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MANUFACTURING, HIGH HEAT FLUX TESTING AND POST MORTEM ANALYSES OF A W-PIM MOCK-UP

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Abstract

Tungsten (W) is an attractive candidate as plasma facing material for future fusion reactors. The selection of tungsten is owing to its physical properties such as the high melting point of 3420 °C, the high strength and thermal conductivity, the low thermal expansion and low erosion rate. Disadvantages are the low ductility and fracture toughness at room temperature, low oxidation resistance, and the manufacturing by mechanical machining such as milling and turning, because it is extremely cost and time intensive.

Powder Injection Molding (PIM) as near-net-shape technology allows the mass production of complex parts, the direct joining of different materials and the development and manufacturing of composite and prototype materials presenting an interesting alternative process route to conventional manufacturing technologies.

This contribution describes the fabrication of tungsten monoblocks, in particular for applications in divertor components, via PIM. The assembly to a component was done by Hot Radial Pressing (HRP). Furthermore, this component was characterized by High Heat Flux (HHF) tests and achieved 1300 cycles @ 20 MW/m².

Post mortem analyses were performed quantifying and qualifying the occurring damage by metallographic and microscopical means. The crystallographic texture was analysed by EBSD measurements. No change in microstructure during testing was observed.

Keywords:

Powder Injection Molding (PIM), Hot Radial Pressing (HRP), tungsten, monoblock, mock-up, HHF testing

1. Introduction

Industrially produced tungsten (W) grades are available in different types of semi-finished products (rods, plates, and sheets). Conditioned by the fabrication route via powder metallurgy (powder compaction, sintering, rolling or forging) the products are characterized by high density and large quantity. But the subsequent mechanical machining is very time and cost intensive. An alternative mass fabrication method is Powder Injection Molding (PIM). This is a time and cost effective near-net-shape forming process that allows complex shapes and a relatively high final density [1, 2].

The divertor concept of the world largest fusion experiment presently under construction, the International Thermonuclear Experimental Reactor (ITER), is based on tungsten monoblocks as plasma facing material which are connected to CuCrZr-pipes by using different manufacturing technologies (brazing, Hot Isostatic Pressing (HIP), or Hot Radial Pressing (HRP)) [3]. An additional requirement (to keep the components performance as high as possible) is to perform the joining process in such a way that the material properties are not altered. To qualify the involved processes and materials, small units of the real component are fabricated (so-called mock-ups). Then the performance of these mock-ups is determined by high heat flux (HHF) tests [4].

This contribution presents investigations on pure tungsten materials. First, the manufacturing process of the monoblocks by W-PIM and the fabrication to a mock-up by HRP are reported. The high heat flux testing section describes the testing of this mock-up: first in the neutral beam facility GLADIS followed by a second test with the electron beam facility JUDITH 2. The results of the post mortem analysis are briefly discussed and suggestions for further investigations are highlighted.

2. Manufacturing

2.1. Powder Injection Molding of tungsten monoblocks

The used tungsten powder (> 99.97 wt.% W) was mixed with a small quantity of a polymer (binder). The finished granulated so-called feedstock was used for injection molding of green parts. After shaping the green parts, the binder was extracted. The final sintering at temperatures above > 2000 °C leads to a density higher than 98%. This process is very time and cost effective. Isotropic materials, equiaxed grain orientation, good thermal shock resistance, and a high possible shape complexity are typical properties of powder injection molded tungsten [5, 6]. Monoblock surface shaping is a key question in the design of plasma facing units [7]. Figure 1 shows W-PIM monoblocks with various sizes and shapes.

Figure 1. Monoblocks in manifold designs produced via W-PIM. Chamfer (with or without), position and size of bore (center or outboard), thickness (thick or thin) - all these parameters may be varied within certain limits by the use of an adaptable PIM tool.

The external dimensions of the produced and used monoblocks were 26 mm x 26 mm x 12 mm. The diameter of the bore in the center was 17 mm.

2.2. Fabrication of a W-PIM mock-up via HRP

At first, the W-PIM monoblocks had to be equipped with a copper cast interlayer. The thickness of this interlayer was 1 mm. CuCrZr was used as cooling tube material. The tube inner diameter was 12 mm and the wall thickness 1.5 mm. The mock-up consisted of 4 W-PIM monoblocks, with 0.4 mm gaps in between. Figure 2 schematically shows all dimensions of the mock-up. The manufacturing of the mock-ups was done by Hot Radial Pressing (HRP) under the following conditions [8, 9]:

- Vacuum environment with pressure lower than 10^{-5} mbar.
- Bonding internal tube pressure of 60 MPa.
- Bonding temperature of 580 °C.
- Pressure holding time of 120 min

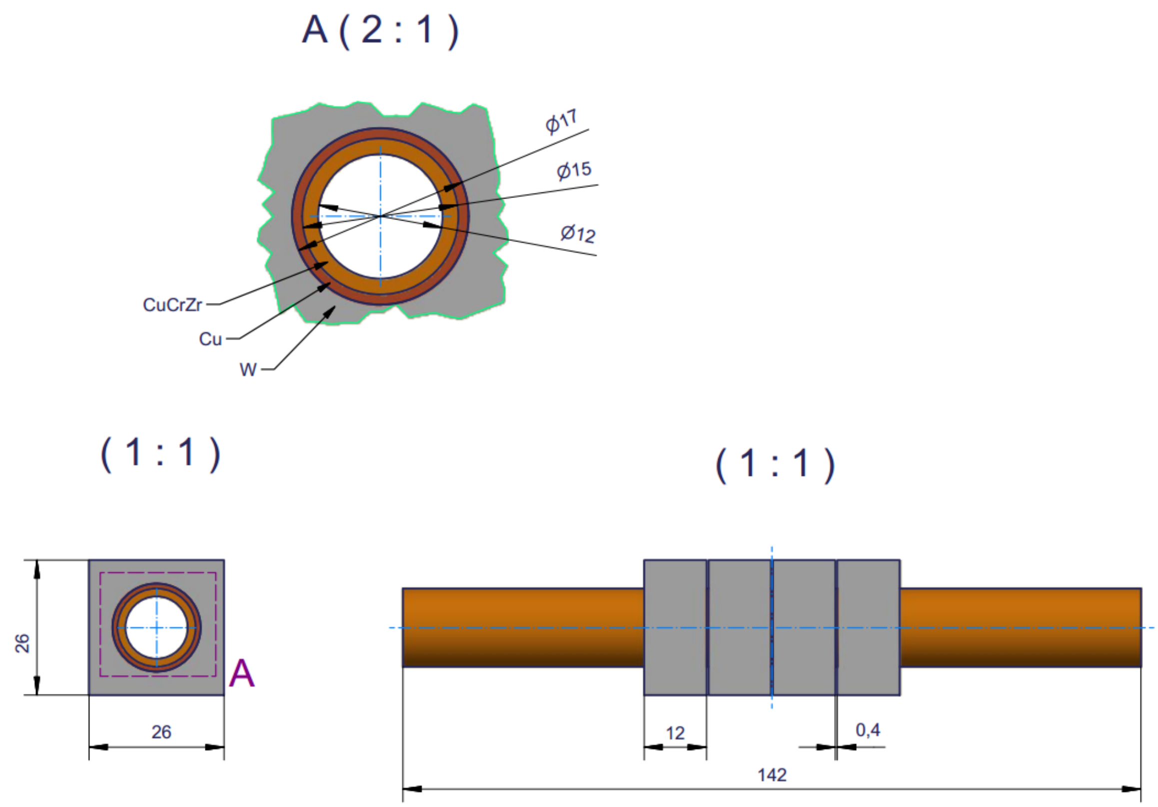

Figure 2. Dimensions of the W-PIM mock-up (schematically).

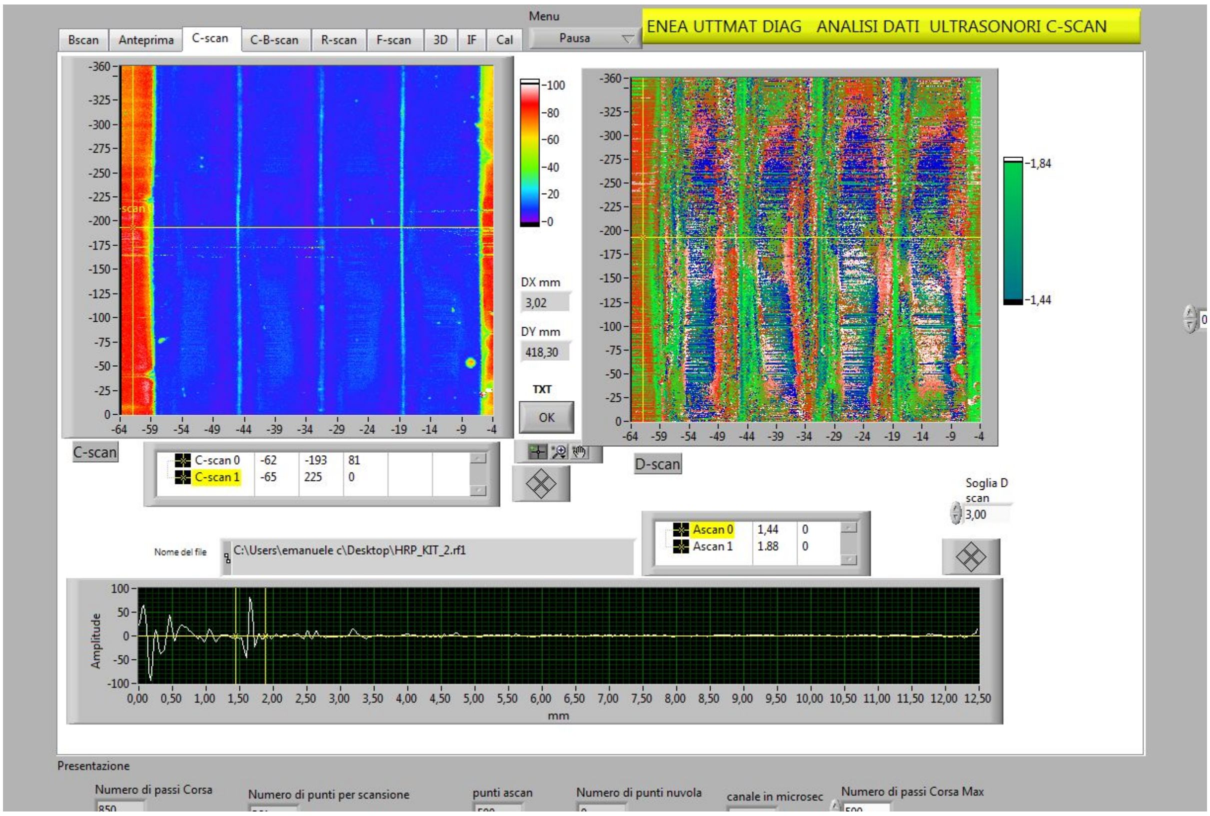

Figure 3. Ultrasonic testing of the W-PIM mock-up after HRP.

The W-PIM mock-up was controlled by ultrasonic testing after the HRP manufacturing (see Figure 3). The tests revealed no visible defects in the joints. For the enhancement of the water-cooling heat transfer capability a twisted tape (swirl) was installed to promote turbulence. High heat flux testing was done consecutively in two different facilities and on two different, but due to the geometric symmetry of the component equivalent, surfaces of the mock-up: first area (1) exposed in the facility GLADIS, second area (2) tested in JUDITH 2 (see Figure 4).

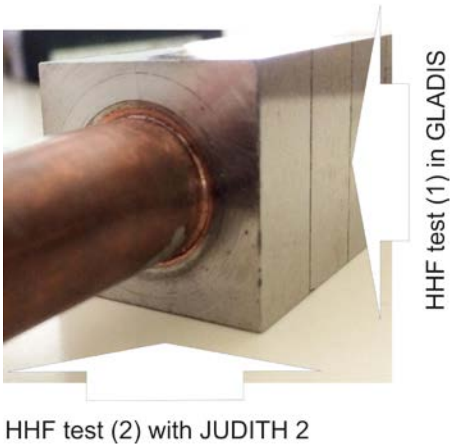

Fig. 4. Order and area of HHF testing.

3. High heat flux testing

3.1. HHF testing at GLADIS

The first high heat flux testing was conducted using the neutral beam facility at IPP Garching, which is called Garching LArge DIvertor Sample test facility (GLADIS). This facility serves for investigating the thermo-mechanical behavior of components subjected to extreme thermal loading, and is equipped with two 1 MW neutral beam sources for homogeneous heating of plasma facing components at heat fluxes up to 45 MW/m² per source and 45 s pulse length [10]. The aim of the HHF tests of the pure W-PIM mock-up was to determine the thermo-mechanical behavior (including the temporally-resolved surface temperature evolution during screening and cycling). Some pre-tests on the PIM material showed already promising results [2, 11]. The initial test was done using room temperature water-cooling conditions (T_{in} = 20 °C, 12 m/s axial velocity) and started with a screening from 6 to 25 MW/m², each pulse 10 s loading, followed by 200 cycles at 20 MW/m², 10 s. Figure 5 shows the infrared images of the mock-up during the screening at 25 MW/m². The screening and cycling at room temperature cooling conditions was performed without any indication of cracks.

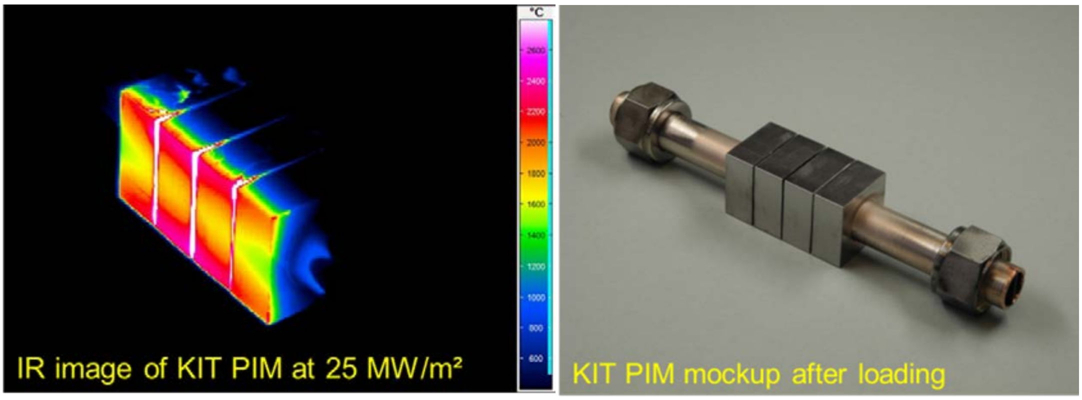

Figure 5. Infrared (IR) image of the mock-up during the screening.

The second test campaign was performed similar to DEMO hot water-cooling conditions (T_{in} = 130 °C, p_{in} = 40 bar, v = 16 m/s) with a heat flux of 20 MW/m² up to 100 cycles for 10 s. The visual inspection showed one thin crack on the outer edge of one monoblock (see Figure 6). Next, the mock-up was sent to Forschungszentrum Jülich to continue the high heat flux testing.

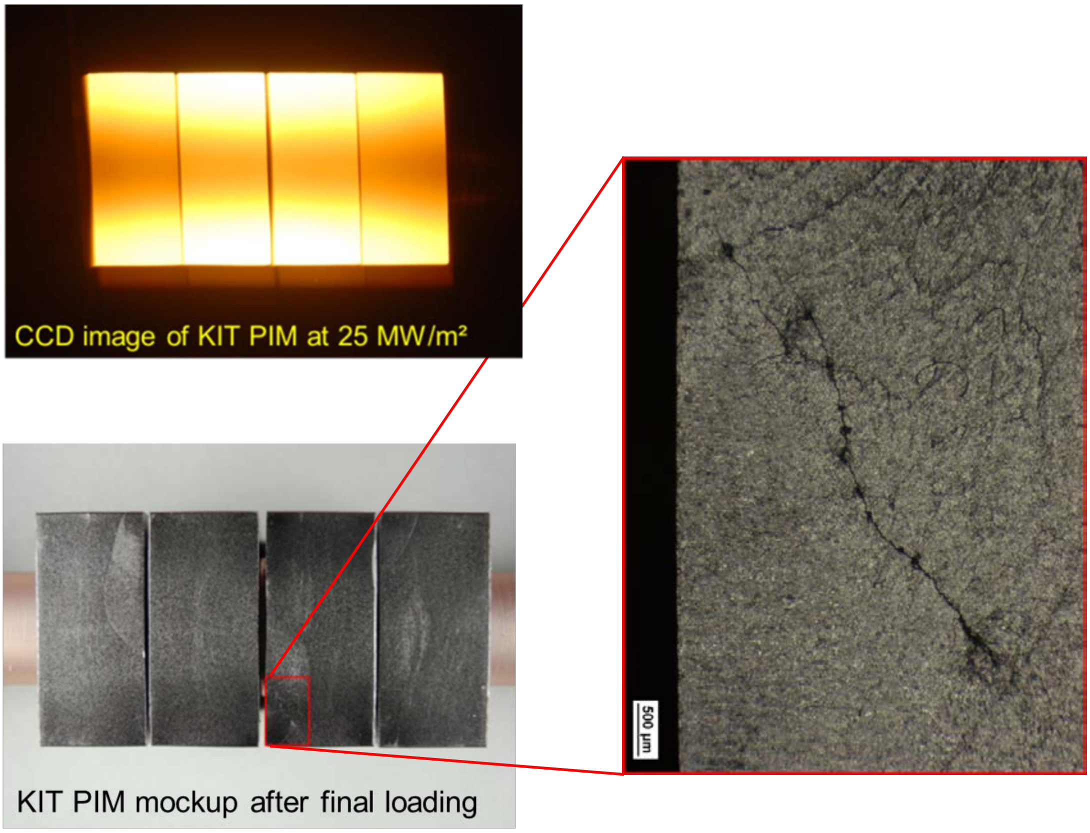

Figure 6. W-PIM mock-up after final loading at GLADIS, small surface crack on one monoblock.

3.2. Thermal shock testing at JUDITH 2

At Forschungszentrum Jülich high heat flux tests with the electron beam facility JUDITH 2 were performed [12]. Pre-tests on pure tungsten materials were very promising [13]. The heat load tests were performed with hot water-cooling similar to ITER conditions (T_{in} = 70 °C, p_{in} = 30 bar, v = 11.5 m/s) applying 100 cycles of 10 MW/m² and 1000 cycles of 20 MW/m². Due to inappropriate covering of the surface by the electron beam (i.e., block 4 was only partially loaded), the absorbed power density on blocks 1 – 3 (measured by water calorimetry) was calculated to about ~22 MW/m².

4. Post mortem analyses

4.1. Microstructure

Figure 7 shows the mock-up after high heat flux testing.

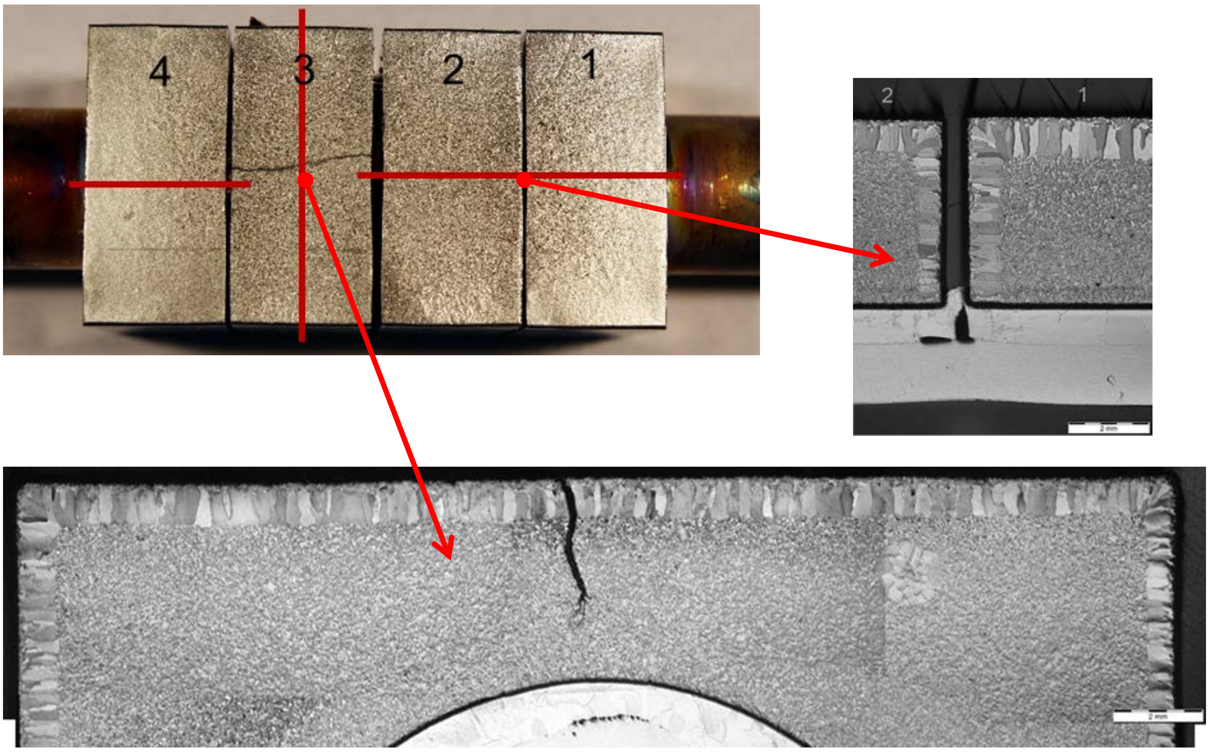

Figure 7. W-PIM mock-up after final loading at JUDITH 2, one crack on monoblock #3.

Monoblock # 3 showed one crack on the top surface (testing area) with a depth of 3.4 mm. The cross section in Figure 7 showed that it is still > 1 mm away from the cooling tube. Between block 1 and 2 flaws in the Cu-interlayer were found which might be a result of the high heat flux tests but could also be a pre-existing defect considering the location and the difficulty of detection of such imperfections via non-destructive means prior to testing. However, the CuCrZr tube showed no damage of any kind (Figure 8).

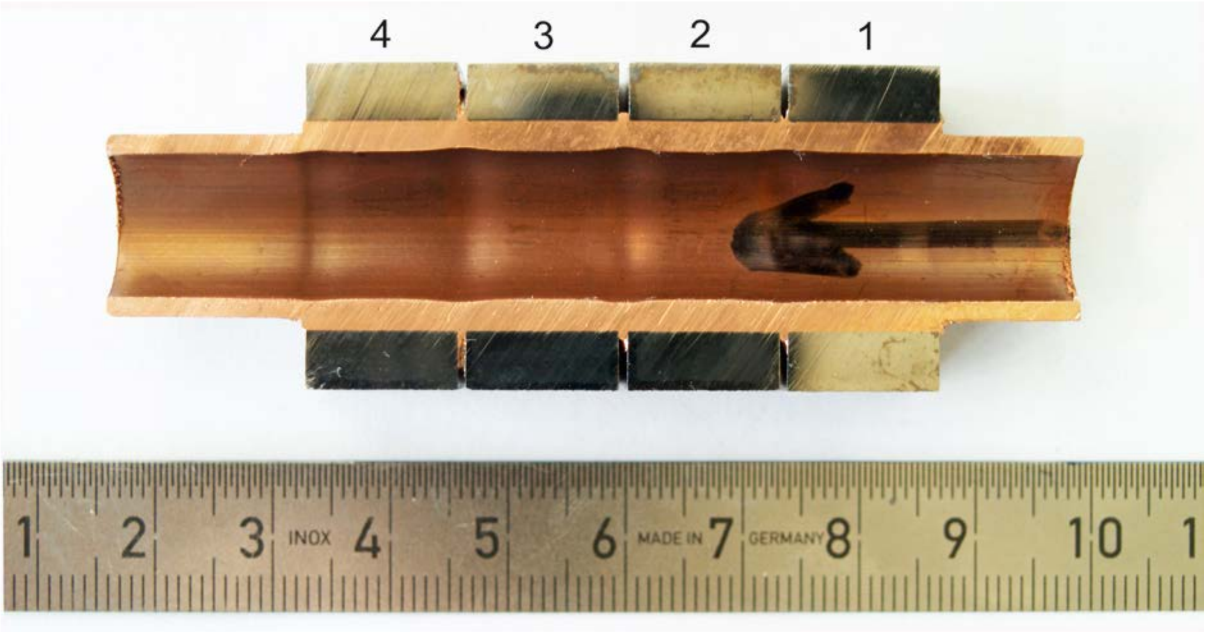

Figure 8. Cross-section of the W-PIM mock-up after HHF testing. The arrow (right) marked the flow direction of the cooling water.

4.2 Crystallographic texture (EBSD)

Electron backscatter diffraction (EBSD) is a powerful microstructural characterization tool in combination with SEM and allows descriptive analyses of the grain size, orientation, distribution, and form. Figure 9 shows the initial state and Figure 10 the microstructure after HHF testing. Both tested surfaces (GLADIS and JUDITH 2 tests) are visible in the EBSD map in Figure 10. While we see a change in the surface morphology after testing in JUDITH 2, no damage is visible after the tests in GLADIS. This becomes especially apparent when comparing to Figure 9 where the initial state shows the same microstructural properties. The grain size and state of the microstructure (here: recrystallized state) does not change after both HHF tests. A fine-grained layer on the outer surface which is followed by columnar grains towards the inner material is visible in all states. The gradients visible inside the columnar grains in Figure 9 result from polishing and not from deformation due to the manufacturing process.

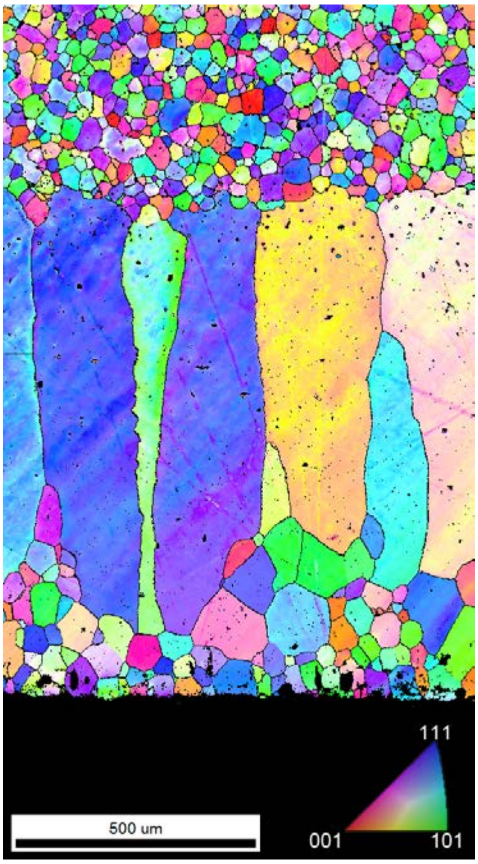

Figure 9. Initial state (IPF grains).

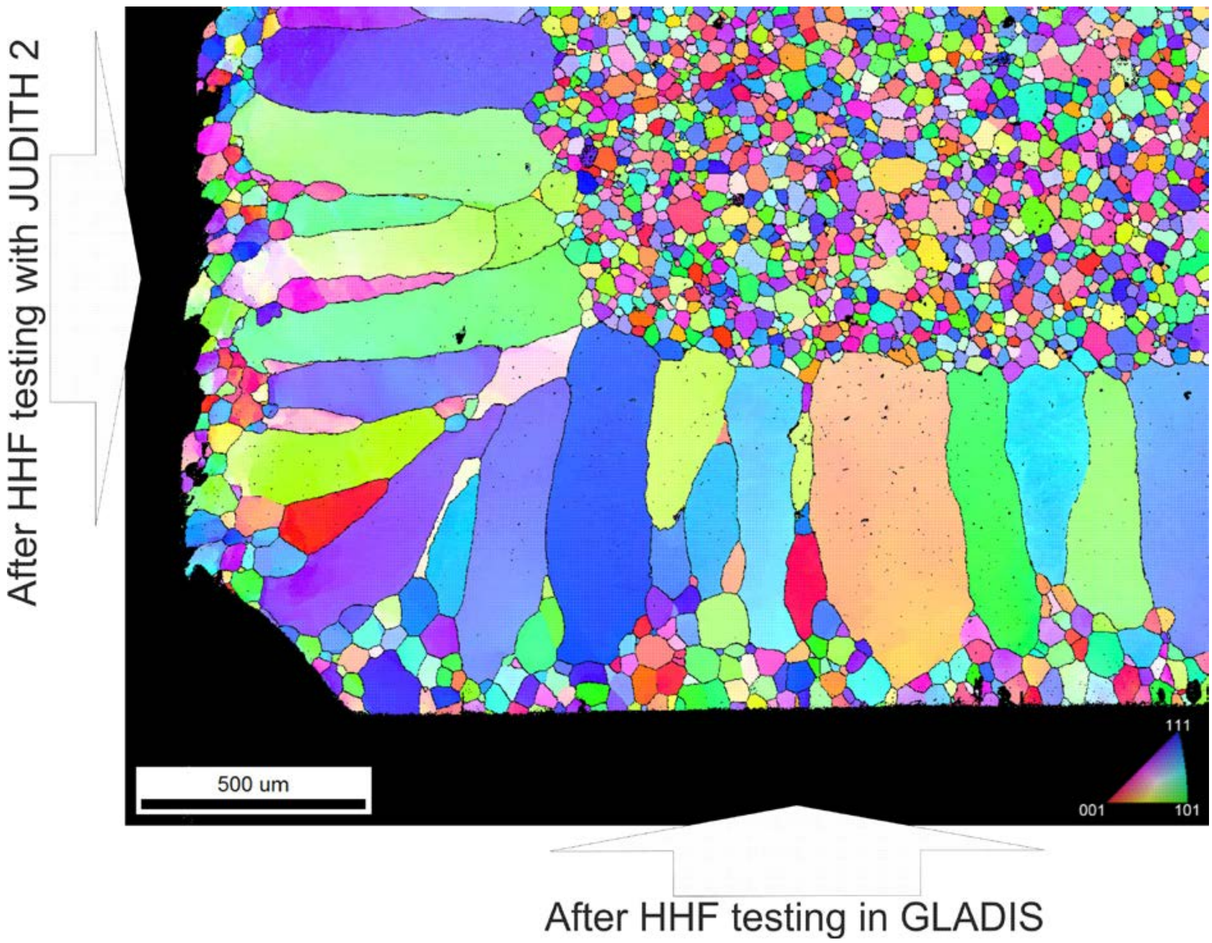

Figure 10. Left: after testing with JUDITH 2, bottom: after testing in GLADIS (IPF grains).

A change of the microstructure in the state before and after HHF testing could not be detected. The clearly visible seam near the surface consists of a 500 µm thick columnar grain structure. The inner part and a thin surface layer consist of regular small grain structure. The authors conclude that the columnar structure could be an artefact of the sintering process. In any case, a change in the grain size and structure is not visible.

5. Conclusions and outlook

This experimental study demonstrates that the manufacturing techniques PIM and HRP can be successfully applied to divertor component fabrication:

- Monoblocks (26 x 26 x 12 mm) produced via PIM
- Assembly to a mock-up by HRP
- HHF testing at GLADIS: Screening up to 25 MW/m²
- HHF testing at GLADIS: 300 cycles @ 20 MW/m²
- HHF testing at JUDITH 2: 100 cycles @ 10 MW/m²
- HHF testing at JUDITH 2: 1000 cycles @ 20 MW/m²
- No change in microstructure during testing
- No recrystallization
- One surface crack

The presence of melting zones between the tungsten blocks and the copper interlayer zone and the formation of surface cracks need to be investigated in more detail in future test series. Particle formation can be easily implemented in the PIM process, which has an enormous effect on the material properties [14, 15]. A side effect of particle introduction is the suppression of the columnar grain structure (seam). Therefore, the performance of particle reinforced tungsten composites, like for example W-TiC will be investigated in similar mock-ups in the near future.

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