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ORIGINAL RESEARCH

Design and Analysis of the Laser Robotic Welding System for ITER Correction Coil Case

C. Fang[1,2] · Y. T. Song[1] · J. Wei[1] · J. J. Xin[1] · H. P. Wu[2] · A. Salminen[2] · H. Handroos[2]

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Abstract ITER correction coil (CC) cases have characteristics of small cross section, large dimensions, and complex structure. The cases are made of heavy thick (20 mm), high strength and high toughness 316LN austenitic stainless steel. The laser welding is used for the case closure welding, due to its low heat input and deformation. According to the structural size and feature of the two types of cases, a set of laser welding workstation for the ITER CC case closure welding is designed. A slip plate module for the welding robot is designed to increase its workspace. According to the result of the movement simulation of the welding robots, the workstation is successful to cover all weld seams on the cases. Also, the welding platform and fixtures (includes the special welding tilter of the SCC) of the BTCC case and the SCC cases are designed. To verify the design structural feasibility of the welding tilter of SCC, the structural analysis for the rotating process has been formed in detail by using ANSYS. The simulating results show that the stress of the welding tilter can meet both static and fatigue criteria, and thus the basic structure is valid.

Keywords Correction coil · Laser welding · Fixture · Static · Fatigue

✉ C. Fang
fangchao@ipp.ac.cn

1 ASIPP, Shushan Hu Road 350, Hefei 230031, Anhui, China

2 Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland

Introduction

The correction coil (CC) is wound with cable-in-conduit conductors (CICC) in the square 316L stainless steel jacket and wound into multiple pancakes embedded into coil cases [1–3]. The layout and geometry of the CCs are shown in Fig. 1. CC cases are made of heavy thick (20 mm), high strength and toughness austenitic stainless steel (316LN) to sustain large electromagnetic force at cryogenic temperature. And the shape of CC cases are same to the shape of coil shape, the side correction coils (SCC, one coil type) cases are three-dimensional curved coils case with 8.3 m length and 7.2 m width, the bottom and top correction coils (BTCC) cases are two-dimensional coils case with 7.2 m length and 2.5 m width.

The BTCC case is divided into a flat cover plate and a U shaped case for the convenience of the winding pack being inserted to the case. While SCC case is divided into two L-shaped parts due to it has more complicated structure than BTCC case. After the winding pack inserting to the case, the two half cases should be welded together.

Considering the tolerance of fabrication imposed on the radius central line of the case along the 7.2 m branch are ±2 mm on BTCC and ±4 mm on the SCC [4]. The multipass laser welding with hot wire technology is selected for the case closure welding. The biggest advantage of the laser welding method is the small amount of heat input and welding deformation [5]. A set of laser welding workstation based on a mobile robot for the ITER CC case closure welding is designed and it can cover all weld seams. In addition, to control the welding deformation, the welding platform with fixtures of BTCC cases and SCC cases are designed. And the related analysis of the welding tilter is carried out to verify its security.

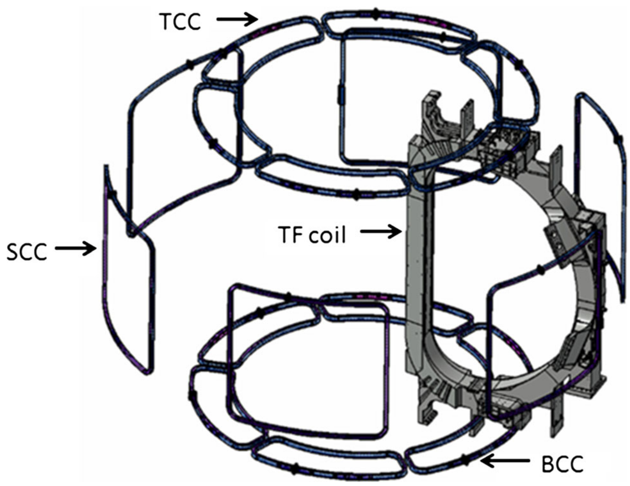

Fig. 1 Overview of ITER correction coils system

Design and Analysis

BTCC Case Platform and Fixture

The BTCC case is one type of the CC case, which is located on the bottom and the top of the ITER device. As we know, BTCC case has a plane structure and consists of a flat cover plate and a U-shaped case. For the laser welding, there is a strip assembly weldment and assembly accuracy is required, due to its huge impact on the welding quality. During the welding process, the welding fixtures will hold the two parts of BTCC case together to ensure the assembly accuracy and decrease the welding deformation. The welding platform scheme of the BTCC case is shown in Fig. 2a, and detailed welding fixture is shown in Fig. 2b. The welding fixture consists of ground support fixture and C type clamp. The BTCC case is put on the welding fixture and fixed by adjusting bolts to control the assembly error and welding deformation. During welding, the located C type clamp which is interference of the welding path will have to be removed ensure the feasible welding process.

SCC Case Platform and Fixture

The SCC case is one type of the CC case, which is located on the outside of the device. The structure of SCC case is more complicated than BTCC case because of its 3D structure. The SCC case consists of two L-shaped case which means the weld seam is located on the two sides of the case and there should have a welding tilter to provide the rotating function during the SCC case closure welding (the SCC structure is shown in Fig. 3). The SCC case closure welding fixture includes welding fixture and the tilter fixture. The overall welding platform is shown in Fig. 4 and the detailed welding fixture are shown in Fig. 5a. As the BTCC case, the SCC case is put on the welding fixture and fixed by adjusting bolt before the welding. As the structure of the SCC case has a concave shape in one side and a convex shape in another, therefore, the welding fixture has two parts with the rotating function, one part for the concave status and the other part for the convex status. After SCC case rotated, the case will be transferred onto the welding fixtures corresponding to the shape of the case.

A framework type of welding tilter tooling is designed base on the special structure of SCC case. Welding tilter is shown in Fig. 4. Welding tilter includes tilter framework, central axis and 20 load-bearing fixtures. Welding tilter has 2 degrees of freedom for linear motion and 1 degree of freedom for rotation. The tilter framework is manufactured by several sub-parts (square tube) welded together and has

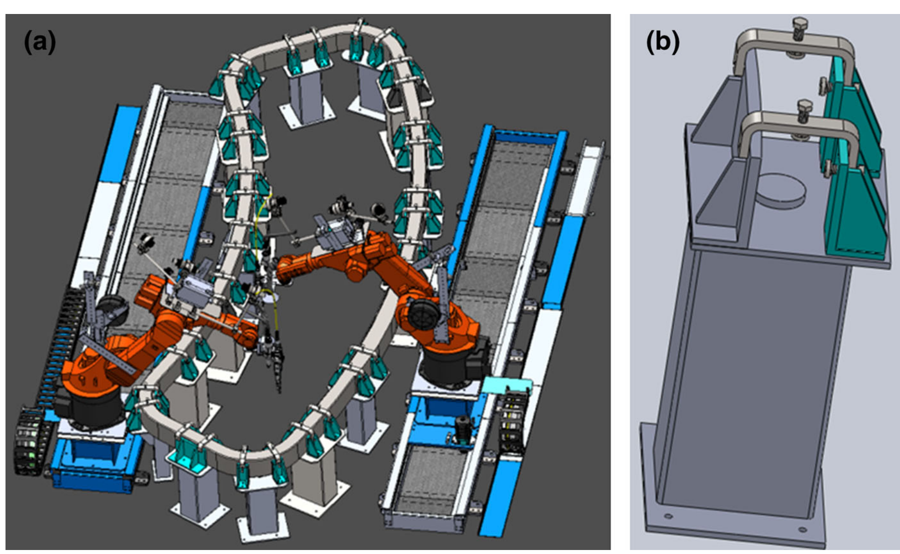

Fig. 2 BTCC case welding platform scheme (**a**) and detailed welding fixture (**b**)

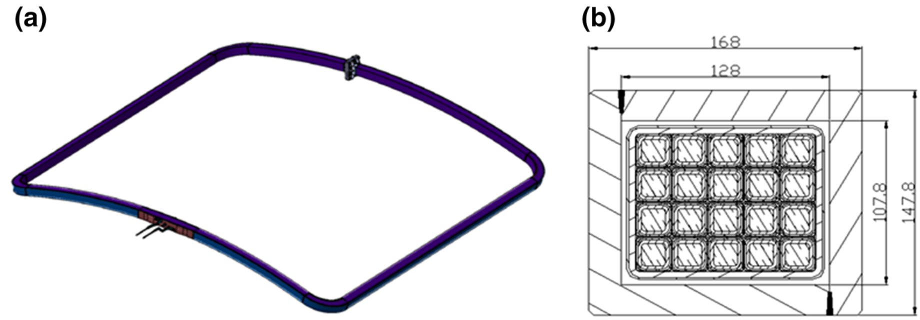

Fig. 3 Overview of SCC case (**a**) and cross-section of SCC case structure (**b**)

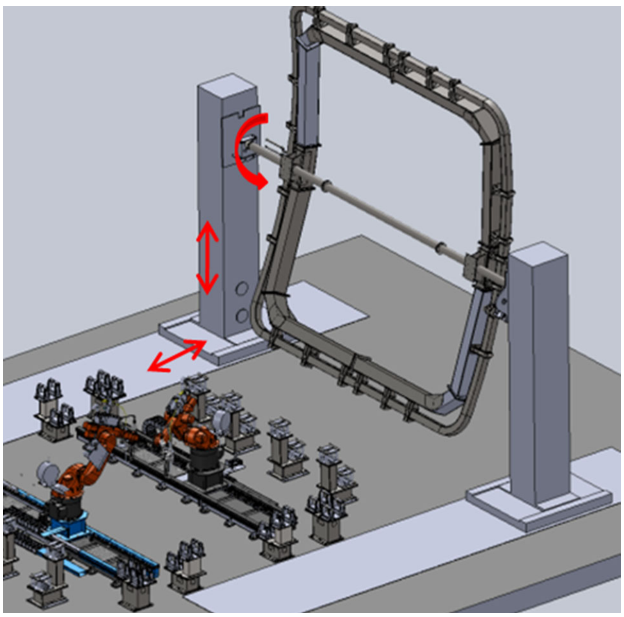

Fig. 4 SCC case closure welding platform

the same shape with the case. The detailed load-bearing fixture is shown in Fig. 5b. During the rotating process, the CC coil is fixed on the load-bearing fixture, the welding tilter will rising to a certain height and travel on the rail to avoid the welding equipment and start the rotation process. After the rotating process, the welding tilter will back to the welding workspace and put the case on the welding fixture.

Case Closure Welding System

According to the requirements of CC case closure welding, the biggest difficulty is to control the minimum deformation for such a large size weldment. The traditional welding methods obviously can't reach the requirements of the deformation control. As a high-energy beam welding, laser welding do not need a vacuum environment, is considered the most suitable method for the CC case closure welding.

As an automatic welding, laser welding usually has two ways to work. One is the laser head is stationary but the weldment move, the other is laser head move but the weldment is stationary. Considering the situation of the CC case welding, laser head traveling along the CC case weld seam is chosen and the robot arm is used as the laser welding tooling. The fiber laser is used as the laser source because of its feature of laser transmitted in the fiber and high absorptivity of stainless steel because of its laser wavelength. Based on the laser welding tooling and laser transmission, the detailed laser welding system (show in Fig. 6) is designed to apply on the CC case closure welding. The system includes two welding robots which have 6 degrees of freedom, two lineal rails with the 6000 mm length, welding platform and other equipments (laser, cooling system, robot computer, hot wire feeder and PLC). According to structural feature and the size of two types of case, the BTCC case is located in the middle of the welding area and the SCC case is located outside of the BTCC case. And the two lineal rails are designed and locate between the SCC and BTCC case. The laser head is mounted on the robot arm. The two robot arms can travel on the two lineal rails. During the welding, the robot will not travel on the linear rail. After the one time welding, the robot arm will travels on the linear rail to arrive the next welding area. By this way, the robot motion error on the linear rail will not accumulate and affect the welding process by separating the welding and motion control. The manufacturing precision of linear rail is low, while the welding system motion precision is improved by the robots.

According to the kinematics of the robot arm, the movement of the robot is simulated. The result shows (shows in Fig. 7) there are some blind areas in the middle of the arc segment of SCC case could not be reached even the robot is adjusted by all the motion axes.

In order to cover these blind areas, a simple and practical slip plate is design in the base support of the robot arms (shown in Fig. 8a). I.e. move the slip plate to increase the workspace of the robot arm and arrive further welding area. After add this slip plate module, the simulation result

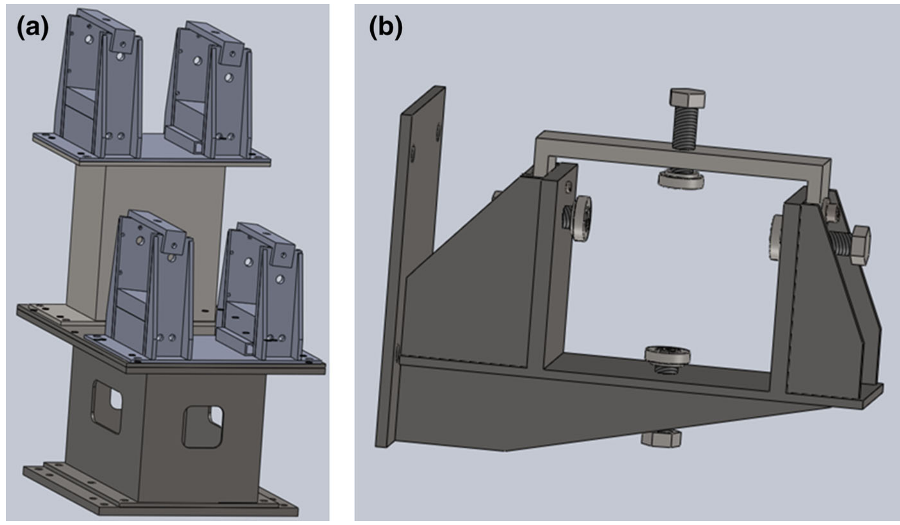

Fig. 5 Detailed SCC case welding fixture (**a**) and detailed load-bearing fixture (**b**)

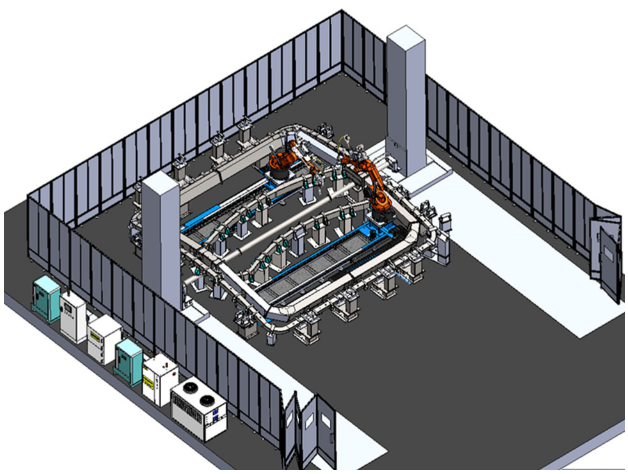

Fig. 6 Laser welding system

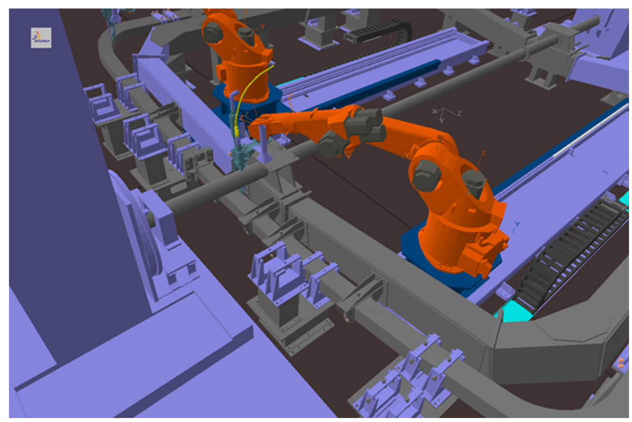

Fig. 7 Blind area in the simulation

shows that the robots can arrive the previous blind area easily (shown in Fig. 8b).

Analysis of Welding Tilter

Due to the requirement of stability of the SCC case rotating process, the stiffness of the rotating process of welding tilter is analyzed by ANSYS. The analysis process is described by three typical cases. One is the welding tilter in 0°. Second is the welding tilter in 45°. And third is the welding tilter in 90°.

The FE model consists of the major components of the workpiece including rotating framework, central axis, load-bearing jigs, ground-bearing jig and correction coil is shown in Fig. 8. In order to improve the modeling and loading accuracy, the whole model is simulated by solid model. Total number of nodes and elements are 667,227 and 1,785,448, respectively (Fig. 9).

The rotating framework, ground-bearing fixtures and load-bearing fixtures use Q235B, central axis uses Q345B for higher strength. The correction coil consists of coil case (316 LN) and winding pack (composite material).

The loading for analyzing of the rotation process is the self-weight load. The whole self-weight is 8.39 t includes the Correction Coil and the welding tilter. The central axis and the ground-bearing fixture is bonded contact. All nodes on the two ends of the central axis are held fixed.

The stress result from the analysis of case 1 is shown in Fig. 10. The highest stress of the welding tilter is 318 Mpa which is located on the two sides of central axis. Define a path in the section for the maximum linearization stress for Pm and Pm + Pb (shows in Fig. 11). The Pm stress is 24 MPa and the Pm + Pb stress is 30 MPa. According to the ITER design criteria [6] and material properties of central Q345B, the highest stress value is much less than

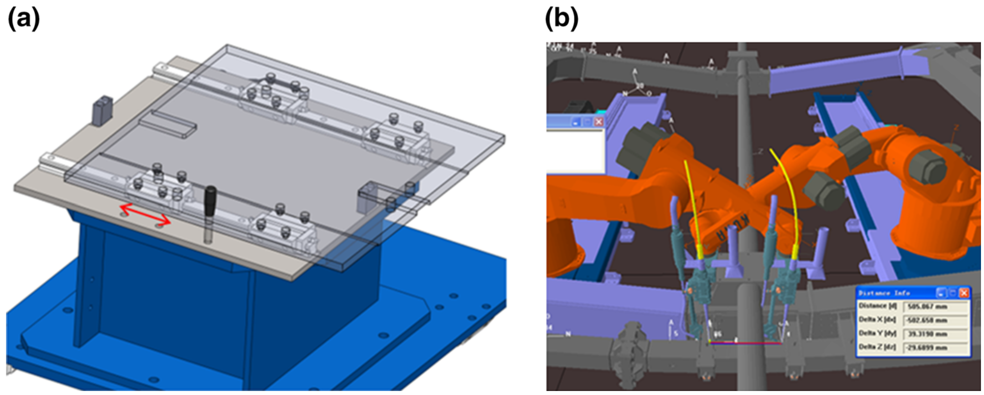

Fig. 8 Slip plate for the robot arm and its simulation result

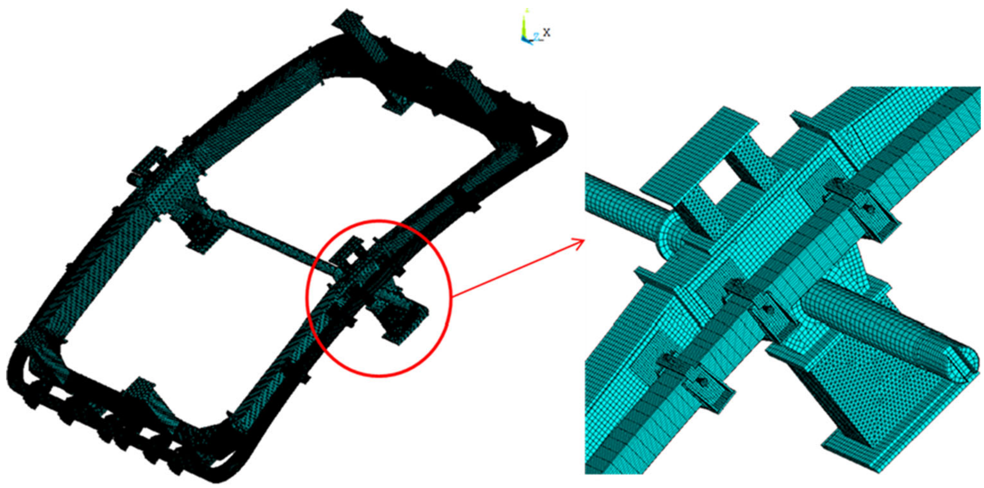

Fig. 9 Finite element model

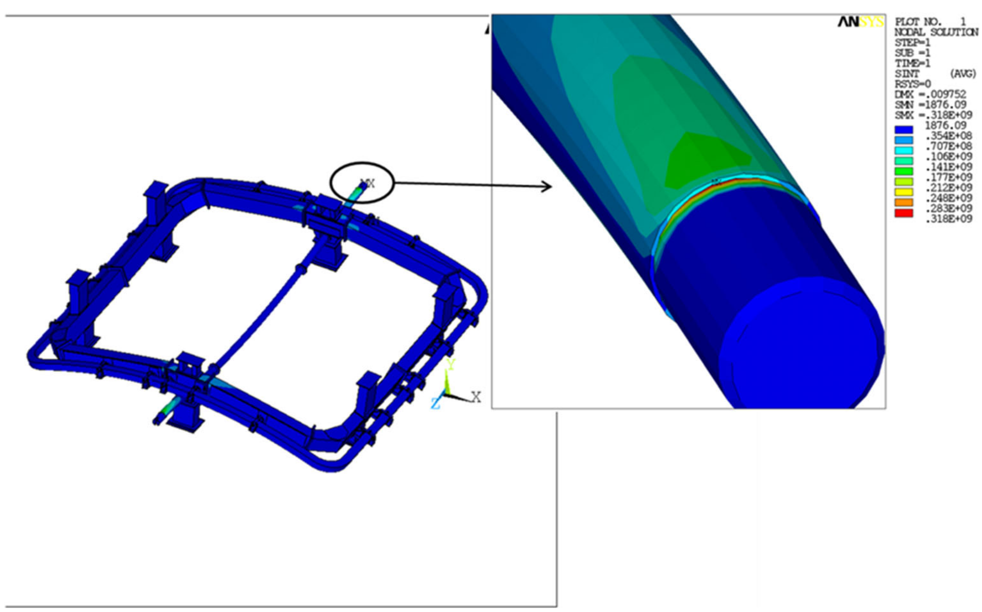

Fig. 10 Stress distribution of the welding tilter

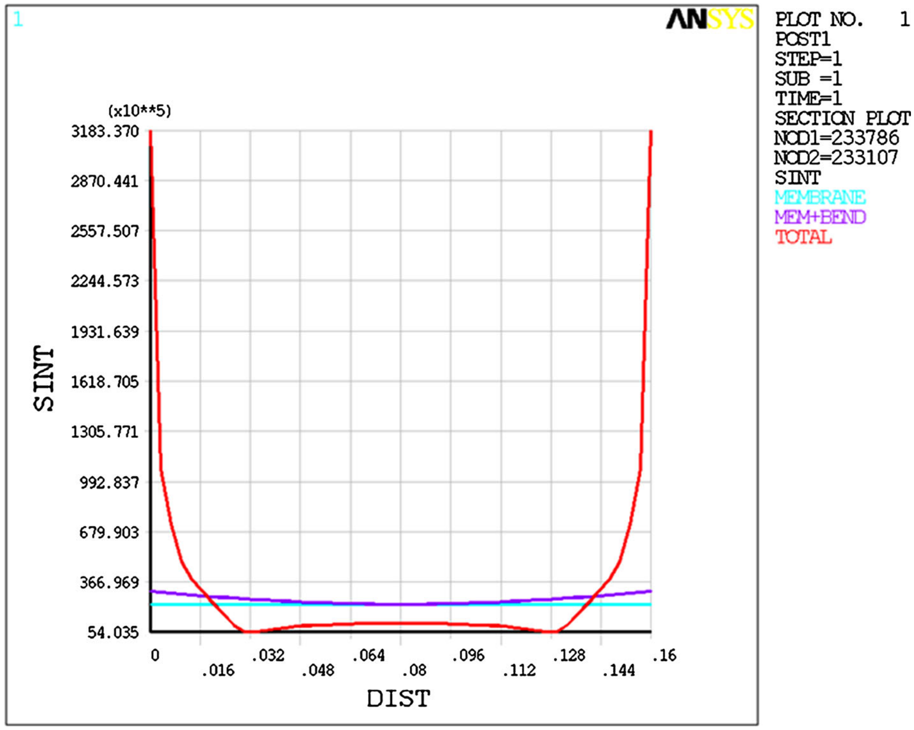

Fig. 11 Stress distribution plot on the path defined on maximum section

Table 1 Stress assessment of the rotating process

Case	Pm (MPa)	Allowable stress (MPa)	Pm + Pb (MPa)	Allowable stress (MPa)
Case 1 (0°)	24	Sm = 230	30	1.5 × Sm = 345
Case 2 (45°)	22		28	
Case 3 (90°)	21		26	

the allowable value of the central axis. The results of 3 cases are shown in Table 1. From the table, it is found that the maximum stress of case 1 is the biggest in the three cases and all results are satisfied the requirement. Compared with the total stress and Pm + Pb stress, the peak stress is high. The structural discontinuities lead to the high peak stress and the fatigue analysis is necessary. During the process of SCC case rotation, the loading is changing. The maximum stress in a load cycle S_{max} is 318 MPa when the SCC case is in case 1, and minimum stress in a load cycle S_{min} is approximately 0 when the welding tilter is placed on the ground. The alternating stress amplitude $S_{alt} = \frac{S_{max} - S_{min}}{2} = 159\,\mathrm{MPa}$. According to the S–N curve of the ASME code [7, 8], the appropriate number of cycle is 10,000 which is far more than working frequency of welding tilter (approximately 100 times). From the analysis results of the static and fatigue, the welding tilter is valid and can reach the design requirements.

Conclusion

1. According to the structural size and feature of the two types of cases, a set of laser welding workstation for the ITER CC case closure welding is designed.
2. A slip plate module of the robot is added, the welding robots can cover all weld seams on the cases base on the movement simulation.
3. The welding fixtures of the BTCC and the SCC are designed base on their structures. Because of the welding process of the SCC, a special welding tilter of SCC is designed.
4. In order to verify the design structural feasibility of the welding tilter of SCC, the structural analysis of the rotating process has been formed in detail by using ANSYS. After these efforts, the stress of the welding tilter can meet the static and fatigue criteria and this means the basic structure is valid.

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