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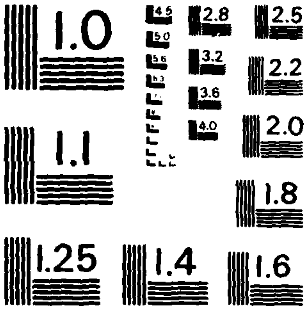

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DEFORMATION AND FRACTURE OF P/M TITANIUM ALLOYS

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20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Progress is reviewed for a research program which is examining selected processing-microstructure-property relationships which limit the mechanical properties of P/M Ti alloys in particular and aspects of ductile fracture in general. The approach is quite broad and ranges from experimental and analytical studies of the effect of porosity on the fracture of engineering alloys to be an experimental examination of the hot isostatic pressing of metallic powders. Progress for the period 10/1/82 - 9/30/83 is reviewed for the following aspects of this research program:

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1) the tensile deformation and fracture of alloys containing porosity; experiment and modeling of P/M titanium alloys,

2) the influence of strain-rate on the flow and fracture behavior of titanium and nickel containing porosity,

3) a modeling study of the influence of void distributions on the mechanism of ductile fracture.

4) hot isostatic pressing of metallic powders

and 5) the influence of plastic anisotropy on the hydrogen embrittlement of titanium under multiaxial states of stress.

Introduction

Titanium base alloys are used extensively in applications which require high strength, good fracture resistance, and low weight. Understanding the deformation and fracture behavior is thus essential not only for an accurate prediction of in-service behavior but also as a basis for improving properties. However, the limiting factor in utilizing Ti alloys is very often not their properties but rather their high cost. This is especially the case for parts of complex shapes in which a large amount of starting material is required to produce a finished part. In these cases, powder metallurgy (P/M) as well as casting techniques are becoming attractive, alternate methods of producing Ti alloys to near-net shape, thus reducing costs. However, inherent in these processing methods is the problem that the resultant alloy may contain defects, notably porosity or inclusions, not normally present in cast and wrought Ti alloys [1-3]. These defects can seriously limit the properties which otherwise can be obtained in Ti alloys.

The primary goal of the present research program is twofold: (1) to examine selected processing-microstructure-property relationships which limit the mechanical properties of P/M Ti alloys, and (2) to extend our fundamental understanding of aspects of mechanical behavior, such as ductile fracture, which control the failure of high strength structural alloys in general. As such, the approach is quite broad and ranges from experimental and analytical studies of the effect of porosity on the fracture of engineering alloys to an experimental examination of the hot isostatic pressing of metallic powders. Substantial progress has been achieved in this research program during the period Oct. 1, 1982 to Sept. 30, 1983 in the following areas:

1) the tensile deformation and fracture of alloys containing porosity: experiment and modeling of P/M titanium alloys,
2) the influence of strain-rate on the flow and fracture behavior of titanium and nickel containing porosity,
3) a modeling study of the influence of void distributions on the mechanism of ductile fracture
4) hot isostatic pressing of metallic powders

and 5) the influence of plastic anisotropy on the hydrogen embrittlement of titanium under multiaxial states of stress.

A significant aspect of this program is the educational experience it provides to the graduate students involved. In the past fiscal year the program has supported: Roy Bourcier, Ph.D., August 1983; Barbara Lograsso, Ph.D. candidate (M.S., November 1982), Paul Magnusen, Ellen Dubensky, Dale Gerard, and Susan Kestner (all of whom are M.S. candidates).

The Tensile Deformation and Fracture of Alloys Containing Porosity: Experiment and Analysis of P/M Titanium Alloys

[with R. J. Bourcier, Ph.D., R. E. Smelser (U.S. Steel Corp.), and O. Richmond (Alcoa)]

Ductile fracture in engineering alloys is usually the result of the nucleation, growth and link-up of voids or cavities. In fully dense materials, voids are formed during straining, usually by the decohesion or fracture of large inclusions or precipitates (for a review, see Goods and Brown [4]). However, void nucleation in most alloys often begins early in the deformation process, and the fracture behavior of many alloys is thus controlled by void growth and void link-up. Furthermore, many technologically important materials contain pre-existing porosity, such as may be present in castings and powder metallurgy (P/M) consolidated alloys.

The influence of porosity on yielding, plastic flow and instability/ fracture has been studied extensively on experimental bases (for example, see refs. 5-12) with physical models [13-15] and with mathematical models (for example, see refs. 16-21). A limitation of previous studies is that little critical comparison has been made between the models and observed material behavior. The result is that the validity of the modeling techniques remains unproven, and no basis exists to suggest modifications or improvements. The purpose of this study is not only to characterize the parameters which control the deformation and fracture of porous or cavitating alloys but also to relate these data to existing theory. The present research thus examines the effects of pre-existing porosity on the deformation and fracture of high strength engineering alloys in general and of two P/M Ti alloys in particular.

The study is based on the contrasting deformation and fracture behavior of two Ti alloys, commercially pure (CP) Ti and Ti-6Al-4V, which possess considerably different strain hardening characteristics and which have been consolidated via P/M techniques to similar levels of rounded porosity (CP Ti containing 0.3, 4.5, and 7.8% porosity and the Ti-6Al-4V containing 0.1, 0.8, and 3.5% porosity). An examination of the stress-strain response in uniaxial tension and, to a limited extent, in plane strain tension shows that the yield strength and ductility of both alloys decrease rapidly with increasing porosity level.

The yielding and flow behavior has been modeled using a large strain finite element (FE) analysis and a continuum imperfection analysis for porous materials. The FE model is in reasonable agreement with the measured values of void growth but underestimates the observed degradation of strength with increasing porosity level. In large part, this appears to be due to the excessive stiffness of the "microcell" model used (especially in the inability to develop shear instabilities) and the presence of a network of imperfections within the material due to random nature of the pore distribution.

In a unique approach to examining the influence of porosity on the ductility of P/M alloys, the continuum imperfection model Saje, Pan and Needleman [22] has been used to analyze measured values of tensile ductility. The imperfections consist of planes of weakness containing a higher than bulk density of pores. Direct evidence for the presence such planes is the observation that the amount of porosity on the fracture surface is about ten times that in the bulk. This ratio may be taken as an upper limit estimate to the imperfection size; a lower limit estimate may be obtained from the ratio of yield strengths in the porous and fully dense materials. Although the imperfection theory used is limited by simplifying assumptions, it is in reasonable agreement with experimental observations at porosity levels of greater than 1-2% as is shown in Fig. 1. Agreement below these levels is precluded by the absence of a failure criterion for a fully dense material which therefore contains no imperfections. Finally it should also be noted that the analysis also predicts a stabilizing influence of strain hardening on flow localization and failure in porous materials. For example, at 4% porosity, increasing the strain rate hardening exponent by a factor of 2½ would increase tensile ductility by a factor of about 3.

<u>The Influence of Strain-Rate on the Flow and Fracture Behavior of Titanium and Nickel Containing Porosity</u> [with Paul Magnusen, M.S. Candidate and Paul Follansbee, Los Alamos National Laboratory]

At high strain-rates, the kinetics of void formation can be a controlling factor in determining the degree to which ductility is affected by strain rate [23]. However, the strain to failure depends not only on the rate of void

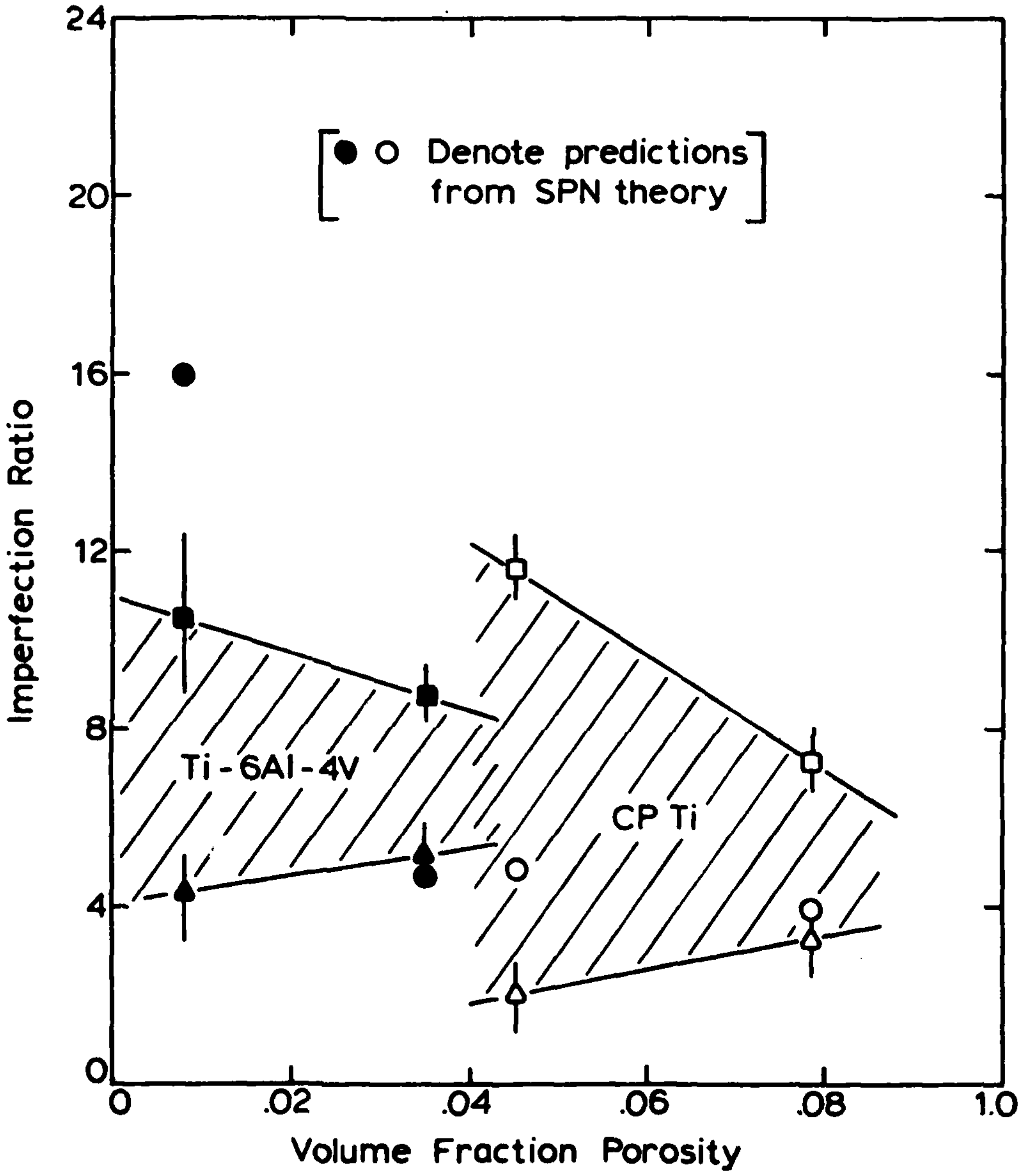

Fig. 1. The dependence of the imperfection ratio, which is defined as the ratio of the upper or lower limit of imperfection size to bulk porosity level, on the volume fraction of porosity. The calculated values of the imperfection ratio based on the SPN analysis [22] and observed fracture strains are also included.

formation but also on the rate of void growth and ease of void link-up. An adequate separation of these processes must be made before the influence of strain rate on ductile fracture can be understood. In an effort to understand more fully influence of strain rate on fracture, as well as failure of porous alloys, the tensile behavior over a wide range of strain-rates is being studied in two materials which contain pre-existing porosity and which possess widely different strain hardening characteristics. The materials are commercially pure Ti, whose flow stress is sensitive to strain-rate [24] and temperature [25], and whose strain hardening exponent ($n=d\ln\sigma/d\ln\varepsilon$) is about 0.15, and pure Ni whose flow stress is comparatively insensitive to temperature and strain-rate ($\dot{\varepsilon}\leq 10^2 s^{-1}$) and whose strain hardening exponent is about 0.40, or nearly three times that of Ti. The range of strain-rates employed in this study range from $10^{-4} s^{-1}$ to $10^2 s^{-1}$.

To date, results have been obtained for CP Ti containing rounded porosity at four densities: 99.9, 98.5, 96.0, and 93.3% of theoretical density. Results on the nearly fully dense material confirm that the flow stress of Ti is sensitive to the strain-rate: $m=d\ln\sigma/d\ln\dot{\varepsilon}=0.0165$ from 10^{-4} to $10^2 s^{-1}$. The most significant of the current results are shown in Fig. 2 in which the effect of strain-rate on ductility of the Ti is shown in terms (a) the maximum principal fracture strain $(\varepsilon_f)_{local}$ as measured locally at the fracture surface and (b) the total strain to fracture $(\varepsilon_f)_{total}$ as measured over the specimen gauge section. Regardless of which fracture strain parameter is considered, Fig. 2 shows that: there is no major effect of strain-rate on the ductility of Ti at any of the four levels of porosity; this includes the 0.1% porous material whose flow and fracture behavior appear to be controlled by the matrix properties. There does appear a minor effect at low levels of porosity near full density (see Fig. 2) in which case the ductility shows a weak minimum at intermediate strain-rates of $\sim 1\ s^{-1}$.

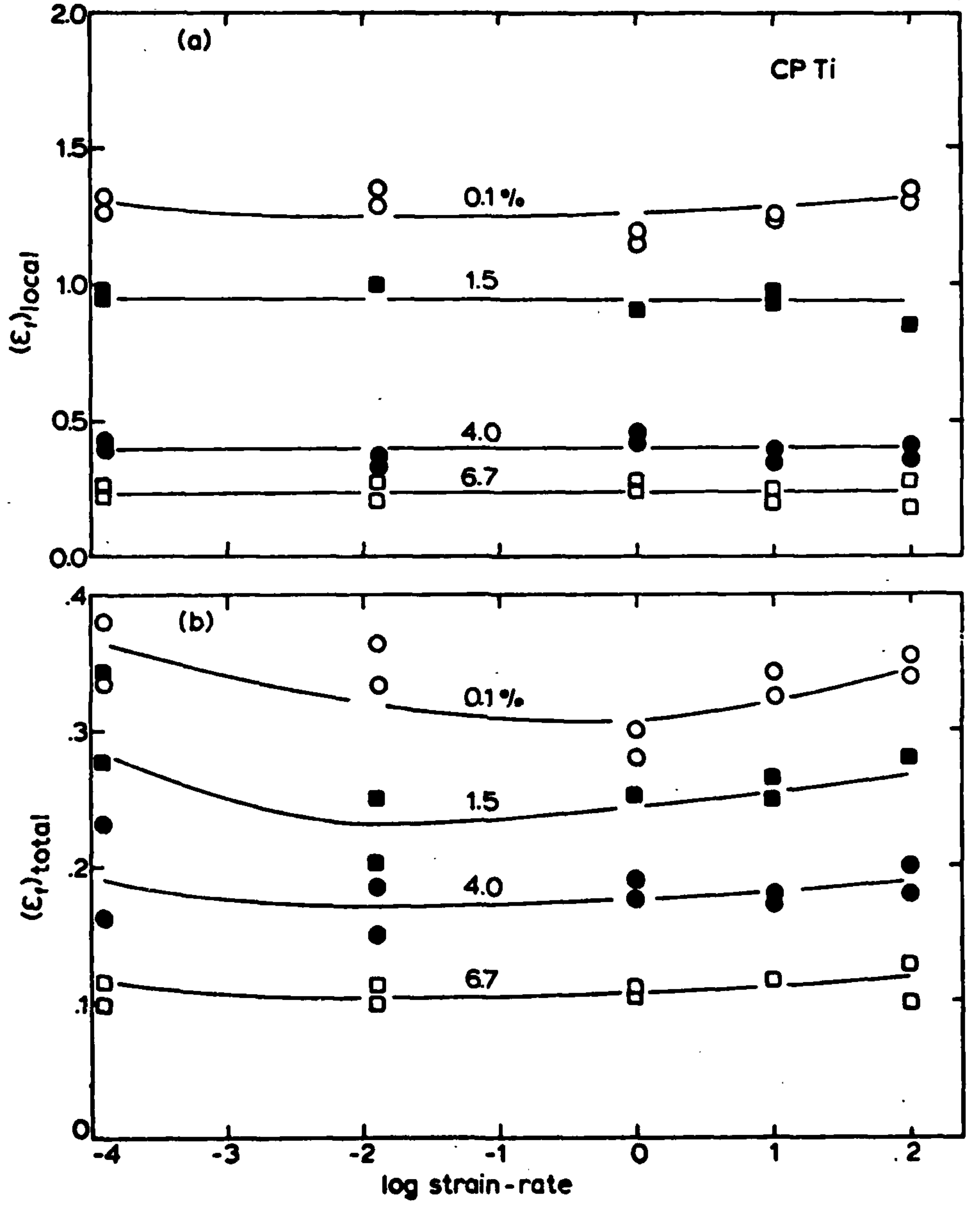

Fig. 2. The influence of strain-rate on the fracture strain as measured (a) locally at the fracture surface and (b) over the total length of the gauge length of the tensile specimen. Date is for commercially pure titanium at room temperature.

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These results suggests several related conclusions: (1) in fully dense Ti void nucleation, void growth and link-up are not strongly affected by absolute strain-rate, at least up to $10^{+2} s^{-1}$, (2) in Ti containing pre-existing porosity, tensile ductility is independent of strain-rate at least to rates of $10^{2} s^{-1}$, and (3) if, as previously concluded, imperfections in pore distribution control ductility in alloys containing porosity, then the resultant flow localization process is not sensitive to the absolute imposed strain-rate (although it should be sensitive to the strain rate hardening of the material). The above conclusions are tentative and will require verification by experiments involving Ni containing porosity.

A Modeling Study of the Influence of Void Distributions on the Mechanism of Ductile Fracture [with Ellen Dubensky, M.S. candidate]

Ductile fracture in fully dense engineering alloys usually involves the sequential processes of void nucleation, void growth, and void link-up. The latter two stages have been analyzed in terms of continuum plasticity but under the assumption that the voids are distributed in a periodic manner [16, 17, 26, 27]. Our previous study of the influence of porosity on the deformation and fracture of Ti alloys clearly shows that it is the random, non-periodic distribution of pores/voids which controls ductile fracture in these alloys. The purpose of this study is to model experimentally the influence of void/pore distributions on ductile fracture. The only previous study concerning fracture in a material with a random distribution of voids is a theoretical analysis developed by Melander [28] who used computer simulation to apply his theory to two arrays of voids; no experimental verification was attempted. Thus the present study is the first aimed at developing a sound experimental basis for the theory of ductile fracture as influenced by void distribution.

In the present study, void distributions are modeled in two dimensions as arrays of holes whose positions are predicted by a random-number generator in an appropriate computer program. Initially, the experiments are being conducted on arrays of equi-sized holes in which the (a) area fraction of holes, (b) size of the holes and (c) spacing of the holes is controlled. Figure 3 shows three examples of hole distributions in which the area fraction and hole size are fixed but the minimum separation between adjacent holes is allowed to vary, being the largest in Fig. 3c in which case the hole spacing is most uniform [note that the holes are being drilled in a computer-controlled milling machine.]. The study is based on two materials (1100 Al and 7075 Al) of differing work hardening rates which are tested under conditions of plane stress vs. plane strain: (a) 1100-TO Al in the form of 1mm sheet (plane stress deformation), (b) 7075-T6 Al also as 1mm sheet and (c) 7075-T6 Al plate (∿6 mm thick) in which deformation between the holes is predominantly plane strain. Preliminary tests for one hole array show that the fracture path is sensitive to work hardening/state of stress and differs among the three above conditions.

Hot Isostatic Pressing of Metallic Powders [with Barbara Lograsso, Ph.D. candidate]

The use of hot isostatic pressing (HIP) to compact both powders and castings to full density has been a commercial practice for more than a decade. Over that time period, the pressure-time-temperature conditions required to achieve a fully dense material have been developed by each industrial user on an empirical basis. While expedient to the industrial engineer, such an approach hardly is the basis for the efficient utilization of HIP to

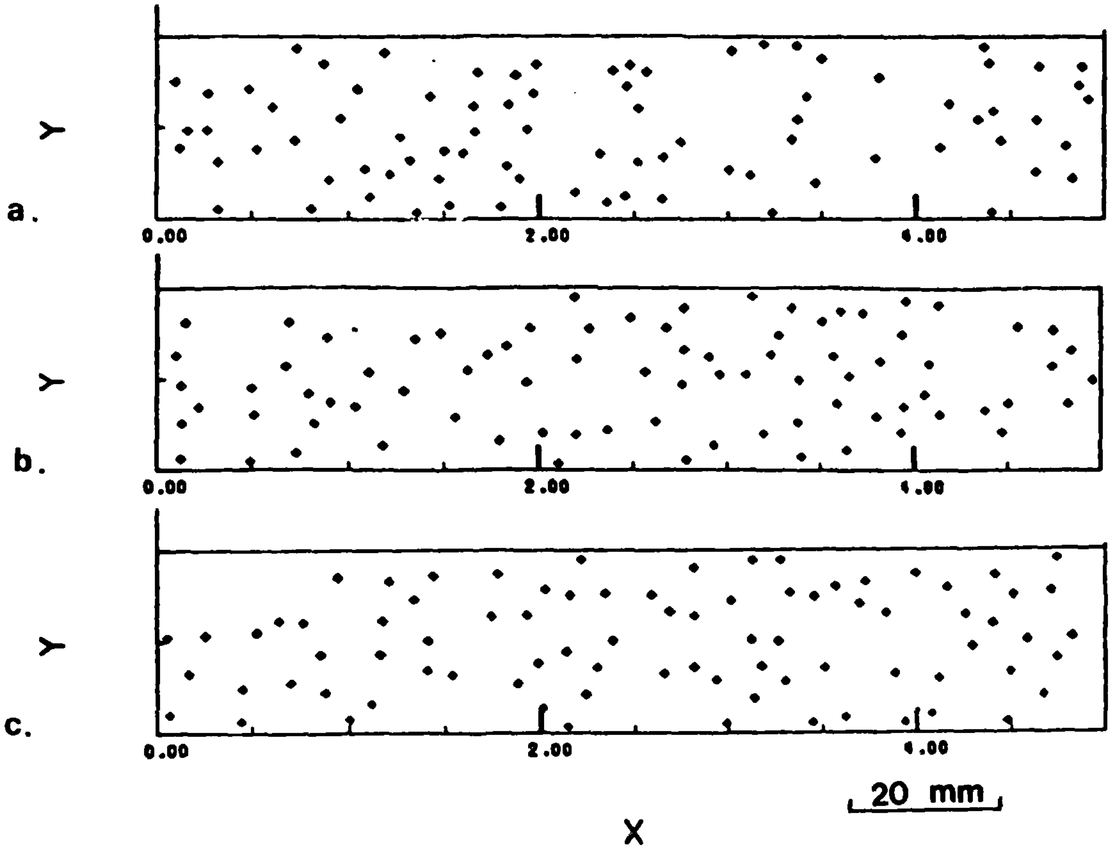

Fig. 3 Examples of positions of arrays of holes in which the minimum spacing between holes is varied from (a) 0.5 mm, (b) 1.0 mm and (c) 1.5 mm. The condition shown is for a tensile specimen containing 82 holes each with a diameter of 1.6 mm, which is equivalent to an area fraction holes of 5%.

new and different conditions. In a study unique to HIP, this program seeks to establish the pressure-time-temperature relationships which control the HIP process for well characterized metallic powders. The results of this study will serve as an experimental basis to test and extend the recent theory of Arzt, Ashby, and Easterling [29] which proposes the construction of "HIP maps". To date, nearly all alloy data available for such maps is for metals compacted to 99+% of theoretical density; there is no data over the range of densities of 70-99% required to establish the controlling mechanisms.

The present program utilizes an ASEA Pressure Systems Mini-HIPper which to our knowledge is the only HIP unit operational at this time in a U.S. university. The study is based on the contrasting behavior of both spherical and irregular powders of controlled sizes and on alloys which readily dissolve their oxides (Ti and its alloys) and those which do not (Ni, stainless steel). Preliminary efforts have focused on simple but reliable means of canning specimens in a material sufficiently soft so as not to interfere in low temperature (650°-900°C) compaction. Techniques for the compaction of specimens wrapped in Ta foil and compacted in Cu cans have been developed. Initial efforts will focus on: (a) spherical Ti powders (plasma rotating electrode process-PREP), (b) irregular Ti powders (hydride de-hydride), (c) spherical Ti-6Al-4V (PREP), d) spherical nickel (PREP), and (e) spherical 316 stainless steel (PREP). In addition to measuring densities after HIP at a given pressure and time on powder of controlled sizes, quantitative metallography and fractography will be performed to characterize not only the pore population but also the degree of interparticle bonding.

The Influence of Plastic Anisotropy on the Hydrogen Embrittlement of Titanium under Multiaxial States of Stress [with Dale Gerard, M.S. candidate]

In a previous study, we have examined the hydrogen embrittlement (HE) of

Ti under multiaxial states of stress [30]. Based on measurements of fracture strains measured locally from grids, the data show a decrease in ductility with increasing hydrogen content as the degree of biaxiality of the tensile stress increases. The tests were performed on Ti sheet with a strong degree of plastic anisotropy and clearly for this material hydrogen embrittlement is most severe under equibiaxial tension. Quantitative metallography indicated that these "multiaxial" HE effects are due to hydrides fracturing at comparatively small strains in equibiaxial tension.

A theoretical analysis of the above results was performed and concluded that hydride failure obeys a critical normal stress criterion and that the principal source of the large normal stresses in equibiaxial tension is the plastic anisotropy of the Ti sheet [30]. Thus it is predicted that HE of plastically <u>isotropic</u> Ti sheet should be relatively immune to effects of multiaxial stress state; that is, the degree of HE in equibiaxial tension should be comparable to that in uniaxial tension.* Such a prediction is significant in that it identifies a basis for heat-treatment and processing which would impart a resistance to HE in a Ti sheet under multiaxial loading. The purpose of the present study is thus to examine experimentally the hydrogen embrittlement of Ti sheet which is nearly isotropic (plastically) and which is tested in uniaxial and equibiaxial tension. At the present we are fabricating isotropic sheet by: (a) beta-anneal treatments of sheet as starting stock and (b) hot rolling Ti plate to sheet thickness at temperatures in the beta phase field.

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*Note: The reason is that during deformation of plastically isotropic sheet, the maximum principal stress in uniaxial tension should be identical in magnitude to the two equal principal stresses in equibiaxial tension at a given equivalent strain. For the anisotropic sheet tested previously, the principal stresses in equibiaxial tension were greater than that in uniaxial tension by a factor of ∿1.5.

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Publications, Reports, and Presentations: 9/30/82 - 10/1/83

1. "Deformation and Fracture of Strongly Textures Ti Alloy Sheets in Uniaxial Tension," (with K. S. Chan), Metall. Trans. A, 14A, 1333 (1983).

2. "Stretch Forming and Fracture of Strongly Textured Ti Alloy Sheets," (with K. S. Chan), Metall. Trans. A, 14A, 1343 (1983).

3. "Localized Necking of Sheet at Negative Minor Strains," (with K. S. Chan and A. K. Ghosh), Metall. trans. A (in print).

4. "The Effect of Hydrogen on the Multiaxial Stress-Strain Behavior of Titanium Tubing," (with C. W. Lentz, M. G. Stout and S. S. Hecker), Metall. Trans. A, (in print).

5. "Deformation and Fracture at Isolated Holes in Plane-Strain Tension," (with R. J. Bourcier, R. E. Smelser and O. Richmond), Int. J. Fracture (accepted for publication).

6. "Hydrogen Embrittlement of Titanium Sheet Under Multiaxial Deformation Paths," (with R. J. Bourcier), Office of Naval Research Tech. Rep. No. 22, Contract No. N00014-76-C-0037, NR 031-756, Aug. 1983.

7. "Deformation and Fracture at Isolated Holes in Plane-Strain Tension," (with R. J. Bourcier, R. E. Smelser, and O. Richmond), presented at the TMS-AIME Meeting, St. Louis, Oct. 1982.

8. "The Influence of Hydrogen on the Multiaxial Deformation of Beta and Alpha-Beta Ti Alloy Sheet," (with B. Lograsso), presented at the TMS-AIME Meeting, St. Louis, Oct. 1982.

9. "Aspects of Hydrogen Embrittlement and Stress Corrosion Cracking," Seminar presented at Northeastern University, Nov. 1982.

10. "Stress Corrosion Cracking and Hydrogen Embrittlement Under Multiaxial Loading," Seminar presented at Vanderbilt Univ., Feb. 1983.

11. "Hydrogen Embrittlement and Multiaxial Loading," Seminar presented at Univ. of Pittsburgh, March 1983.

12. "Localized Necking of Sheet at Negative Minor Strains," Seminar presented at General Motors Technical Center, Warren, Michigan, Aug. 1983.

13. "Deformation of Alloys with a Lamellar Microstructure," International Symposium on Mechanics of Dislocations, Michigan Technological University, Aug. 1983.