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Fracture toughness of polycrystalline tungsten alloys

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ABSTRACT

Tungsten and tungsten alloys show the typical change in fracture behavior from brittle at low temperatures to ductile at high temperatures. In order to improve the understanding of the effect of microstructure the fracture toughness of pure tungsten, potassium doped tungsten, tungsten with 1 wt.% La_2O_3 and tungsten rhenium alloys were investigated by means of 3-point bending, double cantilever beam and compact tension specimens. All these materials show the expected increase in fracture toughness with increasing temperature. The experiments demonstrate that grain size, texture, chemical composition, grain boundary segregation and dislocation density seem to have a large effect on fracture toughness below the DBTT. These influences can be seen in the fracture behavior and morphology, where two kinds of fracture occur: on the one hand transgranular and on the other hand intergranular fracture. Therefore, techniques like electron backscatter diffraction (EBSD), Auger electron spectroscopy (AES) and X-ray line profile analysis were used to improve the understanding of the parameters influencing fracture toughness.

1. Introduction

Most studies related to the ductility of tungsten and tungsten alloys were performed in the sixties and seventies. A good example is Raffo et al. [1]. As fracture mechanics was not well established at that time studies on fracture toughness were scarce. Riedle and Gumbsch [2–5] extensively studied the fracture toughness of tungsten single crystals in the nineties. The effects of crystallographic orientation, crack propagation direction, loading rate and temperature were investigated. Compared to the single crystal, the fracture toughness of polycrystalline tungsten is not yet well examined.

We started an extensive investigation of the fracture toughness of pure tungsten (W), potassium doped tungsten (AKS-W), tungsten with 1 wt.% La_2O_3 (WL10) and tungsten–26 wt%-rhenium (WRe26). The results of a few selected microstructures are presented in this paper. A very large effect of the microstructure, especially below the ductile to brittle transition temperature, was observed. These investigations indicate that the change from transgranular to intergranular cleavage fracture plays an important role. Especially crystallographic analyses are presented to improve understanding of the interaction of these fracture processes.

This paper was also presented at the 12th International Conference on Fracture—July 12–17, 2009.

2. Experimental

The fracture toughness of W, AKS-W, WL10 and WRe26 were investigated by means of 3-point bending (3 PB — Fig. 1-a), double cantilever beam (DCB — Fig. 1-b) and compact tension specimens (CT — Fig. 1-c). All specimens were manufactured out of rods at different stages of the processing route. Fig. 1 shows specimens prepared to investigate the materials in rolling direction and radial direction. The experiments were performed in the range of −196 °C to 1000 °C.

In order to examine the local variation of the fracture resistance, DCB-specimens (Fig. 2-a) with a length of 30 mm, a height of 3.5 mm and width of 7.5 mm and CT-specimens with a length of 7.5 mm, a height of 3 mm and a width of 6 mm were manufactured out of W, AKS-W, and WRe-rods. The notches were prepared with a diamond-saw, refined with a razor blade and fatigue-precracked under cyclic compression [6]. The areas in front of the crack-tips were scanned using electron backscatter diffraction (EBSD) after a heat treatment of 2000 °C for an hour in hydrogen atmosphere (Fig. 2-b). Some specimens were then loaded under tension within the range of stable crack growth (Fig. 2-c). After that, the previously scanned areas were scanned again using EBSD (Fig. 2-d) to quantify changes of the grain orientation in the obtained orientation imaging maps (OIM).

The tests performed at room temperature were done with a microtensile-testing machine from *Kammrath & Weiss*, while the tests at elevated temperatures were done by use of a *ZWICK* universal-testing machine. The fractographic and crystallographic analyses were

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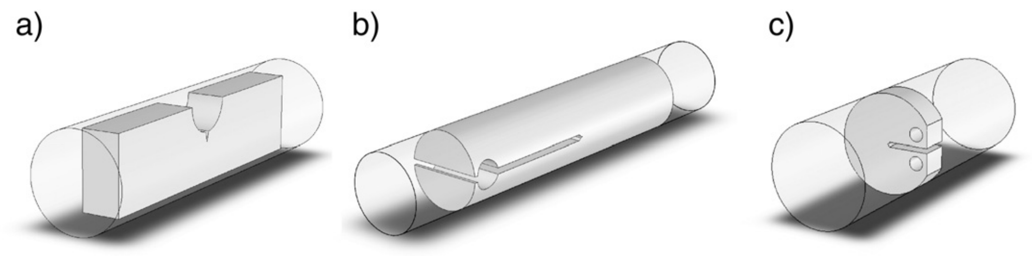

Fig. 1. Different specimen types manufactured out of tungsten rods. 3PB-specimen with crack direction in radial direction (a). DCB-specimen with crack direction in rolling direction (b). CT-specimen with crack direction in radial direction (c).

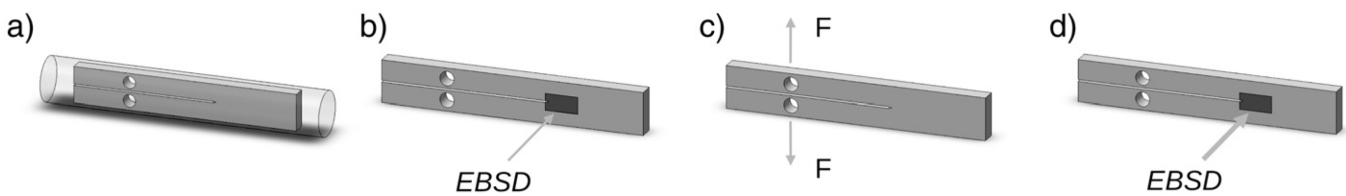

Fig. 2. Experimental setup to investigate the local variation of the fracture resistance: position of a DCB-specimen in a AKS-W rod (a). Scanning the area in front of the crack tip using EBSD (b). Apply a tensile load on the specimen (c). Scanning the previously scanned area again (d).

made by use of a Zeiss 1525 scanning electron microscope equipped with an EDAX EBSD system.

3. Results and discussion

3.1. Fracture toughness investigations

All tested specimens showed the expected increase in fracture toughness with increasing temperature, examples are shown in Fig. 3 with the associated values shown in Table 1.

At low temperatures, the fracture toughness was determined by use of linear elastic fracture mechanics whereas at temperatures above 600 °C the critical crack tip opening displacement *CTOD* [7] was used to determine the critical stress intensity factor. The fracture toughness determined by stereophotogrammetric techniques is then calculated by

$$K_{IC} = \sqrt{m \cdot \sigma_y \cdot E \cdot COD_C} \tag{1}$$

where σ_y represents the yield strength, E the Young's modulus and m a coefficient which depends on the work hardening factor n of the material. For low hardening m is about 1.5 [8,9].

σ_y for recrystallized and stress relieved W as a function of the temperature are shown in Fig. 4 as well as in Table 2 which show the expected decrease of the yield strength with increasing temperature [10].

Table 3 shows fracture toughness values of CT and 3 PB specimens tested at room temperature. The two letter code in the brackets describes the crack plane orientation of different specimens with respect to the geometry of the manufactured material. The first letter designates the *direction normal* to the crack plane, and the second letter the *expected direction of crack propagation* [11]. φ is the technically degree of deformation, referring to a rolling process, given by $\Delta A/A_0$ where ΔA is the cross-sectional reduction in area and A_0 is the original area of the cross-section. Due to the extreme differences of the determined K_Q values, the processing route seems to have a great influence on the results as well as the direction the specimens have been manufactured out of the rods. While sintered materials have equiaxed

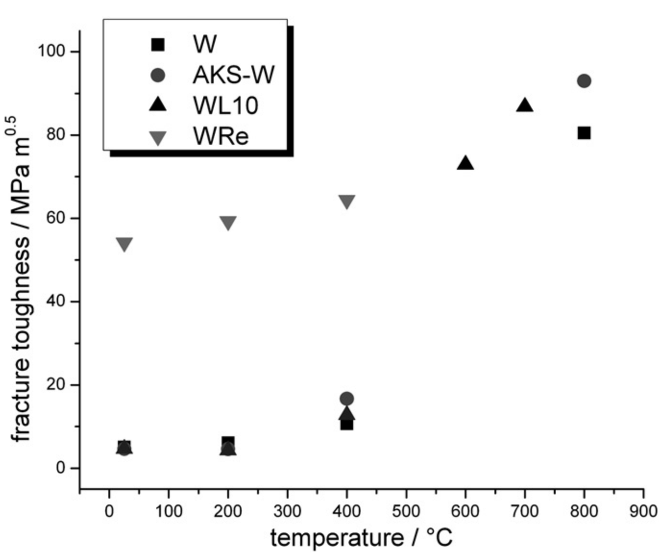

Fig. 3. Fracture toughness K_Q of W, AKS-W, WL10 (sintered) and WRe26 (rolled and stress relieved) as a function of temperature T. All values above 400 °C have been calculated from their COD_C values using Eq. (1).

Table 1
Table of K_Q values of W, AKS-W, WL10 (sintered) and WRe26 (rolled and stress relieved) tested in the temperature range from room temperature to 800 °C.

Temperature [°C]	Fracture toughness [MPam$^{0.5}$]			
	W	AKS-W	WL10	WRe
RT	5.1	4.7	4.7	54.2
200	6.1	4.6	4.3	59.3
400	10.7	16.7	12.8	64.4
600	–	–	72.9[a]	–
700	–	–	86.3[a]	–
800	80.5[a]	93.0[a]	–	–

[a] These K_Q values have been estimated from the COD_C values using Eq. (1).