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DEVELOPMENT OF A FIRST WALL CLAMP FOR REMOTE HANDLING

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RFX is equipped with a graphite first wall made up of 2016 tiles individually supported from the vacuum vessel. Due to the small dimensions of the ports, human access inside the vacuum vessel is prevented and a robot manipulator has been designed to perform remote operations on the graphite tiles. The clamping system that withstands the applied loads must accomplish the remote handling requirements.

A bayonet clamp has been chosen because it is simple, safe and can be built with clearances and chamfers that, with a proper compliance of the manipulator wrist, allow the compensation of the positioning errors between the parts that have to be matched. To avoid the vacuum welding of the clamp, the surfaces in contact under vacuum are coated with an anti-welding coating.

The paper first describes the main design choices, then deals with the load capability of the clamping system and reports the results of experimental and FE analyses; the last section gives the results of the tests that were performed on anti-welding coatings.

1. Introduction

The inner surface of the RFX vacuum vessel is covered by a full graphite armor acting as thermal shield for the Inconel 625 wall and avoiding heavy ion pollution of the plasma [1].

The armor is composed of 2016 tiles arranged in poloidal rows of 28, each corresponding to one of the 72 solid rings forming the skeleton of the torus. To hold the tiles in the correct position a joint is required with the vacuum vessel to balance any applied load. The problem of mechanical continuity between two separated pieces is generally solved by preparing the two matching surfaces and by pre-loading them with a force higher than the maximum foreseen load. The abutment surfaces withstand compressive forces, the reduction of pre-load equilibrated tensile forces, and friction absorbs shear forces. This principle is exploited for the support of graphite tiles in JET [2], TFTR [3], DIII-D [4] and Tore Supra [5].

The pre-load is generally applied by screws with elastic washers or springs for a better control of the force pressing graphite against the support. In some cases the risk of cracking the graphite with excessive squeezing is avoided by brazing an intermediate molybdenum plate on which screws are tightened. This solution allows a better thermal contact with the backing system and is properly applied for very high heat load components, e.g. the limiter and divertor plates in Tore Supra and in Asdex Upgrade [6].

All current solutions have been reviewed for the development of the clamp for the RFX tiles. However, some special conditions have to be satisfied in RFX with respect to tokamaks.

First, the support and tile overall thickness have to be reduced to a minimum since the plasma cannot be kept too far from the aluminium shell that surrounds the vacuum vessel, owing to stability requirements.

Moreover, no man-hole is provided across the vacuum vessel wall since the openings are limited to a maximum diameter of 150 mm due to magnetic requirements.

A manipulator has been planned for the maintenance of the first wall [7] inside the vented vessel. Hence, the tile attachment must be simple, safe, and with proper clearances to compensate misalignments and simplify the engagement of the fastener. These features are consistent with a bayonet system rather than a screw which cannot engage in the presence of significant positioning or orientation errors.

Screws have also been discarded as fasteners because any seizure of the thread would require a difficult recovery to be accomplished by the manipulator.

A full graphite design has been developed for the

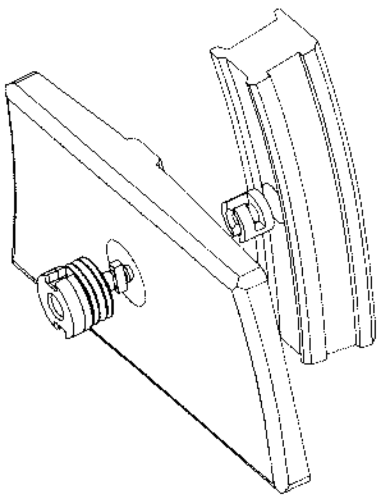

Fig. 1. Exploded view of the RFX graphite tile clamping system.

tiles, which are built with a supporting rib that presents all the matching surfaces required for the correct positioning with reference to the vessel (see fig. 1).

2. Design concepts

2.1. Applied loads

The main mechanical load on the clamping system is caused by the electrodynamic forces and torques that act on the tile, especially during fast plasma current terminations. In the case of an exponential plasma current decay with a time constant of 0.1 ms the equilibrium of the tile requires a traction force of approximately 200 N to be exerted by the key.

This force is larger than the force that the key must apply to pre-load the contact surfaces of the tile and the vessel, because in RFX the thermal contact conductance to the cooled vessel is not a critical problem and the pre-load can be quite small (60 N).

2.2. Clamp description

The bayonet clamping system is made up of two typical components: the bush and the key (fig. 2). The bush is welded to the stiffening rings of the vacuum vessel and is made of Inconel 625 to ensure a sound welding and to avoid thermal stresses due to the differential expansions; it presents a central hole and two L-shaped grooves in which the key enters, thus fastening the system.

The key has a circular head and a T-shaped stem that matches the L-shaped grooves of the bush when the clamping system is locked. The head of the key, exposed to the plasma, is protected by a graphite cap. For this reason the base material of the key is a molybdenum alloy which is best suited to brazing with graphite. The tile is closed between the surface of the vacuum vessel and the head of the key. The deflection of a set of Belleville springs, interposed between the tile and the head of the key, ensures the correct pre-load of the system.

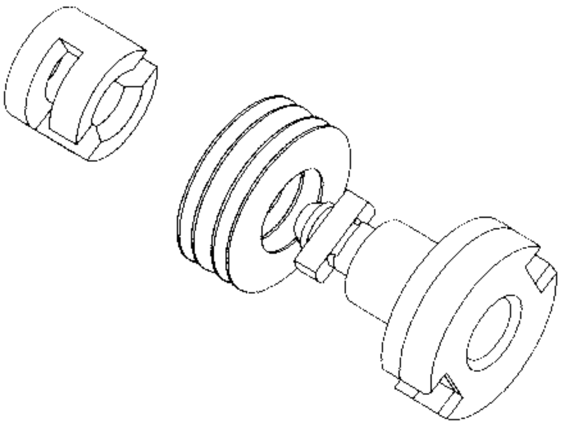

Fig. 2. The components of the locking device.

2.3. Remote handling

The remote handling operations include the tile installation and removal. In the first operation the tile, grasped by the end effector of the manipulator, must be accurately positioned with reference to the vessel so that the positioning error between the bush (welded to the vessel) and the key (pre-assembled into the tile) is smaller than the maximum error allowed by the clamping system, that in our design is ± 0.5 mm. In the dismounting operations the end effector of the manipulator must position itself with reference to the tile so that it can operate on the tile and the clamping system without damage them.

The maximum positioning error is unlikely to be smaller than 1–2 mm because there are limits on the accuracy of the manipulator and the manufacturing allowances influence the position of the objects inside the vacuum vessel. To reduce the positioning error with a self-centering system, it was decided [8,9] to give passive compliance to the wrist of the manipulator by an RCC device and to design proper chamfers in the mating parts as shown in fig. 2. The chamfers in the bush hole and on the key tip are used for the self-centering of the tile during the mounting operation, while the chamfered hole in the head of the key allows the self-centering of the manipulator during the removal operation.

The RFX manipulator will work inside the vented vacuum vessel on objects that remain under vacuum at high temperature for long periods. For this reason, the possibility of vacuum welding of the mating surfaces must be taken into account. To improve the anti-welding performance of the bayonet clamp, the key is coated with a TiN layer.

3. Working conditions and load capability

Molybdenum has been adopted for manufacturing the key since its thermal expansion coefficient is very near to that of graphite. The small dimensions of the piece and the requirements for a wide contact area with the bush excluded the possibility of building the stem and the teeth of the fastener with other materials. This would allow a more conventional solution since molybdenum is seldom used as structural material even if its tensile properties are good, as is shown in table I, where the minimum values of alloy 363 adopted in RFX are reported [10]. However, molybdenum has an unstable behaviour at room temperature since the interval of transition temperature from the brittle to the ductile behaviour is 20–150 °C and the tensile properties are affected by the loading mode.

Due to the geometry, a peak of stress is expected at the junction between the teeth and the stem where a fillet cannot be realized (due to the need for leaving enough clearance between the key and the bush) and only a receding circular groove is allowed, with a small radius in order to avoid weakening of the stem.

3.1. Stress under nominal load

An elastic stress analysis of the key has been carried out to check the actual working condition of the

Table 1
Mechanical properties of molybdenum alloy 363 at room temperature

Yielding stress	Tensile strength	Elongation	Young's modules
655 MPa	760 MPa	15%	320 GPa

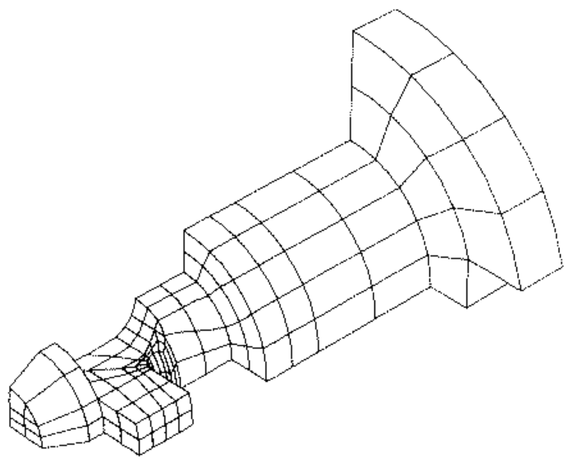

Fig. 3. Finite element mesh of the bayonet key.

material. The finite element model, reduced to a quarter of the key owing to the symmetries, has been prepared with a particular care for the zone where the teeth join the stem: fig. 3 shows the mesh prepared with 20 nodes isoparametric solid elements by using the solid modeling and the meshing modules of IDEAS [11].

A load of 200 N has been applied as uniform pressure on the teeth while the head was restrained along the line of intersection with the stem. The solution has been calculated with the computer code NASTRAN [12].

The distribution of the Von Mises equivalent stress at the end of the key is illustrated in fig. 4, the peak in correspondence of the groove reaches 56 MPa.

3.2. Destructive test

Some prototypes, built to check the manufacturing technology, have been submitted to a traction rupture

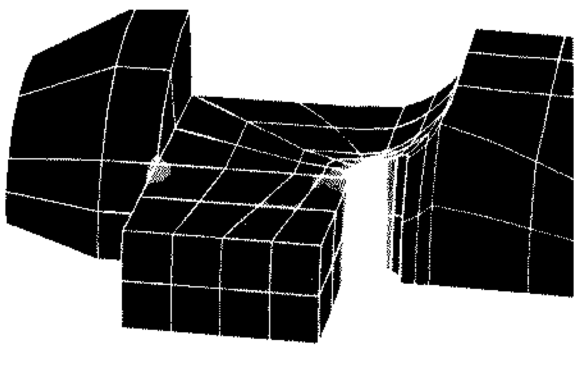

Fig. 4. Stress distribution in the key under nominal load, the lighter tones indicate higher stress values.

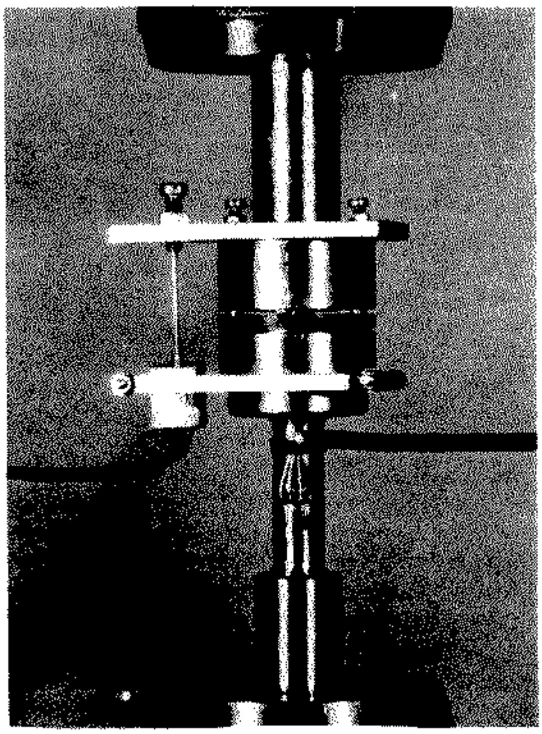

Fig. 5. View of the apparatus for tensile rupture test: the stem of a key is visible in the center, between the hooks.

test to ascertain actual strength of the key. A special piece of equipment illustrated in fig. 5 has been prepared with two hooking heads instrumented with strain gages and a LVDT transducer for accurate force and displacement measurements.

After the completion of some tensile tests up to failure, we established a minimum rupture value of 7 kN at an elongation of 0.02 mm without any evident plastic deformation of the material (see fig. 6) since the fragments matched together in a perfect way (see the right key in fig. 7). During the tests the load was applied at a rate of about 100 N/s.

3.3. Interpretation of test results

The fact that all the keys failed, exhibiting no permanent elongation and no appreciable deformation of the fragments, called into question the ductility of molybdenum. Since an elastic stress of 1960 MPa, calculated on the base of the aforementioned elastic analysis, was unrealistic, it was clear that some plastic deformation occurred during loading. For this reason, we performed a stress analysis of the key under a load

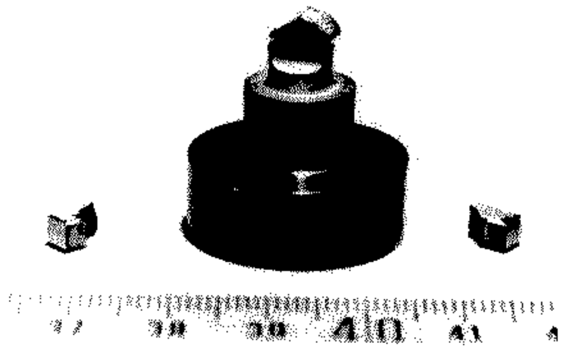

Fig. 6. View of the cracked key evidencing the rupture surfaces.

of 7 kN taking into account the plastic behaviour of the material with a bilinear law based upon the values reported in table 1.

The model is similar to that used for the elastic analysis, but composed of 8 nodes solid elements with incompatible shapes. It has been solved with the computer code ANSYS [13].

The contour of the Von Mises equivalent stress is shown in fig. 8, the maximum value reaches 763 MPa, just in the lower zone of the groove, where the ruptures originated during the tests.

From the results it is evident that under the ultimate load a plastic deformation actually originates in the groove, but the yielded zone is limited and, while the stress and the elongation reach the rupture values here, the surrounding material is in elastic condition. This

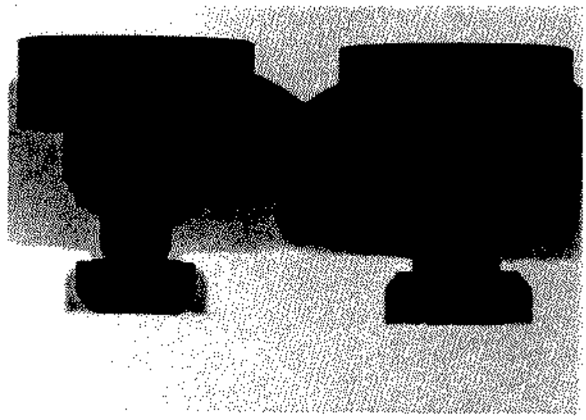

Fig. 7. Right: the matching of the fragments after a typical rupture. Left: a key exceptionally deformed under a constant applied load.

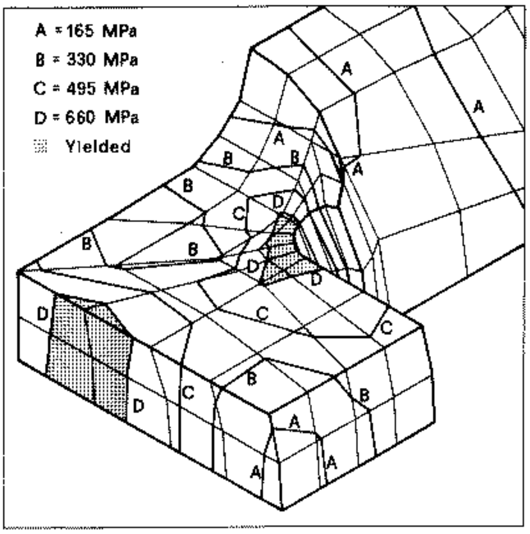

Fig. 8. Elasto-plastic stress distribution in a prototype key at rupture conditions.

condition causes a crack in the groove before the plastic deformation extends. Therefore the permanent elongation is not appreciable and the rupture appears to be brittle.

The reliability of numerical simulations is confirmed by the calculated maximum displacement of 0.037 mm. This is in good agreement with the measurements.

During the tests we also experienced unstable behaviour of molybdenum: by leaving the key under load just below the rupture value we observed the oncoming of a slow plastic deformation above the value reported in table 1.

The left key in fig. 7 has been deformed by such a technique up to a permanent teeth deflection of 0.13 mm.

4. Vacuum welding

Vacuum welding can take place when two surfaces in UHV conditions are kept in contact under load for many hours at a high temperature [14,15]. The phenomenon depends strongly on the nature of the mating surfaces, on the load conditions and on the temperature.

In the RFX operating conditions (pressure as low as 10^{-8} mbar, temperature up to 350 °C) vacuum welding can take place between the teeth of the key and the planes of the two L-shaped grooves of the bush.

To investigate this phenomenon and the effectiveness of anti-welding coatings, some tests have been carried out, in which the keys were either uncoated or coated with CVD Titanium Nitride, PVD Silver and CVD Alumina.

To control the load conditions on the clamping elements, helical springs were interposed between the head of the key and the bush. In this way the clamping force was easily determined by measuring the deflection of the spring. A clamping force of 60 N was used which is equal to the average clamping force during the operation of the machine.

The tests were carried out on 15 specimens for each coating, in a vacuum oven at a pressure lower than 10^{-4} mbar, measured with a cold cathode ionization gauge, and at a steady temperature of 300 °C, measured with three thermocouples. The duration of the test was 127 h.

After cooling in vacuum and then in nitrogen, the clamps were taken out of the oven and unlocked using a dynamometric wrench. All the specimens were unlocked with a torque lower than 1 Nm and no trace of vacuum adhesion appeared in the uncoated clamps.

In spite of the positive result of the test, it was decided to coat the tip of the key because the conditions in the machine can hardly be predicted. The CVD TiN coating was chosen because it shows a better adherence to the substrate than the other coatings and has already been applied in similar conditions.

Conclusions

A first wall clamp for the RFX graphite tiles has been developed fulfilling the remote handling requirements. The working conditions of the tile locking device have been carefully analyzed. The strength capability of the molybdenum key has been checked with destructive tests and theoretical analyses, showing a large safety margin. The anti-welding coating of the key has been tested for many hours in a vacuum oven, exhibiting a satisfactory performance. The components are now under construction.

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