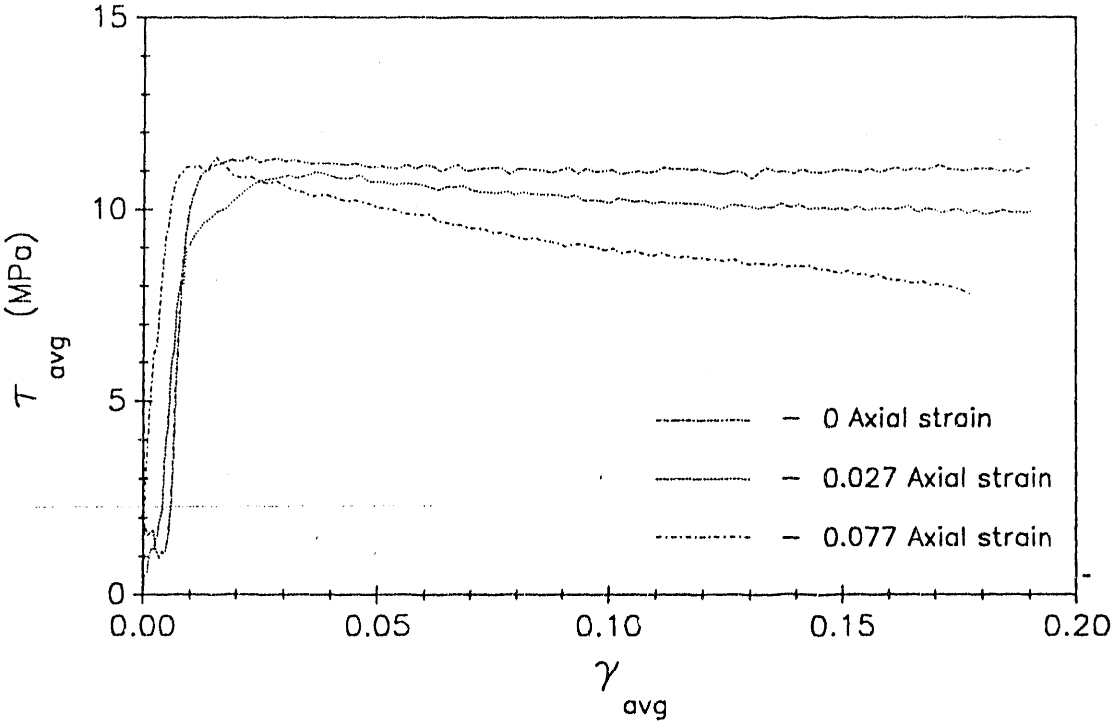

Figure 1. Average shear stress vs average shear strain for three levels of extensional strain in tension-torsion tests of powder aluminum at 425° C.

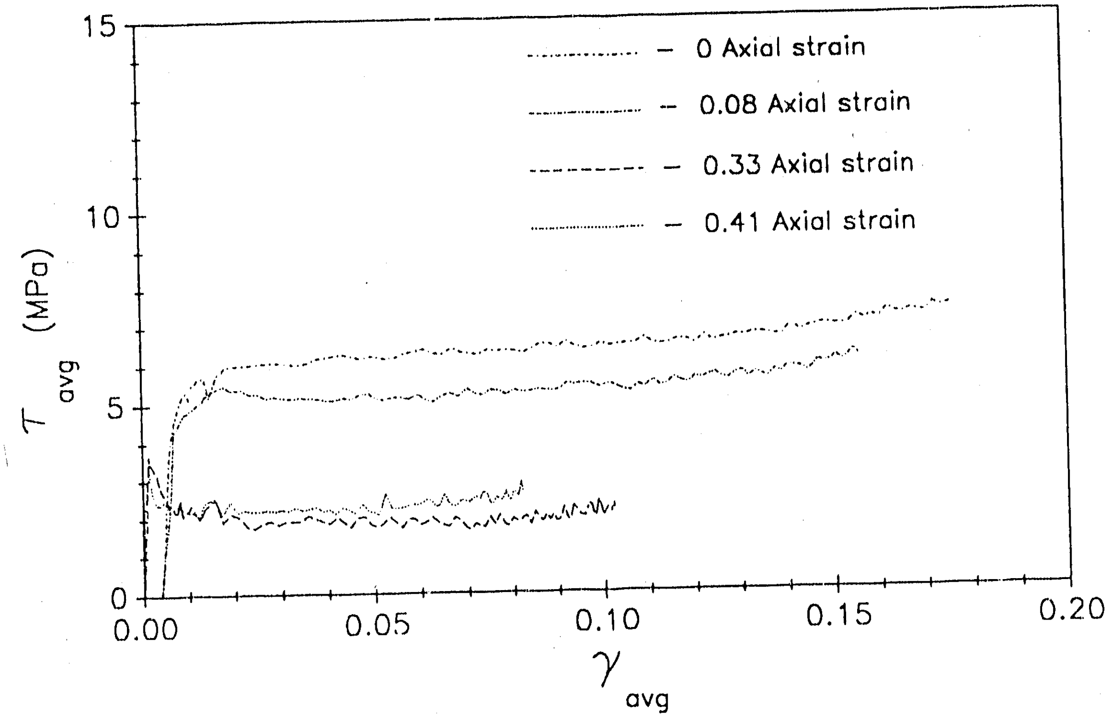

Figure 2. Average shear stress vs average shear strain for four values of extensional strain in tension-torsion tests of 1100 aluminum at 425° C.

BIAXIAL MATERIAL FAILURE MODEL

Previous investigation of extruded powder aluminum in uniaxial tension indicates that the oxide stringers distributed throughout the material have a significant impact on the material's behavior. In simple tension tests, the oxide initially provides a rigid supporting structure which produces a greater ultimate strength in the powder aluminum than in the 1100 aluminum. As loading continues beyond the yield point, the oxide then contributes to the failure of the material by inhibiting adhesion between the aluminum ligaments. The particle terminations are regions where loading is shifted between the ligaments, producing shearing loads and relative motion between the ligaments. As a result, during the test there is a reduction of the *internal* cross-sectional area of the specimen. Simultaneously, the axial load and corresponding axial stress decrease with increasing axial elongation. A similar decrease in internal cross-sectional area will occur in biaxial tension-torsion tests of extruded powder aluminum (figure 3).

In the torsion and tension-torsion tests, it is useful to consider the stress components in a coordinate system aligned with the rotated ligaments, the x-y system shown in figure 3. In particular, the effects of the normal stresses in the x-y system can be used to understand the deformation behavior of the powder aluminum. In a pure torsion test, the magnitudes of σ_x and σ_y are the same. The relatively large compressive stress, σ_y, acts to clamp the ligaments together, inhibiting relative motion, lessening the decrease in internal cross-sectional area, and causing the torque (and average shear stress) to remain relatively constant. In contrast, in the tension-torsion tests, the magnitude of σ_y is less than that of σ_x [7]. As a result, the clamping effect is less, and there is a decrease in internal cross-sectional area and a corresponding drop in the torque (and in the average shear stress).

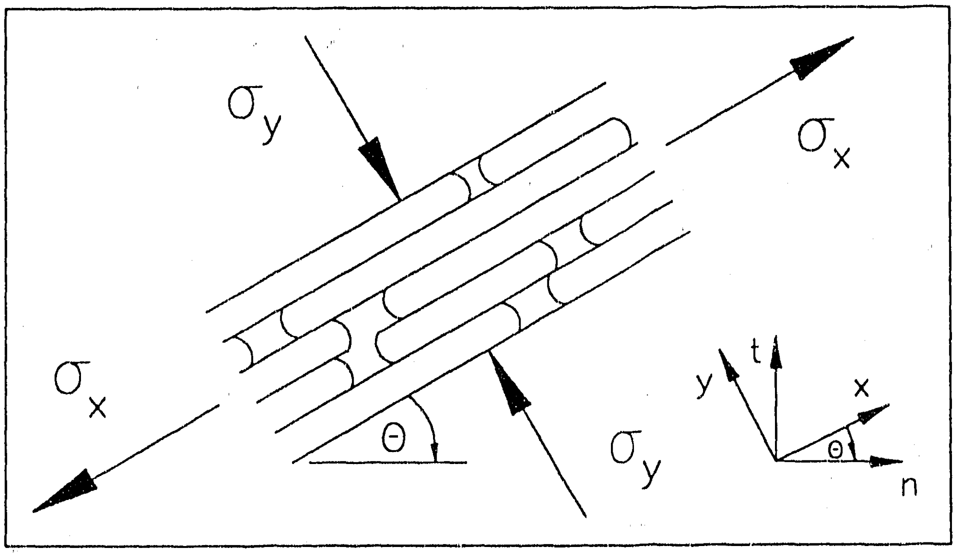

Figure 3. Normal stresses acting on an enlarged region in a powder aluminum specimen loaded in tension and torsion. The extrusion axis (and the axis of tension and torsion) is the n-axis. The x-axis is aligned with the aluminum ligaments. Shear stresses are not shown.

For a rod in torsion,

$$T = \int_A \tau \, r \, dA \tag{4}$$

where

T = torque
r = radius
A = cross-sectional area

In pure torsion, the internal cross-sectional area remains relatively constant, and the torque and average shear stress also remain relatively constant as seen in figure 1. As the internal cross-sectional area deceases with increasing axial elongation in tension-torsion tests however, equation 4 shows that the torque should decrease. This decrease in torque (and average shear stress) is observed experimentally (figure 1). Next, an expression for the torque in the powder aluminum in the post-yield region will be developed.

Rearranging equation 4,

$$T = \frac{\tau J}{r} \tag{5}$$

Now, in the post-yield region for 1100 aluminum (figure 2), assume

$$\tau = \tau_0(1 + c\gamma) \tag{6}$$

with

τ_0 = yield stress in pure shear
c = strain hardening coefficient

where τ_0 and c are determined from the pure shear curve in figure 2. Then, the expression for torque can be rewritten as:

$$T = \frac{Q\, \tau_0\, (1 + c\gamma)\, J_r}{r} \tag{7}$$

where

Q = constant representing stiffening effect of aluminum oxide
J_r = polar moment of area, considering the reduced cross-sectional area

Assume that the cross-sectional area decreases linearly with strain along the ligament direction. Also assume that the area decrease is affected by the transverse clamping stress, σ_y, then

$$J_r = \frac{1}{2}\left\{A_I\, r_o^2\left[1 - k\, \varepsilon_x \left(\frac{\sigma_{yl} - \sigma_y}{\sigma_{yl}}\right)\right] + \pi\, r_i^2\left(r_o^2 - r_i^2\right)\right\} \tag{8}$$

where

A_I = initial cross-sectional area
k = constant representing decrease of cross-sectional area with strain
r_o = outer radius
r_i = inner radius
ε_x = extensional strain along the ligaments
σ_y = normal stress transverse to ligament direction
σ_{yl} = normal stress transverse to ligament direction which will lock the ligaments and prevent them from slipping over each other

and the expression for the torque can be rewritten as:

$$T = \frac{Q\,\tau_o\,(1 + c\gamma)}{2r}\left\{A_I\, r_o^2\left[1 - k\,\varepsilon_x\left(\frac{\sigma_{yl} - \sigma_y}{\sigma_{yl}}\right)\right] + M\right\} \qquad (9)$$

where

$$M = \pi\, r_i^2\left(r_o^2 - r_i^2\right)$$

The constants Q, c, and τ_o can be determined from the pure shear curves for 1100 aluminum and extruded powder aluminum shown in figures 1 and 2. Values for k and σ_{yl}, the stress for which there is no decrease in internal cross-sectional area, can be found numerically by setting the derivative of the torque with respect to shear strain equal to zero.

$$\frac{\delta T}{\delta\gamma} = 0 = \frac{Q\,\tau_o\,c}{2r}\left\{A_I\, r_o^2\left[1 - k\,\varepsilon_x\left(\frac{\sigma_{yl} - \sigma_y}{\sigma_{yl}}\right)\right]\right\}$$

$$- \frac{Q\,\tau_o\,(1 + c\gamma)}{2r}\left\{A_I\, k\, r_o^2\left(\frac{\sigma_{yl} - \sigma_y}{\sigma_{yl}}\right)\frac{\delta\varepsilon_x}{\delta\gamma}\right\}$$

$$+ \frac{Q\,\tau_o\,(1 + c\gamma)}{2r}\left\{\frac{A_I\, k\, r_o^2\,\varepsilon_x}{\sigma_{yl}}\left(\frac{\delta\sigma_y}{\delta\gamma}\right)\right\} \qquad (10)$$

The constants k and σ_{yl} can be found using a nonlinear least squares method in the post-yield region.[1] Finally, equations 1 and 9 can be combined to give:

$$\tau_{avg} = \frac{T\, r_{avg}}{J} = \frac{Q\,\tau_o\,(1 + c\gamma)}{2J}\left\{A_I\, r_o^2\left[1 - k\,\varepsilon_x\left(\frac{\sigma_{yl} - \sigma_y}{\sigma_{yl}}\right)\right] + M\right\} \qquad (11)$$

Figures 4, 5, and 6 show the fit from equation 11 with the experimental data from figure 1. All graphs have the following values for the various constants: c = 1.8, σ_{yl} = -18.4 MPa, k = 6.5, Q = 1.9, and τ_o = 5.6 MPa. While the model does not perfectly predict the shear stress vs shear strain behavior, it does demonstrate the effect of the drop in area on the torque and shear stress, particularly in the specimen with the greatest extensional strain (figure 6). These results indicate that the drop in area increases with increasing extensional strain along the

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[1] The PC-MATLAB software package produced by The Math Works Inc. was used to solve the system of nonlinear equations which were formed in the least squares solution.

ligaments, suggesting that the model might be modified to include a higher order dependence on the extensional strain in the ligament direction.

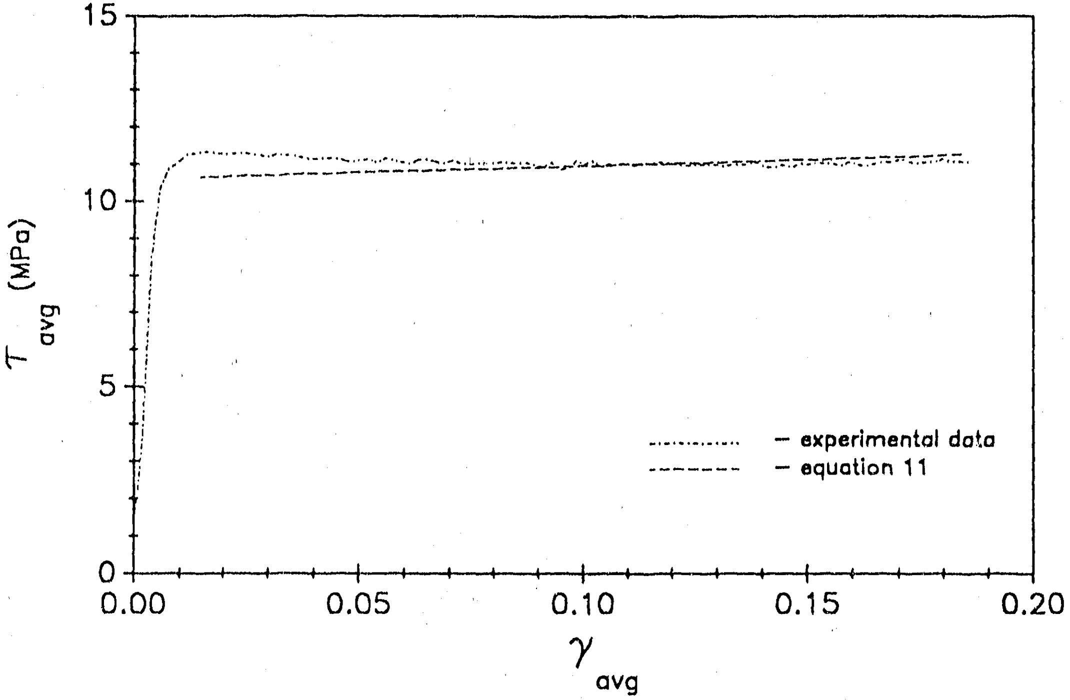

Figure 4. Average shear stress vs average shear strain for extruded powder aluminum specimen tested in pure torsion at 425° C. Curves show experimental data and fit from equation 11.

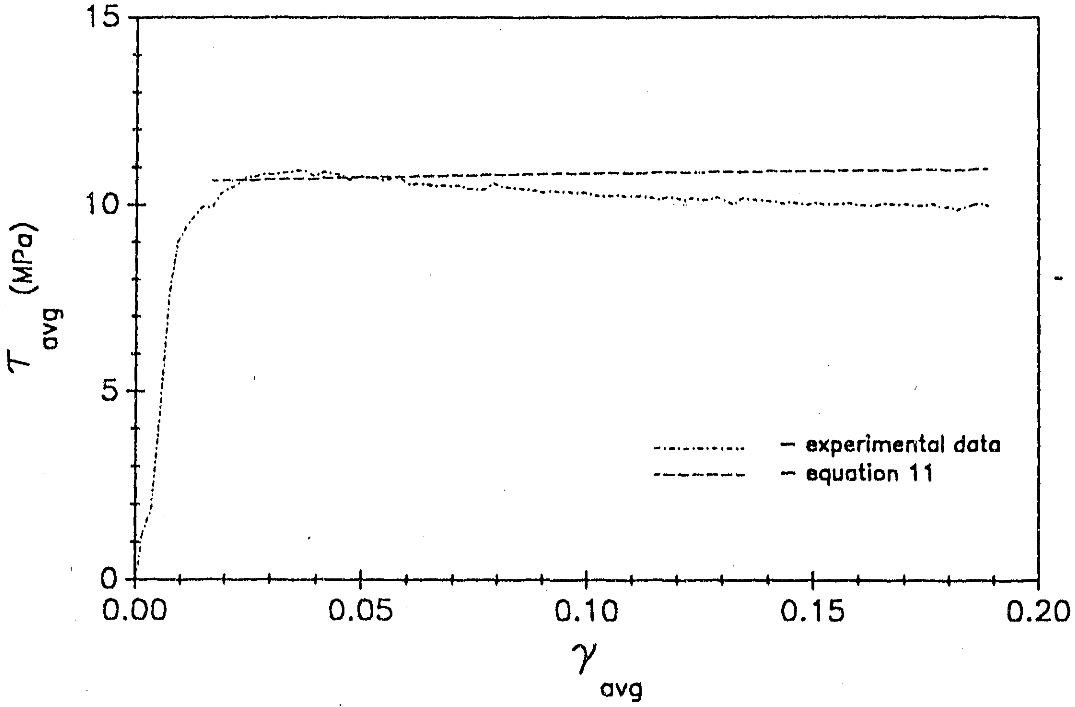

Figure 5. Average shear stress vs average shear strain for extruded powder aluminum specimen tested biaxially in tension and torsion at 425° C. Maximum axial strain is 0.027. Curves show experimental data and fit from equation 11.

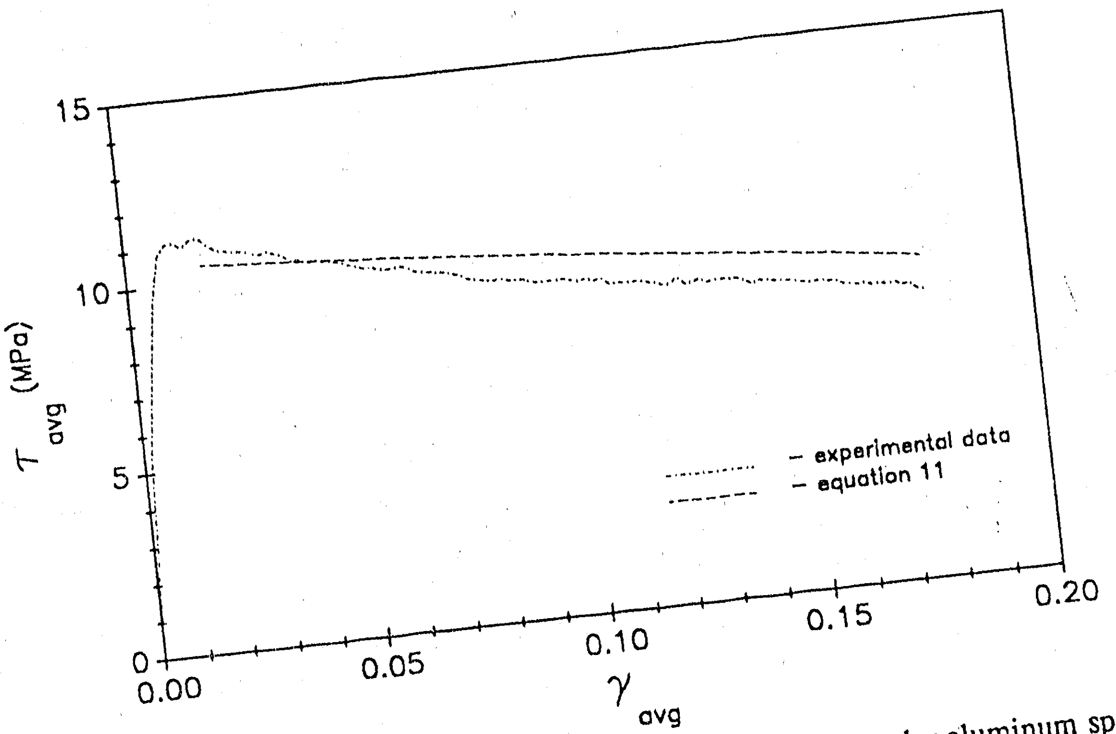

Figure 6. Average shear stress vs average shear strain for extruded powder aluminum specimen tested biaxially in tension and torsion at 425° C. Maximum axial strain is 0.077. Curves show experimental data and fit from equation 11.

CONCLUSIONS

The model for the high temperature biaxial behavior of extruded powder aluminum is the current version in an ongoing investigation of the behavior of this material. The goal of the investigation is to develop a quantified description of the macroscopic material behavior which includes information relating to the microscopic structure. Although the current model does not provides a superb fit of the data, it does show the trends present in the test. That is, it does show effect of the decrease in internal cross-sectional area in the biaxial tests with greater levels of tensile loading. Further, it suggests that this decrease should not be modeled as a simple linear decrease with increasing strain. Work is continuing on an improved model which assumes that the rate of decrease of internal cross-sectional area increases with increasing axial strain.

ACKNOWLEDGMENT

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