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Three-dimensional investigation of grain orientation effects on void growth in commercially pure titanium

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ABSTRACT

The fracture process of commercially pure titanium was visualized in model materials containing artificial holes. These model materials were fabricated using a femtosecond laser coupled with a diffusion bonding technique to obtain voids in the interior of titanium samples. Changes in void dimensions during in-situ straining were recorded in three dimensions using x-ray computed tomography. Void growth obtained experimentally was compared with the Rice and Tracey model which predicted well the average void growth. A large scatter in void growth data was explained by differences in grain orientation which was confirmed by crystal plasticity simulations. It was also shown that grain orientation has a stronger effect on void growth than intervoid spacing and material strength. Intervoid spacing, however, appears to control whether the intervoid ligament failure is ductile or brittle.

1. Introduction

A better understanding of damage phenomena in hexagonal close-packed (HCP) metals is needed to improve the prediction capabilities of fracture models. To date, most of the research has focused on understanding the deformation mechanisms in some of these HCP materials, including titanium [1–10] for aerospace applications, zirconium [11–14] for the nuclear industry and magnesium [15–17] for manufacturing industries. The deformation behavior of HCPs is quite complex as it is affected by twinning and grain orientation. Various studies have shown that grain orientation can significantly affect deformation and mechanical properties [2,3,18–26]. In deciding the deformation mode in HCP materials one should consider the c/a ratio [5]: (i) when $c/a < 1.632$ (Ti, Zr, Be, etc), a sufficient number of slip systems is provided by prismatic and pyramidal slip; (ii) when $1.63 < c/a < 1.73$ (Mg), only one basal slip system is available; and (iii) when $c/a > 1.73$ (Zn, Cd) deformation is accommodated by basal slip and twinning. Propensity of twinning is also related to the grain size [4]: smaller grains cannot accumulate dislocations and twin boundaries, and hence twinning decreases. Some work on fracture in HCP materials showed that ductility is also affected by the HCP crystal structure, grain orientation and twinning. Yoo [1] proposed a relation between ductility and the ratio of elastic bulk modulus to shear modulus, K/G. High value of K/G were associated with ductility (titanium, zirconium) and a low value with brittleness (magnesium). Fracture in Ti was also proposed to be a result of void nucleation, growth and coalescence. Krishna Mohan Rao et al. [10] reported fracture at room temperature by void nucleation and growth in a near-α aircraft titanium alloy. It was shown that during fatigue testing, a crack nucleated at a hard grain – soft grain interface propagates through the hard-orientated grain, suggesting that the driving stress intensity depends on the local morphology and crystallographic orientations [27]. Furthermore, the plastic zone which develops at the tip of a crack in an hcp single crystal is strongly dependent on crystallographic orientation [27]. Even grains with similar orientations can follow different orientation trajectories depending on their misorientation with respect to neighboring grains [28]. The importance of neighboring grains can be understood in terms of the stress intensities resulting from grain misorientations [27].

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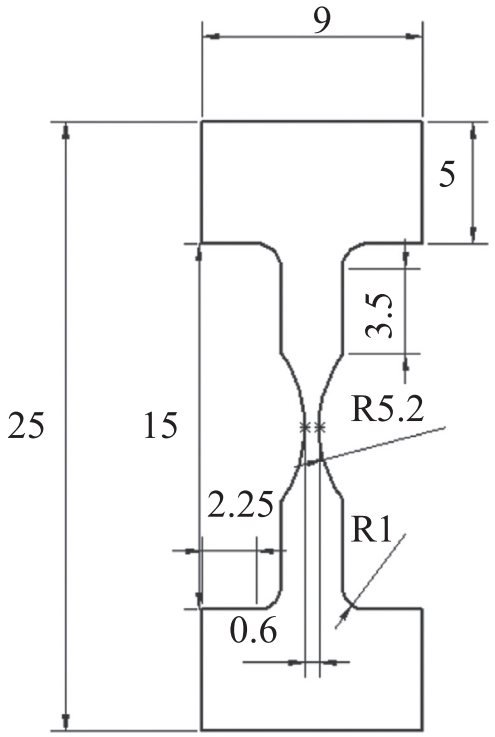

Fig. 1. Sample dimensions in mm. Sample thickness was approximately 0.5 mm.

A review on the effect of twinning, grain orientation and other parameters on fracture processes (experiments and modeling) was provided by Roters et al. [29]. The effect of grain orientation on the void growth process has been numerically studied at different length scales: at the nanometric scale using Molecular Dynamics [30,31], at the microscale by discrete dislocation dynamics [32–34] and at the continuum level using crystal plasticity [35]. In all these studies the general conclusion is that under uniaxial loading, void growth in single crystals slightly depends on the orientation of the tensile axis with respect to the crystalline lattice.

Most experimental studies in literature are devoted to FCC materials, and orientation effects in HCP metals are lacking. Models have been proposed to predict deformation mechanisms, evolution of crystallographic structure, texture, twinning, hardening and mechanical properties during deformation [6–9]. However there is a lack of models to predict fracture in HCP structures.

From the results presented in the literature, fracture in Ti can be the result of a ductile fracture process where voids are nucleated, grow and finally coalesce. The approach taken in this paper is to verify whether standard ductile fracture models, which were proven successful for some isotropic materials [36], are able to predict fracture and in particular void growth in an HCP structure. Experimental data on void growth and coalescence are difficult to obtain, making model validation difficult. To simplify the study of ductile fracture, laser-drilled model materials similar to those of Weck et al. [37] were produced out of commercially pure titanium, tested, and visualized using x-ray tomography. Void growth was followed in-situ and compared to the Rice and Tracey model for void growth, and to crystal plasticity simulations.

2. Experimental methods

Commercially-pure titanium (Grade 1) was purchased from the company NewMet in the form of thick 0.25 mm titanium foil (99.8% Ti) and AlfaAesar in the form of thin 0.032 mm titanium foil (99.7% Ti). Arrays of voids were introduced in the thinner titanium foils using femtosecond laser micromachining, a technique which allows precise manufacturing of voids without the formation of a heat affected zone. This technique has already been successfully implemented to create model material out of copper and aluminum [37–39]. Different void configurations were used: (i) rectangular array with intervoid spacings of 70 μm, 100 μm and 120 μm, and (ii) holes at 45° with intervoid spacing of 70 μm, 100 μm and 130 μm. All samples had an initial void diameter of 35 μm. After laser drilling, the samples were polished down to a mirror finish using a 0.05 μm colloidal silica suspension. Sheets containing voids were then diffusion bonded to sheets without voids in a vacuum furnace at 10^{-5} Torr. Different annealing temperatures and times were used in order to obtain different levels of strength, from 950 °C for 2 h to 1000 °C for 3 h. Two types of samples were obtained: one with a 2-dimensional array of voids inside the material and one with a 3-dimensional array of voids to

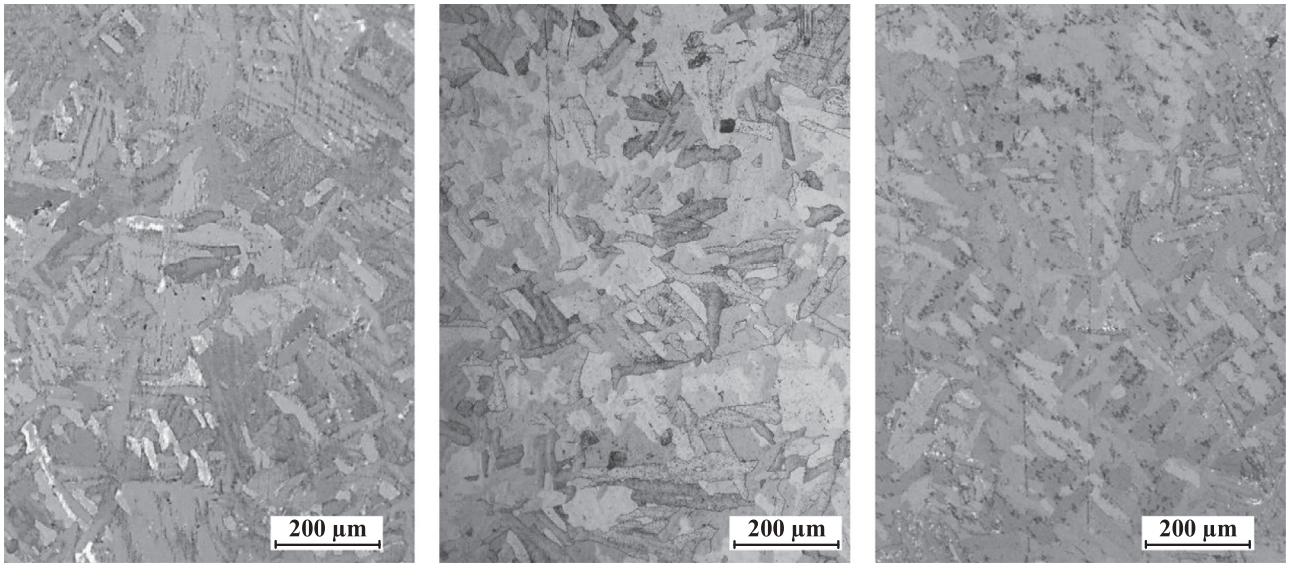

Fig. 2. Typical sequence of microstructures (× 100) versus diffusion bonding temperature and time: (a) 960 °C, 2 h, (b) 1000 °C, 2 h, (c) 1000 °C, 3 h.