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Self-castellation of tungsten monoblock under high heat flux loading and impact of material properties

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ABSTRACT

In the full-tungsten divertor qualification program at ITER Organization, macro-cracks, so called self-castellation were found in a fraction of tungsten monoblocks during cyclic high heat flux loading at 20MW/m^2. The number of monoblocks with macro-cracks varied with the tungsten products used as armour material. In order to understand correlation between the macro-crack appearance and W properties, an activity to characterize W monoblock materials was launched at the IO. The outcome highlighted that the higher the recrystallization resistance, the lower the number of cracks detected during high heat flux tests. Thermo-mechanical finite element modelling demonstrated that the maximum surface temperature ranges from 1800 °C to 2200 °C and in this range recrystallization of tungsten occurred. Furthermore, it indicated that loss of strength due to recrystallization is responsible for the development of macro-cracks in the tungsten monoblock.

1. Introduction

Among the components constituting the ITER divertor, the plasma-facing units (PFUs) of vertical targets are designed to withstand the highest surface heat fluxes, i.e. 10 MW/m^2 during steady state operation and 20 MW/m^2 during slow transients [1]. To meet these requirements, the PFUs employ a monoblock technology, made of pure tungsten armor joined to the copper alloy pipe via a pure copper interlayer [2,3,4], see Fig. 1(a). In order to validate and demonstrate the performance of available technology, the full-tungsten divertor qualification program was launched [2]. The main part of the program was to examine the performance of tungsten monoblock components in high heat flux (HHF) tests. As a result, monoblocks made out of several different tungsten products showed rather frequently macro-cracks, so-called self-castellation. The macro-cracks developed at the loaded surface, propagating through the tungsten armor toward the copper interlayer [3,5,6], but not impaired the monoblock integrity and thermal capability. An extensive modelling [7] was performed to understand the fracture modes, i.e. causes of the macro-crack initiation. In parallel, various tungsten monoblock materials were characterized to investigate the correlation between HHF test performance and tungsten properties.

In this paper, the summary of HHF test results and essential results of the tungsten material characterization program are presented. The correlation between HHF test performance and tungsten material properties is also discussed.

2. High heat flux test results of W monoblock components

Small-scale mock-ups, made of 5 or 7 monoblocks, and full scale prototype PFUs were tested under high heat fluxes in two electron beam facilities: FE200 in France [8] and IDTF in Russia [9]. In these tests, 5000 cycles at 10 MW/m^2 followed by 300 cycles at 20MW/m^2 were applied on the actively cooled monoblocks and full-scale prototype PFUs [10]. Each cycle had a duration of 20 s, including 10 s of heating followed by a 10 s dwell time. At least 280 monoblocks were successfully tested [3,5,11,12]. Interestingly, in average 30% of them showed macro-cracks. These macro-cracks were not observed after the cycling at 10 MW/m^2 and they were observed on a fraction of the monoblocks after a few tens up to a few hundreds of cycles at 20 MW/m^2 [3]. The cracks all exhibit the same features: initiated at the loaded surface (yz plane; see Fig. 1(a)), oriented along the cooling tube axis, and propagating

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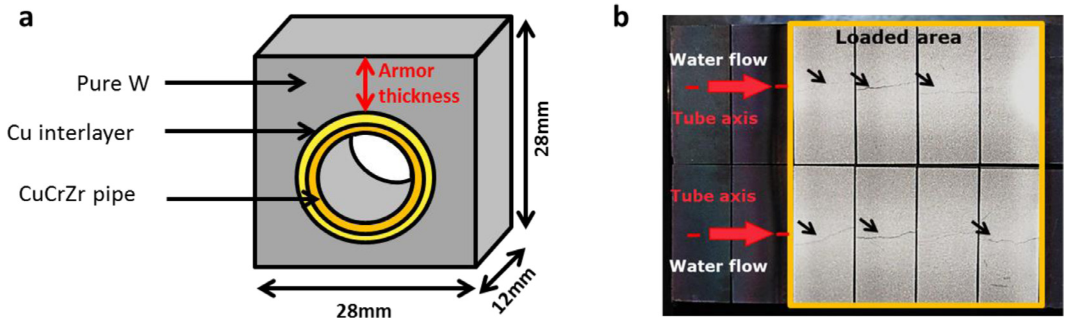

Fig. 1. (a) monoblock geometry, made of a rectangular tungsten armour, a copper interlayer (typically OD/ID = 17/15) and a CuCrZr tube (OD/ID = 15/12). (b) top view of the loaded area of 2 tested mock-ups showing 6 self-castellations marked by black arrows after 5000 cycles at 10 MW/m^2 followed by 300 cycles at 20MW/m^2[16].

Table 1
Summary of ~280 monoblocks tested in the frame of the full-tungsten divertor qualification program [3,5,11,12]. Each tested component is described with the tungsten product, the tungsten production process, the final surface finish of the loaded surface, the component manufacturing process (HIP = Hot Isostatic Pressing [15], HRP = Hot Radial Pressing [13], brazing [14]), the electron beam used, and the tungsten armor thickness (mm). The percentage of monoblocks with macro-cracks after 5000 cycles at 10 MW/m^2 and 300 cycles at 20MW/m^2 is given as well as the total number of loaded monoblocks.

Tungsten product	Production process	Surface finish	Bonding technology CuCrZr to W+Cu	Device	Cracking (300 cycles 20MW/m^2)	Number of monoblocks	Armour thickness
P5	forged Bar	grinded	HIP	FE200	**0%**	5	5.5
P5	forged Bar	grinded	HIP	IDTF	**0%**	6	5.5
P4	rolled Plate	grinded	Brazing	IDTF	**0%**	6	7.7
P1	rolled Plate	grinded	Brazing	IDTF	**0%**	3	7.7
P3	rolled Plate	grinded	Brazing	IDTF	**0%**	3	7.7
P1	rolled Plate	grinded	Brazing	IDTF	**0%**	6	7.7
P2	rolled Plate	EDM	HRP	IDTF	**0%**	4	6
P2	rolled Plate	EDM	HRP	IDTF	**0%**	4	6
P1	rolled Plate	grinded	Brazing	IDTF	**0%**	120	7.7
P3	rolled Plate	grinded	Brazing	IDTF	**0%**	10	7.7
P4	rolled Plate	grinded	Brazing	IDTF	**0%**	5	7.7
P5	forged Bar	grinded	HRP	IDTF	**0%**	6	6
P3	rolled Plate	grinded	HIP	IDTF	**8%**	24	6
P5	forged Bar	grinded	HIP	IDTF	**33%**	3	7.5
P5	forged Bar	grinded	HIP	IDTF	**66%**	6	7.5
P2	rolled Plate	EDM	HRP	IDTF	**66%**	3	6
P5	forged Bar	grinded	HIP	FE200	**75%**	4	7.5
P5	forged Bar	grinded	HIP	FE200	**100%**	10	5.5
P5	forged Bar	grinded	HIP	IDTF	**100%**	3	5.5
P5	forged Bar	grinded	HIP	IDTF	**100%**	4	5.5
P5	forged Bar	grinded	HIP	FE200	**100%**	8	7.5
P2	rolled Plate	EDM	HRP	FE200	**100%**	4	6
P2	rolled Plate	EDM	HRP	FE200	**100%**	4	6
P2	rolled Plate	EDM	HRP	FE200	**100%**	12	6
P5	forged Bar	grinded	HRP	FE200	**100%**	8	6
P5	forged Bar	grinded	HRP	FE200	**100%**	4	6
P5	forged Bar	grinded	HRP	FE200	**100%**	4	6

into the tungsten armour perpendicular to the y-direction, in the x-direction (see Fig. 1(b)).

The summary of the high heat flux test results, including the number of cracks detected after 5000 cycles at 10 MW/m^2 and 300 cycles at 20 MW/m^2 is shown in Table 1. It should be noted that the tests were aimed at examining the performance of the armor heat sink joints under cyclic heat loads but not at studying the behavior of the tungsten armor under high heat flux loading. Therefore, these high heat flux test results include many variables (Table 1), which makes the interpretation of the results more difficult:

- Variations in monoblock manufacturing: tungsten production route (rolling / forging), loaded surface grinding after EDM cutting, joining technology.
- Variations in monoblock geometry: armor thickness, copper interlayer thickness.
- Variations in the high heat flux test facility: electron-beam spot size and energy.
- Number of tested monoblocks for each manufacturer and tungsten product.

Typically, each manufacturer is associated to a specific tungsten supplier, a bonding technology, and a copper interlayer thickness. Two main tendencies were extracted:

- First, results are electron-beam dependent [16]. FE200 (spot size between 2 and 10 mm and an acceleration voltage of 200 keV [8]) has tendencies to damage more than IDTF (spot size approximately 50 mm and acceleration voltage of 60 keV [9]). Indeed, FE200 has a more focused beam; as a consequence a larger local power density is deposited in FE200 than in IDTF yielding in more damages due to local thermal shock loads. This was illustrated by HHF test results: for P2 tungsten with 6 mm tungsten armor only ~20% of the monoblocks tested in IDTF showed macro-cracks while this was the case for 100% of the monoblocks tested in FE200.
- Focusing on the comparison on IDTF results for the reasons explained above, results show that the tungsten product used in the monoblock armor plays a key role. While all materials are fulfilling the requirements of the ITER tungsten material specification [3,4], rolled plate tungsten products show cracks on