Study on Butt Weld Joint of Thick Plate Superconducting Coil Structure to Reduce Welding Residual Deformation*)

Arata NISHIMURA

National Institute for Fusion Science, Toki 509-5292, Japan

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In a large fusion experimental device, the magnetic field in the coil is rather high to create higher magnetic field at the plasma center, and the coil current is very large resulting in generation of huge electromagnetic force. To sustain such huge electromagnetic force, thick section components are required for the coil structure of which material is generally an austenitic stainless steel to avoid magnetization. On the process of the welding design, the welding residual deformation must be taken into account to keep the position of the current center of the coil and to avoid the degradation of the superconducting conductor by the excessive welding residual strain. In this paper, a partial welding which was used for the LHD construction will be focused and the image of the conceptual welding design of ITER TF coil butt joints will be discussed for an example of the fusion application.

Keywords: partial welding, welding residual stress, welding residual deformation, LHD, ITER, TF coil

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1. Introduction

When a large-scale plasma device or a fusion DEMO is designed conceptually, it is very important to consider the assembly process including welding procedures at the same time. As the size scale of the plasma device or the DEMO becomes large, the electromagnetic force which is generated by the coil current and the magnetic field becomes large and the stiffer support structure is requested to maintain the magnetic surface of the plasma. This means that the welding of the thicker components will be necessary, and the non-destructive inspection must be considered to ensure the soundness of the weld joint. In addition, the welding deformation must be taken into account when the tolerance of the manufacturing and assembling processes are determined. Therefore, the welding design to reduce the welding residual deformation must be investigated during the design activities.

When a full penetration welding is performed on a thick section weld joint with a normal welding groove such as J-shape groove and a general multi-pass welding process, the shrinkage of the weld joint in the vertical direction to the welding line will become the same level as one-half of the plate thickness. Also, the angular distortion will occur at the weld joint, which will cause an out-of-plane deformation and produce a large mismatch at the end of the product. Generally, it is difficult to correct the angular distortion after the welding. Therefore, consideration of the welding process during design activity is very important.

When the Large Helical Device (LHD) was designed, the assembly procedure was investigated and considered as a part of design activity. The partial weld joint with deep narrow grooves was proposed to reduce the shrinkage, and the symmetric welding process with small welding heat input was adopted to prevent the angular distortion.

In this paper, the countermeasures taken in the LHD design and construction to reduce the welding shrinkage and the residual deformation are summarized succinctly [1]. The conceptual design on the butt weld joint of ITER TF coil cases will also be discussed and the weld joint image will be presented based on the recent ITER NEWSLINE [2].

2. Outline of LHD Support Structure

The LHD design activity started in 1991 and the first plasma was produced in March 1998 [3]. The LHD project was lasted 8 years, and the practical design activity and many research and development efforts were carried out in the early stage of the project. The plasma experiments are continuing, and D-D experiments started in March 2017 and interesting results have been obtained [4, 5].

The LHD has one pair of helical coils and three pairs of poloidal field coils. All these coils are superconducting and have been operated for almost 20 years, since 1998. All coils are supported by a cryogenic support structure called a support shell. A lower shell and an upper shell were manufactured separately. Figure 1 shows the trial-assembled lower shell in the LHD Experimental Hall. The support shell consists of ten sectors, and the shell was formed by butt-joining of these sectors. The outer diameter was about 11 m. After setting the pair of helical coils in the lower shell, the upper shell was put on the lower

author's e-mail: nishimura.arata@toki-fs.jp

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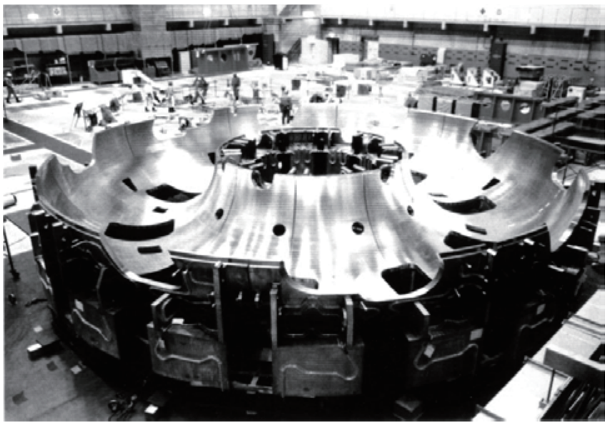

Fig. 1 Field assembly of lower support shell of LHD.

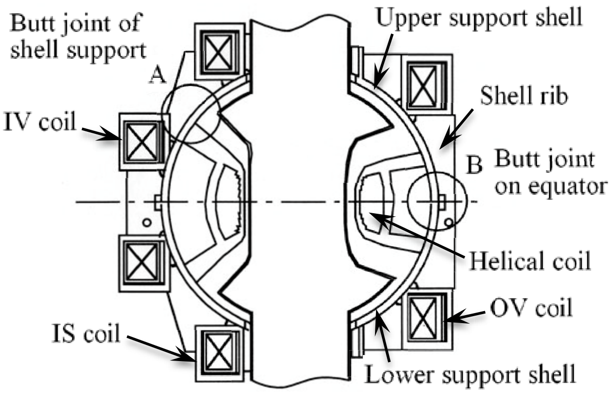

Fig. 2 Cross section of LHD support structure and coils.

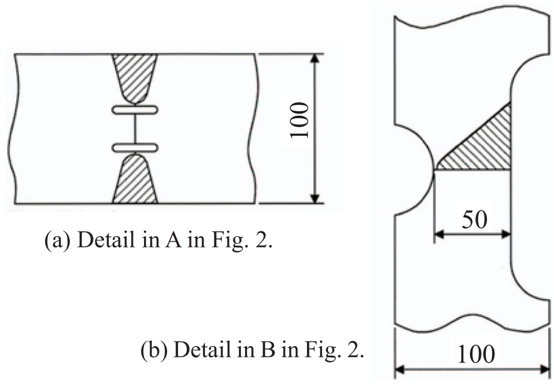

Fig. 3 Sketches of weld groove of each butt joint.

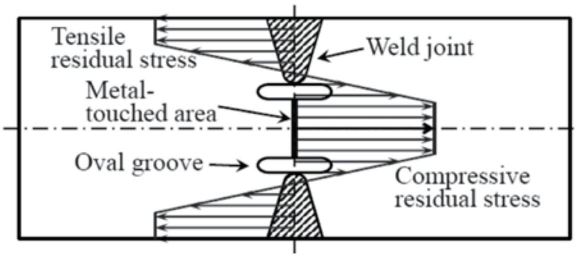

Fig. 4 Configuration of thick plate butt weld joint and residual stress distribution.

shell and the equator line was welded. The cross section of the LHD is shown in Fig. 2. The left side is a device center and the right side is out-board side of the LHD. There are pairs of Inner Vertical (IV) coils, Inner Shaping (IS) coils, and Outer Vertical (OV) coils outside of the support shell, and the helical coils are located inside the shell.

As shown in Fig. 1, the inside of the support shell was machined out in the factory after being trial-assembled by tack welding. Then, the shell was disassembled and transferred to the LHD experimental building. Since the inner surfaces of all sectors were machined out with a severe tolerance, the welding residual deformation must be reduced to as small as possible at the construction site. Therefore, a special welding groove was investigated and designed, as shown in Fig. 3 (a). The plate thickness was divided into three parts. The middle one-third of the plate was a metal-touched zone with narrow grooves, and the remaining cross-sections were fully welded. The expected residual stress distribution and the role of the narrow grooves will be discussed below.

After setting up the lower support shell and the upper support shell, the equator line was welded from outside because the helical coils were already installed inside the support shell. The welding groove at the equator is shown in Fig. 3 (b). The upper side had triangular groove and the lower side was flat, which made the horizontal welding easier. The inner side (left side of the drawing) was cut out in a semicircle to make welding ripples when the first weld pass was performed and to avoid the concentration of the welding residual stress.

3. Design of Partial Welding Joint

When the butt joint is welded by arc welding, the joint will shrink due to the melting filler metal and high temperature beyond the mechanical melting point. In addition, the residual stress will remain after cooldown, for the multi pass welding will cause the temperature difference which may generate angular distortion, i.e., out-of-plane deformation. Therefore, the butt joint weld groove was designed taking account of the practical welding process.

The images of the butt joint configuration and the residual stress distribution are shown in Fig. 4. In the mid-section of the joint there is a metal-touched area and both surface sides are weld metals. The narrow oval grooves are located at both ends of the metal-touched area. Regarding the welding process, it was assumed that the same weld passes on both grooves would be welded at the same time, though the welding heat input would be different depending on the welding position, for example, flat position or overhead position. Under these conditions, the residual stress distribution was supposed, as shown in Fig. 4. The distribution will be symmetric about the plate center and the tensile stress remains near both surfaces and the com-

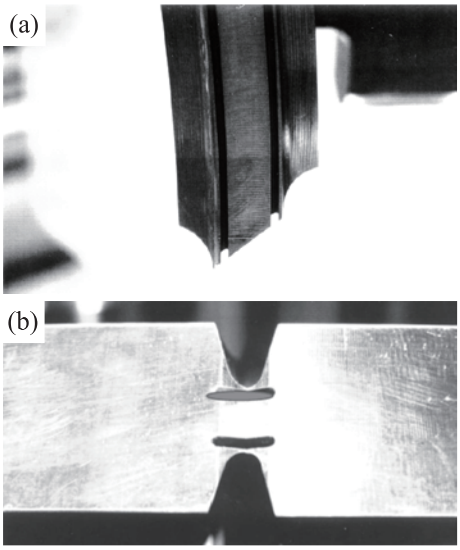

Fig. 5 Weld grooves of butt joint of support structure on equator (a), and butt joint on horizontal port (b).

pressive stress exists in the midsection of the plate.

When the first pass was welded on both grooves, the weld ripples were formed on the back surface of the weld pass in the narrow oval grooves, and these grooves would reduce the stress concentration and prevent creation of the crack-like defect at the weld root. If the first passes on both grooves would be welded at the same time, both weld metals would tend to shrink. However, the metal-touched area would deform only elastically because of low temperature rise, and that prevents the shrinkage of the weld metal. As the results, the weld metal could not shrink enough, and it would be pulled. On the other hand, the metal-touched area would be pushed. Therefore, the tensile and compressive residual stress would be generated in the weld metal and the metal-touched area, respectively. Since the total tensile stress must be equal to the total compressive stress, it is expected that the stress around the narrow groove would be compressive. If the residual stress distribution should not be symmetric about the plate center, this means that there is a bending stress component and the plate will be bent by the residual stress. This is the so-called angular distortion which is out-of-plane deformation and known as one type of the welding residual deformation.

The welding grooves of the butt joints are shown in Fig. 5. Figure 5 (a) shows the welding groove of the upper support shell which has the triangular-shape groove on the equator. Figure 5 (b) shows the butt joint on the horizontal port after temporary assembly. The top surface is flat, and the narrow oval grooves and J-shape grooves are very clear.

To achieve the symmetric residual stress distribution, the symmetric welding process was adopted in the practical manufacturing. The welding heat input was reduced, and the small bead was formed little by little. Finally, the upper and the lower support shells were constructed with an excellent manufacturing tolerance.

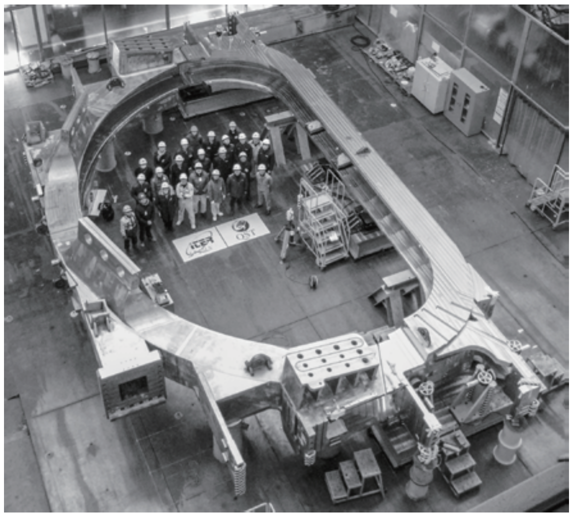

Fig. 6 First assembling of in-board and out-board coil cases of TF coil (Republic of Korea, 2017).

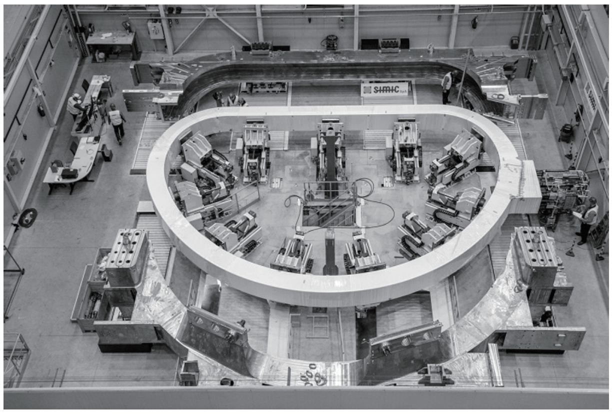

Fig. 7 Integration of in-board and out-board coil cases and winding pack. (Italy, 2018).

4. Butt Joint of ITER TF Coil Case

Generally, a large-scale superconducting magnet is designed with a very tight tolerance to fit the principal devices. ITER TF coil case was also designed with the severe manufacturing tolerance of +/− 1 mm order, although the magnet height is approximately 14 m, and the width is approximately 9 m. Therefore, the ITER TF coil case will be taken here as an example of a thick section welded structure.

The first assembly of the in-board coil case and the out-board coil case was carried out in the Republic of Korea at the end of 2017. The assembly was succeeded, and it was announced that both components could be adjusted to less than 1 mm. The success photo is shown in Fig. 6 [2]. In autumn 2018, the coil cases were integrated with the winding pack of the superconductor as shown in Fig. 7 [6]. The winding pack set at the center and the in-board and the out-board coil cases were placed separately. The in-board and out-board coil cases were shifted slowly to the winding pack, and the winding pack was inserted in both coil cases. At the bottom of the winding pack (right side in Fig. 7), there is a large rectangular space, and all conductor joints and the cooling pipes were placed in this space. The butt joints at the top and the bottom of the coil cases will be welded, and the cover plates of the winding pack will be attached by welding.

The butt joint at the top of the coil case is shown in Fig. 8. The configuration of the joint is U-shape and narrow grooves for coil case cooling pipes can be seen. The bottom view of the coil case is shown in Fig. 9. The rectangular space is for the conductor joints and the cooling pipes of the winding pack, and the butt joints are located at the upper and the lower plates of the space.

As discussed above, there are two types of the welding residual deformation. One is the shrinkage in-plane and the other is the angular distortion of out-of-plane. The residual deformation would cause the following matters.
(1) The shrinkage in-plane will deform the winding pack and degrade the critical current of the coil when the winding pack is supported by the coil case with some GFRP spacers.
(2) The angular distortion will generate a large mismatch and make it difficult to connect with the neighboring coil cases with keys and bolts. Additional field work to match the joints may become necessary.
(3) Both deformations will shift the coil current center and produce unexpected magnetic fields. If the winding pack is supported by only the resin which will be filled in the gap between the winding pack and the coil case, the coil current center must be evaluated after the integration work of the winding pack and the coil cases, and the results must be used for the adjustment of the divertor set-up. The position of the coil current center would be different in each TF coil.

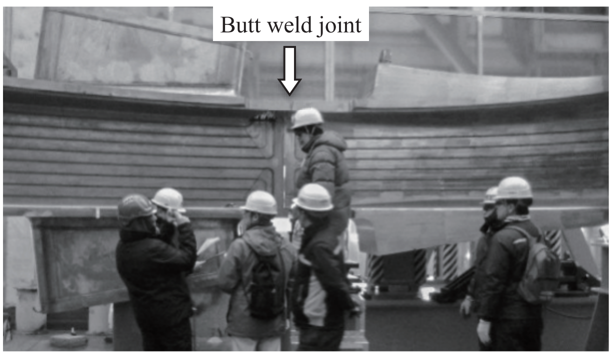

Fig. 8 Butt joint of the top of the TF coil case.

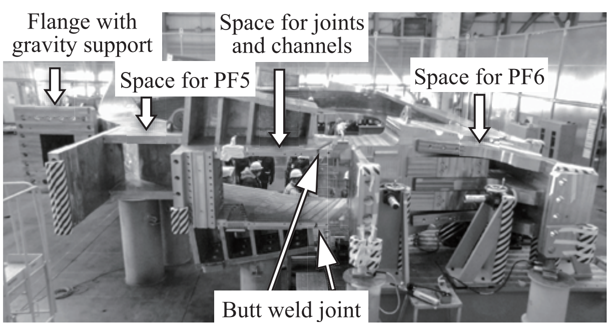

Fig. 9 Bottom view of TF coil case.

5. Conceptual Design of Butt Joint

The butt joints of the TF coil case were investigated and designed conceptually. Mainly, it was taken account to avoid and reduce the welding residual deformation. The proposed weld joint shapes are shown in Fig. 10 for the top joint and Fig. 11 for the bottom joint.

In both figures, the dashed part shows a metal-touched area to reduce the shrinkage in-plane around the joint, and the J-grooved area will be welded. The welding can be done only from the outside, because the winding pack is already installed inside the coil case. Therefore, a large groove was designed for one side welding. Since the total weld metal will become a large amount, the welding must be carried out slowly keeping the interpass temperature lower, and the welding must be performed symmetrically about the coil case center. The order of the welding will be important. The end part of the side plate will be

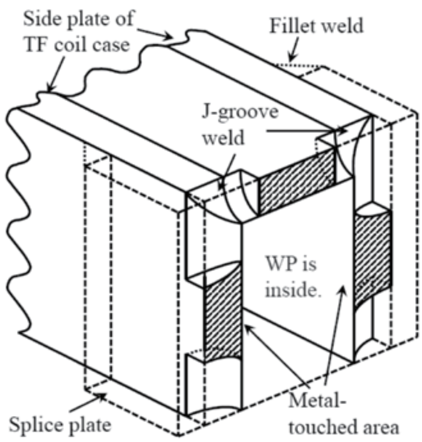

Fig. 10 Proposal of weld groove for the top joint of TF coil case.

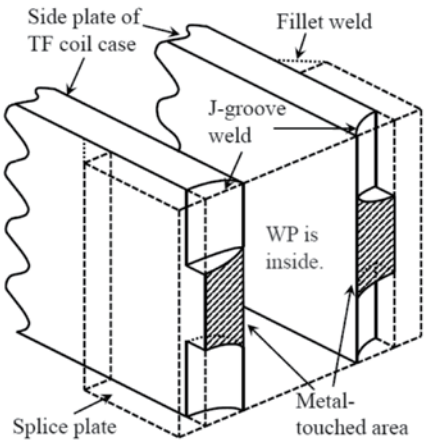

Fig. 11 Proposal of weld groove for the bottom joint of TF coil case.

welded first following the corner part welding in the case of the top joint (Fig. 10). All first pass must be formed, and then the color check will be carried out to check the cracking on the bead. After that, the second pass will be welded. The generation of the symmetric residual stress distribution about the joint center is one of the key issues to reduce the angular distortion. The welding heat input also must be controlled to be lower for all welding positions.

Since the metal-touched area does not support the shear stress, and the area is supposed to be about one-third of the total cross-section of the joint, the splice plate will be required to maintain enough cross-section against the torsion. Therefore, two splice plates were attached outside the side plates of the coil case in these figures.

As the welding of the coils case can be done only from outside and the space for welding machine and for non-destructive inspection (NDI) is needed, the weld joints will be welded first and then the splice plates will be welded. After the NDI is performed and the soundness of the weld joints of the coil case is confirmed, the reinforcement of the weld joints will be removed, and the splice plate will be welded. To reduce the total welding time, a large plate will be attached as a splice plate and the both ends will be fillet welded. As the large torsion stress will act on the fillet weld joints, the throat thickness of the fillet joint must have enough margin.

After welding of the coil case joints and the fillet weld joints, the NDI of the ultrasonic test (UT) and the radiographic test (RT) is required to certify the soundness of the weld joint. Generally, the attenuation of the ultrasonic wave is remarkable in the thick section component of the austenitic stainless steel. Therefore, the phased array UT procedure will be applicable to achieve high resolution. Also, the RT is useful as a volumetric test. The identification minimum dimension must be clarified when the RT is carried out.

6. Summary

The large-scale superconducting magnet generates huge electromagnetic force and the large support structure with thicker components are required. Generally, the thick section welding causes the large shrinkage and severe angular distortion, and the welding residual deformation cannot be corrected because the winding pack is already installed inside the coil case. Therefore, the welding groove design and the welding procedure are very important for avoiding and reducing the residual deformation. In this paper, the experience learned in the LHD design and construction was introduced and the basic design concept of the thick section welding was summarized. Then, the conceptual design on the weld joints of the ITER TF coil case was carried out based on the partial welding and the symmetric welding procedure.

On the design of the LHD, the special welding groove was designed based on the consideration of the symmetric residual stress distribution about the plate center. There was a metal-touched zone at the midsection of the plate. The size is about one third of the plate thickness. And the narrow oval grooves were machined at both ends of the metal-touched zone to produce the welding ripples to avoid the crack-like defect at the weld root and to release the stress concentration. Both surface sides of about one-third of the thickness were welded symmetrically to generate the symmetric residual stress distribution. The metal-touched area would reduce the shrinkage of the joint, and the symmetric residual stress distribution would prevent the bending of the joint so called "angular distortion." Regarding the welding of the joint, the order of welding, the welding heat input, and the weld bead length were controlled carefully, and both grooves were welded symmetrically. The welding of the support shell of the LHD was successful and achieved an excellent tolerance.

The weld joints of the ITER TF coil case were investigated and the images of the joint were presented. The joint of the top of the coil was U-shaped, and three parts of the metal-touched zone were designed. The length of each zone would be about one-third of the plate width. The metal-touched area would resist the shrinkage of the weld metals and reduce the total shrinkage of the joint. Also, the welding order was considered in that the edge part of the side plate will be welded first and the corner of the joint will be welded second. In the case of the bottom joint, two plates are welded at the same time to keep the symmetric residual stress distribution.

In both cases, the cross section must be considered against the torsion. Since the metal-touched area does not support the share stress, the splice plates will be requested to attach the side plates.

The non-destructive inspection on the weld joints is important to certify the soundness of the weldment. The tests will be rather complicated because of the thick section joints, but they must be carried out.

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