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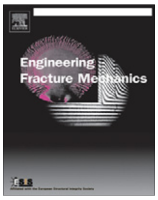

A study into the crack propagation resistance of pure tungsten

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ABSTRACT

Recrystallized and deformed tungsten were investigated regarding their crack resistance as a function of crack extension. The compact tension specimens were manufactured with different crack plane orientations with respect to the axis of a rod. All recrystallized samples fractured predominantly intergranularly, whereas the deformed samples fractured transgranularly in certain crack propagation directions. Both showed an increase in the fracture resistance with crack extension, i.e. they exhibit *R*-curve behavior. It was determined in this study that the consolidation of the various fracture planes and crack bridging cause this *R*-curve behavior in tungsten.

1. Introduction

Fracture toughness is an important parameter for the characterization of the mechanical behavior of materials and describes the resistance of a material against crack propagation. For ductile materials it is – given small scale yielding – usually assumed that the fracture resistance is independent of the crack extension, based on the concept of Irwin [1]. The energy to generate a fracture surface under linear elastic fracture mechanic conditions is the specific surface energy plus the specific plastic work to extend the crack, both are assumed to be independent of the absolute crack length. As a consequence the critical energy release rate and therefore also the critical stress intensity factor should not depend on crack extension. In the case of ceramics it is well known that – due to pseudo-plastic effects – the fracture resistance increases with crack extension until it reaches a steady state value, see for example [2]. This increase of the fracture resistance is called *R*-curve behavior. To characterize the resistance against fracture, a curve, for example the critical stress intensity versus crack extension, is required instead of a single parameter like the plane strain fracture toughness, K_{IC}, or the critical energy release rate G_{IC}. Due to their ductile behavior the fracture toughness of metals and alloys is – assuming plane strain conditions – usually characterized by a single parameter determined according to a certain standard, for example the ASTM standard E399 [3]. Bcc metals show a ductile to brittle transition with a relatively high fracture resistance at high temperatures caused by the microductile fracture process and a low fracture resistance at low temperatures induced by a cleavage like crack propagation. Despite the different fracture processes, the fracture toughness below as well as above the ductile transition temperature is usually determined by the same procedure.

The aim of this paper is to show that the fracture resistance of tungsten shows *R*-curve behavior at low temperatures similar to toughened ceramics despite plasticity being involved in the fracture process. Microstructures which exhibit

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Nomenclature

K_{IC}	plane strain fracture toughness
G_{IC}	critical energy release rate
K	stress intensity
Δa	crack extension
$C\ (T)$	compact tension specimen
C	circumferential
R	radial
L	longitudinal
EBSD	electron backscatter diffraction
IPF	inverse pole figure
IQ	image quality
SEM	scanning electron microscope
FIB	focused ion beam microscope
λ	width of the bridge between FIB-cut notches

predominantly intergranular fracture and transgranular cleavage are analyzed. Furthermore, special attention is paid to the pre-crack and the effect of different pre-cracking procedures on the resulting *R*-curve.

Rupp and Weygand previously reported a strong temperature dependency on the fracture toughness of sintered and rolled tungsten. [4] Their work, however, concentrates more on the effect of crystallographic and grain shape anisotropy on the brittle-to-ductile transition temperature rather than on the crack propagation resistance of intergranularly and transgranularly fractured tungsten.

2. Experimental methods

The crack propagation behavior of technically pure tungsten in the recrystallized and deformed state was investigated under monotonic loading. The material – provided by Plansee SE – was received as a rod with 20 mm diameter. The main impurity elements were determined by a chemical analysis and the obtained composition can be seen in Table 1.

Compact tension, $C\ (T)$, specimens (width 6 mm; thickness 3 mm), with different crack propagation directions according to ASTM standard E399 [3], were manufactured out of the rod. After notching with a diamond wire saw and polishing by razor blade, most samples were recrystallized at 2000 °C for one hour leading to a slightly elongated grain structure, as shown in Fig. 1a. (The diameter d of the grains in the cross section is about 80 µm while the length l is approximately 150 µm.) Afterwards, the specimens were fatigue pre-cracked under cyclic compression ($R = 20$). In this case – recrystallization *before* pre-cracking – the crack-tip is generally in the interior of the grain. Some of the samples were fatigue pre-cracked right after polishing the notch, followed by the recrystallization step. In this case – recrystallization *after* pre-cracking – the crack-tip is expected to lie at a grain boundary.

Compared to these recrystallized samples, a part of the original 20 mm tungsten rod was recrystallized and subsequently deformed to 110% at 650 °C in compression. This leads to flattened, platelet-like shaped grains ($d \approx 200$ µm, $l \approx 50$ µm), as

Table 1
Main impurity elements of the technically pure tungsten ($W > 99.97\%$) investigated.

Element	C	H	N	O	P	S	Si
Guaranteed analysis (max)/µg/g	30	5	5	20	20	5	20
Typical analysis/µg/g	10	2	<2	5	<10	<2	5

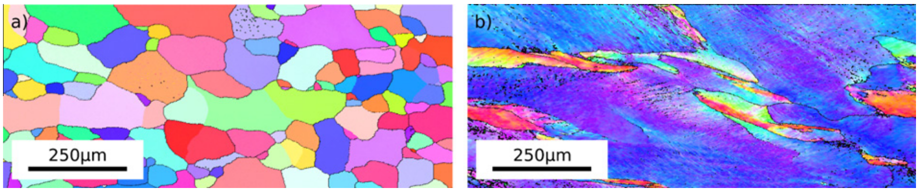

Fig. 1. Microstructures of the tungsten samples investigated. The inverse pole figure (IPF) maps show that both materials, the recrystallized (a) and the deformed tungsten (b), have an elongated grain structure. Compared to the recrystallized material the deformed sample shows a pronounced substructure, obvious from the changes of the crystal orientation.