Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

The effect of microstructure anisotropy on low temperature fracture of ultrafine-grained iron

Barbara Romelczyk-Baishya [a,*], *Krzysztof Łęczycki* [a], *Magdalena Płocińska* [a], *Mariusz Kulczyk* [b], *Rafał Molak* [a], *Zbigniew Pakieła* [a]

[a] *Warsaw University of Technology, Faculty of Materials Science and Engineering, 141 Woloska St., 02-507 Warsaw, Poland*

[b] *Institute of High Pressure Physics, Polish Academy of Sciences, 29/37 Sokolowska St., 01-142 Warsaw, Poland*

ARTICLE INFO

Article history:
Received 14 December 2017
Accepted 26 February 2018
Available online

Keywords:
Iron
Nanomaterial
Fracture
Low temperature
Small punch test

ABSTRACT

This papers deals with the character on low (−180 °C) temperature fracture of iron. Microcrystalline and ultrafine-grained (UFG) iron rods were investigated. To obtain UFG material 20 mm in diameter iron rod was hydrostatically extruded (HE) in two steps: from 20 to 12 mm and from 12 to 8 mm. Because of microstructure anisotropy caused by HE mini-disc and mini-beam samples were cut off from perpendicular and longitudinal cross-section of the rods. Microcrystalline rod fractured in brittle manner at low temperature for both cross-sections, but in UFG iron fracture character depended on grain's shape. For samples were crack propagates parallel to the grain's elongation axis intercrystalline fracture occurred. For mini-beams were crack propagates crosswise to the grain elongation axis transcrystalline fracture occurred and force deflection curve was similar to those obtained for room temperature.

* *Corresponding author.*
E-mail address: barbara.romelczyk@inmat.pw.edu.pl (B. Romelczyk-Baishya).

Abbreviations: DBTT, ductile–brittle transition temperature; UFG, ultrafine-grained material; MC, microcrystalline material; HE, hydrostatic extrusion; SPD, severe plastic deformation; SPT, small punch test; Fe20, iron rod of 20 mm in diameter; HE8, iron rod of 8 mm in diameter obtained via hydrostatic extrusion; HE8F, iron rod of 8 mm in diameter obtained via HE and then flattened.; YS, yield stress; UTS, ultimate tensile stress; RT, room temperature used as the environment for test; −180 °C, temperature used as the environment for low temperature test; F_y, yielding force for SPT; F_u, ultimate (maximum) force for SPT; F_f, fracture force for SPT; U_y, yielding deflection for SPT; U_u, ultimate deflection for SPT; U_f, fracture deflection for SPT; F_y_RT, yielding force at room temperature; F_u_RT, ultimate force at room temperature; F_f_RT, fracture force at room temperature; U_y_RT, yielding deflection at room temperature; U_u_RT, ultimate deflection at room temperature; U_y_RT, fracture deflection at room temperature; F_y_-180 °C, yielding force at −180 °C; F_u_-180 °C, ultimate force at −180 °C; F_f_-180 °C, fracture force at −180 °C; U_y_-180 °C, yielding deflection at −180 °C; U_u_-180 °C, ultimate deflection at −180 °C; U_y_-180 °C, fracture deflection at −180 °C.

https://doi.org/10.1016/j.acme.2018.02.014

1. Introduction

Metals with a body-centred cubic structure such as iron exhibit a ductile–brittle transition temperature (DBTT) which results in a brittleness threshold below a particular temperature. At low temperatures, dislocation mobility is limited and a crack tip cannot be blunted, which results in a fracture process [1]. For bcc materials it was found that cleavage fracture mainly occurs for the 100 plane. The temperature of brittle fracture depends on deformation velocity [2], the shape and size of the specimens investigated [3] and also on the material's purity [4], grain size [5] and texture [6].

It is known that grain refinement can be an efficient way to shift transit temperature. For example, microcrystalline iron brittle fracture usually occurs below −70 °C [7], while the ultrafine-grained (UFG) counterpart preserves ductile fracture even in liquid nitrogen. Romelczyk et al. have obtained ductile fracture after Charpy impact test for iron sinter deformed via hydrostatic extrusion (HE) [5]. Gizynski et al. observed ductile behaviour for technically pure UFG iron rod while dynamic tensile test [2]. Hohenwarter et al. obtained a higher DBTT for submicrocrystalline grain Armco iron than for the microcrystalline counterparts [8]. The most popular group of methods that leads to obtaining UFG and nanocrystalline-grained (NC) products is severe plastic deformation (SPD). This includes: equal-channel angular pressing (ECAP) [9], high-pressure torsion (HPT) [10], hydrostatic extrusion [11], accumulative roll bonding (ARB) [12], and many others. The main idea of SPD is to generate big amount of new dislocations during the deformation process that result in fine-grained microstructure [13]. In general NC materials have high strength and low ductility due to their high dislocation density. The high density of dislocations quickly reaches saturation, which contributes to an early, localized deformation in the form of necking [14]. Indeed, some experiments show that it is possible to preserve ductility after SPD [15].

The basic criterion of ductile or brittle fracture was proposed by Rice [16], and can be explained as a competition between cleavage and dislocation emission from the crack front. Based on this, Gizynski et al. [2] proposed that to obtain ductile fracture, the dislocation must be closer than a certain critical distance to the crack front. In this case, the dislocation near the crack front is subjected to a slip in the stress field of the crack front. As the stress rapidly decreases with the distance from the crack front, when the dislocation is too far from the front, the stress will be too low to move the dislocation and slip will not occur. In UFG materials the dislocation density can be large enough that the average distance between them is less than the critical and ductile fracture can occur. When the dislocation density is too low, the average distance between them is greater than the critical distance and in such case a cleavage is observed. Gizynski et al. [2] have shown that the iron with dislocation density greater than a critical one breaks in a ductile manner even at impact tensile test in liquid nitrogen. They tested UFG iron produced by hydrostatic extrusion, with grains elongated parallel to the extrusion direction, but only specimens where cracks were propagating perpendicularly to the direction of grain elongation was investigated. In their work, they did not analyze the influence of the cracks propagation path on the behaviour of the material.

According to Ovid'ko's and Sheinerman's [17] theoretical analysis of UFG materials, dislocations emitted from a crack are blocked at grain boundaries as crack blunting. This results in decreasing ductility, but it must be added that this mechanism is not popular in nanomaterials. Armstrong and Antolovich [18] have proposed that the cracking mode depends on a piling up of dislocations. He assumed that cleavage cracking should not occur in the case of small numbers of dislocations in the pile-up at the front edge of the crack.

Hohenvarter and Pippan proved that the crack propagation, path and fracture resistance of a material is strongly dependent on grain orientation. In [6] they reported about iron produced via HPT. Specimens were prepared in such way that three different crack plane orientation were investigated. It was found that fracture toughness value strongly depended of crack propagation path. Similar results were obtained for iron produced via ECAP [19]. Iron produced via HPT was investigated by Leitner [20]. Specimens from four different direction was prepared for fatigue crack propagation test. The

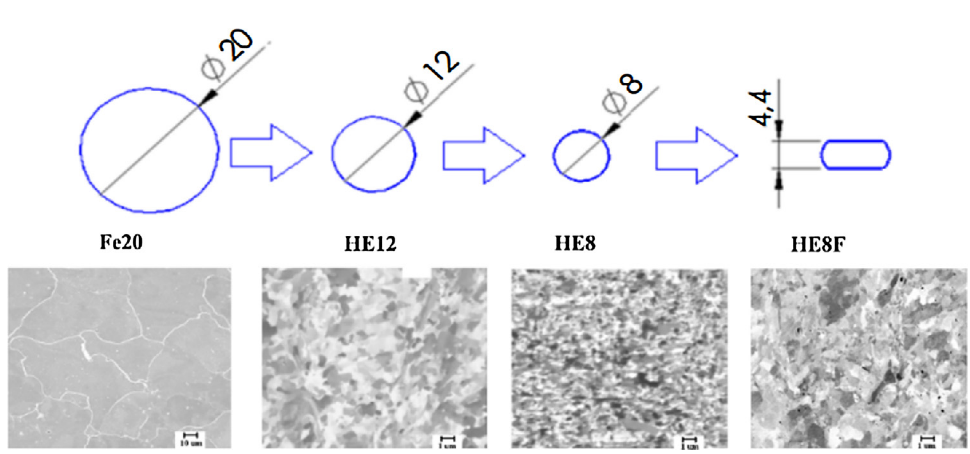

Fig. 1 – The scheme of material processing.