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Procedia Structural Integrity 6 (2017) 196–200

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XXVII International Conference "Mathematical and Computer Simulations in Mechanics of Solids and Structures". Fundamentals of Static and Dynamic Fracture (MCM 2017)

Strength and fracture of ultrafine-grained titanium Grade 4

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Abstract

Processing of metallic materials by methods of severe plastic deformation (SPD) provides a possibility to reduce grain sizes to nanocrystalline (NC) or ultrafine-grained (UFG) conditions. Such a structure can lead to high strength of the material, but can also reduce material ductility. The majority of papers on this topic consider deformation parameters of NC and UFG materials only for the case of quasi-static tensile tests. Parameters of fracture toughness, dynamic strength, as well as fracture processes of UFG materials remain poorly understood. However, a reduction in ductility may result in low values of important constructional strength characteristics. This reduces the attractiveness of NC and UFG materials for industrial applications. This work presents the study an influence of SPD on the constructional strength parameters and fracture character of commercially pure titanium Grade 4. The UFG structure of the material was obtained by means of equal-channel angular pressing according to the Conform scheme (ECAP-Conform) and subsequent drawing. The combination of the utilized modes of ECAP and heat treatment makes it possible to obtain the maximal known degree of ductility for the UFG titanium. Quasistatic tensile tests, impact toughness tests on samples with U-shaped notch, and fracture toughness test for the case of three-point bending were carried out. The test results of the UFG titanium showed an increase in the tensile strength by 40%, an increase in the impact toughness by 15% and a reduction in the fracture toughness by 30% as compared to its coarse-grained analog. Fracture surface corresponding to localized plastic deformation is observed for all of the performed tests.

Peer-review under responsibility of the MCM 2017 organizers.

Keywords: severe plastic deformation, ultrafine-grained structure, pure titanium, tensile strength, impact toughness, fracture toughness.

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Peer-review under responsibility of the MCM 2017 organizers.
10.1016/j.prostr.2017.11.030

1. Introduction

The formation of ultrafine-grained structure in titanium and its alloys by means of severe plastic deformation (SPD) methods makes it possible to increase significantly its tensile strength and yield strength (Sergueeva et al., 2001), as well as endurance limit (Semenova et al., 2008). However, most papers on this topic are devoted to studies of the connection of these mechanical parameters of titanium with the SPD regimes and the formed structure. Fracture processes and parameters that characterize it, such as fracture toughness, impact strength, etc., remain poorly understood (Sabirov et al., 2010; Pippan and Hohenwarter, 2016). Nevertheless, these characteristics are critically important for evaluating the potential application of ultrafine-grained materials. The purpose of this work is to begin the development of data on the constructional strength parameters and fracture processes of ultrafine-grained titanium.

2. Experimental procedures

The studies were conducted on commercially pure titanium Grade 4 (produced by Dynamet Company, USA). The chemical composition of the material, in wt.%, was 0.05C, 0.15Fe, 0.05N, 0.007H, 0.36O, residuals<0.3, and Ti as the balance. The initial material was supplied in the form of hot-rolled rods with ∅12 mm.

The ultrafine-grained structure was produced using equal-channel angular pressing (ECAP) combined with the Conform process (in Ufa State Aviation Technical University). The installation was with an angle of 120° in the ECAP abutment and the rod was processed through a total of six passes using route BC at a temperature of 200 °C. Before the ECAP, the rod was annealed at 680 °C for 1 hour. After the ECAP, the rod was annealed at 250 °C for 1 hour and then drawn with a die diameter of 12 mm. This combination of processing regimes makes it possible to produce UFG titanium with high strength and the greatest ductility, and also to ensure uniformity of mechanical properties along the volume of a rod.

The characteristic parameters of the materials are given in Table 1. A more detailed description of the processing regimes and the corresponding properties of the produced titanium, as well as its structure, can be found in the works of Polyakov et al. (2012) and Polyakov et al. (2013).

Table 1. Characteristic parameters of titanium Grade 4 before (CG) and after (UFG) ECAP.

Structure/ Parameter	**CG**	**UFG**
Av. grain size along the rod d_l, **μm**	**20**	**2.4**
Av. grain size across the rod d_c, **μm**	**11**	**0.7**
Microhardness along the rod HV_l	**243**	**317**
Microhardness across the rod HV_c	**234**	**268**

All tests were carried out on small samples. The samples were cut from the rod using an electro erosion machine, so that the largest length of the sample was located along the longitudinal direction of the rod.

The uniaxial tensile tests were carried out on plane samples with working part dimensions of 6×1.7 mm and a thickness of 0.8 mm and at a strain rate of $\sim 6 \cdot 10^{-5}$ 1/s.

The impact toughness tests were carried out using the Charpy method according to GOST 9454 (1978) using a drop tower machine and samples with a U-shaped notch. The speed of the impactor at the time of impact was 5 m/s that corresponded to the impact energy ~68 J. The samples had dimensions allowed by the standard: a length of 55 mm, a height of 8 (working 6) mm, a width of 2 mm, a radius of the notch curvature of 1 mm.

The fracture toughness tests were carried out according to the three-point bending scheme and the standard ASTM 1820 (2011). The samples were made in the form of a notched beam according to the proportions of the standard and had a length of 25 mm, a height of 5 mm, a width of 2.5 mm, a notch length of 0.6 mm and a fatigue crack length of 0.3-0.5 mm. The punch speed was 0.02 mm/s.

The fracture surfaces were examined by scanning electron microscopy on the Zeiss AURIGA Laser workstation.