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Manufacturing of JT-60SA Cryostat Base

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HIGHLIGHTS

- JT-60SA Cryostat Base has been fabricated in seven structures fastened by bolts.
- The pieces are fully welded structures further machined to get required tolerances.
- The pre-assembly of the Cryostat Base will be done at the factory to check final tolerances as well as to anticipate problems which could be encountered during final assembly.

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ABSTRACT

JT-60SA is a superconducting tokamak to be assembled and operated at the JAEA laboratories in Naka (Japan) [1]. The tokamak has been designed to prepare, support and complement the ITER experimental programme and will be manufactured and operated under the funding of the Broader Approach Agreement (between the government of Japan and the European Commission) and of the Japan Fusion National Programme. Within the European contribution to JT-60SA, Spain has to provide the cryostat. Due to functional purposes, the cryostat has been divided in two large assemblies: the Cryostat Base (CB) and the Cryostat Vessel Body the latter subdivided into Cryostat Vessel Body Cylindrical Section (CVBCS) and the Top Lid. Spain is committed to provide the design and subsequent manufacturing of the CB and CVBCS (excluding the Top Lid) through the National Laboratory of Fusion at Ciemat. The design of both components has been concluded and the CB is currently being manufactured by a Spanish company, IDESA. This paper aims to present the status of the manufacturing and pre-assembly at the factory of the CB that has to be delivered in November 2012.

1. Introduction

The JT-60SA cryostat is the stainless steel vessel which encloses the tokamak and provides a vacuum environment necessary to limit the transmission of thermal loads to the components at cryogenic temperature. The cryostat assemblies as well as the main parameters are shown in Fig. 1 and Table 1, respectively.

The CB consists of a heavy construction that due to the transportation limits in Japan, will be fabricated in seven structures. The 7 pieces are fully welded structures, further machined to get the required tolerances. The CB will be assembled by mechanical connection, fastened by bolts, between the structures and the final vacuum sealing will be done on site by means of light welds.

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2. Cryostat Base Design

The CB has been validated by Finite Element Calculations [2] (elastic and limit load analyses) according to ASME Section VIII, Div. 2, 2007. The CB has very demanding structural requirements since it must bear the weight of the entire tokamak as well as the loads originated from the operation of the machine (in normal/abnormal conditions) such as pressure, temperature, Vertical Displacement Events (VDE) or external ones such as seismic loads. The component transfers all the loads to the tokamak building foundations consisting of high resistance concrete plates embedded in the floor of the torus hall. The manufacturing of the CB is made from stainless steel plates (SS304) of different thicknesses. The CB total weight is 253 ton, 12 m external diameter and 2.9 m height with requirements in total tolerances of ±2 mm in height, ±4 mm in external diameter and ±0.25 mm flatness on machined surfaces.

The whole structure will be pre-assembled, adjusted and dimensionally inspected at the factory before dispatching to Japan where it will be finally assembled on-site.

Table 1
Main parameters of JT-60 SA cryostat.

JT-60SA cryostat	
Operational pressure	Vacuum, 10^{-3} Pa
Potential accidental overpressure	0.12 MPa
Surface exposed to vacuum	1368 m^2
Volume	1410 m^3
Leak rate against air	10^{-4} Pa m^3/s
Cryostat dimensions	ϕ 13.47 m × 15.85 m
Cryostat Base dimensions	ϕ 11.95 m × 2.84 m
Cryostat Base weight	~240 ton
Cryostat Vessel Body weight	~245 ton
Design temperature of cryostat wall	293 K

The CB comprises three sub-assemblies, the so call Lower Structure – split in 3 sectors – the Double Ring – also split in 3 sectors – and the inner cylindrical shell made in a single piece. The seven pieces are fully welded structures in which partial tolerances must be kept on each sub-assembly through two approaches: on the one hand, the deformations during welding must be minimized (optimization of the welding sequence) while on the other hand, provision of extra material has been made for the final machining in order to absorb the deformations derived from the welding processes. Fig. 2 shows the arrangement of the CB sub-assemblies described next.

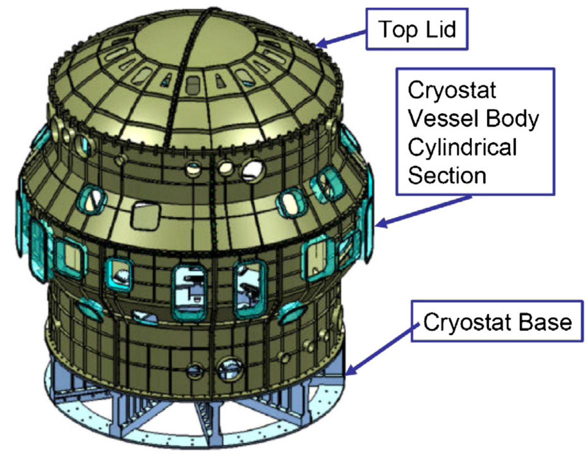

Fig. 1. JT-60SA cryostat.

The *Lower Structure* (LS) constitutes of three nearly identical sectors. The whole sub-assembly comprises one external and one internal ring and 9 radial legs supported on both rings. Each radial leg consists of a U profile beam reinforced internally, a large vertical plate reinforced with ribs and a plate on top of it. All plates are 80 mm thick except the ribs which are 50 mm. Each sector is

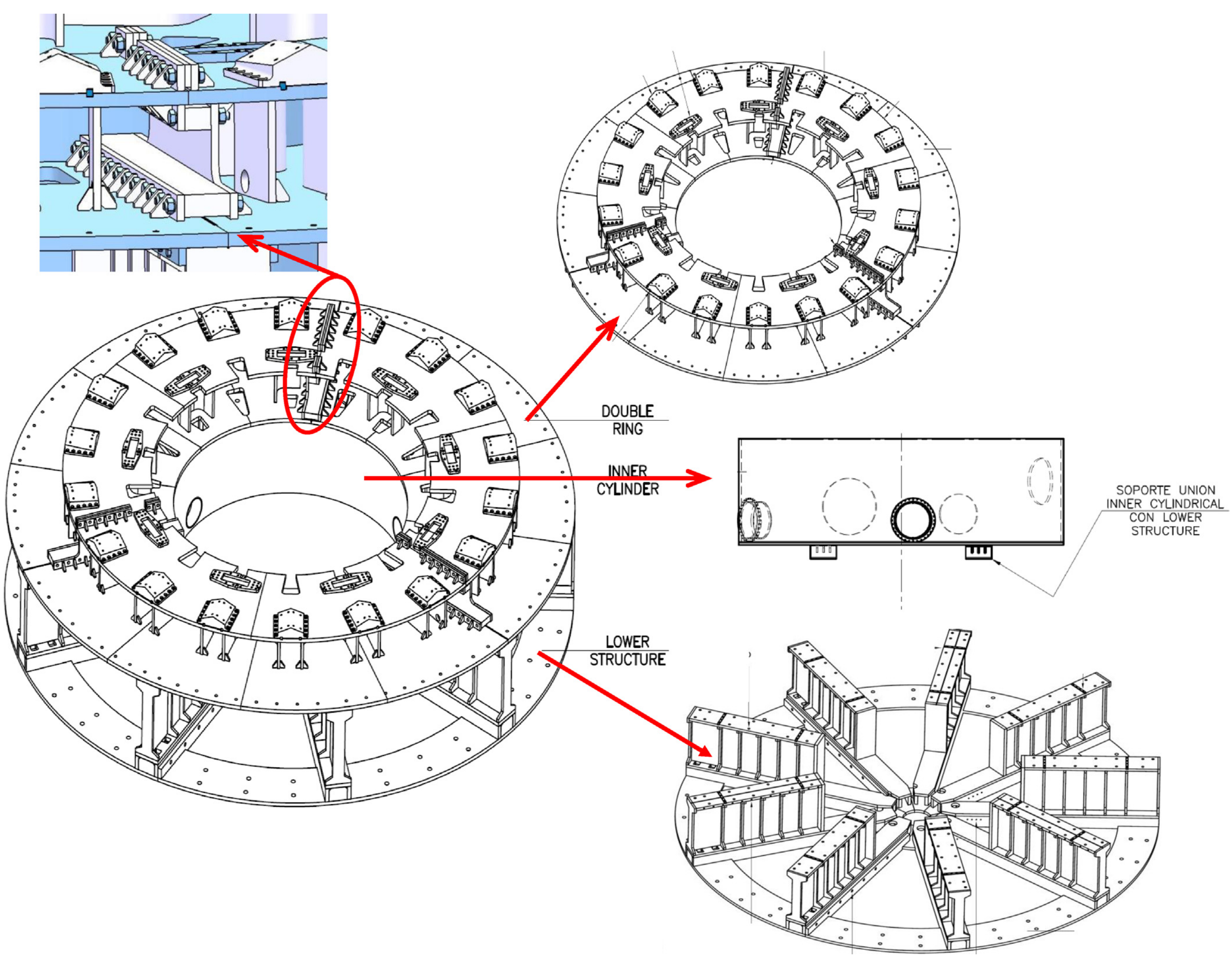

Fig. 2. Cryostat Base sub-assemblies.

connected to the adjoining sectors through bolted flanges with two dowels for alignment. The CB will be connected to the foundations of the tokamak by means of existing M64 studs bolted to the LS rings. The flatness required for the LS rings surfaces seated on the tokamak base plates is ±0.25 mm.

The *Double Ring* (DR) is formed of three identical sectors; each one consists of two horizontal Plates 90 mm thick joint by U-shape ribs between both and flanges at both ends for the connection between sectors. The Vacuum Vessel (VV) gravity supports and the Toroidal Field Coils (TFC) gravity legs will rest on the top surface of the DR. The VV is attached to the 9 plates welded to the DR, while the TFC rests on 18 forged pieces bolted to the DR and keyed in the toroidal direction by means of shear keys. The DR is assembled onto the LS attached to it by means of bolts, 4 dowels per sector for alignment and shear keys. The connection between DR adjoining sectors is designed by means of vertical flanges and stainless steel blocks (spacers) in between. The sectors are fastened by M52 bolts through the spacer and flanges. A detail of the DR sectors connection is shown in Fig. 2.

These connections between adjacent DR sectors are shifted 40° with respect to those in the LS in order to improve the mechanical behaviour of the whole assembly. The CVBCS will be seated on an outer area of the lower plate connected by bolts.

The *inner cylindrical shell* (ICS) is 5020 mm external diameter and 1626 mm height. The cylinder is fabricated from a base plate and a cylindrical shell, both 40 mm thick. The former is made up from two semicircular plates welded along the diameter while the cylindrical shell is formed by two rolled plates welded in longitudinal direction. There are two ports and three openings in the shell to allow access for the installation of equipment through the CB. The ICS rests on the 9 legs of the LS, fixed to them through 9 L-shape supports – welded to ICS base plate and bolted to each of the radial legs – aimed at limiting the deformation of the base plate during operation (because of vacuum forces).

Vacuum sealed welds: vacuum tightness of the CB will be done by means of light welding between the different DR sectors at the lower plate as well as between the ICS to the DR lower plate. These welds will be made after the final assembly of the seven pieces in Japan.

3. Material

The base material for the CB consists of hot rolled austenitic stainless plates (S30400) fabricated by Outokumpu (Sweden) according to the standard ASTM-240. Some special requirements for the material have been specified such as magnetic permeability $\mu < 1.05$ (on surface), Co content (Co < 0.05 wt%) and surface finish Ra ≤ 12.5 μm. The thickness of the different plates ranges from 40 to 92 mm (except for the spacers located between the DR flanges which have been provided with 130 mm thickness). The forged pieces where TFC gravity legs are seated have been fabricated according to the standard ASTM-473 with the same requirements as the base material.

In addition to the tests required by the standards applied, extended mechanical tests and microstructure characterization of the material in different directions (especially in thickness), have been carried out by the laboratory of Structural Materials at Ciemat [3]. Tensile and impact tests were performed down to −60 °C. Although the operating temperature of the CB external walls is 20 °C, a minimum temperature of −30 °C is reached locally at the VV supports. Results of these tests show highly ductile behaviour of the material presenting as average (in rolling direction) of up to 75% elongation, 350 MPa yield strength and 850 MPa ultimate tensile strength at −60 °C. Charpy tests according to ASTM E23-07 show maximum absorbed energies above 200 J.

Fig. 3. Lower Structure sector after welding phase.

4. Manufacturing of the CB

The CB is being manufactured according to ASME Section VIII, Div. 2. The industrial process comprises the following steps: cutting of the plates by water jet, edge bevelling for welds, qualification of required processes, welding phase, Non Destructive Examination (NDE), machining phase, pre-assembly of the whole component at the factory and final dimensional inspection by laser tracker. These processes are roughly described next.

- *Cutting of the plates* for the fabrication has been made in a high pressure water jet machine, to avoid heating of the pieces (Heat Affected Zone) and taking advantage of the good quality finishing of the cut surfaces. For large thickness plates (92/130 mm) the cutting speed has been limited to 10 mm/min. After cutting, the edges of the plates were bevelled by machining.
- *Welding phase*: SAW and GMAW have been used for the welding of the CB sub-assemblies. In order to increase productivity the SAW automatic process has been used for all the welds which have good access and can be made in the horizontal position. On the contrary, GMAW semi manual process has been used in those cases where the SAW machine could not be used because of the access or because the weld had to be performed in the vertical position. Full penetration welds have been performed everywhere except the ribs, which have fillet welds. Exceptionally, partial penetration welds has been designed for the U shape beams internal reinforcements of the LS due to the lack of space inside the beam. All full penetration welds have good enough access to perform volumetric inspection on them. In order to maintain an admissible deformation of the component during the welding processes, a careful welding sequence has been followed and partial dimensional checks have been carried out at intermediate stages to control the deformation during the process. Dimensional corrections were made on some of the components once finished, in order to get the total deformation within the material contour. A LS sector and a DR sector can be seen in Figs. 3 and 4, respectively. A partial stress relief on the subassemblies has been done after welding by means of vibrations.
- *Qualification of welding processes*: Before starting production the welding processes as well as the welders involved in the fabrication of the CB were qualified according to ASME Section IX. The corresponding Welding Procedure Specifications issued have been followed during the welding phase.
- *NDE* on the welds have been carried out as per ASME Section V following written procedures. On the full penetration welds the NDE performed comprises: 100% visual inspection, 100% dye penetrant tests (DPT) and 100% volumetric examination, e.g., radiography (RX) or ultrasonic examination (US). For partial

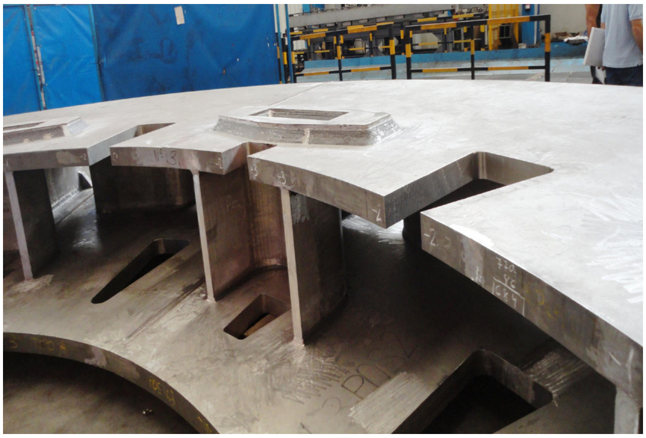

Fig. 4. Double Ring sector after welding phase.

penetration and fillet joints the NDE carried out has been limited to visual and DPT in 100% of welds. Regarding the volumetric examination, RX has been the preferred method used mainly for butt-welds. On those welds where RX was not possible, US tests have been performed. For the latter a specific procedure has been developed considering the different geometries (T or L corner joints), the grain size of the material and the thickness of the plates to be joined: specific probes (in the range of 2 MHz) have been arranged and tested on calibration blocks for the qualification of the process before using it in production.

Helium leak tests have also been foreseen on the structural welds of the ICS. A maximum leak rate per 1 m length of 10^{-7} mbar l/s is allowed.

- *Machining phase*: The final machining of the sub-assemblies is being made by a subcontractor (ASTURFEITO). Once the sub-assemblies have been welded and stress relieved they must be machined to meet the final dimensions and tolerances. Final machining (sector by sector) is basically made on the contact surfaces between sectors, the interfaces of the LS and DR, the seating surfaces of the VV and TFC support plates, as well as those of the LS rings on the foundations and the CVBCS on the CB. Additionally, edge bevelling of the DR sectors have to be made for the final closing welds at Naka.

A large boring machine and a portal milling machine are working in parallel for the machining of the LS and DR sectors. These can be seen in Figs. 5 and 6.

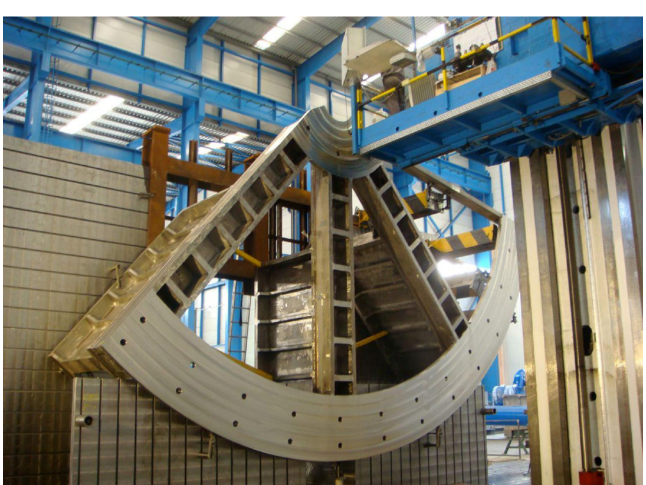

Fig. 5. Lower Structure sector during final machining with the boring machine.

Fig. 6. Double Ring sector during final machining.

Before starting the machining a complete dimensional control of the piece is performed to check the extra material available in all the surfaces and its sharing in the machining process. At present, the complete machining of the LS sectors has been finished.

The machining of the ICS comprises: machining in height and final machining of ports and openings. During this phase the sub-assemblies will be marked with reference lines in order to facilitate the final positioning in Naka.

- *Dimensional inspection* of the pieces is carried out during the different manufacturing phases, i.e., (a) during the welding phase to control the deformation produced by welding; (b) machining phase: dimensional inspections are made in the CNC machines (before starting and during machining) aimed at getting the partial tolerances for the individual pieces; (c) after the pre-assembly of the individual sub-assemblies a partial dimensional inspection is performed by laser tracker (LT); (d) once the pre-assembly of the whole component has been finished a final dimensional inspection by LT has to be performed to check that the CB is within the final tolerances.

5. Pre-assembly at the factory

The pre-assembly of the CB at the factory will follow as much as possible the final assembly process in Japan. The aim is to check that the final dimensions after manufacturing are within tolerance as well as to anticipate problems that could be encountered during final assembly. The foreseen sequence is as follows:

(a) the CB will be assembled onto levelling supports (9 under the LS outer ring and 6 under the inner ring) which define a horizontal plane. The levelling will be done by LT and once the horizontal plane has been defined the support positions will be locked; (b) the LS sectors will be placed one by one onto the levelled supports and adjusted in position according to the reference marks machined on them in the toroidal direction (0°, 90°, 180°, 270°). They will be bolted to each other following a pre-defined sequence and applying an increasing pre-load on them; with the sectors fitted in their correct position the dowels foreseen at the connecting flanges have to be inserted (manual reaming of the holes will be necessary to allow the insertion of these dowels). With the latter in position, the bolts can be pre-loaded up to the pre-assembly torque (around 30% of the final torque); (c) the measurement of the complete LS sub-assembly will be done with the LT; (d) the ICS will be placed according to the reference marks on the LS. After placing in its final position it will be fixed by means of the 9 T-shape supports at the bottom of the LS. At that moment some reference lines will be marked inside the ICS in

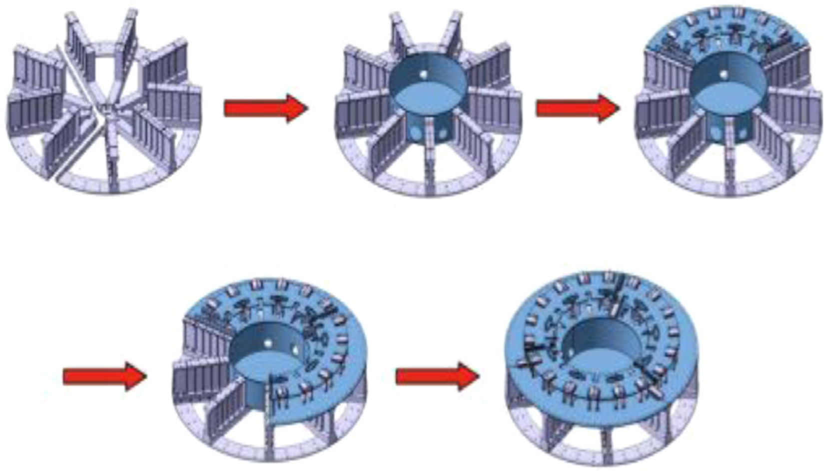

Fig. 7. Conceptual pre-assembly sequence of the CB.

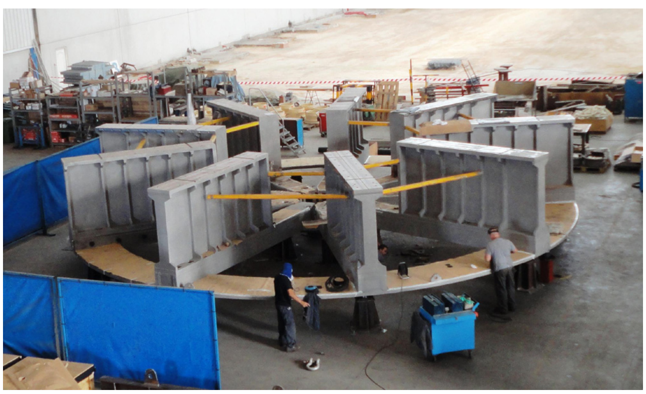

Fig. 8. Pre-assembly at the factory of the LS.

order to determine the centre; and (e) the DR sectors will be assembled one by one, onto the correspondent LS sectors: the shear keys previously machined and adjusted to fit the LS and DR sectors have to be in position. Once the DR sectors are attached to the LS through the connecting bolts, the spacers between the flanges of adjoining sectors have to be adjusted (by final machining). With the spacers in position, the bolted joints in the DR sectors are set up and the dowels inserted (manual reaming of the holes is foreseen). All the joints will be tightened following a pre-defined sequence increasing the pre load step by step up to the pre-assembly torque. The DR will also have reference marks to guide the positioning of the VV and TFC. The conceptual pre-assembly sequence is shown in Fig. 7 and the pre-assembly of the three LS sectors can be seen in Fig. 8.

6. Conclusions

The fabrication of the JT-60SA Cryostat Base is well advanced. The seven pieces that make up the structure have been welded resulting in acceptable deformations on the pieces due to a pre-established welding sequence. Following the welding phase the final machining will get the pieces into required tolerances. The pre-assembly of the whole component will be performed at the factory as well as the final dimensional inspection by laser tracker before acceptance. At present the LS pre-assembly has been finished and the partial dimensional inspection has been done with successful results. The ex-works delivery of the component is committed by the manufacturer in November 2012.

References

[1] P. Barabaschi, Y. Kamada, S. Ishida, Status of design and procurement activities in JT60-SA, Fusion Engineering and Design 86 (October (6–8)) (2011) 484–489.

[2] E. Rincón, J. Alonso, G. Barrera, J. Botija, P. Fernández, M. Medrano, et al., Structural analysis of the JT60-SA Cryostat Base, Fusion Engineering and Design 86 (October (6–8)) (2011) 623–626.

[3] M. Serrano, G. de Diego, Characterization of stainless steel AISI 304 material for JT-60SA cryostat project, 2012.