International Journal of Impact Engineering 82 (2015) 89–102

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

# Numerical study of the deformation and fracture behavior of porous Ti6Al4V alloy under static and dynamic loading

N. Biswas, J.L. Ding*

*School of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164-2920, USA*

A R T I C L E I N F O

*Article history:*
Available online 2 September 2014

*Keywords:*
Titanium alloy
Porous material
Dynamic loading
Pore density
Pore morphology

A B S T R A C T

In a previous work, the dynamic compression behavior of Ti6Al4V with 0, 10 and 20% porosities, at the strain rate of $1 \times 10^{-3}$, $1 \times 10^{3}$, $4 \times 10^{3}$ and $8 \times 10^{3}$/s, was experimentally characterized. The objective of this study is to use numerical simulations to gain insights on the observed material behavior and a general understanding of the dynamic responses of porous metals. The study indicates that the pore in general could serve as both a failure initiator and an inhibitor. The pore would lead to lower strength due to higher stress concentration as a result of the reduction of load bearing area and geometric discontinuity. On the other hand, the pore could also result in lower matrix stress at the onset of failure due to the reduced overall load bearing capacity. This lower stress and associated lower potential energy could lead to slower failure propagation and higher apparent ductility. The study also shows that the pore distribution and pore shape play significant role on the deformation and fracture behavior of porous material. For a fixed porosity, the more densely populated small pores could lead to faster failure propagation due to the enhancement of the failure propagation through void coalescence. However, the distribution does not seem to affect much the stress-stain response prior to the onset of failure. The effects of pore shape are similar to that porosity. Different pore shapes lead to different degrees of stress concentration and the apparent strengths. However, the higher stress concentration could also result in slower failure propagation due to the lower matrix stress and the associated potential energy at the onset of catastrophic failure. Besides pore density and morphology, matrix properties also played important roles on the response of porous metals. Although higher strength enhanced material's resistance to deformation, it could also lead to faster failure propagation once it was initiated due to the higher matrix stress. On the other hand, higher hardening rate could provide increasing resistance to failure propagation.



## 1. Introduction

With their tailored porosity, density, strength, and ductility, porous metals have found a wide range of applications. Examples include energy absorption and/or impact mitigation [1], electromagnetic shielding [2], acoustic insulation [3], fluid filtration [4], heat management [5], and biomedical implants [6], etc. To take full advantage of the unique properties of porous metals and to ensure the reliability of a structural system made of such materials, a good understanding of their deformation and fracture behavior is essential. To date, the research efforts made in this aspect have been mostly focused on static loadings. However, in many applications, particularly those for energy absorption or impact mitigation, a structure could either be likely subjected to, or specifically designed to withstand dynamic loading. For these applications, a good understanding of the dynamic response of porous metals is critical. Some limited research efforts have been made to address this issue, but they are mostly centered on the shock response of porous materials [7]. In these studies, the materials were subjected to a uniaxial strain compression and the strain rates were typically higher than $10^5$/s, and in many cases much higher. Due to the extreme pressure and strain rates imposed in these experiments, the main results from these studies are generally a relation between pressure and volume. The details of the inelastic deformation and fracture, which are important energy dissipation mechanisms, are either smeared out or ignored. For many practical applications involving dynamic loadings, the strain rates that are above quasistatic, but below the shock compression range, i.e.$\leq 10^5$/s, represent an important loading regime. This is also where dynamic inelasticity plays an important role on the performance of

* Corresponding author.
*E-mail address:* ding@mme.wsu.edu (J.L. Ding).

http://dx.doi.org/10.1016/j.ijimpeng.2014.08.011
0734-743X/

both the materials and structures. To date, the limited studies done in this loading regime have been mostly directed towards the overall structural response, such as that of a light-weight, energy absorbing sandwich structure containing porous metals or metal foams [8]. Fundamental understanding and research on the dynamic response of porous metals themselves are very scarce.

In a recent study, the deformation and fracture behavior of laser processed dense and porous Ti6Al4V with 10% and 20% porosities under both static and dynamic loadings was experimentally characterized [9]. The imposed strain rates ranged from $10^{-3}$ to $10^4$/s. The results provided a systematic and unique set of information on the dynamic response of a particular type of porous metal. The goal of this study is to use numerical simulations to gain insights into the observed material behavior and a general understanding of the dynamic responses of porous metals.

## 2. Brief review of the experimental results

The material studied in [9] was processed by the Laser Engineered Net Shaping (LENS) technique whose details were described in [10]. All the samples were tested at four different strain rates, namely, $1 \times 10^{-3}$, $1 \times 10^3$, $4 \times 10^3$ and $8 \times 10^3$/s. The static tests ($1 \times 10^{-3}$/s) were performed with the standard material test machine and the other three were done with the Split Hopkinson Pressure Bar (SHPB) technique [9]. The details of the SHPB setup, dimensions of the components and samples, data validation and analysis were described in [9].

Microstructure examination [10] showed that the fully dense Ti6Al4V had characteristic Widmanstätten microstructure where the widths of $\alpha$ platelets were in the range of 2 and 11 μm(average of 4.6 ± 2 μm), and the lengths were on the order of 10 and 100 μm(average 38 ± 19 μm). The porous Ti6Al4V alloy, which had a mix of open and closed porosities, had more or less equiaxed $\alpha + \beta$ microstructures in which the average $\alpha$ phase size was 9.3 ± 4.5 μm and 13.4 ± 5.5 μm for the 10% and 20% porous samples, respectively. The Widmanstätten microstructure for the fully dense samples resulted in relatively high hardness of the matrix material, 284 ± 6 HV, compared to porous samples with equiaxed $\alpha + \beta$ microstructures, 251 ± 11 HV and 259 ± 10 HV for 10% and 20% porosities, respectively. The hardness of the matrix was measured far away from the pores to avoid their influence. The observed variations in microstructures are attributed to the variations in peak temperatures and cooling rates during the laser processing [10].

For the convenience and continuity of the discussion, some of the experimental results reported in [9] were briefly reviewed here. Fig. 1 illustrated the effects of porosity. It showed that the strength and stiffness decreased with the increase of porosity as expected. For the fracture behavior, Fig. 1(a) and (b) showed that the materials exhibited some initial hardening when deformed at $1 \times 10^3$/s and $4 \times 10^3$/s before catastrophic failure took place. However, for the $8 \times 10^3$/s experiments as shown by Fig. 1(c), the stress started to drop immediately after it had reached its peak. The rate of stress dropping was slower in the beginning probably due to some concurrent hardening and then accelerated at the onset of catastrophic failure. Another important feature displayed by Fig. 1 is that higher porosity in general also resulted in higher ductility. From the viewpoint of structural applications, besides weight reduction and impedance modification, trading off between strength and ductility is another common motivation to introduce pores into materials. To

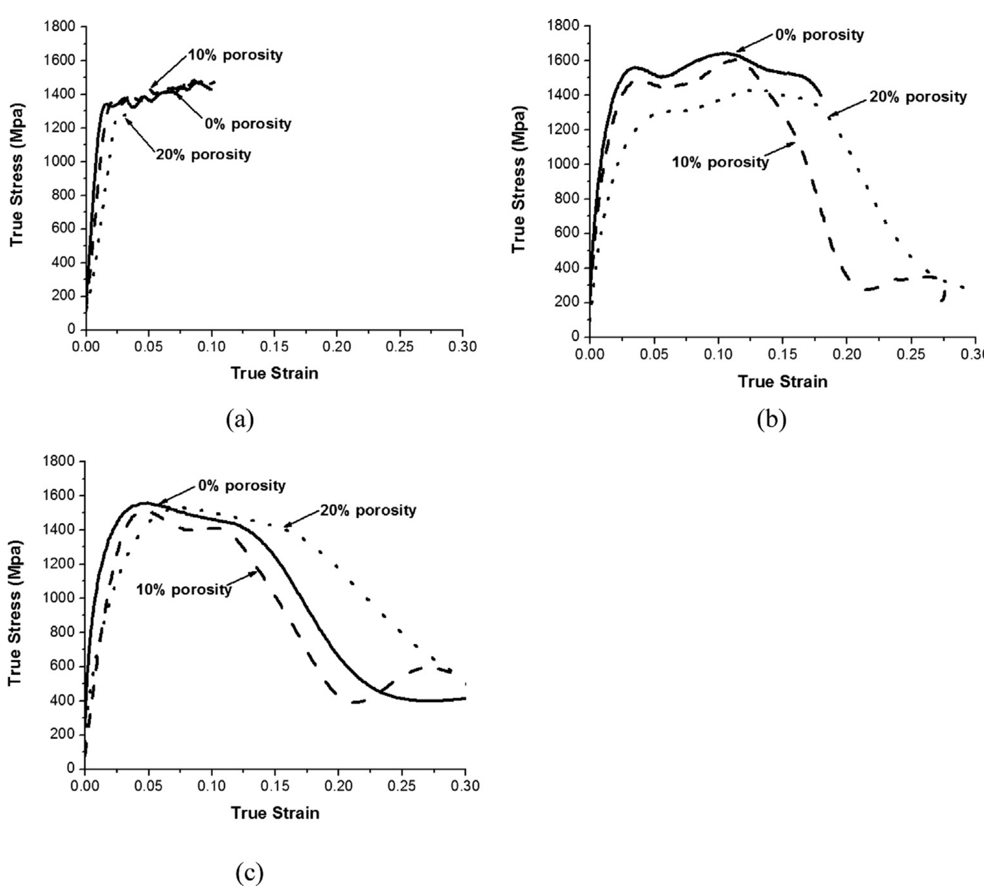


**Fig. 1.** Experimental data on stress-strain relations as a function of porosity for a fixed strain rate: (a) $1 \times 10^3$/s, (b) $4 \times 10^3$/s and (c) $8 \times 10^3$/s.[9].