RECOVERY OF ITER SECTOR MODULES FROM CRITICAL ISSUES
Vacuum vessel bevel and vacuum vessel thermal shield repair

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1. INTRODUCTION

In ITER, the tokamak chamber consists of nine 40-degree sector modules (SM), each composed of a Vacuum Vessel (VV), two Toroidal Field Coils (TFCs), and a VV Thermal Shield (TS), whose role is thermal radiation insulation between the VV and TFC. Once all nine SMs are installed in the pit, the VV modules are welded together to form the VV Torus. In May 2022, the assembly of the first SM was completed, and it was successfully transferred to the pit (Fig.1). Due to non-conformance of VV and TS, first SM was returned to the SSAT and dismantled for repair. In 2024, the repair of the first pair of VV and VVTS was successfully completed and re-assembly started. The first repaired SM is scheduled to be moved into the pit in April 2025, resulting in a successful recovery of both VV and TS. This paper presents the critical issues on VV and TS, recovery strategy, repair process, and lesson learned.

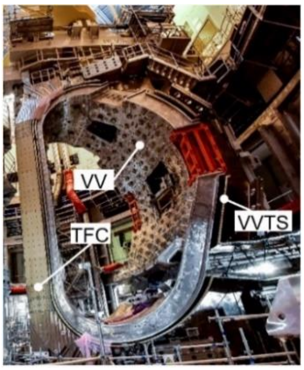

Fig. 1. SM transferred to the pit

2. CRITICAL ISSUES ON VV AND TS

In December 2021, during acceptance tests of the first VVTS, three leaks were found in the Equatorial Ports (E-ports). A Root Cause Analysis (RCA) revealed that these leaks were caused by Stress Corrosion Cracking (SCC) in the cooling pipes, which had been welded onto the VVTS panels for cooling purposes. However, considering that the leaks occurred exclusively in the E-port pipes, which have a total length of 1 km, while no leaks were observed in other components despite a total pipe length of approximately 23 km, SCC was suspected to be a phenomenon specific to the E-ports.
Furthermore, almost simultaneously, in first three delivered VVs, large geometrical deviations were detected in interface regions were the VVs are welded with each other. Remedial Actions (RA), such as correcting these deviations using adapted splice plates and repairing the VV welding bevels in the pit were considered at that time to recover the delay.
The detailed RCA of SCC in the VVTS cooling pipes, along with the feasibility analysis of RA for VV welding bevel repair, took approximately six months. Although disassembling the SM was expected to result in a significant delay of approximately three years, it was decided to proceed with removing the first SM from the pit and disassembling it to facilitate repairs of both the VV and VVTS, thereby mitigating significant future risks.
The following sections provide details on the RA and repair of the VV, as well as the VVTS repairs.

3. RECOVERY OF VACUUM VESSEL

3.1. Critical issues in VV bevel dimension deviation

Welding of VVs in pit is done by narrow-gap mechanized TIG, which requires tight tolerances at the welding joint bevel, some of them are shown in Fig. 2. However, large welding deformation occurred at the field joint bevels during final assembly of VV Sector manufacturing. As a result, critical deviations in bevel dimension were identified, including a) deviations in bevel profile, with the most critical being the bevel nose thickness, b) deviations in the toroidal bevel position, and c) radial deviations (bevel backside undulated surface). These deviations exceeded the range that could be accommodated with splice plates, necessitating the repair of welding bevel was needed.

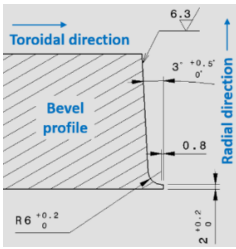

Fig. 2. VV welding bevel

After an intense analysis of the different potential strategies to repair the VV sectors, it was decided to operate with a combination of material build up, to add material where needed, and followed by final machining, the obtain the correct bevel geometry. However, several challenges must be addressed when applying this method to VV repair, as follows: 1) To qualify the build-up process required to repair the bevels, in both vertical and horizontal position. 2) To qualify bevel machining through suitable customized portable machines able to machine sectors on site to final required tolerances, considering that transport of sectors to industry for bevel machining on a portal machine was not feasible, and 3) Dedicated UT qualification needs to be developed for the NDE of the field welding joint between sectors when the build-up is done for bevel repair.

3.2. Recovery strategy and achievements

To avoid delays, it was decided to repair the first two VV bevels in vertical position, which is the position on which they are during assembly with the VVTSS and TFC on a specific tooling named SSAT, where both sides of the bevel are accessible. In addition, customized portable milling machines have been developed to work in any required position. They can be aligned with precise positioning using a temporary metrology network, referred to the permanent VV network. In addition, Radiographic Testing (RT) using a linear particle accelerator (LINAC) will be preferably applied where possible, instead of UT for field joint welding between sectors. Validation of bevel dimensions after final machining is performed by 3D scanning, and the bevel dimension satisfied the required tolerances. Figure 3 shows the before and after final bevel machining. The third VV, which has a much larger deviation, is being repaired in horizontal position. A much longer duration for this repair can be accommodated by optimizing installation sequence of this VV. At present 2 sectors are fully repaired and being assembled on their respective SSAT.A 3rd sector has been delivered fully repaired and two more are being repaired in horizontal position.

Fig. 3. Repaired VV bevel

4. RECOVERY IN VACUUM VESSEL THERMAL SHIELD

4.1. Critical issues in TS and detailed RCA

By using Computed Tomography (CT), Scanning Electron Microscopy (SEM) and other methods, it was confirmed if SCC presents. In the cooling piping of the E-port, SCC with a depth exceeding the 2.2-mm pipe wall thickness was observed (Fig. 4). In the cooling piping of other components, SCC was also detected, but its depth was generally below 0.3 mm. Meanwhile, in the TS panels, only one location at the E-port exhibited SCC with a depth of 2.4 mm; at other locations, only very early-stage SCC or pits were observed, and the number of these occurrences was limited to only a few spots.

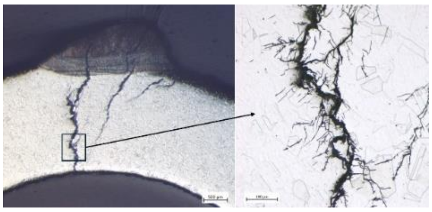
Fig. 4. Crack cross-section by CT scan

4.2. Recovery strategy and achievements

Once SCC has propagated, its removal becomes practically impossible. In the cooling piping and E-port, SCC progression was observed, it was therefore decided to scrap the cooling pipes and E-ports. On the other hand, since no SCC propagation was observed in panels other than those in the E-port, they were deemed repairable. This approach will shorten the time required for the panel material procurement and its forming (≈1 year). Since complete removal of existing chloride to deactivate crack propagation is difficult, panel were machined to remove a 2 mm thick layer in the vicinity of the pipes to ensure the complete removal of the chloride (this method cannot apply to the pipe), and then polished to achieve lower thermal radiation emissivity. After panel machining and grinding, Fluorescent Penetrant Testing (FPT) was performed to confirm the absence of SCC on the panel before new pipe attachment. In addition, the new pipes are 316L grade and ER317L Mn Mod filler material are used to increase corrosion resistance (Fig. 5). Considering the tight tolerances of the TS, controlling welding deformation was the biggest challenge for repair and the welding deformation was properly managed. The success of repair was confirmed geometrically by the pre-assembly test and survey.

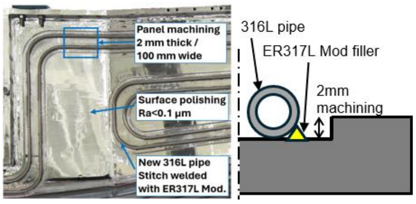

Fig. 5. Repair Strategy

5. SUMMARY

The repair of two VV and VVTS sectors was completed by August 2024, and the repair of other sectors is progressing as planned schedule. The first repaired SM re-assembly was started on September 2024. After approximately three years, the recovery from the critical problem can be successfully accomplished, preventing further delays in the ITER project. These achievements represent a significant contribution to the progress of the ITER.