Progress and Achievements on the R&D Activities for ITER Vacuum Vessel

M. Nakahira 1), K. Koizumi 1), H. Takahashi 1), M.Onozuka 2), K. Ioki 2), E. Kuzumin 3), V. Krylov 3), J. Maslakowski 4), B. Nelson 4), L. Jones 5), W. Danner 5), D Maisonnier 5)

1) JA Home Team, Japan Atomic Energy Research Institute (JAERI), Ibaraki, Japan
2) ITER Joint Central Team, Garching Joint Work Site, Garching, Germany
3) RF Home Team, Efremov Institute, St. Petersburg, Russian Federation
4) Oak Ridge National Laboratory, USA
5) EU Home Team, EFDA, Max-Planck Institute, Garching, Germany

e-mail contact of main author: nakahirm@fusion.naka.jaeri.go.jp

Abstract. The ITER vacuum vessel (VV) is designed to be large double-walled structure with a D-shaped cross-section. The achievable fabrication tolerance of this structure was unknown due to the size and complexity of shape. The Full-scale Sector Model of ITER Vacuum Vessel, which was 15m in height, was fabricated and tested to obtain the fabrication and assembly tolerances. The model was fabricated within the target tolerance of ±5mm and welding deformation during assembly operation was obtained. The port structure was also connected using remotized welding tools to demonstrate the basic maintenance activity. In parallel, the tests of advanced welding, cutting and inspection system were performed to improve the efficiency of fabrication and maintenance of the Vacuum Vessel. These activities show the feasibility of ITER Vacuum Vessel as feasible in a realistic way. This paper describes the major progress, achievement and latest status of the R&D activities on the ITER vacuum vessel.

1. Introduction

The ITER vacuum vessel (VV) is designed to be a water cooled, large double-walled structure with a D-shaped cross-section. Since the vessel forms the first radioactivity confinement barrier for the reactor, the VV must be designed to withstand design basis accidents and off-normal events without losing confinement. The vacuum vessel is divided toroidally into several sectors that are joined by field welding on site during assembly. The fabrication tolerances for the vessel sector height and width should be less than ± 20 mm, and ± 5 mm for the sector wall thickness. To meet this requirement, the Full-scale Sector Model Project has been initiated in 1995 as one of the Seven ITER Large R&D Project. In order to establish the fabrication and assembly/ disassembly technologies, the related activities had been continued with the joint effort of the ITER Joint Central Team, the Japanese (JA), Russian Federation (RF), United States (US) Home Teams.

The major achievement by 1998 was the demonstration of fabrication technology with high dimensional accuracy. The full-scale sector model fabricated by JA Home Team and the full-scale mid plane port extension fabricated by RF Home Team demonstrated the dimensional accuracy of ± 5 mm and ± 4 mm to the design value, respectively [1]. The feasibility of field joint welding for VV sector assembly was also demonstrated by the testing of full-scale sector model. The measured welding deformation of the VV sector model due to field joint welding has been analyzed with FEM analysis to establish the simulation method to accommodate the change of the ITER design. The comparison of analytical result with the measured welding shrinkage showed that the calculation error is up to 30% in shrinkage and up to 40 % in sectional deformation. The further improvement of simulation method is being continued with considering welding procedure and more precise constraints.

In parallel with these activities, EU Home Team is continuing the R&D activity to improve the efficiency of the VV sector assembly and maintenance. The EU Home Team has launched a programme of advanced welding, cutting and inspection tasks [2]. Full wall depth for vertical-wall and lower orientations and partial depths for overhead orientations has been welded by reduced-pressure electron-beam. New combined-total 7 kW Nd YAG laser system has achieved high fill rates for the remaining narrow gap welds, although the technology is not yet ready for industrial use. The same laser system has demonstrated full wall thickness cutting with thin kerf width. Weld fault detection for inspection using phased array ultrasonic (UT) probes is being developed as this has the potential for automation and cost-saving. A new parallel-robot-configured system has been designed to carry the process heads to the field joint area with high dimensional accuracy.

2. Integration Test on Full-scale Sector Model

In addition to these R&D activities, the integration of the mid plane port extension and VV full-scale sector model by using full-remote welding and cutting system developed by the US Home Team, are continued. As a first step of integration test, the port extension connection to VV sector model was performed using remotized welding tools. The port extension is a square-tube-shape structure made of double walls and ribs. The size is 3.4m in height, 2.2 m in width and 1.5 m in length. The initial dimension error of outer wall between the VV sector port opening and port extension was about 2 to 3 mm and up to 9 mm at local area. The optimization of root machining due to the measurement result could reduce this error down to 6 mm. Figure 1 shows the final dimensional error before outer wall welding. In this figure, measured points are named with the edge. For example, “L1” means the point is located on the left straight edge of port (view from port side) and No.1 out of 7. The maximum error was occurred at the center of top and bottom straight edge. The dimensional error of inner wall after outer wall welding was ±5mm and up to 8mm at local area. This error was adjusted within ±1.5mm with splice plates. Figure 2 shows the final dimensional error before inner wall welding. In this figure, the number of measured points is increased for detail machining of splice plates. The points are defined as continuous number of 1 to 230 starting from “L1” of outer wall case. Edge name of L, B, R and T are added in the figure for a reference. The

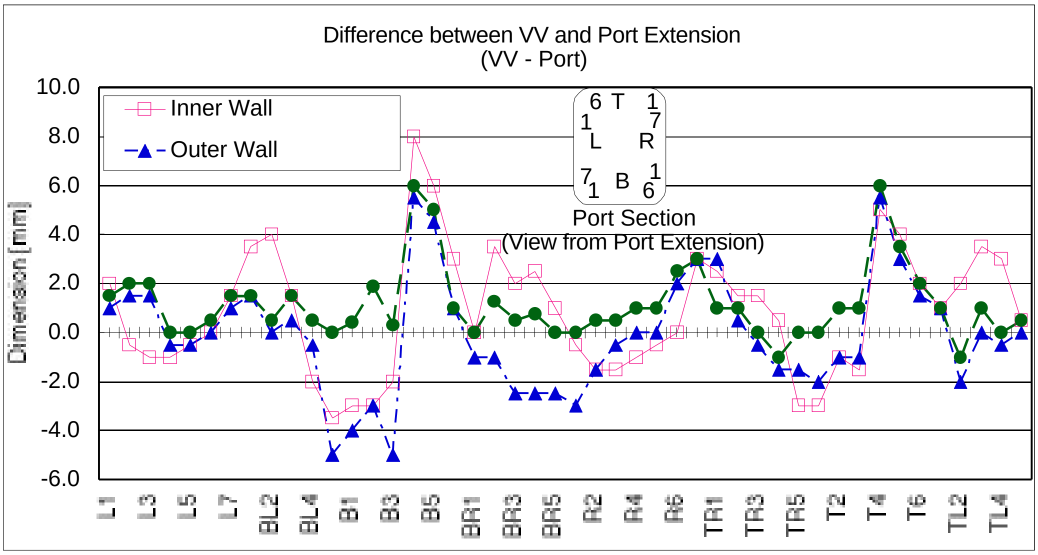

FIG. 1. Relative dimension error between outer walls of VV and Port.

numbers with “#” are the numbers of splice plates. In this case, the root edges of splice plates are offset on purpose, for better J groove welding, with target of 2mm. Thus the deviation from 2mm in the figure is the error value. After these settings, the welding of inner wall was performed with remotized welding tools. The deformation data during welding is obtained and will be used for evaluation of the deformation analysis. It is also planned to perform the cutting test of port extension to obtain the deformation during maintenance by July 2001.

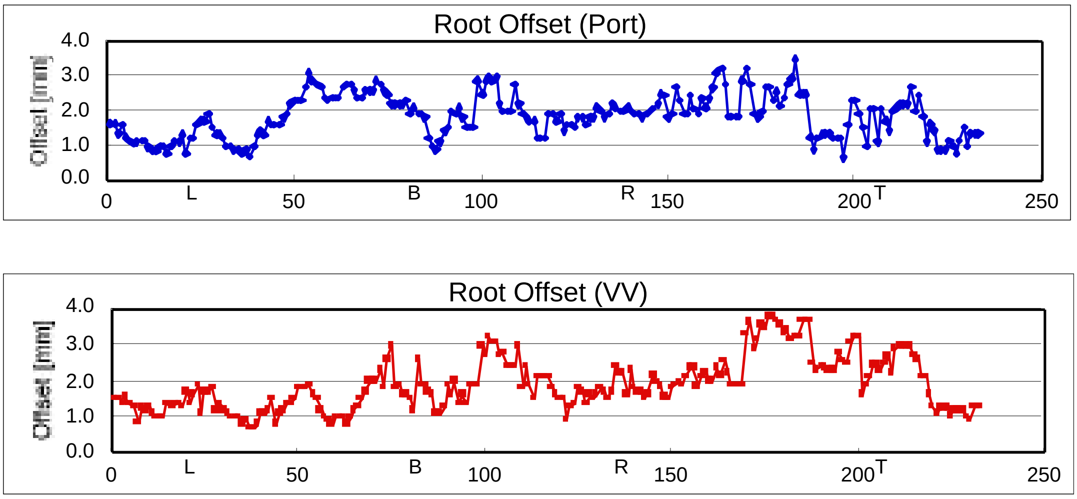

FIG. 2. Relative dimension error between inner walls of VV and Port.

Figure 3 shows the appearance of welding operation using remotized welding tools. This tool is robot arm on rail mounted vehicle having 6 degrees of freedom. The rail is set at the center of the port along the port axis. The vehicle and robot arm are set on the rail to weld the port wall. The concept of this tool is to relax the rail setting accuracy because remote handling must cover the rail setting in actual condition. The robot arm will cover the misalignment of tool setting. The test has been successfully completed by the end of March 2000. It is also planned to perform the inspection test of port extension field joint by using remotized tools by July 2001.

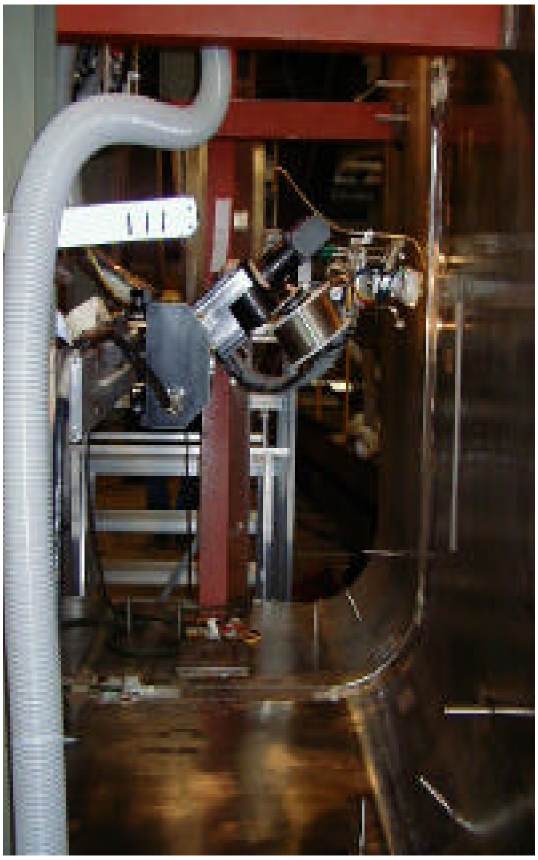

FIG. 3. The remotized welding tool.

3. R&D Activities on Welding, Cutting and Inspection Techniques

The ITER VV walls have single-sided access so the reduced-pressure electron-beam (RPEB) root welds have to finish in a backing strip. Investigations are ongoing to find the limits to weld thickness caused by gravity dropout in all welding orientations. The gun, with special focussing optics and using 150 kV and up to 20 kW, can operate up to 750 mm working distance at 1 mbar or less. Downhand to vertical plate welds of 60-mm penetration can be completed without metal dropout in one pass only (figure 4) but as the inclination goes to overhead, this figure progressively reduces to 25 mm. The necessary inclusion of a narrow gap at the weld cap also assists in chilling and reducing the weld dropout. This process is preferred over laser welding as it offers the potential of a maximum thickness, low distortion (0.6 mm), high quality, welding with consequent minimum number of passes.

There is an on-going investigation of single pass and multipass NdYAG laser welding using a combined 4 + 3 kW TWISTLAS (twin spot system from HAAS, spots separated by 0.6 mm). With 150 mm focal length, partial penetration welds of 18 mm deep occur at 0.15 m/min, although these welds have a wineglass shape with a wide, 13 mm cap. Useful weld depths require longer focal lengths to enable narrower angle (10 degrees) gaps with less metal to be filled above. For root fills 500 mm focal length was used, resulting in a 7 mm penetration at 0.15 m/min. Figure 5 shows a multipass weld built up from a 7 mm root weld and four, 6 mm wire fill passes. Problems with hot cracking, due to the high thermal coefficient of the material, and porosity at the weld root remain to be solved.

FIG. 4. RPEB welds at overhead, vertical plate and 45º.

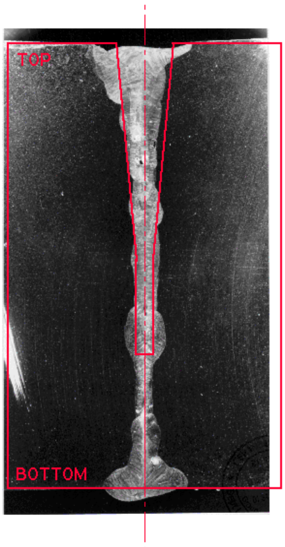

FIG. 5. multipass NdYag laser weld in 40 mm thickness.

The 6 kW NdYAG laser cuts 60 mm plates with ease but at a slow speed of 0.15 m/min.
No oxidation, parallel cross section shape with kerf thickness of about 1.5 mm and low surface roughness were achieved (fig 6). At these low cutting speeds, a nitrogen jet at high pressure cooled the workpiece, so only 4 bar was used. The performance increase (about double) compared to CO_2 laser cutting is due to the increased surface power absorption and improved penetrating ability of the lower frequency of the NdYAG laser (1 micron wavelength compared to the 10.6 of the CO_2 laser) through the hot plasma. The cutting speed can therefore be reduced in this application where set-up times outweigh process times.

The Intersector-Welding-Robot (IWR) design represents a solution for carrying the process end-effectors along the joint seam. A parallel geometry was selected (fig 7) as it provides exceptional stiffness (0.1 mm deflection for a 400 kg payload) and strength (2 tons for arm system). The limited movement range (300 mm and 10 degrees rotation) is sufficient, when combined with a linear slideway, mounted on the reactor wall. Machining may be carried out for weld preparations on the wall. Load pins fitted to the rams provide 6-axis force feedback information. The on-board laser tracking system provides accurate survey information for the precise fit-up requirements. Construction of the IWR is anticipated next year and it will be attached to a mobile mock-up of the wall to produce large demonstration components.

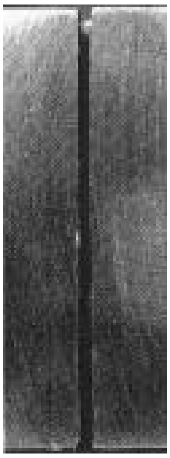

FIG. 6. 60 mm NdYAG laser cut.

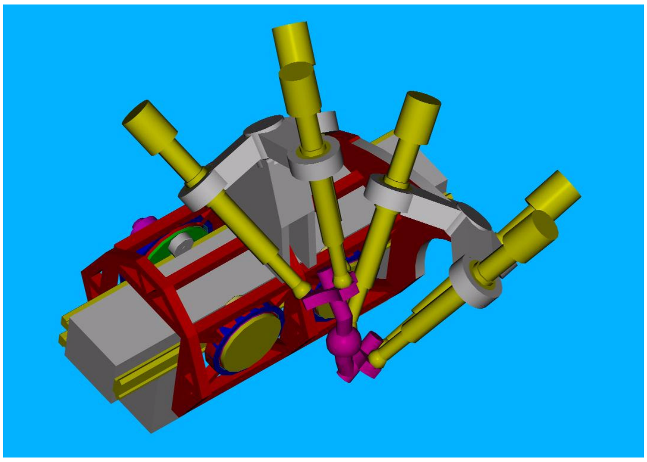

FIG. 7. Intersector Welding Robot, mounted on rail with 6 rams.

4. Conclusion

The R&D related to ITER vacuum vessel has been progressed with the collaborative efforts by the JCT, the Japanese, the European, the United States and the Russian Home Teams. The major goal of the R&D to demonstrate feasibility of industrial fabrication and on site assembling of ITER vacuum vessel was successfully achieved. Advanced methods of on-site assembly fabrication offer possible efficiency improvements but require further work before acceptance.

[1] M. Nakahira et al., 17th IAEA Fusion Energy Conference., (1998) IAEA-CN- 69/ ITERP1/24
[2] L. Jones et al., Fifth International Symp. on Fusion Nuclear Technology, (1999) P3-9-42