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J Boscary et al.

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Summary of the Production of the Divertor Target Elements of Wendelstein 7-X

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The realization of the 19.6 m² highly heat loaded part of the divertor of Wendelstein 7-X (W7-X) requires the installation of 890 target elements. A target element is made of a CuCrZr copper alloy heat sink armored with carbon fibre reinforced carbon CFC NB31 tiles. The industrial production of the target elements by the Austrian company PLANSEE SE needed 5 years. The successful delivery of a total of 973 target elements (armored with ~16,200 tiles) was based on an efficient quality assurance throughout the production by the manufacturer: 44 different quality examinations for 82 manufacturing steps. It was followed by an intensive quality assessment by IPP: visual inspections, dynamic pressure tests, He-leak testing in vacuum oven, high heat flux testing. The quality of the delivered elements, and in particular the reliability of the bonding between CFC tiles and heat sink, was confirmed by high heat flux testing on the basis of a statistical approach. The essential recovery of CuCrZr properties after ageing processes was confirmed by the measurement of hardness and electrical conductivity. 104 target elements (10.7%) were accepted after repair.

Keywords: Stellarator, Wendelstein 7-X, Plasma Facing Component, Divertor

1. Introduction

The installation of an actively water-cooled divertor in the stellarator Wendelstein 7-X (W7-X) is mandatory to achieve stationary power and particle exhaust for a pulse length of up to 30 minutes [1]. The 19.6 m² highly loaded divertor surface is made of 890 individual target elements distributed in ten discrete similar divertor units, two for each of the W7-X five field periods. Each unit has 10 target modules, which are sets of target elements of the same length placed onto a support frame and fed with water from manifolds [2].

A target element is made of a CuCrZr copper alloy heat sink armored with carbon fibre reinforced carbon CFC NB31 tiles. It is designed to remove a stationary heat flux of 10 MW/m² on its main area, 5 MW/m² at the top end adjacent to the pumping gap and 2 MW/m² at the edge tile facing the pumping gap. In 2003 the production was awarded to the Austrian company PLANSEE SE. Four pre-series with the production and intensive testing of ~60 full scale prototypes were needed to improve step by step the initial design. The bi-layer technology which increases the thermo-mechanical performance and lifetime of the bond of the CFC tile to the heat sink was developed [3, 4, 5]; a sealing labyrinth and a central fin to prevent a possible by-pass between adjacent channels and ensure the full cooling at the end of the target element were introduced [6]; the design of the tiles protecting the top end and at the edge was modified [7]; the electron beam welding of the heat sink was optimized; intensive high heat flux (HHF) testing was performed to qualify the 6 different batches of CFC NB31 to be used for the serial fabrication, which have different material properties [8], and to establish a statistical assessment for the serial fabrication based on the results of the pre-series [9]; the repair process of CFC tiles and connector tubes was validated; the quality assurance by PLANSEE SE and reception tests by W7-X were established for the serial production. The result of this extended validation phase allowed the release of the serial production in 2009. This paper summarizes the results of the total production finally completed in 2014 as planned.

2. Production

The production has 5 standard types of target elements with 7 variants for diagnostic integration. Main dimensions are listed in Table 1. The quantity of target elements per chronologically delivered type and the total number of tiles per type are presented in Fig 1 and 2, respectively.

Table 1: Main characteristics of target elements

Type	Length [mm]	Max. Width [mm]	Top tiles	Edge tile
1S	594	57	23	1
1A	594	61.5	23	1
1B	595	61.5	23	1
1C	594	60	23	1
2S	572	55	22	1
2B	573	59.5	22	1
3S	320	54	13	
3A	320	58.5	13	
3C	320	59	13	
4S	250	57	10	
4B	250	61.5	10	
5S	361	55	15	1

A total of 973 target elements was delivered, which includes a reserve of 9.3%. The total quantity of delivered armored tiles is ~16,200.

The industrial production was split in two phases, the successful completion of phase 1 releasing phase 2. Phase 1 was the production of 296 target elements of types 3S and 4S, which is 30% of the total production of target elements or 20% of the total production of tiles. These 2 types were selected because of their simplified

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design: short and no edge tiles. A preliminary step was added for the phase 2 with the first production of 22 target elements of type 1S and 22 of type 5S to validate the manufacturing process of long elements and edge tiles.

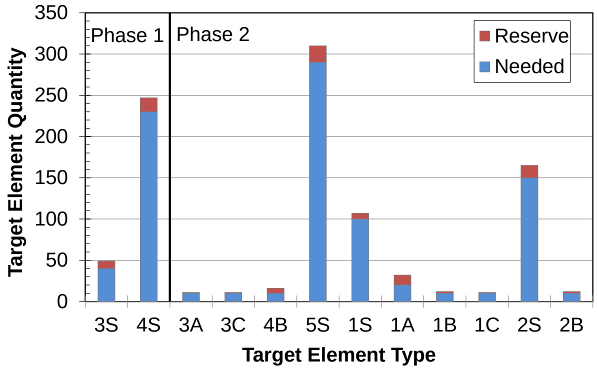

Fig. 1: Quantity of target element per type

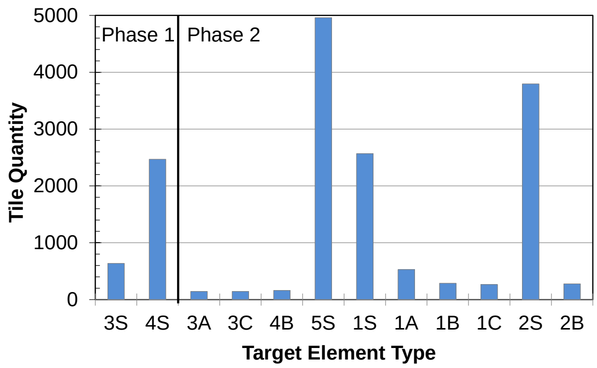

Fig. 2: Quantity of armored tiles per type

3. Manufacturing process

The different parts of a target element are shown in Fig. 3 with type 1S. A copper layer is joined by active metal casting to the laser-treated surface of CFC tiles. For each batch, metallography samples verify the copper infiltration specified to remain below 2 mm. After machining of this layer to a thickness of 0.4 mm, each tile is checked visually and by X-ray. Then an oxygen-free (OF) Cu, 4 mm thick, layer is joined onto the 0.4 mm Cu layer by hot isostatic pressing to produce the bi-layer tiles. Tiles are finally machined to their final dimension: 8 mm CFC plus 3 mm bi-layer. At the final stage, tiles are checked with non-destructive tests (NDTs): ultrasonic inspection for the bond OF-Cu/Cu, X-ray for the bond CFC/Cu, visual inspection (all bonds) and thermography (thermal conductivity of the tiles). 3 types of tiles were produced: top standard (90%), end top (6%) and edge tiles (4%). Tiles cannot be repaired. The quality assurance of the tile is of prime importance for a viable production due to the fact that one defective tile means one defective target element.

The transition between CuCrZr and stainless steel of the inlet/outlet connectors is realized with a 5 mm long nickel adapter. Thick tubes are electron beam welded and then machined to their final dimension (12 mm outer diameter, 1 mm thick) to remove porosities generated by this process. All connectors are the same for all target elements. NDTs are: dimensions, He sniffing leak testing at atmosphere, X-ray and dye-penetration.

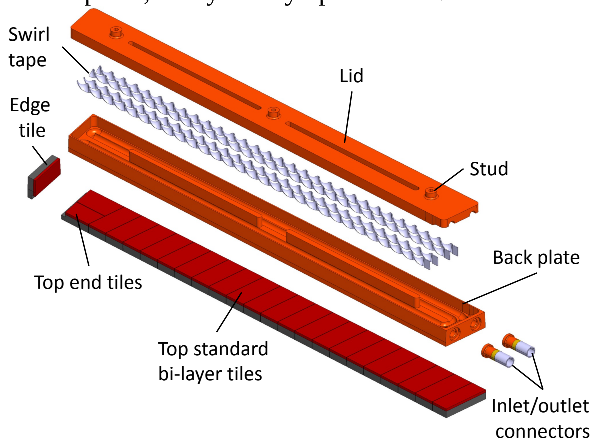

Fig. 3: main parts of a target element of type 1S

The CuCrZr heat sink is made of a lid and a back plate in which half-channels and central fin are machined. They are joined together by electron beam welding. Before closing, 1 mm thick stainless steel twisted tapes twist ratio of 2, are placed in the 4 straight part of the channel and are mechanically attached with a key-slot system. After welding, heat sinks are aged at 475°C for 3 hours and then straightened. Seams are checked by ultrasonic. Then inlet/outlet tubes are electron beam welded to heat sinks. After being aged again, heat sinks are straightened and seams are inspected with ultrasonic again.

In the final stage, standard bi-layer tiles are electron beam welded on the top of the heat sinks. After straightening, bonds are inspected by thermography [10]. For the target element types with edge tiles, these tiles are then welded to heat sink and inspected by thermography. At this stage, the shape of the target element is rectangular. After ageing, the target elements are straightened and machined to reach their final dimension, which is trapezoidal shaped across and along the element. Final NDTs are: Thermography, He sniffing leak testing at atmosphere, dynamic and static pressure tests, hardness and electrical conductivity measurements at different location of the heat sink. In addition test connectors are welded to the stainless steel tubes to allow the incoming inspections of the delivered target elements.

Altogether, the production of a target element requires 82 steps for manufacturing and 44 steps for quality assurance. A major effort was dedicated to the documentation to allow a full traceability throughout the production in order to be able to quarantine and/or reject only well-identified batches of parts which did not pass examinations. All materials used for the target elements are provided with certificates, taking into account the material requirements of W7-X.

4. Result of the quality assessment

The quality of the delivered target elements was systematically assessed as follows: visual inspection and in particular pictures and archiving of the interface between tiles and heat sink on both sides (~32400 pictures) to detect possible cracks [11]; dynamic pressure test and the measured values have to lie within ±15% of the mean measured value per type; He-leak testing in a vacuum oven with a leak rate ≤ 5.10^{-7} Pal/s at room temperature and 3.2 MPa internal He pressure, and a leak rate ≤ 5.10^{-6} Pal/s at 160°C and 2.5 MPa internal He pressure (1 cycle). In case of repair, the number of cycles is increased to 3.

In addition HHF tests in the GLADIS facility [12] were performed to assess the thermo-mechanical behaviour of individual CFC/Cu joints in order to detect any possible de-bonding of CFC tiles. An acceptable target element has to show no crack initiation or development after 100 cycles in standard test conditions (10 MW/m², 10 s loading for top tiles with 8 m/s axial water velocity, 1 MPa static pressure) and no He leakage after HHF testing.

4.1 HHF testing

The applied procedure was based on a statistical assessment of the standard tiles with the further possibility of tests on demand to detect any quality deviation [13]. Only a reduced number of the lower loaded edge tiles, typically 2-4 edge tiles per element type, were tested. Previous HHF tests confirmed a high safety margin in the design.

In phase 1, the first 19 delivered target element of type 4S were HHF tested. The results confirmed the same high thermal performance as achieved in the last pre-series and allowed the release of phase 2. The results of the testing of 13% of phase 1 and 8% of phase 2 taking into account the various types of CFC batches confirmed the same high quality of the bonding throughout the industrial production.

However, some deviations occurred in phase 2. 5 batches of bi-layer tiles showed a significant higher percentage of tiles which did not pass the ultrasonic examination during the manufacturing (31% on average) than phase 1 (< 2%). To solve this issue, a special target element was manufactured with tiles of the different concerned batches and HHF tested. Results confirmed the weak quality of these tiles with a visible de-bonding of tiles after a few cycles. The adopted solution was an additional step: bi-layer tiles were systematically annealed at 600°C for 2 hours (simulation of temperature conditions of the bond in operation) before ultrasonic examination. This solution ensured a stable quality of the produced bi-layer tiles.

Another defect was the leakage of one element of type 5S at the end of a standard HHF test (element randomly selected), which was confirmed by following He-leak testing in vacuum oven with a leak rate ≥ 2. 10^{-3} Pal/s; the leakage was located in the slit between the 2nd and 3rd tile close to the water connectors. The analysis showed that the leakage came from the combination of the porosity content in the centre part of the element (overlapping of beam seams: due to its width, tiles are welded successively from the two sides) and the reduced CuCrZr thickness of the heat sink at this location due to machined slots for twisted tapes. This level of porosities in the centre part was detected during pre-series activities but thermal fatigue tests (10,000 cycles with 10 MW/m², cycling up to 16 MW/m²) were always successful. Nevertheless this result questioned the reliability of this target element type in operation. The selected solution was to seal the slit by electron beam welding after the complete delivery of the 5S target elements. This approach was validated with prototypes and its efficiency confirmed by intensive HHF testing.

A HHF test facility such as GLADIS with well-defined loading conditions and sensitive diagnostics was a very important tool throughout the pre-series activities to achieve the performance required for the W7-X divertor operation. During the series activities, this facility allowed the assessment of the stable quality of the industrial production and the validation in short-term of technological solutions while minimizing effect of on-going fabrication.

4.2 Repair

Fig. 4 shows the distribution of repair carried out per target element type.

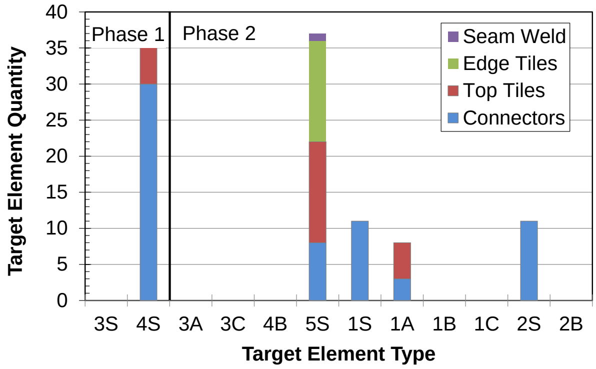

Fig. 4: distribution of repaired target elements

A total of 104 (10.7%) target elements has been successfully repaired 6.5% water connectors, 2,7% top tiles and 1.5% edge tiles. This figure shows that it would have been impossible to reach the minimum required quantity of target elements without validated repair processes available before starting the serial fabrication.

The most repaired parts were the water connectors. At the beginning of the production in phase 1, connectors of 30 target elements needed to be replaced due to mishandling. In phase 2, 33 target elements did not pass the He-leak inspection because at least one of the connector was leaking. The leak was always found at the bond between stainless steel and nickel adapter and in the range of 10^{-5}-10^{-6} Pal/s. The explanation of this leak is based on logical assumption which is a combination between possible impurities in stainless steel raw material and cleaning issues during the electron beam welding. The selected solution was the local galvanic copper-coating, 0.3 mm thick and 20 mm long, of all target element connectors of phase 2 [11].

Repair of CFC tiles was due to damages occurring during the final machining of the target element to its final shape (broken corner or damaged edges) and to the slit machining up to the copper between adjacent tiles after the welding of the tiles onto the CuCrZr heat sink and before the final machining of the element. During the production of phase 1, it became clear that the machining of the slits was not a suitable industrial process: 20 elements had slits too large (> 1mm) or not well-positioned. As a result, the slit process needed to be modified during the serial fabrication. The solution was the machining of the side of the adjacent bi-layer tiles before welding to the heat sink for phase 2. The number of tiles to be repaired was reduced by positioning target elements (with slits up to 1.2 mm) in special location of the divertor.

5. Conclusion

The successful delivery of the target elements was achieved thanks to an intensive quality assurance with a very detailed documentation (traceability) of PLANSEE SE confirmed by the quality assessment by W7-X in which HHF testing played an important role. Pre-series activities were essential to set up and validate the basis for assessing the serial fabrication. Without validated repair process, it would have been impossible to complete the delivery as scheduled.

At the beginning of the production, the two main concerns were the reliability of the bond of CFC tiles to heat sink and of the electron beam welding process of the heat sink on a larger scale: 16,200 armored tiles, 1250 m of seam welds CuCrZr-CuCrZr. The delivered target elements demonstrated a stable high quality of the bonds between tiles and heat sink; no cracks were detected during HHF testing performed on a statistical basis. The reliability of the quality control organization allowed the identification of weak batches of bi-layer tiles before welding to heat sink, which allowed minimizing effect on on-going production. Only one delivered element has a repaired weld seam. The stable recovery of CuCrZr properties after ageing processes was due severe control in particular of the chemical composition of delivered raw materials. The unexpected issue was the reliability of the joint of the nickel adapter of the water connectors. The adopted solution is the galvanic copper-coating of this location.

Next step is the on-going individual 3D-machining of the target element before assembly as target modules [15]. The completion of the target modules is planned by mid-2018 to allow operation in 2020.

Acknowledgements

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