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Enhanced fatigue strength of commercially pure Ti processed by severe plastic deformation

I.P. Semenova[a,*], G.Kh. Salimgareeva[a], V.V. Latysh[a], T. Lowe[b], R.Z. Valiev[a]

[a] *Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, 12 K. Marx St., Ufa 450000, Russia*
[b] *Materials Science and Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

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ABSTRACT

The high-cycle fatigue behavior of smooth and notched samples of ultrafine-grained titanium prepared by severe plastic deformation is compared with the corresponding properties of conventional titanium. It is shown that the combination of high strength and enhanced ductility of ultrafine-grained titanium lead to an increase of the fatigue endurance limit. Using a combination of equal-channel angular pressing and subsequent thermal and mechanical treatment, it was possible to increase the fatigue endurance limit of commercial-purity titanium by a factor of 1.5. Furthermore, it is shown that post-deformation annealing can additionally enhance the ductility of the ultrafine-grained Ti and lower fatigue-notch sensitivity particularly in comparison with Ti-6Al-4V.

1. Introduction

Fatigue properties are often of primary importance when considering the potential of bulk ultrafine-grained (UFG) materials for use in structural application. Some of the earliest investigations of the cyclic behavior of UFG metals were of copper, for example the experiments by Agnew et al. [1] and their continuation by Mughrabi et al. [2–4] and others. Various experimental results on the fatigue behavior of UFG metals and alloys are summarized in [5–9]. In most investigations of ultrafine-grained materials an increase in the fatigue endurance limit is associated with an increase in the flow stress and static strength as a result of structure refinement. At the same time, due to some loss of ductility after severe plastic deformation (SPD), the high-cycle fatigue properties of UFG materials do not increase as much as would be predicted based upon a simple Hall–Petch relationship [9]. One may speculate that susceptibility of UFG materials to localization of the plastic flow is the main factor limiting their ductility. Apparently, the high-cycle fatigue properties of UFG materials can be significantly improved by means of ductility enhancement, i.e. by reduction of susceptibility to deformation localization, which in its turn is characterized by an increase of the uniform elongation during tensile deformation of a sample.

To increase the ductility of UFG materials, it is necessary to employ special approaches to control the size and shape of grains and form grain boundaries with high-angle misorientations [10]. These approaches were applied when developing a pilot technology for the manufacturing of long rods out of UFG Ti. The high-angle grain boundaries in particular allow additional deformation mechanisms to operate including grain-boundary sliding during low-temperature straining. It is possible to implement such approaches through various schemes and regimes of SPD, annealing, additional deformation and thermal treatments [11,12]. Many investigations of mechanical properties have demonstrated that high strength and good ductility can be achieved in bulk UFG materials produced by SPD techniques [10].

Due to its high corrosion resistance and biocompatibility, Ti is widely used to fabricate implants in osteosynthesis, stomatology and traumatology [13–16]. The principal requirement for structural materials for implants is to be biocompatible, but they must also possess high strength and enhanced fatigue resistance [13]. In the case of medical fasteners, special attention is paid to the fatigue-notch sensitivity.

Thus, the aim of this work is to enhance the high-cycle fatigue properties of UFG Ti via achieving of high strength and enhanced ductility that can be realized through SPD combined with thermal and mechanical (deformation) treatments (TMTs).

2. Material and experimental methods

Commercially pure (CP) Ti Grade 4 (Ti: base, C: 0.052%, O: 0.34%, Fe: 0.%, N: 0.015% (wt.%)) was employed to conduct the research. Processing of long rods consisted of several stages which included

* Corresponding author. Tel.: +7 347 2733422; fax: +7 347 2733422.
E-mail address: Semenova-ip@mail.ru (I.P. Semenova).

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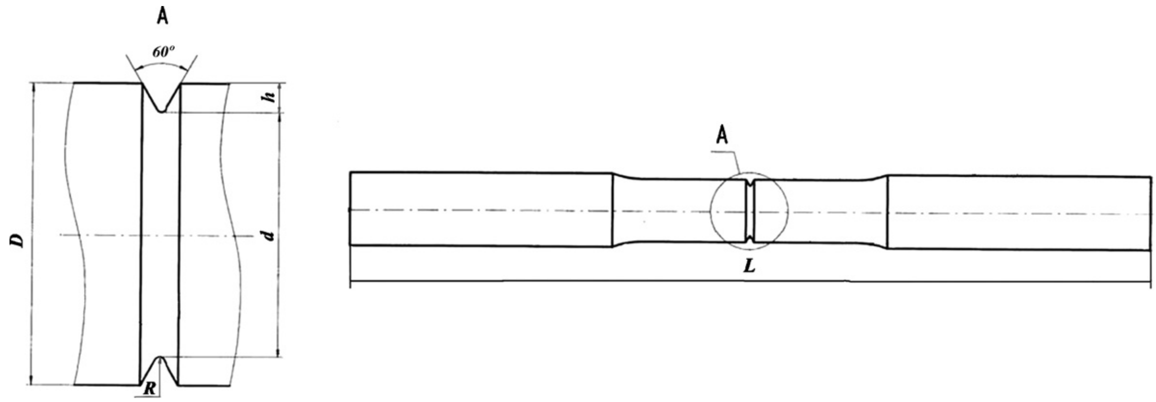

Fig. 1. Notched samples.

Table 1
The sizes of the V-shaped notch of the tested samples and their elastic stress concentration factors (α_T).

	$R=0.1$ (mm)	$R=0.2$ (mm)	$R=0.3$ (mm)
L (mm)	76.0	76.0	76.0
D (mm)	6.0	6.0	6.0
h (mm)	0.660	0.560	0.460
d (mm)	4.68	4.88	5.08
α_T	4.4	3.9	3.3

equal-channel angular pressing (ECAP), thermo-mechanical and shape forming treatments and annealing [14,15]. Ti billets 25 mm in diameter with an initial grain size of 30 μm were subjected to 8 ECAP passes at $T = 450\,^{\circ}$C in the die-set with an angle of channel intersection of 90° along the route Bc (see Ref. [15] for details). Then they were subjected to forge-drawing and additional drawing with the total accumulated strain of about 80% and annealing at 350 °C for 6 h. By use of this treatment, it was possible to produce rods with a diameter of 7 mm and a length of more than 2 m.

The study of the microstructure of the billets was carried out using transmission electron microscopy (TEM). Selected-area electron diffraction patterns were taken from an area of 2 μm^2. Standard samples with a gage diameter of 3 mm and gauge length of 15 mm cut out from the central part of a rod in the longitudinal direction were used for tensile tests. At least 3 samples were tested for each state. The tensile tests were conducted on an Instron machine at room temperature and at a strain rate of $10^{-3}\ s^{-1}$.

High-cycle fatigue tests were carried out on smooth and notched samples. The samples were subjected to testing in the symmetric loading cycle conditions ($R = -1$) under rotational bending with the controlled stress and a frequency $f = 50$ Hz. The number of cycles was $N = 10^7$. To conduct the fatigue tests, the surface of gage section of the smooth cylindrical samples was ground and mechanically polished to a roughness Ra of 0.63 μm. Fig. 1 and Table 1 demonstrate the size and the shape of the channel of cylindrical notched samples. The notch dimensions were chosen to correspond with the standard sizes of the common screw threads. The elastic stress concentration factors (α_T) for notches with a radius of 0.1, 0.2 and 0.3 mm were calculated analytically as 4.4, 3.9, 3.3, respectively (Table 1). The channel surface of the samples was polished to the roughness degree $Ra = 0.2$ μm.

3. Results and discussion

The microstructure of Ti rods after the processing is characterized by equiaxed ultrafine grains and subgrains with an average grain size of about 200 nm and a high dislocation density in the cross section (Fig. 2). The typical structure in the longitudinal section examined along the rod length in several parts represents α-grains elongated along the rod axis. The interior of elongated grains is fragmented by subgrains about 200 nm in size with low-angle boundaries.

Table 2 presents the averaged results of tensile tests of CP Ti samples. Standard deviation of values of the ultimate strength and elongation in the middle and ends of the rod does not exceed 3%. This fact testifies to the homogeneity of the UFG structure formed in the semi-product. The strength of the SPD-processed CP Ti rods with UFG structure is consistently at least 1.75 times higher than the strength of CP Ti in the as-received state. The total elongation to failure of these high-strength rods was always at least 11% (see states 1 and 2 in Table 2). This ductility value is much higher than the elongation of 7% achieved after ECAP and cold rolling that was observed in our previous studies of CP Ti [17].

Post-deformation annealing was used with the aim to additionally enhance the ductility of UFG Ti. The best combination of strength and ductility was achieved after annealing at 350 °C for 1–6 h. Our hypothesis is that enhancement of the ductility in combination with a very high strength of the UFG Ti after this annealing

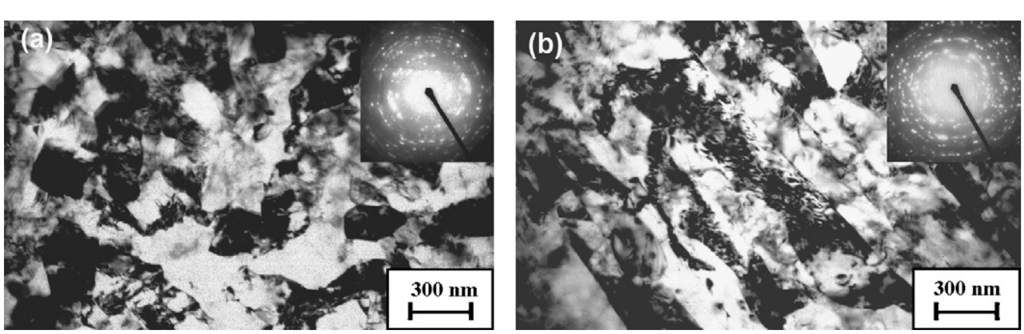

Fig. 2. Microstructure as obtained from TEM examination of CP Ti Grade 4 after combined SPD processing: (a) cross section; (b) longitudinal section.