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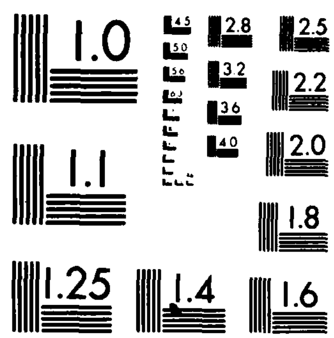

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ON THE INFLUENCE OF STRAIN-PATH CHANGES ON FRACTURE

S. C. KESTNER AND D. A. KOSS

DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING
THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK, PA 16802

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S. C. Kestner and D. A. Koss
Department of Materials Science and Engineering
The Pennsylvania State University
University Park, PA 16802

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ABSTRACT

Abrupt changes in strain path between uniaxial and equibiaxial tension are shown to have a large effect on plane-strain ductility. Data for titanium sheets, both with and without hydrides, show that a significant ductility enhancement occurs at a final strain state of plane-strain tension following multi-stage deformation sequences comprised of uniaxial and equibiaxial tension. While the dependence of ductile fracture on both accumulated damage and strain hardening suggests that failure strains should be sensitive to a nonproportional strain-path history, the detailed cause(s) of the present effect is not known.

I. INTRODUCTION

The influence of strain-path changes on the flow behavior of metals, especially with regard to strain-hardening transients, has been the subject of several recent studies[1-7]. These transients can in turn have several effects on the subsequent flow behavior; for example, recently published finite element modeling indicates that the transients can influence strain localization behavior at strains well beyond the transient region[8]. Thus, formability of sheets can be affected significantly even by strain-path changes at comparatively small strains.

In contrast to the above, the effect of strain-path changes on ductile fracture [wherein failure is a result of void nucleation, growth, and linking] has not been examined in detail. It is very likely that the macroscopic strain localization phenomena examined in the formability studies will translate to microscopic flow localization effects influencing the fracture process. In addition, studies based on proportional loading clearly show that the fracture strain for a ductile, microvoid fracture process is a function of both stress state and strain-path (for example, see ref's. 9-11). Thus, it would be reasonable to expect that ductile fracture should be a function of strain-path history. The purpose of this communication is to present unique data which indicate that ductile fracture, at least in certain cases, is strongly dependent on changes in strain-paths imposed prior to failure. In particular, a multi-stage deformation sequence involving uniaxial and equibiaxial tension can result in a significant ductility enhancement when compared to that achieved by proportional straining ($\rho = d\epsilon_2/d\epsilon_1$ = constant, where ϵ_1 and ϵ_2 are the major and minor principal strains in the plane of the sheet) to the same final strain state. The effect occurs regardless of whether void nucleation is difficult (pure Ti), or relatively easy (a Ti-H alloy in which hydrides provide sites for void nucleation). It should be noted that the ductile, microvoid fracture behavior of Ti and Ti-H alloys has been characterized for proportional loading over a range of stress states.[10] The results presented here are a part of and consistent with more extensive data to be presented later.

II. EXPERIMENTAL PROCEDURE

Inclusion-free, commercially pure Ti sheet (1.0 mm thick) with a grain size of .016 mm and containing 0.196 wt% oxygen was used for this study. The material was tested in an annealed condition (700°C/1 hr at 4×10^{-3}Pa) and after thermally charging with hydrogen, also at 700°C for 1 hr, and helium-gas quenching. Thus, material containing two levels of hydrogen was tested: (a) Ti-30 wt ppm H, and (b) Ti-650 wt ppm H. In the latter case, both inter- and intragranular titanium hydrides are present.[12]

The fracture behavior of the sheets was examined using experiments performed by (a) proportional straining ($\rho = d\varepsilon_2/d\varepsilon_1$ = constant) and (b) non-proportional straining using a multi-stage strain path. All tests were performed at room temperature at an engineering strain rate of $2x10^{-3}$ s^{-1}. Three proportional strain paths were examined: (1) uniaxial tension, (2) plane-strain tension, and (3) equibiaxial tension. The plane-strain specimen configuration is a reduced-scale modification of the Wagoner in-plane test specimen[13,14], while punch-stretch testing was used to obtain equibiaxial tension. Two multi-stage strain paths have been investigated: (1) a pre-strain stage of uniaxial tension (prestrain) followed by equibiaxial tension, and (2) equibiaxial tension (pre-strain) and subsequently uniaxial tension. In the latter case, uniaxial tension was achieved by punch-stretch testing a thin strip cut from the dome of the prestrained equibiaxial specimen. Details of the experimental procedure are contained elsewhere[12].

In all cases, local measurements of strain were made using either square grids (0.508 mm) or circle grids (1.27 mm). The data presented is based on determinations of ε_1 and ε_2 across the fracture surfaces based on the grid displacements and assuming pure homogeneous deformation with respect to the grid element. These data were consistent with measurements of ε_2 and ε_3 (from specimen thickness at the fracture surface) and subsequent calculation of ε_1 from conservation of volume. In the multi-stage testing, grids were re-applied for the second stage of the deformation operation; the sum of these strain data were consistent with final strains as measured from the original grids, which were retained on one side of the specimen.

It should be noted that the Ti sheet is plastically anisotropic. The plastic anisotropy ratios, R and P, were determined to be 1.7 and 4.0 in the Ti-30H sheet and 1.6 and 3.0, respectively, in the Ti-650H. The terms R and P are defined as the ratio of width strain to thickness strain for specimens either parallel (R) or transverse (P) to the rolling direction.

III. RESULTS AND DISCUSSION

A comparison of the fracture strains after both proportional and non-proportional straining is shown in Figures 1 and 2. These figures show the major and minor principal strains in the plane of the sheet (ε_1 and ε_2, respectively) both after the pre-strain stage and after fracture. Since the pre-strains resulted in nearly uniform deformation of very reproducible magnitude, these data are indicated with a single data point. The fracture strain data, especially when measured on a local scale, show considerably more scatter. In both Figs. 1 and 2, a final strain state of plane-strain tension may be obtained by either (a) proportional straining, (b) a nonproportional path of uniaxial -> equibiaxial tension, or (c) equibiaxial -> uniaxial tensile path. As is obvious from Figs. 1 and 2, both of the two nonproportional paths result in significant <u>increases</u> in fracture strain at a final strain state of roughly plane-strain tension. The magnitude of the ductility enhancement is sensitive to the strain-path sequence, being more pronounced for the combination of equibiaxial → uniaxial tension than for uniaxial prestrain followed by equibiaxial tension. The magnitude of the increase is also sensitive to the presence of hydrides, being smaller in the Ti-650H material in which hydrides are present.

The above results, which are unique, are not a result of localized necking on a macroscopic scale. Careful examination of the profiles of the fracture surfaces do not show any evidence of localized necking prior to failure. Furthermore, the ductility enhancement does not depend on how the fracture strain is measured. Indirect measurements of ε_1 from width ε_2 and thickness ε_3 strains at the fracture surface provide the same trends as those in Figs. 1 and 2, which are based on direct measurements of ε_1 and ε_2. Since fractography indicates ductile, microvoid fracture, we conclude that the data clearly indicate that the microvoid fracture process is sensitive to the multi-stage deformation history which preceeds failure.

Our present knowledge of a ductile fracture process, which involves void formation, void growth, and void linking suggests that it should be sensitive to non-proportional straining. For example, several studies have shown that strain-induced void formation, such as by the fracture of hydrides in the Ti-650H material, is sensitive to stress state. Specifically, the strain to nucleate voids should decrease as the magnitude of the maximum principal stress[10] or the hydrostatic stress imposed by the external stress[15] increases. Void nucleation may also be influenced by the strain path as a result of the local internal stresses caused by incompatabilities of strain between the matrix and particles. Such incompatibilities are a major source of local stresses which act either to fracture particles, such as hydrides, or to cause matrix-particle decohesion[10]. It is well known that void growth is sensitive to strain-path, increasing rapidly with an increase in the hydrostatic stress[16]. The sensitivity of void linking to stress state/strain path is not well understood, but both experiment[10] and theory[17] indicate plane-strain and equibiaxial tension to be especially effective in triggering instabilities which cause void link-up. As a result, void linking is triggered at much smaller void densities in equibiaxial tension than in uniaxial tension. Thus, we conclude that, on a damage basis, ductile fracture may be sensitive to strain path. Specifically the above implies that if the fracture strains resulting from multi-stage strain paths are compared, the strain path with the higher degree of stress biaxiality (or triaxiality) in the second stage of straining will exhibit less ductility.

While the above pertains to the accumulated strain-induced damage, strain-path induced changes of strain hardening (or strain-rate hardening) can also influence macroscopic strain localization[8] and, we expect, microscopic fracture strains as well. The effect should depend on the sign and magnitude of the strain-hardening transient following a strain-path change. For a significant enhancement of the fracture strain due to a strain hardening transient, that transient should exhibit a lowered flow stress accompanied by rapid work hardening. Unfortunately there is no appropriate data for Ti or Ti-H alloys which would indicate the strain hardening behavior following an abrupt change in strain path.

On the basis of both damage and strain-hardening considerations, it is not surprising that non-proportional, multi-stage tensile deformation has a significant effect on the total strain to fracture. What is surprising is the relatively large magnitude of the effect, especially in the Ti-30H material, and the fact that it is a ductility enhancement. At this time, we do not have a complete explanation for the above effect. From a damage standpoint, one contributing factor may be the large maximum principal stress associated with plane-strain deformation* in this plastically anisotropic sheet. By using

* $\sigma_1 = 1.4\bar{\sigma}$ for plane strain as compared to $\sigma_1 = 1.0\,\bar{\sigma}$ in uniaxial tension, assuming the Hill criterion for yielding.[18]

multi-stage uniaxial and equibiaxial paths to achieve a final strain state of plane strain, the material avoids being subjected to the large σ_1 associated with plane-strain tensions. This should delay void nucleation and contribute to enhancing ductility, as is observed. However, the magnitude of the effect suggests that other factors are also important. The importance of strain-hardening transients is recognized, but we have neither the appropriate data nor an analysis to predict the effect.

Finally, we wish to make a short comment on the relative <u>sequence</u> of the uniaxial/equibiaxial prestrains and the magnitude of the final fracture strain; compare uniaxial → equibiaxial data to those from equibiaxial → uniaxial in Figs. 1 and 2. As discussed, void growth and linking are accelerated by triaxial states of stress. This implies that, given the same density of voids after two different pre-strain operations, the subsequent strain increment should be greater for the path of lower stress triaxiality. Thus, at a given level of voiding or damage, failure should occur more quickly if equibiaxial tension follows, rather than precedes, uniaxial tension. This appears to be consistent with present data. Figs. 1 and 2 show a larger strain to fracture for the equibiaxial -> uniaxial tension path than that of the uniaxial -> equibiaxial counterpart.

IV. SUMMARY

The present data indicate that ductile, microvoid fracture depends on nonproportional strain-path history. In particular, a combination of uniaxial and equibiaxial tension can result in a significant ductility <u>enhancement</u> at a final strain state of plane-strain tension. The ductility enhancement occurs for Ti either with or without void-nucleating hydides. The effect is most pronounced for material without hydrides (Ti-30H) when subjected to a sequence of equibiaxial prestrain followed by uniaxial strain path to failure. Although we expect the total fracture strain to depend to strain path, we do not have a complete explanation for the above effects. One contributng factor may be a delay of void nucleation during multi-stage straining by using strain paths characterized by small maximum principal stresses.

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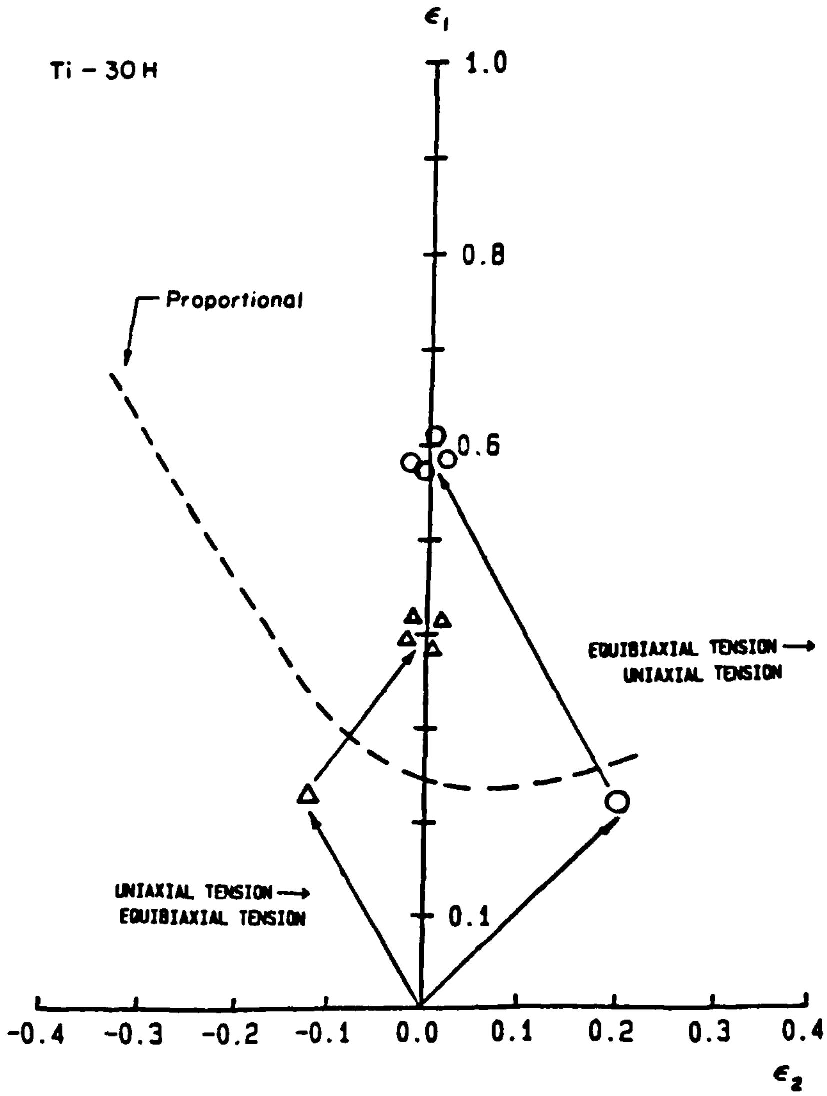
Fig. 1. The influence of strain path on the major and minor principal strains at fracture of titanium sheet containing 30 wt ppm H.

Fig. 2. The influence of strain path on the major and minor principal strains at fracture of titanium sheet containing 650 wt ppm H.



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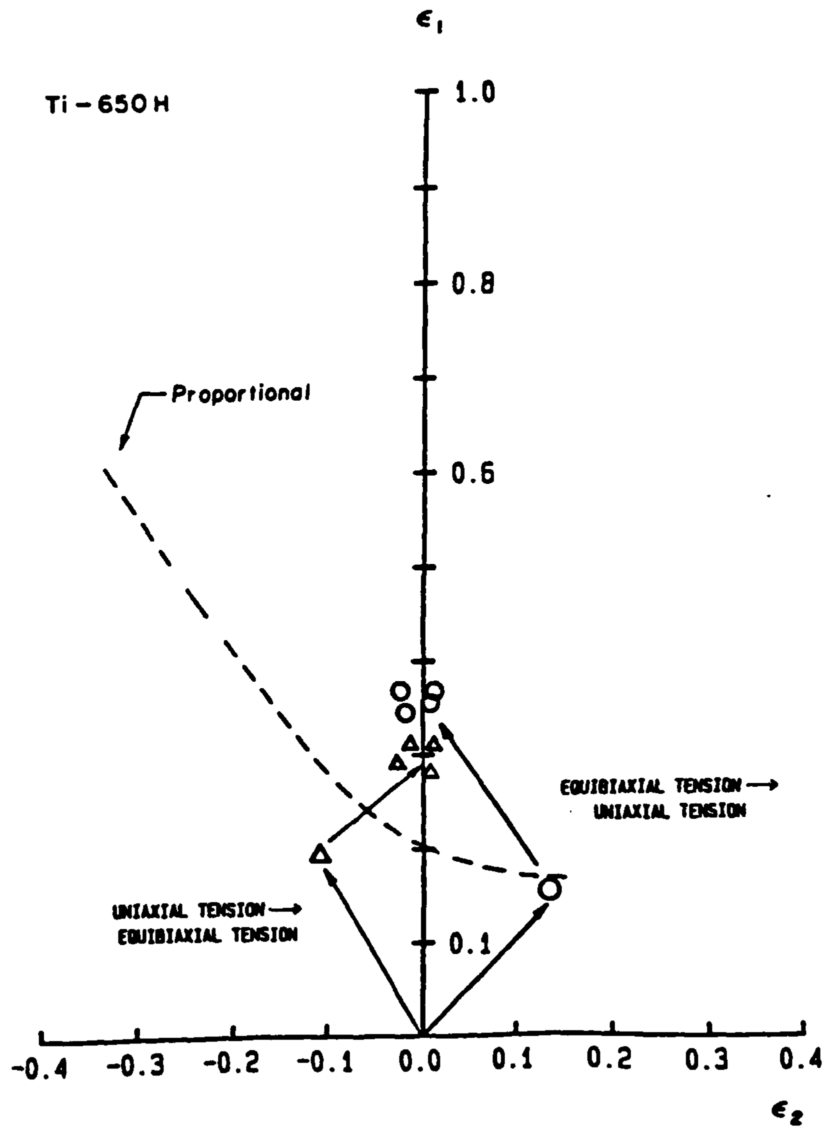

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