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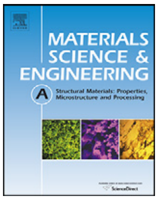

Anisotropic fracture behavior of ultrafine-grained iron

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ABSTRACT

Fracture toughness measurements with ultrafine-grained bcc iron produced by high pressure torsion (HPT) are reported. The measurements were performed with respect to three different crack plane orientations, which showed pronounced differences in fracture toughness as well as in the appearance of the fracture surfaces. The mechanical anisotropy was found to be a result of the elongated and aligned submicrocrystalline microstructure. This causes intergranular fracture for the crack plane orientation of lowest toughness, simultaneously favoring a higher fracture toughness for the other specimen orientations. Since this mechanical anisotropy led to one crack plane orientation with a limited fracture toughness, a strategy for increasing the fracture toughness of this orientation is also presented.

1. Introduction

Different severe plastic deformation (SPD) techniques are nowadays widespread for the production of ultrafine-grained (UFG) and nanocrystalline (NC) metals. In the last years the benefits of this material class, such as the enhanced strength, have been published in a vast number of publications and summarized in various overview articles [1–3]. Although grain refinement through SPD generally leads to an increase in strength and hardness, the deformation behavior is often deteriorated due to a strongly diminished dislocation storage ability and mobility associated with grain sizes typically smaller than 1 μm. For that reason the ductility of this material class and strategies for improving the ductility are currently of great interest [4–6].

Besides investigating the ductility with tensile tests, measuring for example the total or uniform elongation, the fracture toughness of a material can provide a more general insight into the deformation and fracture behavior of a bulk material. Since fracture toughness gives information about the damage tolerance of a material it is of great concern for different structural applications, such as in the aviation industry. Due to the small material quantities and dimensions obtained by most SPD processes, especially in the case of HPT, it is often difficult to conduct fracture toughness tests with reference to general standards, such as the ASTM standards. The compliance with such standards is of great importance, especially when the validity of the measurements is based on fulfilling small scale yielding conditions. This would finally also allow a better fracture behavior comparison of SPD materials with conventional alloys available on the market. Due to the restricted sample dimensions of SPD-processed materials there are only few references in the literature dealing with specific fracture values, such as the plain strain fracture toughness K_{IC} or the J-Integral, see, e.g. [7–9]. A significant increase in the size of HPT samples, as reported in [10], motivated to extend material testing of HPT-deformed materials to fracture toughness experiments. The increase in thickness of the HPT samples also allows the influence of the crack plane orientation on the fracture toughness of HPT-processed materials to be studied.

The aim of this paper is to give new insights into the mechanical properties of UFG iron as a representative for bcc metals. This paper covers the fracture behavior of UFG iron as a function of different crack plane orientations and also presents a method for improving the fracture toughness in the crack plane orientation of lowest toughness.

2. Experimental

The composition of ARMCO-iron used in this study is 0.009 wt% C, 0.060 wt% Mn, 0.009 wt% P, 0.007 wt% S and the balance Fe. For the investigations HPT discs of ARMCO-iron with a diameter of 30 mm and a thickness of 9 mm were machined from a rod and

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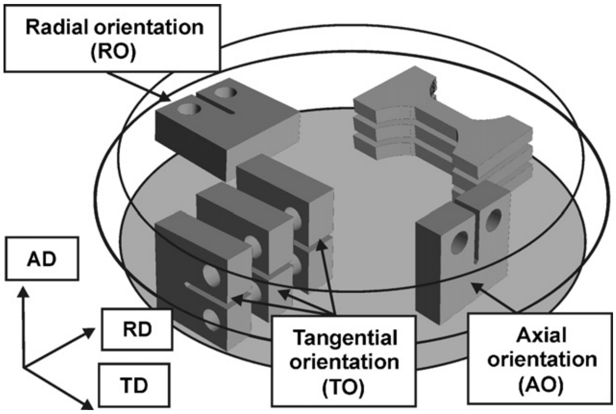

Fig. 1. Schematic representation of the specimens for fracture toughness and tensile tests and their orientation in the HPT disc. The denominations of the specimens is given after the desired crack propagation direction parallel to the chosen coordinate system: the radial orientation (RO), the axial orientation (AO) and the tangential specimen orientation (TO) were investigated.

annealed at 800 °C for 1 h. The samples were then subjected to HPT at room temperature at a nominal pressure of 2.8 GPa up to 10 revolutions, which is equivalent to a von Mises strain, $\varepsilon_{\mathrm{vM}}$, of ~80 at a radius of 15 mm. Compact-tension (CT) specimens were then machined from the HPT disc with different crack plane orientations. The specimen orientations and positions of the single specimens in the HPT disc are illustrated in Fig. 1. The specimen denomination is named after the expected crack propagation direction where the different directions are parallel to the chosen coordinate system, as displayed in Fig. 1. The axes are denoted as the tangential direction (TD), radial direction (RD), axial direction (AD), which results in a tangential (TO), radial (RO) and axial (AO) specimen orientation.

Specimens with a tangential and axial orientation were taken from different disc radii, approximately 13, 10 and 7 mm, which is also illustrated for specimens with a tangential orientation in Fig. 1. These radii refer to the middle of each specimen, respectively. For the radial specimen orientation the crack tip was situated at a radius of 10.5 mm. The geometry of the specimens, the measurement procedure and the calculation of the fracture toughness was based on the requirements and recommendations of the ASTM standard E-399. The specimens had a width, W, of 5.2 mm, an initial crack length, a, of ~2.6 mm and a thickness, B, of 2.6 mm. The fatigue pre-crack was introduced under cyclic compression loading [11].

Additionally, 3 tensile tests were conducted. The tensile specimens had a gauge length of 2.5 mm that was parallel to the tangential direction, see Fig. 1, and a cross-section of approximately 0.75 mm^2. The specimens were taken along the axial direction from +1, 0 and −1 mm with reference to the middle plane of the former HPT disc (Fig. 1). The middle of the specimen gauge corresponds to a radius of 10 mm in the HPT sample. Both the fracture toughness and tensile tests were conducted on a testing machine from Kammrath and Weiss$^{\mathrm{TM}}$ at a constant cross-head speed of 2.5 μm/s. For the fracture tests, the specimen displacement was recorded with a strain gauge named DD1 from Hottinger Baldwin Messtechnik (HBM). The microstructure and the fracture surfaces were characterized with a Zeiss 1525 scanning electron microscope (SEM). Micro-hardness measurements in the middle plane of the HPT disc along the radius were also performed to confirm the homogeneity of hardness after HPT processing. The measurements were performed with a Vickers indenter and a load of 200 gf. For each data point 3 indents were made at equivalent geometrical positions and averaged.

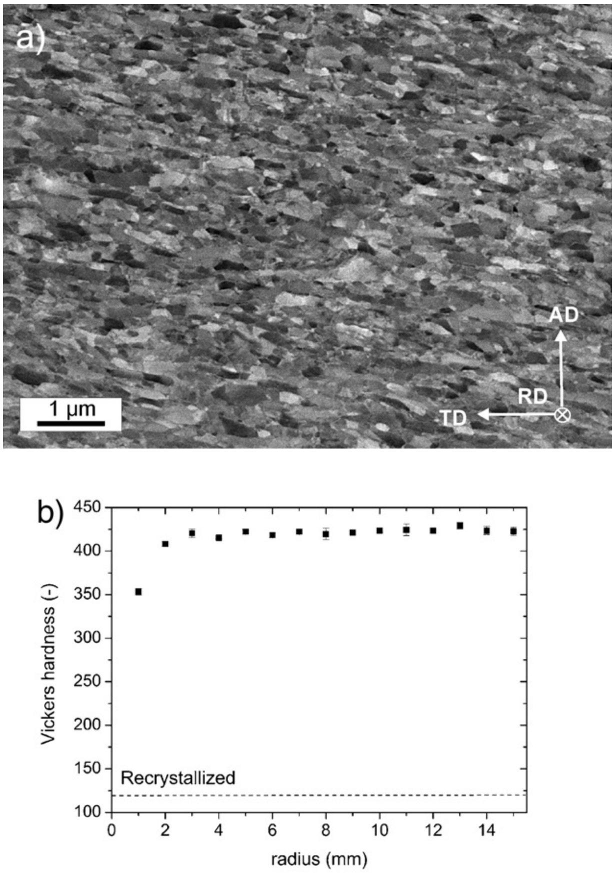

Fig. 2. Features of the investigated material: (a) typical ultrafine-grained microstructure of iron looking in the radial direction, note the ~10° inclination of elongated grains to the tangential direction and (b) hardness plot along the radius of the HPT disc in the middle plane of the disc, showing a pronounced homogeneity of the hardness. The standard deviation as an error bar is only visible for deviations larger than the symbol.

3. Results

3.1. Microstructure

In Fig. 2a a SEM-image taken with back scatter electron (BSE) contrast of the typical saturation microstructure of SPD-iron, looking into the radial direction, is presented. Various features of UFG iron have already been discussed in other references [12–14], however, some features are crucial for the findings presented here and thus some of them are presented and discussed already again here. After reaching a saturation strain, which for iron deformed at room temperature is after an equivalent von Mises strain, $\varepsilon_{\mathrm{vM}}$, of ~16, a minimum mean grain size of about 200 nm evolves and the grains exhibit an elongated structure with an aspect ratio of ~4 at room temperature, referring to measurements in [13]. A steady state in grain size is reached at which larger deformation strains do not lead to a further grain refinement. Another feature typical of the radial viewing direction is that the microstructure is not fully aligned along the tangential shear direction, which is parallel to the long margins of Fig. 2a, but shows an inclination of about 10° with respect to the tangential direction.

The aforementioned saturation strain is also significant for reaching a pronounced homogeneity within the HPT disc, which is important for the later tensile and CT-specimen extraction. In this work, hardness measurements along the middle plane of the HPT disc after deformation, presented in Fig. 2b, were performed to evaluate the microstructural homogeneity throughout the HPT disc. The