THE MECHANICAL BEHAVIOR OF EXTRUDED POWDER ALUMINUM SUBJECTED TO BIAXIAL LOADINGS AT ELEVATED TEMPERATURE.

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SUMMARY

The goal of this investigation is to develop a description of the biaxial behavior of extruded powder aluminum at elevated temperature. Specimens made of extruded 101 ALCOA (Aluminum Company of America) powder aluminum and specimens made from 1100 commercial aluminum rod are tested biaxially in tension-torsion and compression-torsion loadings at the extrusion temperature. The powder aluminum is examined microscopically and stereological methods are used to give a quantified description of the material behavior in terms of changes in the laminar powder material structure. A model for the biaxial(tension-torsion) behavior of extruded powder aluminum is developed. This description is consistent with a previous analysis of behavior in pure tension.

INTRODUCTION

Extruded powder aluminum has a structure which is a consequence of the chemical structure of aluminum powder and the extrusion process. Aluminum particles, each coated with a thin layer of aluminum oxide, are compacted to form a billet which is then extruded to form the powder aluminum rod. During extrusion, the particles are greatly elongated to form a laminar structure which consists of ligaments of aluminum separated by stringers of aluminum oxide. The purpose of this work is to examine the biaxial mechanical behavior of extruded powder aluminum at elevated temperature and develop a description of the deformation behavior of the material.

Both powder aluminum and commercial aluminum rod are mechanically tested in simple tension, simple compression, pure torsion, and combined tension-torsion and compression-torsion loadings. Here, the tension-torsion results are of primary interest. Both powder aluminum specimens and specimens made from 1100 commercial aluminum rod are tested so that material property curves from the two materials can be compared to reveal differences in material behavior which are due to the laminar structure of the powder material. The powder aluminum is also examined microscopically and stereological methods are used to give a quantified description of the material behavior in terms of changes in the laminar powder structure. The final description of the powder material's deformation behavior synthesizes both the macroscopic information from the material property curves and the results of the microscopic examination into a more complete description than could be obtained from either source alone.

EXPERIMENTAL PROCEDURES

Tension specimens composed of powder aluminum and 1100 aluminum, with the axis of tension aligned with the extrusion axis, were tested using a system which has previously been described in detail [1]. To summarize, the mechanical testing is performed using a computer controlled MTS biaxial testing machine. A specimen is mounted in the load frame, enclosed in a furnace, and heated to the test temperature, 425°C, with the system in load feedback control. The constant strain rate test is performed in displacement feedback control as the testing machine ram moves to a specified axial displacement and rotation. Load and displacement data for both axial and torsional loadings are stored during the test.

Tested powder aluminum specimens are sectioned parallel, perpendicular, and at 45° to the extrusion axis. The sectioned material is mounted in epoxy using a vacuum impregnation process, polished and etched for metallographic examination [2]. The microscopic structure is examined to determine the relative volume of the separation regions in the powder material using a quantitative stereological technique, the point count [3].

RESULTS

Curves for average shear stress vs average shear strain with varying levels of axial strain are shown below in figures 1 and 2 for biaxial tests of both powder aluminum and 1100 aluminum. The average shear stress at any instant is equal to the torque multiplied by the average radius of the cross-section and divided by the polar moment of area of the cross-section, with all values measured at each increment. The average shear strain is equal to the angle of twist multiplied by the average radius and divided by the specimen length, again with all values recorded at each instant. The powder specimens experienced greater levels of average shear stress than the 1100 aluminum specimens. The most significant difference in behavior is the drop in average shear stress as shear strain increases in powder aluminum specimens with increasing axial elongation. In the 1100 aluminum specimens, at each level of axial elongation, the average shear stress did not drop off with increasing shear strain; rather it remained relatively constant or increased. The stress fluctuations near the end of two of the 1100 aluminum curves are due to the proximity of specimen failure.

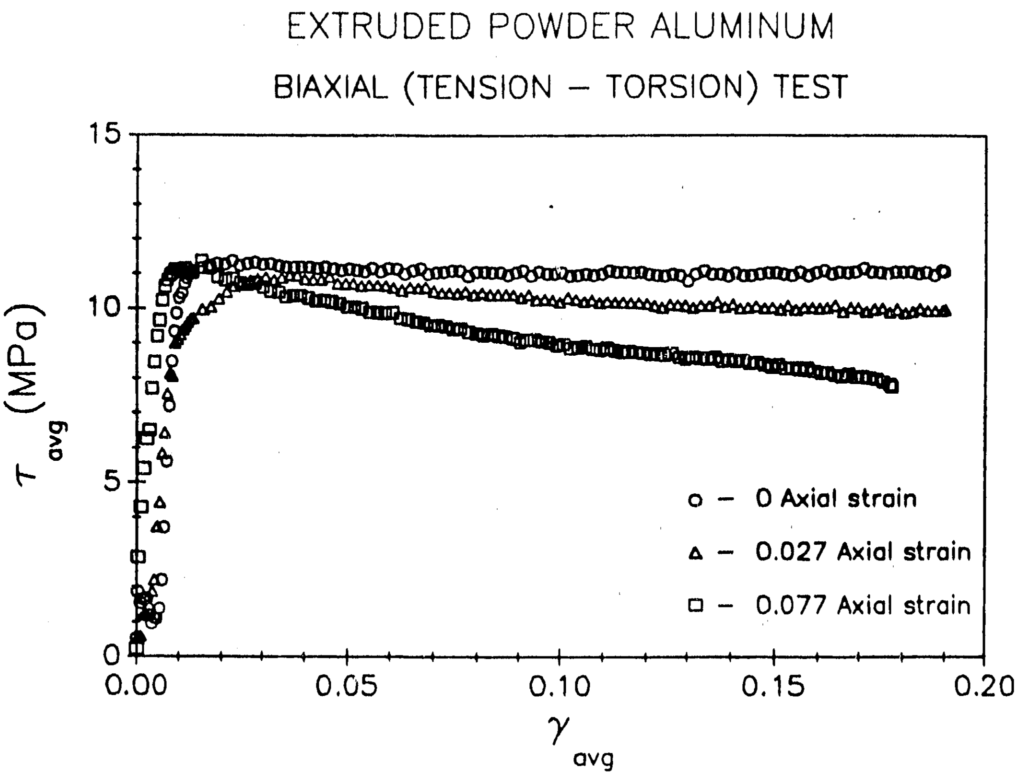

Figure 1. Average shear stress vs average shear strain for various levels of extensional strain in tension-torsion tests of powder aluminum at 425°C.

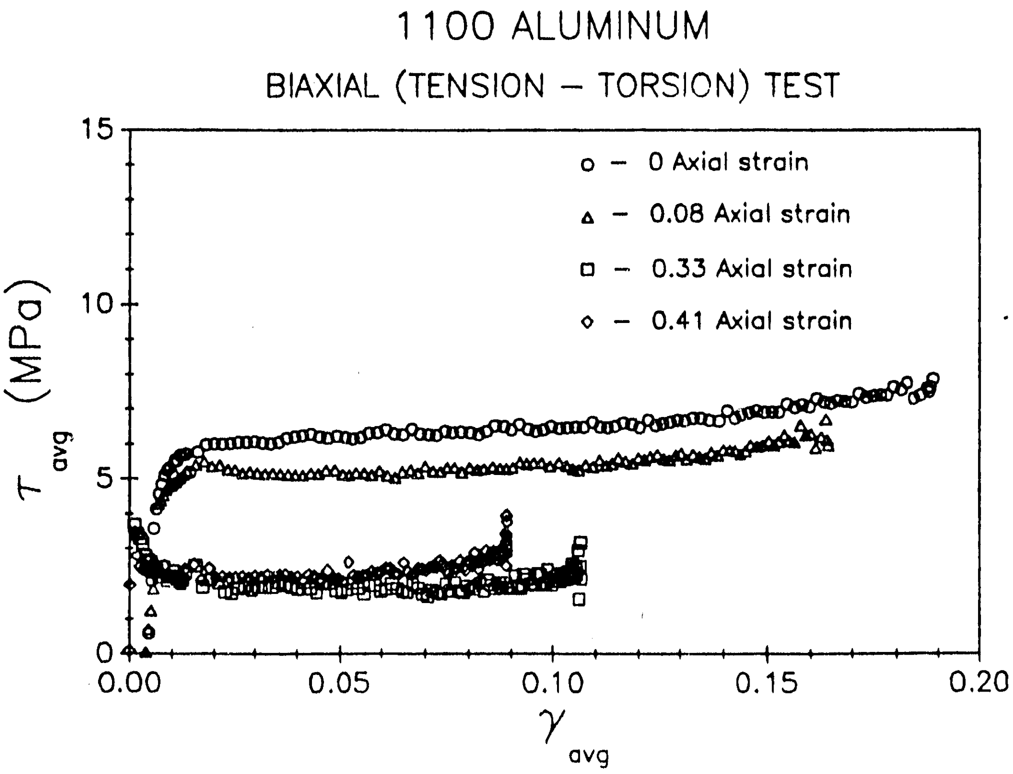

Figure 2. Average shear stress vs average shear strain for various levels of extensional strain in tension-torsion tests of 1100 aluminum at 425°C.

DISCUSSION

Extruded powder aluminum has a laminar structure which consists of ligaments of aluminum (the extruded powder particles) separated by regions containing the aluminum oxide which had coated the precompacted powder particles [4,5,6]. Previous examination of extruded powder aluminum tested in simple tension indicates that the oxide surface on the particles has a central role in determining the material behavior [4]. In this material, the oxide is considered to initially provide a rigid supporting structure which causes the powder aluminum to have a higher ultimate strength than 1100 aluminum. As loading continues, however, the oxide is believed to contribute to the failure of the material by inhibiting adhesion between the ligaments. The particle terminations are also regions of interest because they are locations of discontinuity where loading is shifted between the laminae, resulting in shearing loads and relative motion between the laminae. In the course of a uniaxial tension test, there is a reduction of the internal cross-sectional area which is due to the slipping of the ligaments over each other. At the same time, there is a corresponding decrease in the axial load and in the apparent axial stress (figure 3).

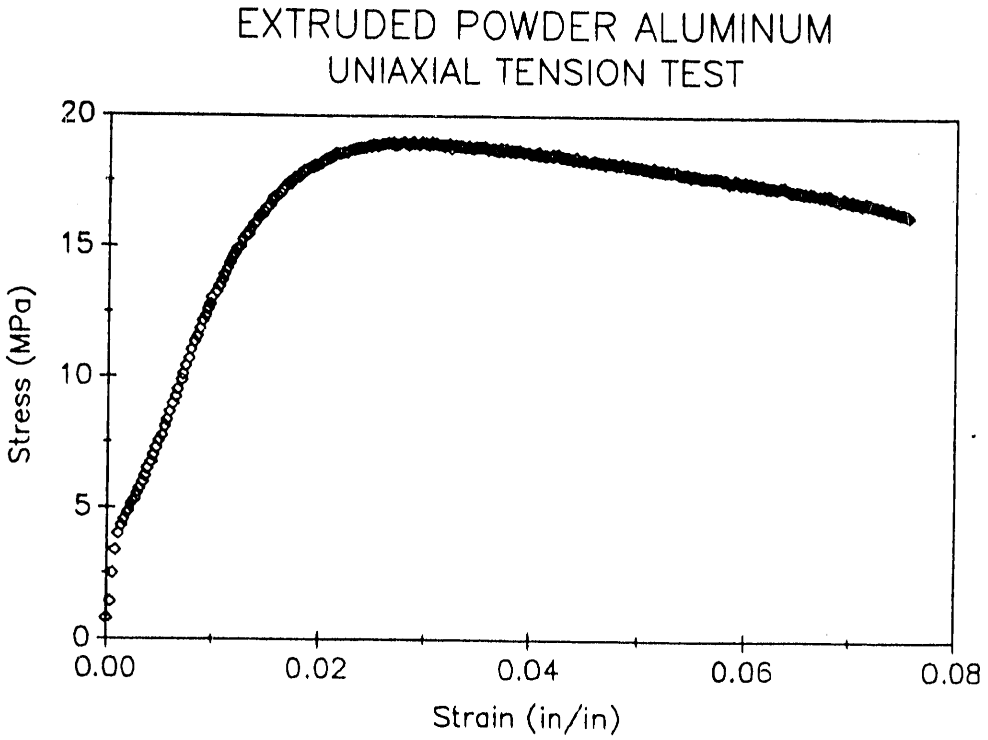

Figure 3. Powder aluminum specimen in uniaxial tension at 425°C.

In pure torsion tests of the powder material, shear stress increases in a linear elastic manner to the yield point, then remains relatively constant in pure-plastic type of behavior. For the biaxial tension-torsion tests, there is an initial linear elastic region up to the yield point. (See figure 1.) Following yielding, the torque (and shear stress) decrease, just as the load decreased in the uniaxial tension tests.

Figure 4 shows a side view of one of the tubular test specimens. The x axis is parallel to the aluminum ligaments, and the y axis is normal to them. The ligaments make an angle of θ with the specimen extrusion axis, which is the axis of tension. Microscopic observation of polished sections of the outer wall of tension-torsion specimens does reveal this skewing of the ligaments.

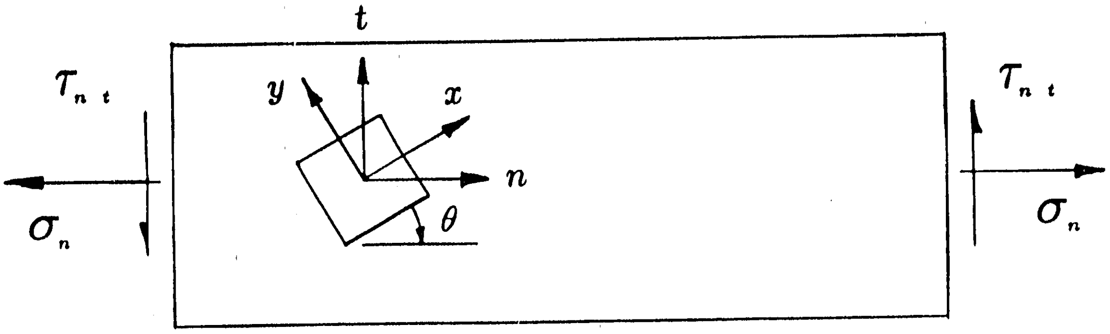

Figure 4. Side view of section of tension-torsion specimen. Extrusion axis and axis of tension-torsion are parallel to the n-axis. Ligaments are oriented parallel to the x-axis.

The relations between the stress components in the two coordinate systems can be observed using the following stress transformation equations.

$$\sigma_n = \sigma_x(1 + 0.5\cos(2\theta)) + \sigma_y(1 - 0.5\cos(2\theta)) + \tau_{xy}\sin(2\theta) \quad (1)$$

$$\tau_{nt} = -0.5\,\sigma_x\sin(2\theta) + 0.5\,\sigma_y\sin(2\theta) + \tau_{xy}\cos(2\theta) \quad (2)$$

It is also instructive to examine these relations using Mohr's circle (figure 5).

The following discussion will consider the biaxial behavior of the powder aluminum (shown in figure 1) in relation to the stresses in the x,y and n,t directions. First notice that there will be a decreasing apparent stress, σ_x, in the direction parallel to the ligaments as is observed in uniaxial tension. This behavior should not be significantly altered by the small transverse compressive stress, σ_y, or by the small shear stress, τ_{xy}. Equation 2 shows that τ_{nt} is affected by σ_x much more than it is by σ_y or τ_{xy}, since both σ_y and τ_{xy} are small. Therefore, the decrease in torque after yielding is produced by this decrease in τ_{nt}, which is greatly influenced by σ_x.

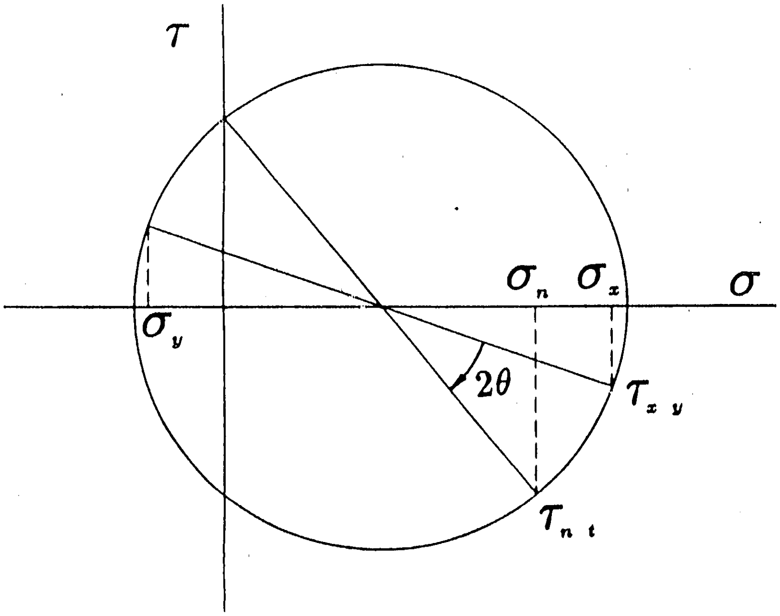

Figure 5. Mohr's circle for tension-torsion test.

For pure torsion, the appropriate Mohr's circle is shown in figure 6. In this case, σ_y is a compressive stress which is equal in magnitude to the tensile stress, σ_x. This relatively large compressive stress can be considered to clamp the ligaments together, inhibiting relative motion, and so lessening the decrease in internal cross-sectional area. The effect is to change the substantially reduced nature of σ_x and make it become a more constant value. The comparatively equal magnitudes and relatively constant values of σ_x, σ_y and τ_{xy} produce a fairly constant τ_{nt} and a relatively constant torque.

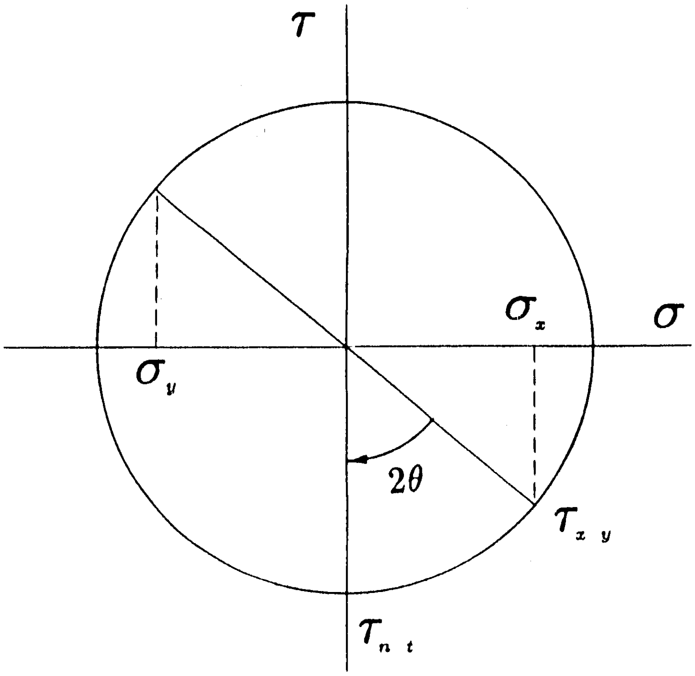

Figure 6. Mohr's circle for pure torsion test.

The following expression relating load and strain in uniaxial tension specimens, including the material behavior of the aluminum ligaments, has been developed [4].

$$P = \sigma_o[A_i + \epsilon_n(A_iC - k) - Ck\epsilon_n^2] \qquad (3)$$

where P = load parallel to the powder aluminum tensile specimen axis

σ_o = yield stress in 1100 aluminum

A_i = initial cross sectional area

ϵ_n = extensional strain along the specimen axis

C = strain hardening constant

k = proportionality constant relating decreasing cross-sectional area to ϵ_n

Now, let $\sigma'_x = P/A_i$, the effective specimen stress parallel to the direction of the ligaments, and with a new constant k_1, equation 3 becomes:

$$\sigma'_x = \sigma_o[1 + (C - k_1)\epsilon_n - Ck_1\epsilon_n^2] \qquad (4)$$

Equations 3 and 4 do not consider the transverse effect which is present with biaxial loadings. The transverse clamping effect due to σ'_y, the effective specimen stress transverse to the direction of the ligaments, is observed experimentally in biaxial tests. It produces a constant stress when the clamping force equals the extensional force in the x direction or when the magnitudes of the compressive and tensile stresses are equal, as is the case in the pure shear torsional loading. This effect is illustrated in figure 7, which shows the forces and stresses acting parallel and perpendicular to the ligaments in an element (enlarged from figure 4.) This behavior may be described by:

$$\sigma'_x = \sigma_o[1 + (C - k_1)\{(\sigma'_{ym} - \sigma'_y)/\sigma'_{ym}\}\epsilon_n$$
$$- Ck_1\{(\sigma'_{ym} - \sigma'_y)/\sigma'_{ym}\}\epsilon_n^2 \qquad (5)$$

where σ'_{ym} is the maximum effective specimen stress transverse to the ligament direction in pure torsion, σ'_y is the effective specimen stress transverse to the direction of the ligaments in the current test, and $C = 0$ for no strain hardening.

Figure 8 shows normal stress in the ligaments as a function of axial strain. The dotted curve is a fit of equation (5) in the post yield region with σ_o = 15 MPa, C = 0.94, k_1 = 1.76, and σ_{ym} = -4.0 MPa. The graph shows that equation (5), the model for behavior in the post yield region which includes information about the material behavior of 1100 aluminum in tension, the stereologically quantified microscopic behavior of extruded powder aluminum in tension, and the effects of the stress transverse to the ligaments, provides an adequate fit to the biaxial data in the post yield region.

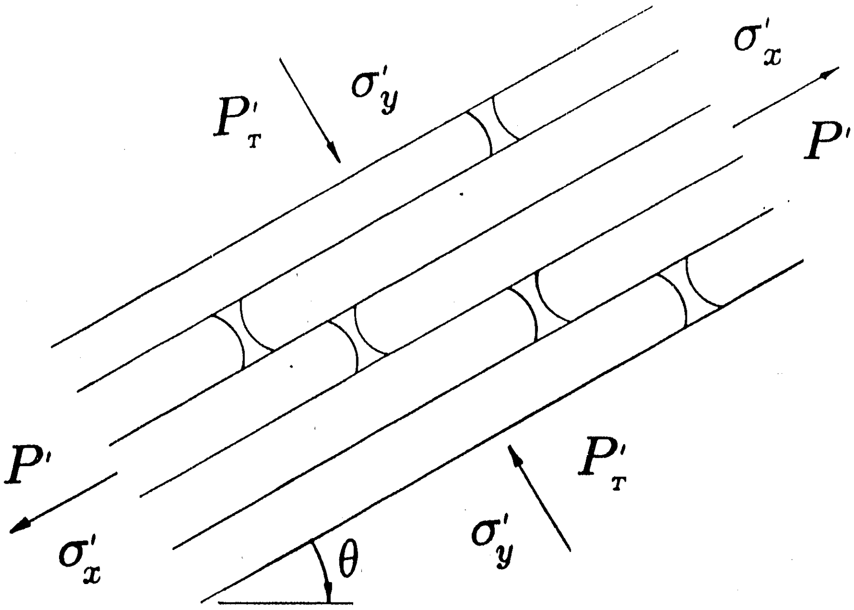

Figure 7. Forces and stresses acting on ligaments in an element enlarged from figure 4. σ'_x and σ'_y are the effective specimen stresses parallel and transverse to the direction of the ligaments, respectively. P' and P'_T are the effective specimen loads parallel and transverse to the ligaments.

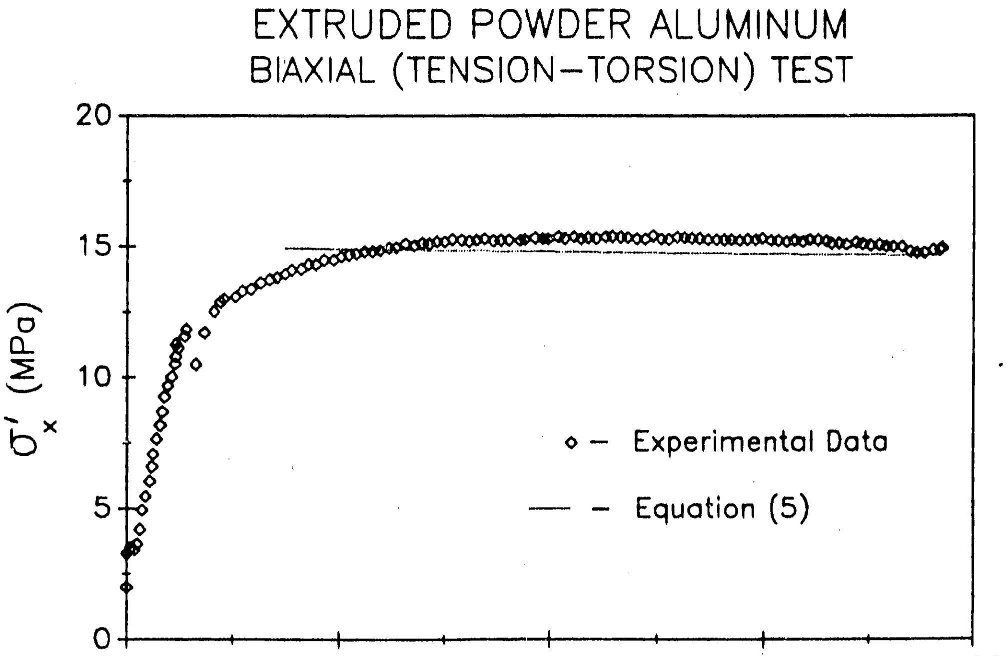

Figure 8. A comparison of experimental data and equation (5) in the post yield region for normal stress along the ligament axis vs axial strain along the specimen axis for a biaxial test of extruded powder aluminum with 0.18 maximum average shear strain at 425°C.

CONCLUSIONS

This paper describes the present state of an ongoing investigation of the high temperature biaxial behavior of extruded powder aluminum. The current description of tension-torsion biaxial material behavior has been developed from both macroscopic (stress-strain) data, and from observations of the microscopic structure of the material. Continuing efforts will be directed towards developing a more quantified mathematical model of this behavior.

ACKNOWLEDGEMENTS

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