Fusion Engineering and Design 86 (2011) 2949–2953

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Deep drawing of tungsten plates for structural divertor applications in future fusion devices

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ARTICLE INFO

Article history:
Received 4 April 2011
Received in revised form 21 June 2011
Accepted 26 July 2011
Available online 7 September 2011

Keywords:
Helium cooled divertor
Deep drawing
Tungsten
Mass production
Grain boundary alignment
Thimble

ABSTRACT

The reference design of a helium cooled divertor for future fusion reactors makes use of hundreds of thousands of finger units consisting of a pressurized structural part called a thimble. Due to the high number of parts needed, the thimble has to be fabricated by mass production techniques like deep drawing. As the thimble is a pressurized part exposed to an internal pressure of 100 bar, the demands for the material are high, which means that it requires the best available tungsten material. Former work has shown that pure tungsten material has the best impact properties and has to be preferred over other commercially available tungsten materials, such as that doped with potassium or strengthened with oxides like lanthanum oxide.

Furthermore the inherent weakness of the grain boundaries has to be taken into account, which requires the need for grains that are aligned to the contour of the part (grain boundary alignment).

This paper describes the successful deep drawing of a 1 mm tungsten plate in high vacuum at 600 °C. In doing this, a thimble can be machined with grains that follow the contour. Furthermore the characterization of a 1 mm tungsten plate is conducted by tensile tests at room temperature and at 600 °C, as well as by Charpy tests taking into account the anisotropic material behaviour.

1. Introduction

Present design concepts for future fusion DEMOnstration reactors include high heat flux components which have to be operated under extreme physical conditions. To enable long-term operation, the plasma has to be cleaned from helium, the “exhaust” of nuclear fusion, and from impurities such as particles from the first wall. These ions are redirected from the burning plasma by auxiliary magnetic fields towards cooled target plates, the plasma-facing parts of the so-called divertors. Refractory materials, in particular tungsten based materials, are considered primary candidates for structural high heat load applications in future nuclear fusion power plants. Promising helium-cooled divertor design outlines make use of their high heat conductivity and strength. In one of the most elaborate helium cooled divertor concept, the plasma-facing structure consists of several hundred thousand single modules which may be roughly subdivided into four components: a thermal shield made of tungsten which acts as armour, which is brazed to a thimble made of WL10 (W – 1 wt.% La_2O_3) with an integrated cooling unit cartridge which forms the helium jets, and the underlying structure (He inlet, outlet, manifold, etc.) of ODS (oxide dispersion strengthened) steel [1–3].

As several hundred thousand single modules are required, the machining of the parts must be done by a mass production technique, e.g. injection moulding or deep drawing. Turning and milling, however, is not regarded as a mass production technique.

The thimble is a pressurized part exposed to an internal pressure of 100 bar and is therefore regarded as a structural part requiring a structural material. However, until now tungsten is only used as a functional material. In addition to the upper limit, the recrystallisation temperature of the material and the lower limit, the ductile to brittle transition temperature (DBTT) has to be improved and taken into account. It has already been shown, that the higher the degree of deformation of the semi-finished tungsten product, the lower the DBTT (see for example [4]). This is why the thimble as a structural element should be made of a semi-finished product with a high degree of deformation.

Previous work shows that tungsten has a strong correlation between its manufacturing history (powder mixing, pressing, sintering, rolling, forging or swaging, hot work, cold work) and its microstructure. For tungsten plate materials, the microstructure looks like several layers of ‘pancakes’ whereas the grains of tungsten rod materials have the shape of long ‘fibres’ (see Fig. 1). Taking into account the weak grain boundaries which make tungsten

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0920-3796/$ – see front matter
doi:10.1016/j.fusengdes.2011.07.011

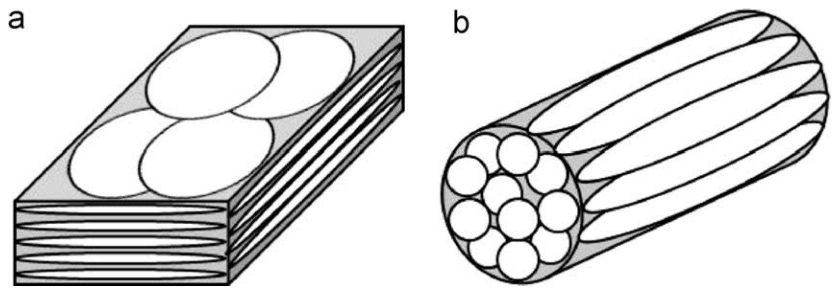

Fig. 1. Microstructure of a tungsten rod (a) and a tungsten plate (b). The grains in the rod can be seen as a bundle of 'fibres' and the grains in the plate can be considered as a stack of 'pancakes'.

materials inherently prone to delamination, it is obvious that different microstructures can lead to different crack behaviour. This in turn means that rods fracture easy along the rod axis direction and that plates show typical crack formation parallel to the surface [5–7]. Furthermore, it was shown that among all commercially available tungsten materials, e.g. doped with potassium (WVM) or strengthened with lanthanum oxide (WL10), pure tungsten exhibits the best crack behaviour (excluding tungsten with rhenium) and must therefore be preferred to all other tungsten materials [8].

So in general one can think of three possible manufacturing routes for the thimble. The first is turning a thimble out of a tungsten rod, the second is by powder injection moulding, and the third is by deep drawing a plate.

Turning a thimble from a rod does not fit to the needs of a mass production technique as the turning and milling of tungsten is very challenging. The greatest disadvantage, however, is that it would result in the worst possible grain orientation. The thimble is a pressurized part and cracks in internal pressure vessel components always appear along axis direction, which would correspond to the weak grain boundaries of a tungsten rod. Therefore rod material can be excluded for machining structural parts for divertor applications.

Powder injection moulding techniques are appropriate to the needs of a mass production technique, however, the extreme brittleness under dynamic loads of materials produced by this technique is the main drawback (see for example [9]).

By choosing the deep drawing technique combined with pure tungsten plate material we obtain the following advantages:

- Plate material is a semi-finished product with a high degree of deformation leading to a low DBTT.
- Pure tungsten exhibits the best crack behaviour among all commercially available tungsten materials.
- 'Grain boundary alignment': deep drawing a plate leads to a microstructure that follows the contour of the thimble which is necessary considering the inherent weakness of the grain boundaries of tungsten materials.
- Deep drawing can be considered as a mass production technique.

2. Characterization of 1 mm pure tungsten plate material

The tungsten plate material which has been chosen for the deep drawing process is unalloyed 99.97% pure tungsten with a thickness of 1 mm. This commercially available material was produced by PLANSEE Metall GmbH, Reutte/Austria. After sintering, the plate was hot and cold rolled with a high degree of deformation resulting in elongated grains leading to a microstructure that can be considered as a stack of 'pancakes'. The optical micrograph of a longitudinal section of rolled tungsten plate can be seen elsewhere [7].

Tensile tests at room temperature and at 600 °C were performed and will be discussed next. To determine the DBTT of the 1 mm tungsten plate material, instrumented Charpy tests were performed at elevated temperatures in vacuum using samples of dimensions 1 mm × 3 mm × 27 mm. It will be shown that 1 mm tungsten plate material is anisotropic, and that the tensile as well as the impact properties depend on the sample orientation. Herein we distinguish between 0° which means in the rolling direction and 90° which means perpendicular to the rolling direction.

2.1. Tensile test of 1 mm tungsten plate material at room temperature and 600 °C

Tensile tests with the 1 mm tungsten plate were performed in three directions: in rolling direction (0°), perpendicular to the rolling direction (90°) and at an angle of 45° to the rolling direction. All tensile tests were performed at room temperature and at 600 °C in a high vacuum in a Zwick030 test device. As the following deep drawing process is carried out at 600 °C it is important to determine the material's behaviour at the same temperature. The experiments were carried out using sub-sized specimens (gauge length 7 mm, width 2 mm). The test specimens were fabricated by electrical discharge machining (EDM) and all tests were performed displacement controlled with a strain rate of 0.1 mm/min.

From each orientation and temperature at least 3 samples were tested, and all samples failed in between the gauge length. Fig. 2 shows the results of the tensile tests at room temperature. As expected, the Young's modulus is isotropic [4]. Due to the high degree of deformation the plate has a high yield stress and a high tensile strength (e.g. at 0° and 45° orientation: $R_{p0.2}$ = 1350 MPa and

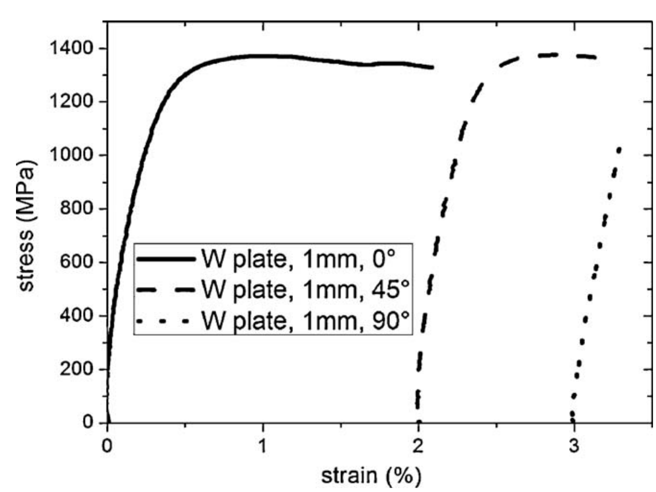

Fig. 2. Stress strain curves from tensile tests with 1 mm tungsten plate performed at room temperature. Left: sample in 0° orientation, middle: sample in 45° orientation, right: sample in 90° orientation.