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Simulation of anisotropic fracture behaviour of polycrystalline round blank tungsten using cohesive zone model

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ABSTRACT

The experimental observation of anisotropic fracture behaviour of round blank polycrystalline tungsten was simulated using finite element (FE) method in combination with cohesive zone model. Experiments in the past had shown that due to the anisotropic microstructure the fracture toughness varies by factor of about two for different orientations. The reason is the crack propagation direction, which is - in some orientations - not the typical crack propagation direction for mode I fracture. In some directions the crack is not growing perpendicular to the crack opening tensile load. Nevertheless, in the present paper, the microstructure is modelled by FE mesh including cohesive zone elements which mimic grain boundaries (GB). This is based on the assumption that GB's are the weakest links in the structure. The use of the correct parameters to describe the fracture process allows the description of the observed experimental orientation dependent fracture toughness.

1. Introduction

For future fusion reactors tungsten is an important candidate for armour and structural application due to its good thermo-physical properties. Nevertheless, one issue is the relatively low fracture toughness and high ductile-to-brittle transition temperature (DBTT). In addition to that, the fracture toughness depends on material orientation due to its anisotropic. For available commercial polycrystalline tungsten, which was investigated many times in literature [1–3], the characteristic grain structure and texture play an important role in fracture toughness.

In the past Gaganidze et al. [4] did fracture mechanical experiments on round blank polycrystalline tungsten and tested the material in different orientations like longitudinal (L-R), radial (R-L) and circumferential (C-R). For the tests sub-size three point bend specimens (so called KLST specimens) with dimension of $27 \times 4 \times 3\ mm^3$ with 1 mm deep U-type notches [4] have been used over a wide temperature range from room temperature up to 1000 °C. For testing at room temperature the authors observed fracture toughness within the brittle regime which lies between 7 and 15 MPa $m^{0.5}$, depending on microstructural orientation. The reason for this variation in fracture toughness is the crack propagation direction, which is - in some orientations - not the typical crack propagation direction for mode I fracture (perpendicular to the crack opening mode).

For this reason, the objective of the present work is to model the microstructure by finite element (FE) mesh including so called cohesive zone elements, which act as grain boundaries (GB). The typical application of cohesive elements is to simulate the delamination of fibre-reinforced composite laminates [5], [6]. Another application, which is used within this paper, is the simulation of crack growth using cohesive elements. As shown for example for three dimensional crack propagation in Ref. [7]. More details about the historical background, the ongoing developments on cohesive zone models or the use of different so called traction separation laws are available in Ref. [8]. Some guidelines for application of cohesive models can be found in Ref. [9].

The novelties in the present paper are that the finite element mesh represents the material specific microstructure with its elongated grains and the nodes of the elements used near the crack tip are not shared within different elements. The connection between all elements in this region is achieved using cohesive zone elements, which act as grain boundaries. This modelling is based on the assumption that GB's are the weakest link in the structure. As a consequence, the crack can grow along grain boundaries and the crack path can kink. Using now the right intrinsic parameters to

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Nomenclature

Abbreviations

3PB	three point bend
C-R	circumferential orientation
CPE4	4 node structural plane strain element of ABAQUS
FE	finite element
GB	grain boundary
KLST	specific specimen geometry name
L-R	longitudinal orientation
R-L	radial orientation
RT	room temperature
UEL	user element

Symbols

F	force N
G	energy release rate Nmm^{-1}
J	J Integral Nmm^{-1}
K_{Ic}	fracture toughness acc. to ASTM E399 $MPa\sqrt{m}$
R	aspect ratio
u	displacement mm
δ_c	critical separation mm
δ_N	normal separation mm
δ_T	tangential separation mm
Γ_c	cohesive energy Nmm^{-1}
σ_c	cohesive stress MPa

describe the fracture process (independent on specimen orientation) allows the description of the observed fracture toughness in the experiment. The objective in the following is to identify the parameters required to describe the fracture process in the cohesive zone (cohesive stress and cohesive energy) and to see if experimental behaviour can be simulated.

2. Material and experimental fracture behaviour

The material of interest is round blank polycrystalline tungsten, which was experimentally tested by Gaganidze et al. [4]. Information about fabrication route can be found in Ref. [16]. The raw material is a round blank with diameter of 180 mm and height of 30 mm. Three point bend (3PB) specimens, called KLST specimens ($3 \times 4 \times 27\ mm^3$), were cut [4] by wire erosion in different orientations like longitudinal (L-R), radial (R-L) and circumferential (C-R) with U-type starter notch of 1 mm depth. To enhance the stress concentration and triaxiality of the U-type notches a specific technique, called razor blade polishing [10], was used. Traditional fatigue pre-cracking is often not successful due to brittleness of tungsten at room temperature. A comparison of razor blade polishing with fatigue pre-cracking has shown that fracture toughness using specimens with razor blade technique is only slightly increased and comparable to fatigue pre-cracking [10]. The quasi-static three point bend tests performed by Ref. [4] used cross-head displacement of $2 \cdot 10^{-3}$ mm/s and were tested in universal testing machine at elevated temperatures.

In case of room temperature (RT) selected force vs. displacement curves of different orientations (L-R, R-L and CR) are shown in Fig. 1. It is clearly visible that all orientations failed brittle without visible plastic deformation. The L-R orientation achieved a lower force value compared to R-L and C-R orientation. The calculated fracture toughness according to ASTM E399 standard is shown in Fig. 2. Fracture toughness K_{Ic} is about two times higher for R-L and C-R orientation compared to L-R orientation.

The reason for the dependence of orientation on fracture toughness can be found in its microstructure. Gaganidze et al. [4] investigated microstructure of round blank tungsten and found platelet shaped flat grains, which are stacked parallel to the round blank. A schematic microstructure of the L-R and R-L orientation of the round blank in combination with oriented crack plane is shown in Fig. 3 a) according to Ref. [4] and will be simulated within the present paper.

With regard to fracture toughness, the increase in applied load leads for L-R orientation to relatively facile increase in crack length, because flat grains are orientated parallel to the crack. In contrast to that, for R-L orientation, the flat grains are perpendicular to the crack opening mode I. In this case the crack can change its direction, because this is energetically the favourable path (principle of minimum energy) for crack propagation. More details on the experimental testing can be found in Ref. [4]. Fig. 3 b) shows the microstructure of the elongated grains. The green area highlights two representative grains with its dimensions. The aspect ratio of these grains lies in the range between 6 and 8.

The idea in the following is to simulate the experimental observed anisotropic behaviour of tungsten using finite element method and specific elements to simulate crack propagation based on the materials microstructure.

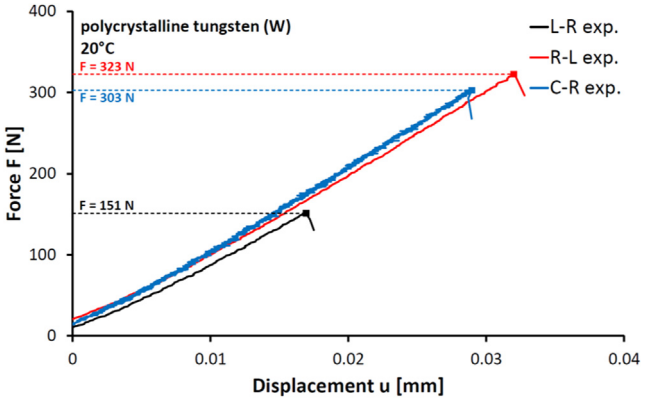

Fig. 1. Experimental load vs. displacement curves for L-R, R-L and C-R orientation [4].

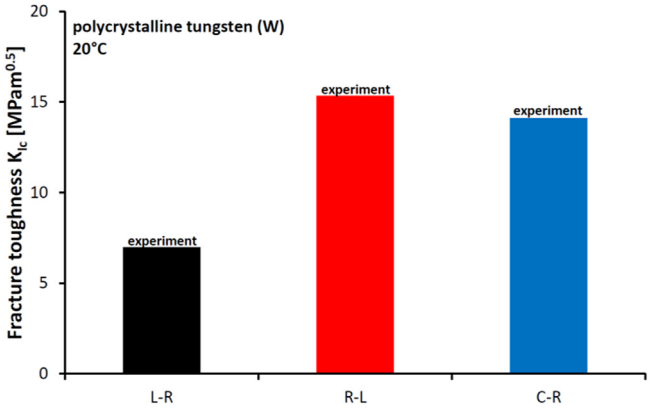

Fig. 2. Experimental fracture toughness for L-R, R-L and C-R orientation [4].