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Application of the novel VTTJ technique (Vacuum Tight Threaded Junction) to fusion reactor relevant geometry and materials

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Abstract

A new technique, called Vacuum Tight Threaded Junction (VTTJ), has been developed and patented by Consorzio RFX, permitting to obtain low-cost and reliable vacuum-compatible non-welded junctions. The technique has been tested up to an internal pressure of 500 bar and up a temperature of 200 °C. The main advantages with respect to existing technologies are an easy construction, a low cost and a high repeatability of the process. Due to these advantages, the new technique has been adopted for several in-vacuum components of the SPIDER experiment and has been also recently accepted by the ITER vacuum group for the usage in the MITICA experiment, the full prototype of the ITER Neutral Beam Injectors. This paper reports the test and qualification, according to the ITER criteria, of the VTTJ technique with geometry and materials compatible with the divertor and other components of future fusion reactors. Namely, a set of junction samples have been manufactured, joining CuCrZr to AISI 316L stainless steel and using tube-to-tube geometry.

Keywords: vacuum, tight, threaded, junction

Introduction

At Consorzio RFX of Padova (Italy), in the framework of the ITER project for thermonuclear Fusion, the PRIMA facility [1, 2] is being built to install and test the neutral beam injector for ITER, hosting the SPIDER and MITICA experiments.

SPIDER (Source for Production of Ion of Deuterium Extracted from RF plasma) is a full-size 40 A negative ion source with a 100 kV electrostatic Accelerator [3, 4], while MITICA (Megavolt ITER Injector Concept Advancement) is a complete 1 MeV 16 MW Neutral Beam Injector system which includes Ion Source, Accelerator, Neutralizer, Residual Ion Dump and Calorimeter [5, 6].

The design and construction of the injector has several criticalities because of the severe requirements in terms of heat loads, mechanical tolerances and long-term reliability. In particular, one of the most critical issues is represented by the junctions between copper and stainless steel of the high heat flux components. During the research activity on this field [7], Consorzio RFX researchers have developed a new technique to make heterogeneous junctions, called Vacuum Tight Threaded Junction (VTTJ). A detailed description on the technique can be found in [8] and [9].

The VTTJ technique has been found to be suitable to manufacture junctions between copper and steel having a perfect seal (compatible with the requirements of high vacuum environments) that are reliable in time also in presence of high temperatures and high structural loads. The manufacturing process is carried out completely at room temperature, hence in any phase the materials are prevented from possible damages due to overheating. On the other hand, using any other existing

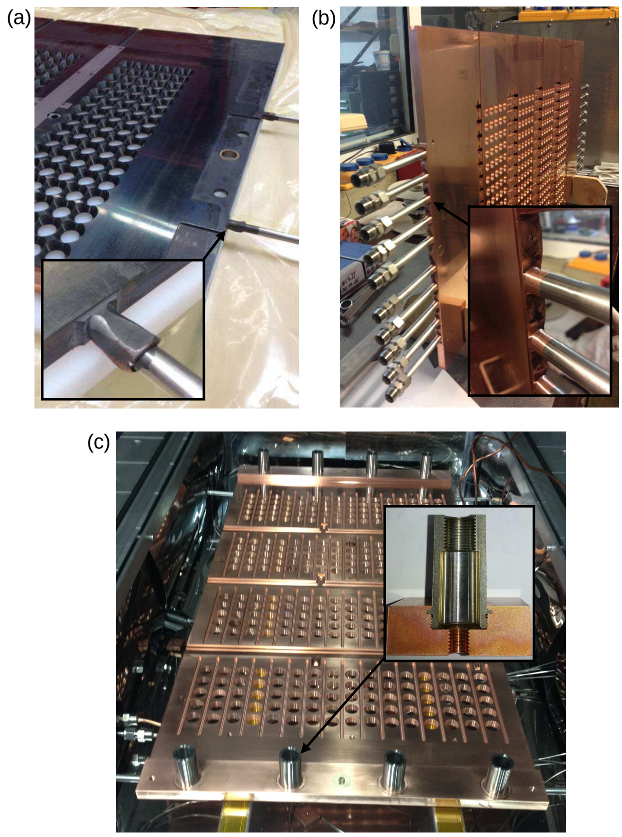

Figure 1: Examples of application of VTTJ in SPIDER: (a) plasma grid; (b) extraction grid; (c) grounded grid.

technique able to give a vacuum compatible seal (like friction welding, electron beam welding, brazing etc.) there is a certain overheating in the junction area, with possible cracks or other types of degradation of the materials (annealing, recrystallization, generation of inclusions etc.).

Due to its advantages in terms of reliability and cost, and after comprehensive test campaigns [7, 8], the VTTJ technique has been chosen for the SPIDER and MITICA experiments, currently under construction in Padova (Italy). Examples of applications to the SPIDER experiment are shown in Fig. 1.

As MITICA is the prototype of the ITER NBI, for the usage in MITICA it was necessary to obtain the approval from ITER. This approval was obtained in October 2015, based on the results of the qualification campaigns [8].

1. Extension of VTTJ to other geometries and materials

VTTJ is presently one of the design options for the junctions of the ITER NBI accelerator grids. In principle, it could be used in other components of the ITER experiment, that are required to operate in vacuum conditions and under high heat loads. Among these, we can cite the Beam Line Components of the Neutral Beam Injectors, the blanket and the divertor.

This paper deals with the tests carried out for the usage of VTTJ with divertor-compatible shape and materials. In fact, the samples, shown in Fig. 2 are manufactured with a tube-to-tube geometry and the materials are AISI 316 stainless steel and Copper-Chrome-Zirconium (CuCrZr), analogously to the heterogeneous junctions of the ITER divertor.

As shown in Fig. 2a, the plastic deformation region is a ring with 18 mm diameter and 1 mm height, with a maximum mechanical interference of 0.1 mm. This plastic deformation generated the first seal that is then covered with a thick layer of electrodeposited copper to make it compatible with high structural and thermal loads. Three different design options of the steel part have been taken into consideration, as shown in Fig. 2b:

- Type A (samples 1,2 and 3): the MITICA-like design. With this option, analogous to the samples tested in [8], the steel tube is continuous, with just a groove along the thread for outgassing.
- Type B (samples 4,5 and 6): a first alternative design, with four continuous slits (2 mm wide) on the threaded part of the tube. This design is tested because it may be better in terms of corrosion issues, as it reduces stagnation of water between the copper and steel threads.
- Type C (samples 7,8 and 9): a second alternative design, with four slits and a stiffening ring. This design solution is similar to the previous one, but is more robust because of the stiffening ring.

For each type, one of the samples was not mounted, so that there is the possibility to see how the samples were manufactures. Moreover, sample 10 was manufactured with type A design, but the manufacturing process was stopped after the screwing of the two tubes, and no copper electrodeposition was carried out. This sample is useful to see how the junctions look like after screwing.

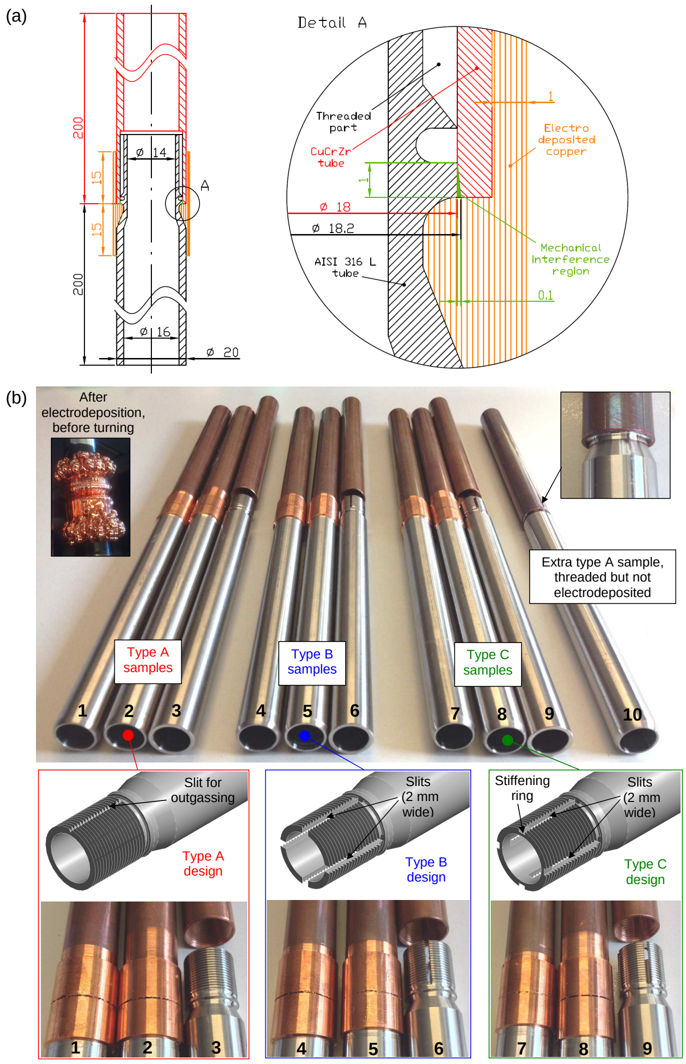

Figure 2: Divertor-like VTTJ samples: (a) section view (dimensions in mm); (b) construction with the three design options.

2. Definition of the testing campaign

The document F4E/2009/ITER/5165 titled "Technical specification for the manufacturing of full tungsten monoblock components", issued by the Fusion for Energy (F4E) organization and downloadable from the F4E database, gives the technical specifications for the construction of demonstrative Vertical Target Qualification Prototypes (W-VTQP) for the ITER divertor. In fact, the ITER divertor features several heterogeneous junctions between CuCrZr and 316L steel, operating in critical conditions with possible high structural and thermal loadings.

The same tests are also mentioned in the ITER_D_254F3P document titled "Manufacturing of Qualification Vertical Target Prototypes for ITER", issued by the ITER organization and downloadable from the ITER database.

Table 1: Test campaign for junction qualification according to the ITER and F4E criteria.

Test session	Description
1. Pressure and leak tests before thermal loading	1.1 Three thermal cycles according to ITER Vacuum Handbook (see Par. 2.1)
	1.2 Pressure test (see Par. 2.2)
	1.3 Leak test (see Par. 2.3)
2. Leak test after static loading at 2/3 of the yielding limit	2.1 Static loading up to 2/3 the yield limit (see Par. 2.4)
	2.2 Leak test (see Par. 2.3)
3. Leak test after cyclic loading	3.1 Cyclic loading with 10000 cycles at 0.1% strain range (see Par. 2.5)
	3.2 Leak test (see Par. 2.3)

These documents, containing very stringent requirements on heterogeneous junctions, have been also considered as a reference for the qualification of the VTTJ junctions for the usage on MITICA [8], ITER HNB, and generally in all possible applications in ITER (including diagnostic neutral beam, divertor, blanket etc.).

In fact, a comprehensive test campaign, summarized in Tab. 1, was carried out at Consorzio RFX on 6 of the divertor-like VTTJ samples (samples 1,2 with type A design, samples 4,5 with type B design and samples 7,8 with type C design). The test campaign has included heat treatments, pressure tests, leak tests and static loading and cyclic loading.

The following paragraphs describe the various stages of the test campaign.

2.1. Specifications of the thermal cycles according to ITER Vacuum Handbook

According to ITER Vacuum Handbook, the components which include joints of dissimilar materials shall be subjected to a minimum of three thermal cycles from ambient to the maximum possible operating temperature prior to leak testing.

Hence, also the qualification samples were subjected to a similar heat treatment. As the maximum operating temperature of the junctions is typically 60 °C, the three heat treatments were carried out at 100 °C, taking into account some margin.

The following procedure was repeated three times: using an oven, bring the samples to 100 °C (in air environment), leave them at that temperature for 30 minutes and then cool them to room temperature (25 °C).

2.2. Pressure test specifications

After the heat treatments, pressure tests have been carried out in agreement to the standard BS 31.3 ANSI/ASME Code for Pressure Piping. The pressure test equipment, shown in Fig. 3a features a nitrogen tank, a pneumatic circuit, with valves and pressure gauges, and special tooling built ad-hoc to maintain the 29 bar pressure difference without risks. The prototypes were subjected to the following pressure cycle: 30 minutes at 30 bar absolute (applied by means of pressurized nitrogen) followed by 10 cycles between 30 bar absolute (kept for 1') and the atmospheric pressure.

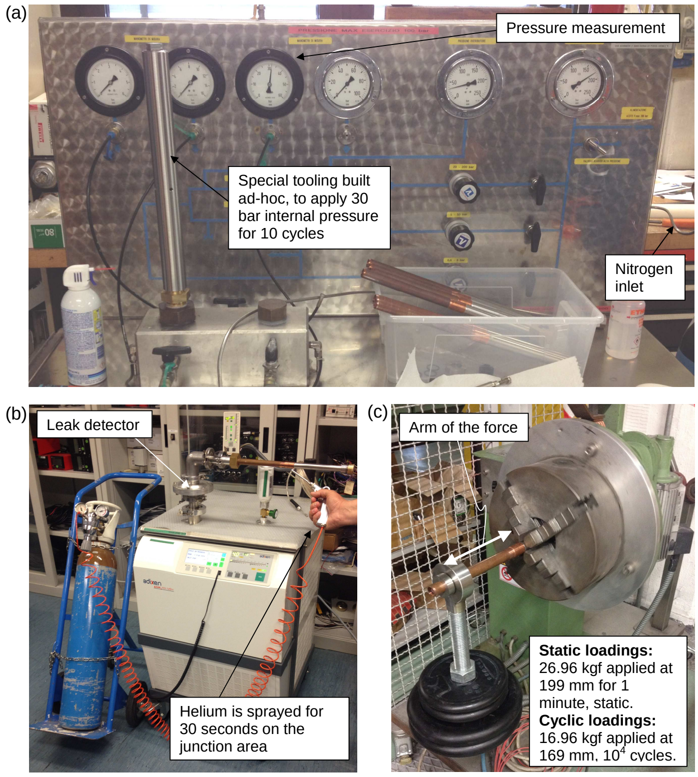

Figure 3: Overview of the tests: (a) pressure test equipment; (b) leak test equipment; (c) equipment for the application of the static and cyclic loadings.

2.3. Leak test specifications

Leak tests with helium as tracing gas have been carried out, in accordance with the general rules stated in the ASME V, Art. 10. The leak test equipment, shown in Fig. 3b is made of a vacuum pump and a leak detector. When high vacuum conditions are created inside the sample by means of the vacuum pump, the leak detector, based on a mass spectrometer, is able to detect even extremely small quantities of helium inside the cooling circuit. Helium is sprayed over the sample, in particular over the heterogeneous junctions. If no helium is detected by the mass spectrometer connected to the cooling channel, perfect vacuum tightness is demonstrated. For the considered samples, during helium spraying over the junction no variation was recorded in the helium signal, that remained at the background noise level (around $4{\cdot}10^{-11}$ Pa m^3 s).

2.4. Specifications of the static loading

A dedicated equipment (see Fig. 3c) has been set up to apply all structural loadings, featuring a customized support that permits to apply different weights and a rotating clamp that permits to keep the samples in the correct position during the static loading and to apply them a controlled rotation during the cyclic loading.

According to the ITER and F4E specifications (see Par. 2), a bending load able to induce a stress of two thirds the yield limit (point 2.1 of Tab. 1) was applied by means of a suitable bending force at a calibrated distance from the junction area:

$$F_{bend,\frac{2}{3}yield} = \frac{\frac{2}{3} \cdot \sigma_{yield} \cdot J_{xx}}{y \cdot b_1} = 264.2N = 26.96kgf \quad (1)$$

where:

- σ_{yield} is yield stress of stainless steel, equal to 170 MPa;
- J_{xx} is the flexional moment of inertia of the tubular section around the bending axis xx, that can be calculated as $\frac{\pi \cdot (10^4 - 8^4)}{4}$;
- y is the maximum distance from the bending axis. In this case, it is 10 mm (external radius of the tube)
- b_1 is the arm of the applied force (distance between the application point of the force and the junction), taken equal to 199 mm.

The bending load, applied with the equipment shown in Fig. 3c, has been kept for 1 minute.

2.5. *Specifications of the cyclic loading*

According to the ITER and F4E specifications (see Par. 2), the cycling (or fatigue) loading must be carried out with 10000 rotary bending cycles at room temperature under $\Delta\epsilon = 0.1\%$ cyclic strain range and with a frequency lower than 1 Hz. The maximum bending strain reached in the most critical section of the tube can be calculated as:

$$F_{bend,0.1\%} = \frac{E \cdot \epsilon_a \cdot J_{xx}}{y \cdot b_2} = 164.2N = 16.96kgf \quad (2)$$

Where:

- E is the Young's modulus of stainless steel, equal to 200 GPa;
- ϵ_a is the strain amplitude to be applied, that can be calculated as $\frac{\Delta\epsilon}{2} = 0.05\%$;
- b_2 is the arm of the applied force, taken equal to 169 mm. In this case the maximum stress to be applied is of 100 MPa (equal to $E \cdot \epsilon_a$), that can be obtained using a lower weight (164.2 N) and a shorter arm b_2 (169 mm) than in the previous case.
- the other parameters are as in the previous paragraph.

The cycling loading were applied using the same equipment (see Fig. 3c), with the difference that the arm of the force is 169 mm instead of 199 mm, the weight is 16.96 kgf instead of 26.96 kgf and the support rotates with the frequency of 0.12 Hz instead of being fixed.

3. Result summary

All the tests foreseen for the qualification of the VTTJ junction according to the ITER criteria (from 1.1 to 3.2) were passed by all the tested samples. Hence, the VTTJ junctions between AISI 316 L and CuCrZr tubes were found to fully satisfy the ITER and F4E qualification process for the usage in ITER.

Conclusions

The VTTJ technique, developed in Consorzio RFX, permits the execution of heterogeneous junctions capable to maintain an optimal tightness also in aggressive environments, for example in high vacuum and with high thermal or structural loads. Its main advantages are low cost, high reliability and easiness of construction.

After the application in all the accelerator grids of the SPIDER experiment and the acceptation by the ITER Vacuum Group for the usage in the ITER NBI prototype (MITICA experiment), the VTTJ technique has been extended to geometry and materials suitable for the divertor of ITER and other fusion devices. This paper presents the qualification of divertor-like junctions according to the ITER and F4E test specifications.

All the samples have satisfied the ITER and F4E qualification process. Hence, the VTTJ technique is proposed as a possible option for heterogeneous junctions in ITER and other fusion devices.

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