



ITER divertor materials and manufacturing challenges



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ABSTRACT

Since the signatures of ITER divertor Procurement Arrangements, material purchases, process qualification as well as manufacturing of full-scale prototypes have progressed. This paper provides a brief summary of the ITER divertor materials, the requirements for these materials, and the requirements for manufacturing and inspection of the divertor components. Experiences to be acquired through the prototype manufacturing activities are also discussed.

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1. Introduction

A single null divertor is to be installed in the bottom area of the vacuum vessel of the ITER tokamak. The divertor functions are maintaining the plasma purity as well as extraction of the power coming from the conductive/convective heat flux in scrape-off layer and radiation. The divertor components shall tolerate high heat loads as the main interface with the plasma and material surfaces, while at the same time contributing to neutron shielding for the vacuum vessel and superconducting magnets. Moreover, the divertor shall house various diagnostics for physics studies and machine protection. A number of 54 divertor cassette assemblies (CAs) will be installed by remote handling operation in the vacuum vessel. Each standard CA includes one Cassette Body (CB) and three Plasma-Facing Components (PFCs), i.e. the inner and outer vertical targets (IVT and OVT), and the Dome [1–4].

The decision to start with a fully tungsten (W)-armoured divertor was implemented into the baseline at the end of 2013, after completion of design activity at the ITER Organization (IO) [3–6] and successful technology R&D development in collaboration with Domestic Agencies (DAs) [6–8]. Regarding the procurement activity, the Procurement Arrangements for divertor components have been all signed and the materials have already been partially purchased. Meanwhile, manufacturing of full-scale prototypes is in

progress. In this paper, the ITER divertor materials and the challenges in manufacturing are discussed.

2. Material specifications for ITER divertor

Selection of materials is based on a comprehensive assessment of the various functional, operational and technological requirements, namely: (1) armour materials – plasma compatibility, erosion lifetime and stability; (2) radiation protection requirements i.e. limit of activation (contact dose, waste, activated corrosion products and dust, confinement); (3) adequate properties under all operational conditions (including fatigue, neutron irradiation effects); (4) vacuum compatibility for vacuum quality components; (5) magnetic property requirements; (6) corrosion performance of materials in contact with coolant; (7) compliance with codes and standards for design & manufacturing; (8) Sufficient manufacturability such as welding, brazing, re-welding, fabrication, tribology, etc.; (9) Industrial availability and cost consideration. Status of materials selection and its justification of performance for the ITER components is described in [9].

A large fraction (~80%) of the ITER divertor mass is structural materials e.g. austenitic steel 316L(N)-IG and XM-19. In addition to these austenitic steels, copper alloy such as CuCrZr-IG and NiAl bronze, steel grade 660 and nickel based Alloy 625 and Alloy 718 are selected. Oxygen free copper (OFCu) as interlayer material (and also as swirl tape) and tungsten as armour material are used in the divertor. The mass of the main materials in final shapes are roughly estimated to be stainless steels – 360 ton, CuCrZr – 7 ton,

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NiAl bronze - 27 ton, and W - 46 ton for the first set of divertor (54 cassettes). For the procurement of these materials, material specifications were defined by the IO. These specifications were based on industrial standards, i.e. ASTM and EN standards with addition of ITER specific requirements. Prior to the delivery, visual examination and dimension inspection of the products are performed. For the plate products ultrasonic tests need to be performed. For pipe products, leak tightness tests such as eddy current tests or hydrostatic tests are to be executed instead of ultrasonic tests. Regarding the steel forgings and NiAl bronze products, dye penetrant tests and ultrasonic tests are required to be performed. The material certificates are issued by a department independent of the production department e.g. quality assurance department (corresponding to EN10204 type 3.1).

2.1. Stainless steels

Austenitic stainless steel 316L(N)-IG was selected as the main structural material (L stands for a low carbon content, (N) for a controlled nitrogen content, and IG for "ITER Grade"). The closest analogy is X2CrNiMo17-12-2 controlled nitrogen content austenitic stainless steel described in the RCC-MR Code Edition 2007. 316L(N)-IG steel is grade 316L steel with narrower alloying element ranges and controlled impurities. This modification leads to a significant reduction in the spread of the material properties and to an increase of the minimum tensile properties in the specification. The narrow specification provides a good control of the batch-to-batch variation of mechanical properties. The products shall be delivered in solution annealed condition (at 1050–1150 °C).

For seamless steel pipes, standard material 316L, i.e. grade X2CrNiMo17-12-2 (No.1.4404) was adopted. Less stringent requirements on impurity contents and magnetic properties are set for this material because of the limited amount of use in the components. The products shall be delivered in solution annealed condition (at 1020–1120 °C).

Austenitic steel XM-19 was selected for the attachments and as structural material for PFCs and CB. The steel XM-19 (UNS S20910, Nitronic 50) is nitrogen-strengthened austenitic stainless steel with good corrosion resistance and approximately twice the yield strength at room temperature in comparison with conventional steels, due to higher Cr and Mn contents (Table 1). The products shall be delivered in solution annealed condition (above 1065 °C).

Grade 660 was selected for bolting and shaft material. The grade 660 is a precipitation hardened iron-base superalloy designed for applications requiring high strength up to ~700 °C. The main advantages of this steel are high tensile properties (combined with high toughness). This material is used for the parts that are not in contact with water. The parts shall be used after solution heat treatment (980 °C for 1 h and quench) and precipitation hardening heat treatment (705–760 °C for 16 h, air cool or furnace cool).

In addition to the requirements in standards, requirements of impurity content (e.g. Co, Ta, Nb), tensile properties at 250 °C, magnetic permeability (for 316L(N)-IG, 316L and XM-19; ASTM A 342), grain size (≥ 2 for plate, bar and forging; ≥ 3 for pipe; EN ISO 643), non-metallic inclusions (for plate and forging; ASTM E45-05), intergranular corrosion resistance (for XM-19 plate and forging; ASTM A 262-02), hardness test (for XM-19 plate; ASTM A240) and stress rupture test (for grade 660; ≥ 23 h, $\geq 3\%$ elongation at 650 °C at 450 MPa; ASTM E139) need to be fulfilled. Table 1 shows the requirements for the chemical compositions, mechanical properties and magnetic properties.

The dpa levels in the first divertor set were estimated to be maximum 0.3 dpa in steel [10]. The impact on mechanical properties imply an increase in yield stress and ultimate tensile strength and reduction in uniform elongation and total elongation [11]. How-

ever, in the range up to 0.3 dpa, the effects of neutron irradiation on mechanical properties are considered to be negligible and properties of un-irradiated materials are used for the design assessment. At this dpa level, there is no significant influence on thermal properties of steel. For confirmation, the radiation resistance of XM-19 steel was determined via neutron irradiation experiments at ~0.1 dpa 300 °C [12].

2.2. Copper alloys and coppers

Ni-Al bronze was chosen as a structural material in forms of bars and forged blocks. The main advantages of this material are anti-seizing properties proven also in vacuum, absence of sparking, high mechanical properties and good resistance against mechanical shocks [13]. Among the various available grades, the Al bronze UNS C63200 (high strength) has been selected. The material shall be delivered at the heat treated condition (850 °C for ≥ 1 h, quench in water and temper anneal at 700 °C for 3–9 h). The microstructure showed multi-phase structure, α -phase (solid solution), β -phase (Cu_3Al) and κ -phase (Fe and Ni rich) [14]. The material specification of Ni-Al bronze defines the chemical composition and mechanical properties (Table 1).

The precipitation-strengthened copper alloy, CuCrZr alloy is used as the heat sink material in forms of pipes and plates. It has a combination of good electrical conductivity ($> 75\%$ International Annealed Copper Standard (IACS)), i.e. good thermal conductivity, and high strength and it is possible to be joined by fusion welding. The CuCrZr alloy is available in semi-finished products such as rolled plates and cold-drawn tubes. CuCrZr-IG is similar to UNS C18150, with narrower alloying element ranges and controlled impurities [15]. The properties of CuCrZr alloy is sensitive to heat treatment. Dedicated heat treatment is required to obtain optimal combination of strength, ductility and conductivity, i.e. solution annealing at 980 °C for 0.5 h followed by quench (typically faster than 1 K/s) and aging at 475 °C for 2–4 h. By quenching to a lower temperature, a supersaturation of alloying elements in the matrix is generated. A subsequent aging treatment below the solvus temperature results in precipitation of fine second-phase particles [16]. The microstructure shows fine Cu_nZr and Cr-rich precipitations in the matrix [17,18]. These fine precipitates are responsible for the high tensile properties and high conductivity by reducing the solute content in the matrix. Rapid cooling after solution annealing is important to recover strength by aging heat treatment [19]. Over aging cause the microstructural change – coarsening of precipitates – as a consequence, the material loses its mechanical strength, and slightly gains ductility [17] and conductivity [20]. The material specification of CuCrZr-IG defines the requirements on the chemical composition, electrical conductivity ($\geq 75\%$ IACS; ASTM B193 or E1004-02), grain size (average grain size $< 100 \mu\text{m}$, occasional grain size up to $200 \mu\text{m}$ ($< 10\%$ of grains) is acceptable after manufacturing heat cycle; ASTM E 112) and mechanical properties (Table 1). Since the properties of CuCrZr-IG are affected by heat treatment during the manufacturing such as HIP and brazing, the sufficient mechanical properties after the heat treatment [15,18,19] are also required (Table 1).

Oxygen free Cu (OFCu) is used as compliant layers at joints and for the swirl tapes (see Fig. 1(b)). The material specification of OFCu defines the chemical composition (Table 1), electrical conductivity (OFCu for casting $\geq 101\%$ IACS; OFCu sheet $\geq 100\%$ IACS; ASTM B170 or ASTM B152M) and hydrogen embrittlement test (ASTM B 577).

The dpa levels in Cu alloy in the first divertor set were estimated to be maximum 0.4 dpa at area exposed to lower surface heat flux (baffle area) [10]. Low-temperature ($< 300^\circ\text{C}$) neutron irradiation of Cu and Cu alloys lead to hardening, increase of yield strength, decrease of elongation and loss of strain hardening capability. The radiation effect on tensile properties of Cu alloy show tendency

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