Tungsten materials for structural divertor applications

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Introduction

Present design studies for extremely high loaded plasma facing cooling components make use of the high temperature strength and good heat conductivity of tungsten [e.g. 1, 2]. The most critical issue of tungsten materials in connection with structural applications is their brittleness. It is known that fracture behaviour as well as thermal conductivity depends on textures. Therefore, the microstructure, the chemical composition and their influence on thermal conductivity as well as on impact bending properties were investigated, using commercial tungsten and other refractory alloys.

Results and Discussion

Heat conductivity was measured by the laser-flash method for a tungsten plate (4 mm thick), for a W-1wt.%La_2O_3 (WL10) rod and plate, for a DENSIMET (W-3.5wt.%Ni-1.5wt.%Fe) plate, and for a Ta-10wt.%W (TaW10) rod and plate. DENSIMET and WL10 are binary phase materials while TaW10 is an alloy (solid solution). The measurements were performed perpendicular to the plate surfaces and parallel to the rod axis. The results are given in Fig. 1.

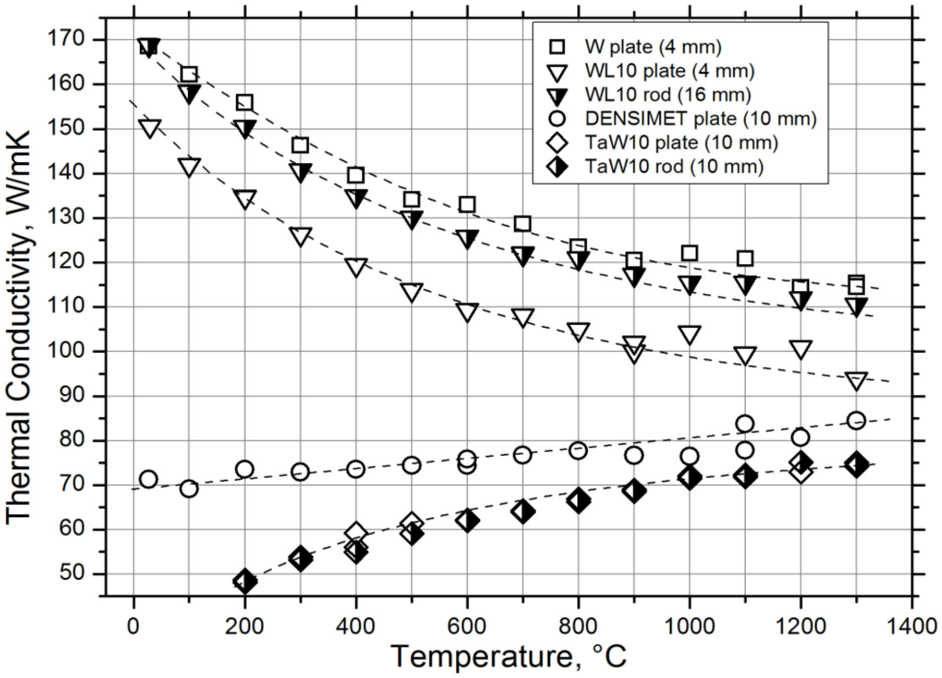

Fig. 1: Thermal conductivity of various refractory materials.

With rising temperatures, the tungsten plate and WL10 materials show a continuous decrease of conductivity whereas TaW10 and DENSIMET show an increase. With values higher than 90 W/mK at 1300°C, pure tungsten and WL exhibit the best results. However, a clear reduction of the conductivity can be observed in the case of the pure tungsten and WL10 plates. On the one hand, this behaviour is a consequence of the lanthanum-oxide content, and of the microstructure (compared to the WL10 rod), on the other.

Fabrication and testing of Charpy specimens has been performed according to the EU standards DIN EN ISO 148-1 and 14556:2006-10. That is, small size specimens (27 mm x 3 mm x 4 mm, 1 mm notch depth, 22 mm span) have been used. To avoid oxidation the whole Charpy testing machine was placed inside a vacuum vessel which was operated at typical pressures of about 10^{-3} mBar.

The Charpy tests were performed on specimens fabricated from rods as well as from plates. Five different tungsten rod materials were considered: pure W, WL10 standard and with highest possible level of deformation (WL10opt), potassium (0.005 wt.%) doped tungsten (WVM), and WL10 with 1 wt.% Re (W1Re1-La_2O_3). Plates of pure W, WL10, WVM, and molybdenum-Ti-Zr (TZM) were also used for the investigation. More detailed information about material fabrication, microstructure examinations, and Charpy test results can be found in [3, 4].

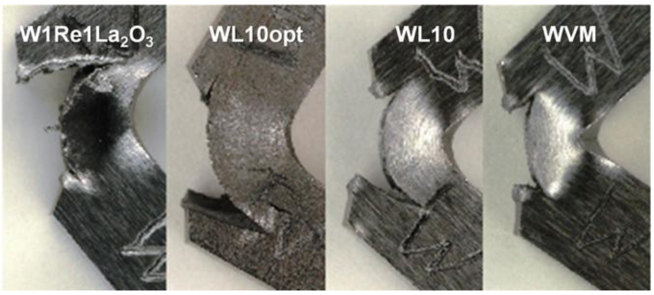

Fig. 3: Side view of delamination fractures in Charpy specimens of various tungsten rod materials.

Typically, bcc metals show a transition from brittle (trans-crystalline) to ductile fracture. But the tungsten based rod materials don’t show this single transition. Moreover, only specimens of pure tungsten and WVM show fully ductile fractures, starting at 900 °C and 1000 °C, respectively. However, all materials tend to exhibit brittle fracture at temperatures below 600 °C. Above that temperature, the specimens show fractures which propagate along the rod axis, that is, parallel to the specimen’s long side and perpendicular to the notch (see Fig. 3). There are obviously similarities to the fracturing of fiber reinforced materials and, therefore, this type of fracture is usually called delamination. In summary, there are three types of fracture (brittle, delamination, and ductile) which are linked by a brittle-to-delamination transition and a delamination-to-ductile transition.

Compared to the rod materials, the Charpy energies of specimens of the plate materials are lower by more than 50 %. Moreover, all plate material specimens don’t show fully ductile fractures, even at test temperatures up to 1100 °C. Below 500 °C the tungsten and below 200 °C the TZM plate specimens fracture brittle (trans-crystalline). But at and above these test temperatures the fracture mode, and therefore, the fracture surfaces change significantly (see Fig. 4).

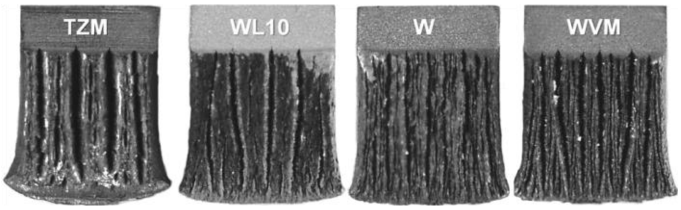

Fig. 4: Fracture surface of Charpy specimens of molybdenum and tungsten-based plate materials.

The explanation for the heat conductivity as well as for the fracture behavior is based on the different microstructures which are depicted in Fig. 5 and 6. An explanation for the different fractures can be given with help of the sketches given in Fig. 7 and 8. In rod specimens the grains are shaped needle-like and oriented perpendicular to the notch.

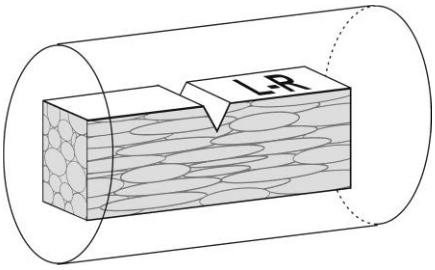

Fig. 5: Microstructure and specimen orientation in rod materials.

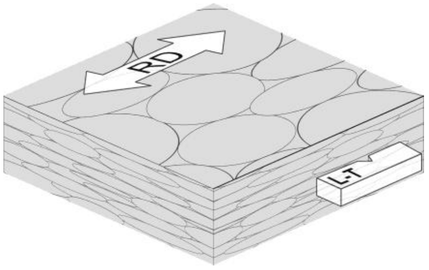

Fig. 6: Microstructure and specimen orientation in plate materials.

By applying a force F to the specimen during loading (Fig. 7b), it is bended which generates not only tensile stress, but also stresses parallel to the notch direction (indicated by the white arrows). For a certain strain rate and within the right temperature range, the grain boundaries are the weakest link in the microstructure. Therefore, inter-granular fracture is most likely to appear (Fig. 7c).

In the plates, the grains are shaped like pancakes which are more or less elongated in rolling direction (RD). During loading, the Charpy specimen is bended which generates a tensile stress σ, but applies also perpendicular stresses (Fig. 8a, b), indicated by the white arrows. These stresses compress the grains normal to their flat surface. Therefore, the maximum tensile stress which acts normal to the grain boundaries, appears at the tips. Due to the reduction of the effective cross-section the stress on the remaining grains is increased. Therefore, the grains which are still conjunct are further elongated. This in turn leads to necking of the conjunct grains and then to fast (inter-granular) crack propagation along the grain boundaries (Fig. 8c).

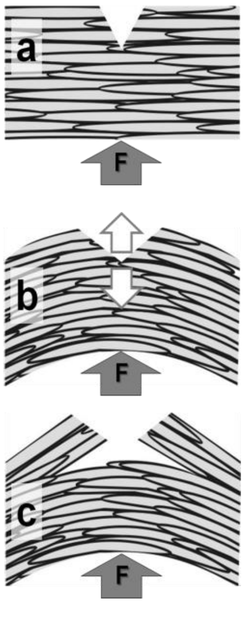

Fig. 7: Side view of a bended rod specimen.

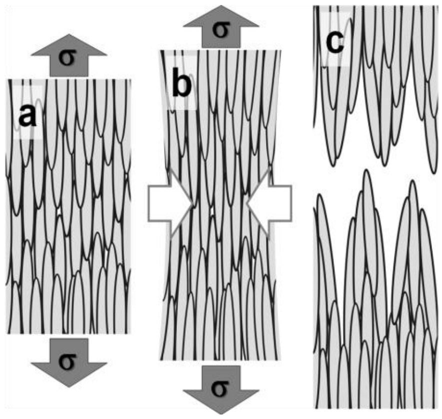

Fig. 8: Top view on the notch root of a plate specimen.

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