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Fatigue testing and microstructural characterization of tungsten heavy alloy Densimet 185

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ABSTRACT

A rotating target consisting of helium-cooled tungsten has been chosen for the European Spallation Source (ESS) facility to be built in Lund. Thermo-mechanical cycling due to the incidence of the proton beam every 2 s on any given tungsten slab in the rotating wheel could lead to crack formation and failure over the lifetime of the target. This work reports tensile and fatigue data obtained at room temperature for the Densimet 185 alloy in the non-irradiated condition. Methods for extracting relevant parameters from fatigue curves with small sets of data are discussed. Fatigue results show a large spread of data for which the application of such methods is challenging. Stress controlled fatigue testing was carried out in this study with mean stress approaching zero and amplitudes in the range 250 to 450 MPa, with 50 MPa increments. A frequency of 25Hz was employed and the fatigue tests lasted until failure was registered or until the upper limit of 2×10^6 cycles was reached. No failure due to fatigue occurred in specimens subjected to stress amplitudes below 300 MPa. Microstructural and fractographic studies on the fatigue samples using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) showed that the samples had low porosity, large and nearly spherical tungsten grains, and with a fairly uniform distribution of the ductile phase rich in nickel and iron. However, bonding between tungsten grains in some areas was found to be inadequate. Intergranular fracture was predominant in the specimens at room temperature. Data for the D185 alloy are compared to those for IT180 and D176 alloys obtained in a previous study and strategies for improving the fatigue strength are discussed.

1. Introduction

Characterization of materials using light/electron microscopy as well as X-ray diffraction is well established and used as a standard procedure for examining materials. However, the use of neutrons in materials research is still not widespread although its usefulness and advantages over conventional methods are now well recognized. In this context, it is interesting to note the setting up of a neutron facility at the European Spallation Source (ESS) site in Lund. This facility can be likened to a gigantic microscope that uses neutrons instead of light to examine materials. Tungsten alloys were initially considered as potential target materials in this facility and this paper examines the suitability of tungsten heavy alloy Densimet 185 (W–2 wt.% Ni–1 wt.% Fe), primarily from a fatigue viewpoint.

The pulsing of the proton beam during the spallation procedure results in rapid changes in temperature and thermal expansion or shrinkage, leading to stresses in the material. It is therefore necessary to cool the target material effectively in order to minimize thermal stresses. In this context, rotation of the target is beneficial and needs to be optimized to maximize the time between beam pulses impinging on the same region of the target. Limiting the increase in target temperature to a minimum is desirable in order to minimize the negative effects on the mechanical properties of the target material. Although the magnitude of the peak stresses caused by the proton beam impinging on the target may be considerably less than the yield stress of the material, failure due to material fatigue must be taken into consideration. The suitability of various tungsten alloys as target materials can be evaluated with a good knowledge of the fatigue properties of these alloys. However, a scan of literature indicates limited data reported for these alloys. Fracture toughness of tungsten heavy metal alloys has been studied by

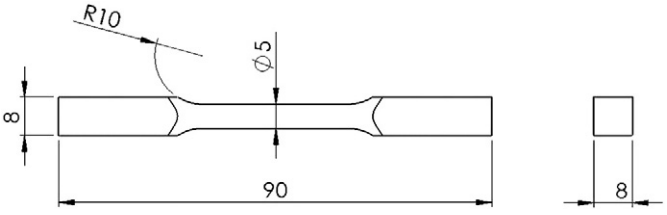

Fig. 1. Sample dimensions (in mm).

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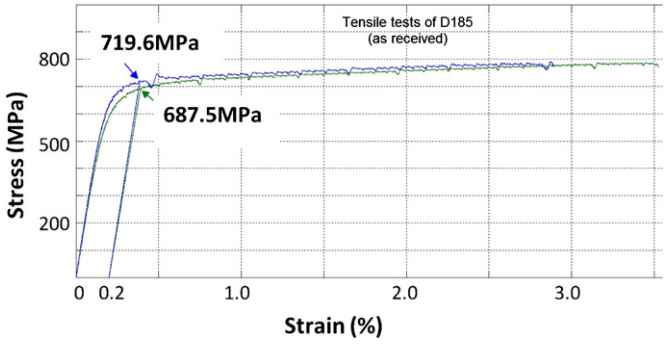

Fig. 2. Stress–strain curves for D185 alloy at 25 °C.

Table 1
Fatigue test data for D185 alloy at room temperature.

Specimen no.	σ_a (MPa)	N_f (10^5 cycles)	Specimen no.	σ_a (MPa)	N_f (10^5 cycles)
1	350	1.067	9	450	1.446
2	350	11.411	10, 11	250	Run-out[a]
3	350	2.459	11a	300	15.307
4	350	3.297	12	300	Run-out[a]
5	350	4.031	12a	350	3.803
6	350	Run-out[a]	13	400	1.046
7	450	4.720	14	300	Run-out[a]
8	450	2.740	14a	400	0.607

[a] Run-out: 2×10^6 cycles.

Zamora et al. [1]. They considered the effects of composition, grain size, prior plastic strain and the ductile phase surrounding the tungsten grains on fracture toughness. Rittel and Weisbrod [2] used a short beam experimental technique to characterize the mode I dynamic fracture toughness of a commercial tungsten heavy alloy (W–7 wt.% Ni–3 wt.% Fe) at loading rates of about 10^6 MPa $m^{1/2}$ s^{-1}. They found that the dynamic fracture toughness is rate sensitive and anisotropic. Ryu et al. [3] studied the microstructure and mechanical properties of a mechanically alloyed and solid-state sintered tungsten heavy alloy (W–5.6 wt.% Ni–1.4 wt.% Fe). For this alloy, they report an increase in yield strength due to the nanoscale microstructure, but reduced ductility due to the low volume fraction of the ductile phase present. Apart from these studies on fracture, not much data have been reported on the fatigue behavior of tungsten heavy alloys. Recently, Lorenzo et al. [4,5] studied the fatigue behavior of tungsten heavy alloys IT180 and D176 at room temperature. Along similar lines, the present study focuses on stress-controlled High Cycle Fatigue (HCF) experiments for the determination of fatigue properties and the establishment of a Stress–Life (S–N) curve for the tungsten heavy alloy Densimet 185 at room temperature.

2. Materials and methods

Seventeen specimens of the alloy Densimet 185 were supplied by Plansee and the specimen dimensions are shown in Fig. 1. After tensile testing, fatigue tests were conducted in the relatively high cycle fatigue region of 10^4 to 10^7 cycles, followed by microstructural characterization of the fracture surfaces.

An MTS Ramen machine (maximum capacity: 250kN) connected to an Instron Digital Electronic control system was used for tensile and fatigue testing (at zero mean stress). For metallographic examination using a Leitz optical microscope and an ESEM, the specimens were sectioned and mounted using a Predopress Struers machine. Fractographic studies and microstructural characterization were followed by Energy Dispersive Spectroscopy (EDS) and X-ray mapping.

3. Results and discussion

3.1. Mechanical testing

Two tensile tests on specimens (5.01 mm in diameter) in the as-received condition were carried out according to the ASTM practice E8 [6]. A gauge length of 12.5 mm was used and the loading rate was set to 3 mm/min until failure. The resulting stress–strain curves are shown in Fig. 2. Within the limits of experimental error, a small variation in the values of the Young's modulus and the 0.2% Proof stress were observed in the two sets of data.

Fifteen specimens were used for fatigue testing at various stress amplitudes in the interval 250 to 450 MPa, with 50 MPa increments and a mean stress equal to zero. A sinusoidal load with a frequency of 25 Hz was applied until specimen failure or up to the run-out limit which was considered to be 2×10^6 cycles.

Initially, three fatigue tests were performed using specimens in the as-received condition at a stress amplitude (σ_a) of 350 MPa. As seen in Table 1, for specimens 1 to 3, the test results showed a ten-fold variation in fatigue life from about 10^5 to 10^6 cycles. Further, all three specimens failed near the shoulder area. Examination of the surface roughness of the specimens revealed deviations from the ASTM standard [7]. In order to decrease the surface roughness, a grinding and polishing procedure was carried out prior to fatigue testing of the remaining specimens. Silicon carbide paper (320 and 1000 grains/in^2) and diamond paste (3 and 1 μm) were used for wet grinding/polishing of the specimens using a Struers Rotopol-2 equipment. Even after surface preparation, some striations from the specimen manufacturing stage were visible at a magnification 20×. Surface porosity was observed before and after the grinding/polishing operation. While some of the pores could be removed through grinding, sub-surface pores were visible after surface preparation. Fig. 3 shows the surface condition of Specimen 9, prior to and after polishing, at a magnification 25×. Surface roughness and the number of visible pores were observed to be more in the specimen shoulder region.

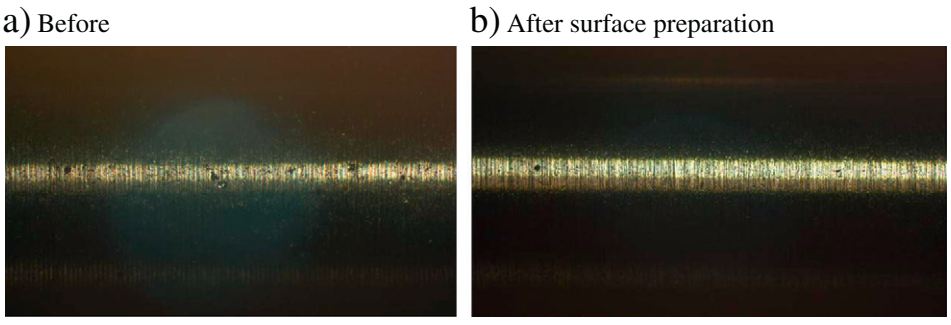

Fig. 3. Surface condition at the center (a) prior to and (b) after grinding and polishing (specimen 9, 25×).