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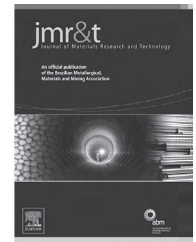

SHORT COMMUNICATION

Anomalous Strain Rate Effect in Ultrafine Grained Titanium

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An anomalous effect was found in the strain rate dependence of severe plastic deformed commercially pure titanium with ultrafine-grained structure. A maximum tensile strength was obtained for $\dot{\varepsilon} = 10^{-3}$ s^{-1}. This did not allow a single strain rate sensitivity parameter to be defined in the interval from $\dot{\varepsilon} = 10^{-5}$ to 10^{-1} s^{-1}. Distinct deformation mechanisms for lower and higher strain rates might be the reason for this anomaly.

KEY WORDS: Titanium, Ultrafine-grained, Severe plastic deformation, Strain rate effect.

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1. Introduction

Severe plastic deformation (SPD) has, in recent years, been extensively used to increase the strength of metals and alloys in association with an exceptional grain refinement[1-5]. Ultrafine grained (UFG) materials can thus be obtained by several SPD metal forming procedures that impose very high strains[6,7], such as high pressure torsion (HPT), twist extrusion (TE), multi-directional forging (MDF) and equal-channel angular pressing (ECAP). This later is currently the most investigated and even industrially applied. Owing to limitation in the repetitive insert-remove technique of the conventional ECAP, different procedures are under development for continuous processing[6]. In particular, the ECAP-conform process[8] permits the continuous extrusion of long UFG rods.

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Commercially pure titanium, cpTi, is among one of the most investigated metals for the effects of SPD[2-5,7]. Semenova *et al.*[3] reported that four passes of ECAP of a cpTi rod, combined with thermo mechanical treatment and annealing at 350°C for 6 hours, resulted in an ultimate strength of 1250 MPa and 13% elongation. This enhancement in both strength and ductility were attributed to changes in the structure of grain boundaries[9]. The simple processing of cpTi by ECAP is enough to produce an increase in strength, which parallels that of the Ti-6Al-4V alloy commonly used in biomedical applications[10]. This opens the possibility of using titanium dental implants free of possible toxic elements, like Al and V[10,11]. Table 1 illustrates the tensile strength of ECAPed cpTi and Ti-6Al-V obtained at room temperature and strain rates of the order of 10^{-3} s^{-1}.

The submicron structure of SPD cpTi has unique characteristics and its response to changes in strain rate still requires detailed investigation.

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Table 1 Tensile strength of cpTi an Ti-6Al-V from different works[4,7,11]

Material	Tensile strength (MPa)
ECAPed cpTi	589-882
Ti-6Al-V	900*-982

*Minimum for annealed cpTi.

2. Strain Rate Effect on UFG cpTi

The mechanical strength of most metals and alloys is sensitive to the rate at which the material is deformed, i.e., the strain rate $d\varepsilon/dt = \dot{\varepsilon}$. The strain rate sensitivity parameter, *m*, is defined as:

$$m = \left.\frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}\right|_{\varepsilon,T} \quad (1)$$

and indicates a power dependence of the strength with the strain rate[12]:

$$\sigma = K\dot{\varepsilon}^{m} \quad (2)$$

In general, *m* varies between 0.02 and 0.2 corresponding to a sensible increase in strength with the strain rate[12]. In the case of conventional coarse-grained cpTi, *m* is less than 0.05, while ultrafine-grained, DPD (HPT-processed), cpTi revealed 0.12–0.15, as values of *m* obtained by strain rate jump test around $\dot{\varepsilon} = 10^{-3}$ s^{-1} at room temperature (RT)[9].

To report preliminary results on the strain rate sensitivity of ECAP-conform processed cpTi, by means of tensile stress-strain curves at three different strain rates within the limits of quasi-static deformation, was the objective of this communication.

3. Methods, Results and Discussion

ASTM grade 2 cpTi containing (wt%) 0.07 C, 0.12 O, 0.01 H, 0.04 N, and 0.18 Fe with initial average grain size of 15 μm was ECAP-conform processed at 450°C to a cumulative strain about 8. After processing, the grain and sub grain size decreased to 0.4 μm. Tensile specimens with gage length of 10 mm and gage diameter of 2.4 mm were room temperature tested in a model 5582 Instron machine at cross head speeds of 10^{-4}, 10^{-2}, and 1 mm/s, corresponding to strain rates of 10^{-5}, 10^{-3}, and 10^{-1} s^{-1}, respectively. Below 10^{-5} s^{-1}, creep and relaxation and above 10^{-1} s^{-1} inertial and wave propagation effects start to become important[12]. Three specimens were tested for each strain rate condition and the results were reproducible.

Table 2 presents the average value of the ultimate strength directly obtained from the stress-strain curve for each strain rate. Fig. 1 shows the log-log plot for the strength vs. the strain rate which corresponds to the linear transformation of Eq. (2). The results in Table 2 and Fig. 1 reveal an anomalous strain rate effect in SPD cpTi, not observed at RT in coarse-grained metals, including conventional Ti. In fact, rather than a single direct or inverse strain rate sensitivity associated with either a positive or negative value of *m*, respectively, the strength has a maximum (892 MPa) for $\dot{\varepsilon} = 10^{-3}$ s^{-1}. In other words, a unique *m* value cannot be associated with this interval of strain rate, which corresponds to the limits for quasi-static tensile tests. The values presented in Table 2 are within the range, Table 1, expected for SPD cpTi. It is surprising, however, that the higher strain rate, 10^{-1} s^{-1}, corresponds to a lower strength than that for 10^{-3} s^{-1}.

Table 2 Average ultimate strength for SPD cpTi at different strain rates

Strain Rate (s^{-1})	Ultimate Strength (MPa)
10^{-5}	762 ± 23
10^{-3}	892 ± 14
10^{-1}	855 ± 20

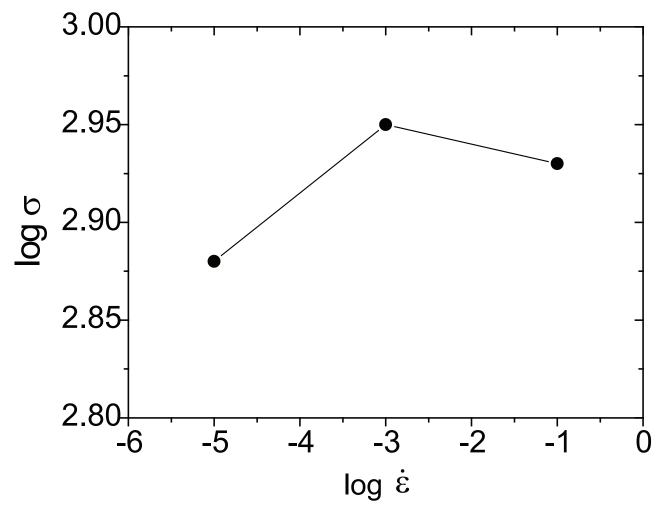

Fig. 1 Logarithm of the ultimate strength vs. logarithm of strain rate plot for SPD cp Ti

A possible explanation for this anomalous strain-rate effect could be a change in deformation mechanism. No experimental evidences exist so far. But one may speculate that for lower strain rates, close to creep conditions, ($\dot{\varepsilon} = 10^{-5}$ s^{-1}), room temperature grain boundary sliding (GBS) might be the predominant mechanism. As previously suggested[2], GBS in SPD materials may take place at relatively lower temperatures. Since GBS is a diffusion controlled process, one would expect diffusion to be faster in ultrafine-grained cpTi with highly non-equilibrium grain boundaries[3]. By contrast, for higher strain rates, close to wave propagation effects ($\dot{\varepsilon} = 10^{-1}$ s^{-1}), twinning and dislocation-assisted deformation[4] might be the rate controlling mechanism. TEM observations are being conducted to confirm this assumption.

Acknowledgements

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