Manufacturing and Assembly of ITER Cryostat - Welding Challenges and Experiences

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Abstract

The ITER Cryostat- the largest austenitic stainless steel vessel provides ultra-cool environment for the ITER Vacuum vessel and the Superconducting Magnets. It weighs ~3500 t and measures up to ~29 meters in diameter and ~29 meters in height. Material of Construction is dual marked SS 304/304L and thickness varies from 25 mm to 200 mm.

The Design, manufacturing and inspection of the cryostat is as per ASME Section VIII Division 2 with supplementary requirement of ITER. Due to large number of penetrations and transportation limitation at Site calls for the segmentation which results in number of subassemblies. Massive amount of welding deposition is required to join these subassemblies to fabricate the segment.

ITER Specification for Cryostat demands stringent dimensional tolerance requirement (0.3% out of roundness) as compare to ASME. Other challenges are higher thickness weld joints in all position, space constraints, welding accessibility and stringent ITER vacuum requirements. Austenitic Stainless steel is prone to distortion due to low thermal conductivity and high coefficient of thermal expansion. This paper covers improvements done in the traditional welding process SAW, FCAW and to achieve dimension requirements and results are discussed. This paper also covers application NG Hot wire TIG for Site weld joints.

In order to simulate the job conditions, mockup of 40° segment on base section and 60° segment for lower cylinder segment was performed for Welding & NDE feasibility, Welding sequence establishment for dimensional achievement. This paper also highlights the Learnings acquired from the mockups and implementation during manufacturing.

Keywords: ITER Cryostat; dimensional control; high thickness; SAW, Hot Wire TIG

1.0 Introduction

Cryostat is a large Austenitic stainless steel structure providing vacuum environment to ITER Machine components. It will be evacuated to a pressure of 10-4 Pa thermally insulate the magnets and thermal shields during operation. Weight of Cryostat is ~ 3500 t and it measures up to ~29 meters in diameter and ~29 meters in height. [1] For the entire vessel, material of construction is Dual marked SS 304/304L and thickness varies from 25 to 200 mm. It is a single wall cylindrical construction, reinforced by horizontal and vertical ribs.

Cryostat is being delivered to ITER Organization by Indian Domestic agency ITER-India. All modules of the cryostat will be manufactured and installed by L&T Heavy Engineering.

The Design, manufacturing and inspection of the cryostat is being carried out as per ASME Section VIII Division 2 [2] with supplementary requirement of ITER Vacuum Handbook [3]. Cryostat is classified as Protection important component (PIC-2) as per French quality order. Due to large number of interfacing components, cryostat consists of large number of penetration results in number of subassemblies to be manufactured.

Due to size restriction for road transportation at ITER site France, cryostat has been divided in to four main sections: Base Section, Lower Cylinder, Upper Cylinder and Top Lid. Each section has been sub divided into two tiers in vertical direction. Each of these tiers has been toroidal divided into six sectors. Top lid has been divided into 13 sectors. Thus, this massive structure is made up of 52 assemblies. **Fig. 1** shows three Dimensional view of ITER Cryostat sections. Cryostat manufacturing has been planned at three location: Indian Factory, ITER Site workshop building and Installation in Tokamak Pit. Current work presents the manufacturing of Cryostat at Factory and ITER Site workshop.

Final assembly of these manufactured sections is being done at Tokamak PIT (Machine Assembly hall), where base-sections, lower cylinder, Upper cylinder are connected through welded connection at the required stage of installation and with a constraint radial distance of 500mm between cryostat cylinder wall and wall of tokamak hall. This requires stringent control on the overall dimensions of the cryostat starting from assembly stage at Factory to final assembly in Pit. In current paper this will be in form of future scope which is yet to be proven with the help of mock-up.

Table 1 shows the important critical Dimensional tolerances like flatness, profile and position requirement of penetrations for the Cryostat sections in the Tokamak Pit.

Requirement of profile is three times more stringent than that of required as per ASME Section VIII Div.2 [2].

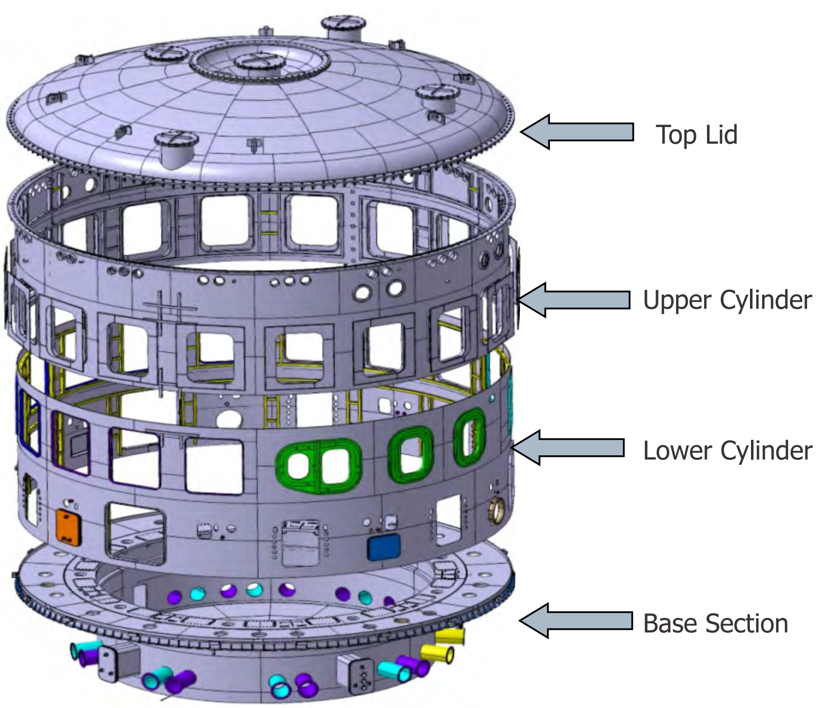

Fig. 1. : 3D-View of ITER Cryostat

Table 1 : Tolerance Requirements for ITER Cryostat

Cryostat Components	Tolerance Requirement
Pedestal Ring Flatness	12 mm
Lower and Upper Cylinder Profile	±50 mm
HNB/DNB Area Profile	±32 mm
Upper Cylinder and Lower Cylinder Ports Position	±20 mm
Top Lid Profile	±50 mm

Austenitic Stainless steel is though easy to weld, due to low thermal conductivity and high co-efficient of thermal expansion can make it difficult to maintain its shape specifically during welding when temperature gradient plays a major role. This tendency of getting distort become worse when it is under restraint conditions. Another factor contributing to distortion is thickness involved (25-200 mm) in fabrication. Manufacturing of Cryostat involves critical requirement of dimensional control, higher thickness weld joints in all position, welding accessibility and stringent ITER vacuum requirements at factory and Tokamak Pit. These demand innovation in existing welding technique and application of advanced welding processes. One of the important key factors for the manufacturing of welded components is to design weld edge preparation which facilitates the welder/welding operator to produce sound welds.

This paper covers modifications of traditional welding processes i.e. SAW, FCAW etc. for different configuration of weld joints in order to achieve dimensional requirement and facilitates manufacturing through elimination of chip-back grinding and usage of welding manipulator. All developments were validated on prototype prior to implementation and results are discussed.

As manufacturing of cryostat is critical and consist of number of welded joints it is necessary to develop a Mock-up representing each of these types of welds. Mock-up also involves critical dimensional requirements, critical weld thicknesses, welding process and positions, accessibility and Non-destructive examinations. These mock-ups are also important in terms of establishment of welding sequence to establish for manufacturing. In some cases ITER specific requirement of Helium leak test is also established through this mock-up.

In order to simulate the job conditions of base section, it was decided to perform mock-up of 40° segment on base section and 60o segment for lower cylinder segment. Current work also highlights the job mock-up of representing entire base section and Lower cylinder and Top Lid. After completion it has been successfully implemented in manufacturing.

Another challenge is to design and validate all vacuum boundary weld joints as full penetration weld joints as per ITER Vacuum Handbook requirement. Due to difficult geometry, some of the weld joints are not covered by ASME Section VIII Div.2. This paper covers the design of weld joints for sandwich structure and its validation through mockup and its successful implementation on the job.

Fillets welds (Non-vacuum boundary joints) of ribs to ribs joints are to be done in vertical position due to its large size and complex design. As SAW is not feasible in vertical possible, FCAW among SMAW was selected due to higher deposition rate and better bead finish. The current work also presents improvement done in bead finish by establishment of Welding parameter.

Top Lid Flange (290 mm) is the highest thickness to be welded in Cryostat which will be further machined to suit the lip seal seating face with Upper cylinder flange. Procedure qualification was performed to establish the welding parameters and its quality weld assessment. Results are also discussed in the current paper.

To measure the huge cryostat segments in factory and sections in ITER Site cryostat workshop is also one of the challenge. Sections are measured intermediately to observe the distortion. Application of Laser Tracker is successfully implemented at factory and ITER Site workshop.

At present, Fabrication of cryostat segments of Base section, Lower cylinder and Upper Cylinder are completed and Top Lid is in progress at Factory. Assembly of Base section and Lower Cylinder are completed and Upper Cylinder assembly is going on at ITER Site Cryostat Workshop, France.

Section II describes this specific developments that has been done for welding processes, the mockups are presented in Section III and their implementation in Section IV which followed by conclusion in Section V.

2.0 Welding Mockup And Procedure Qualification

A. SAW (Sub Merged Arc Welding) for Pedestal Ring Plates

The pedestal ring of Base section (**Fig. 2**) upper part withstands load of entire vacuum vessel and magnet which transfers to bio shield. The plates and forgings comprising the pedestal ring are set up one by one and welded to form a box.

The internal stiffeners in the pedestal ring are welded at intermediate stages during pedestal ring welding. Plates forming the horizontal base segment are set up and

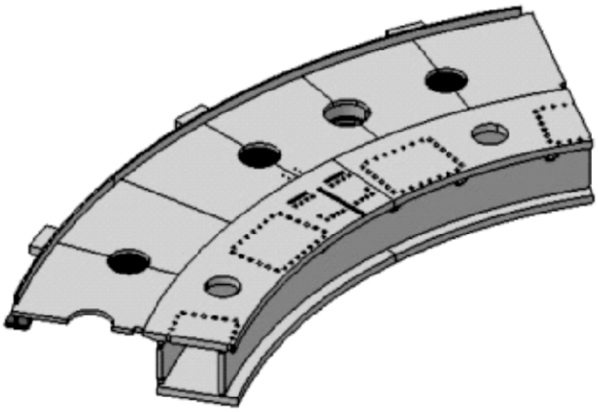

Fig. 2 : Sketch of Pedestal Ring

welded together. The plates forming the skirt support are welded together. The horizontal base segment and pedestal ring segment are welded together and NDE performed at each stage of welding. Various T-joints with varying thickness (80 and 120 mm) were involved in fabrication of pedestal joint.

SAW was considered as most appropriate process for these welds. Conventionally, such joints are welded using double sided full penetration configuration involving back chip. For stainless steel material, grinding will be difficult & will lead to longer cycle time. Hence, efforts were made to avoid chip back by taking several mockup trials with combination of various WEP and welding parameters. Also, narrow gap weld edge preparation was finalized to minimize overall weld metal deposition. Top and Bottom plate weld joints were subjected to 100% Radiography and found satisfactory.

B. Pedestal Ring T-Joints

Fig. 2 shows the T-joints with different thickness are welded to make the box structure of Pedestal Ring of Base section.

All Pedestal ring T-joints were welded in horizontal position due to its large size and to minimize distortion. To control distortion, Double Welder Technique (DWT) or Double Operator welding Technique (DOT) for GTAW was selected for welding of T-joints of Pedestal ring to avoid back chipping. SAW process was finalized for welding of subsequent layers in order to improve productivity. Accordingly, weld edge preparation was finalized to facilitate application of these processes. Curved torch was used for SAW for proper wire access and bead placement in the weld joints

Various trials were made, for both the processes, to produce sound weld in horizontal position and Ultrasonic testing was performed. Based on the results, welding parameters were finalized. All the joints were Ultrasonic Tested and found satisfactory.

C. Sandwich Structure Weld Joint

Sandwich Structure is part of Cryostat base section which withstands vacuum loading and limits the deformation under service conditions. Sandwich structure consists of top and bottom plates internally strengthened with radial and circular ribs [4].

Fig. 3 shows the 3D view of Sandwich Structure from Bottom Side.

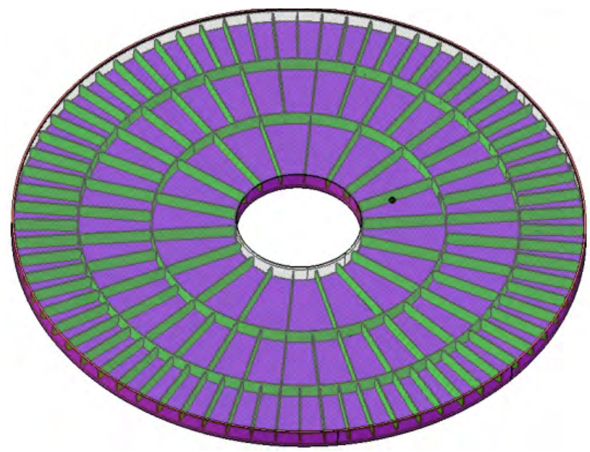

Fig. 3 : Sketch of Sandwich Structure

As per ITER Load specification requirement for Cryostat, Sandwich structure bottom plate has been designed with 100% joint effieciency which asks for 100% voumetric examination of weld joint. The Weld joint between bottom plate to rib was design such that to meet the welding and NDE Feasibility. Since this joint was not convered through ASME Section VIII Div 2, it was validated thorugh Mockup.

Welding Sequence was also established during qualification mockup to meet the tolerance requirement. Test Coupon of the Mockup was subjected to Tensile and Macro examination. Due to restricted access from the back side scanning for UT Examination, Each Layer LPE were carried out as per RCC-MR code[5] All tests were found satisfacotry.

D. FCAW (Flux Cored Arc Welding)

Sandwich structure rib to rib joints are fillet welds having length ~110 meter. Due to complex shape of sandwich structure, flat position for the fillet welds were not feasible. Therefore, it was decided to perform welding in vertical position.

Due to limitation for vertical position welds by SAW, FCAW was selected due to its higher deposition rate and better bead finish. Trials were done in the welding mockup for 3G FCAW and parameters were established to get the better bead finish.

E. Top Lid Flange Weld Joint Procedure qualification

Top Lid flange **(Fig. 4)** having highest thickness of 290 mm in cryostat which connects with the Upper Cylinder flange.

This will be further machined at ITER Site workshop to suit the Fasteners assembly and Lip assembly installation in Pit.

240 mm Thick Test Coupon was welded to qualify the procedure for the Top Lid Flange as per ASME Section IX [6]. Tensile Testing and guided bend test was performed and found satisfactory.

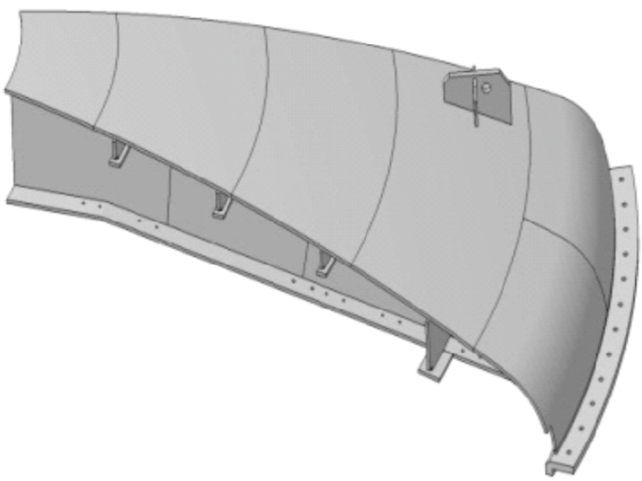

Fig. 4 : Top Lid Flange Procedure Qualification

F. Hot Wire TIG (HWT)

ITER Cryostat is vacuum vessel which requires stringent cleanness requirement in the Tokamak Pit installation. Traditional applied processes like SMAW, SAW and FCAW will produce slag and difficult to ensure clean atmosphere inside the pit. Therefore, GTAW process is most referable option. However, conventional GTAW process due to it lower deposition rate would be uneconomical. Hence, Hot Wire TIG (HWT) was finalized which gives higher deposition rate.

For welding of higher thickness joints, Narrow Groove HWT torch was used which is suitable for welding of joints up to 250 mm thickness. Oscillated Tungsten in the torch ensures complete side wall fusion. Additionally, Due to limited view access for narrow groove high thickness joints, two cameras, one for front side image & other for rear side image, have been in-built into this torch.

Several trials were conducted for different position and thicknesses and welding parameters were established.

For all trials, distortion and shrinkage data were observed and were recorded which were further analyzed to optimize WEP. All welding mockups were subjected to radiography and found satisfactory.

3.0 Mockup For Simulation

Typical Mock-up of Base section Tier-2 (40o sector) was planned **(Fig. 5)** to achieve the combine pattern of distortion of high thickness welds as the critical flatness requirement of 12mm is targeted to achieve on top plate (200mm thick) of pedestal ring (Magnets & VV resting face).

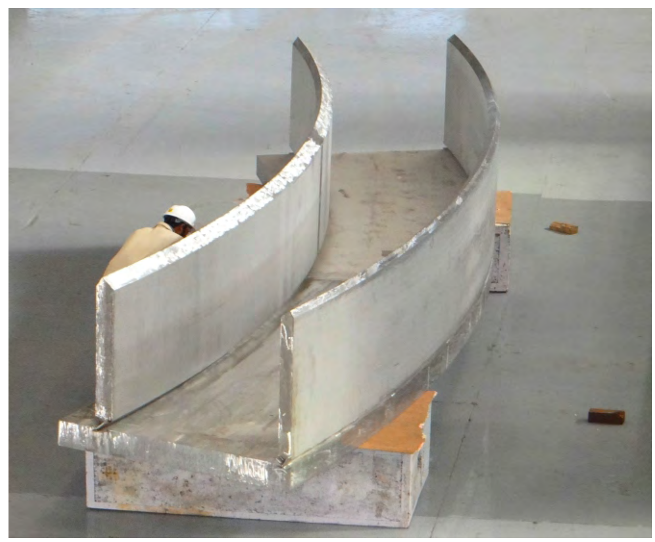

Fig. 5. : Base section Tier 2 Mockup

In order to achieve the same inner, Top and bottom plates are individually manufactured using pre-cambering arrangement followed by appropriate sequence of upside down turnover such that final result would be fairly flat at the weld locations. After successful achievement inner and outer plates were welded. As a result, Flatness have been achieved within 3mm on 40° sector mock-up which was reproduced on each 60° sector cryostat Base section Tier-2 within target requirement of 12 mm at factory.

Similarly, Lower cylinder Mock-up **(Fig. 6)** was planned to achieve the final profile requirement of 100 mm at tokamak pit. 60° mockup was again strategically plan to simulate the exact dispatch condition. Sub-segment sizing and weld sequence was successfully established in the Mockup.

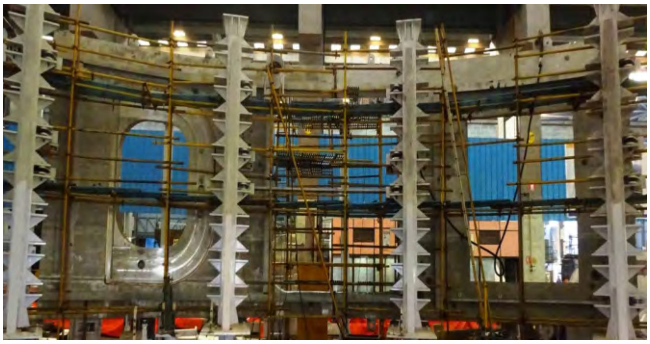

Fig. 6 : Lower Cylinder Mockup

All measurements were performed by Laser Tracker with defined targets on the job. Measurement data are intermediately analyzed to check the behavior of distortion and welding sequences are finalized accordingly. Dimensional protocol are finalized at the Mockup stage.

Mockup for Top Lid is currently in progress at Factory.

Additionally, Fixtures design for positioning and handling the job is also devised during mockup manufacturing.

4.0 Implementation On Manufacturing

After welding mockup and Prototype completion, learnings are implemented on job at factory and ITER Site workshop.

- Manufactuirng in Factory :

Each section of Base Section tier 1 and tier 2 weigh around ~60 t and ~120 t respectively. The base section central disc is being fabricated as a separate subassembly.

For Sandwich Structure Rib to Rib Fillet Joints, Established Parameters during welding mockup was successfully implemented for production weldsin Vertical Position **(Fig. 7)**.

Sanwich Structure bottom plate to rib welding was successfully implemented on the job.

Base section Tier 2 **(Fig. 8)** which is the heaviest Cryostat segments manufactured in Factory. Established parameters in the welding mockup was successfully impleted in welding of Top and botoom Plate of Pedestal Ring. Learnings from the prototype was successfully implemented during Pedestal ring manufactuirng and Targeted tolerances in high thickness are achieved in the Factory.

Lower Cylinder and Upper Cylinder **(Fig. 9)** are similar geometrical cylindrial shape. Tolerances for Several Segments are found beyound the targetd value of profile in the Factory but it meets the final requirment in the Pit assembly.

Top Lid flange to flange welding is successfully completed. Established Welding parameters were implemented in job and radiography examination was found satisfactory for all Factory

Fig. 7 : Base Section Tier 1 Sandwich Structure Segment

Fig. 8 : Base section Tier 2 Pedestal Ring in Factory

Fig. 9 : Upper Cylinder Tier 2 manufacturing at Factory

Joints. Top lid manufacturing is in final stage in Factory.

- Assembly at ITER Site Cryostat Workshop

Hot wire TIG was successfully implemented during the Base section pedestal ring subassembly at ITER Site workshop **(Fig. 10)** and ultrasonic examination results were found satisfactory. Flatness are achieved within the final requirement in the Pit. **Fig. 11** shows the manufacturing of Base section at ITER Site workshop.

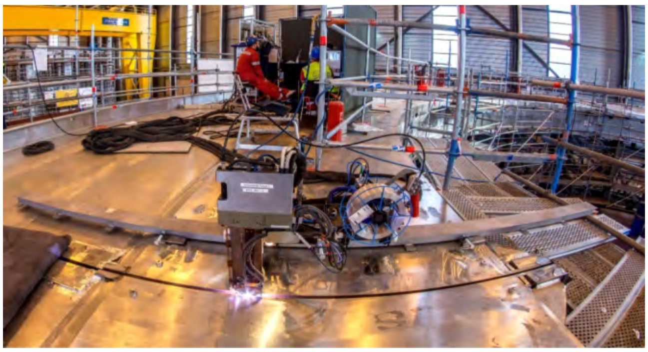

Fig. 10 : NG TIG Machine Welding Setup during Pedestal Welding at ITER Site Cryostat Workshop

Established methodology for the measurement by Laser tracker was successfully implemented. Most of the measurement was done by Laser Tracker at the time of Final dimensional inspection.

Lower Cylinder manufacturing at site is completed. Targeted profile was deviated than that of targeted at Site workshop. However, it was within the limit of final Pit requirement. Upper Cylinder is in current in final stage of assembly at ITER Site Cryostat Workshop.

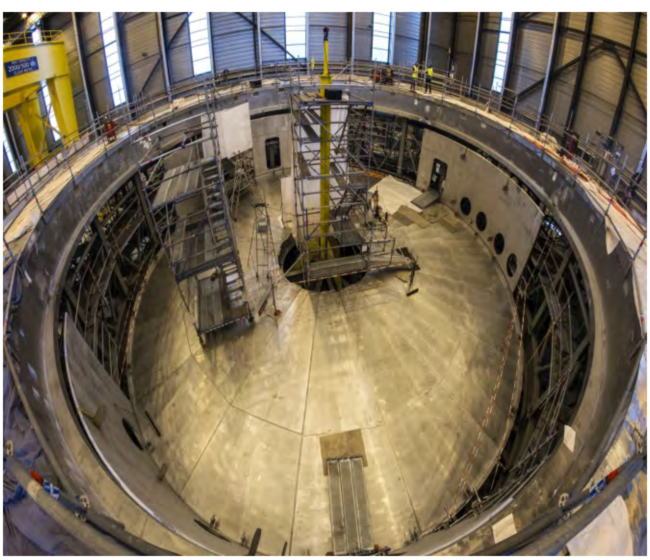

Fig. 11 : Base Section Manufacturing at ITER Site Workshop

5.0 Conclusion

Based on work carried out following conclusions can be drawn:

1. For welding of high thickness austenitic stainless steel welds, Modification in the welding techniques and unique application of Double Operator technique are successfully implemented in Mockup and in the Base section.
2. Weld related modifications are considered with the application of balance heat input and minimization of weld deposition for the finalization of the weld Edge preparation.
3. During Manufacturing, Result of the complete pedestal ring assembly conform the Specification required.
4. Measurement technique by Laser tracker was successfully established for such large structure.
5. Result of the components in the dimension inspection conforms within the most of the cryostat segments Pedestal ring Flatness are achieved within the similar range achieved in the Prototype. However, Profile of few sectors are exceeding the targeted requirements at factory and ITER Site workshop but are within the final pit requirement.
6. Successful implementation of HWT in Base section in ITER Site workshop proves to be preferred process for welding in clean environment. High deposition rate can be achieved in comparison to cold wire irrespective of position.

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