R & D of the Fabrication Technology for ITER Magnet Supports

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Abstract. The R&D of the manufacture related technology for ITER magnet supports is one of the tasks for construction. 316LN as the main raw material has been developed tested. The material shows excellent mechanical property at room temperature, 77K and 4.2K. An alternative design for toroidal field support (TFS) manufacture without welding was carried out, the structure analysis shows that no stress concentration and buckling in the present design during ITER operation. However, the further engineering test of the structure stability under various load combinations is also scheduled. For cooling pipe, brazing connection to attach the cooling pipe to support-plates is suggested. Several kinds brazing filler as candidates, including Sn-Pb, Ag- based and Cu-based alloy has been developed. The tensile strength of brazed solders is up to 400MPa at 77K for Ag-based and Cu-based fillers. In PF3-4 support system, Ion implantation was utilized to modify the surface condition of the strut dowel due to its non-boundary modification of the microstructure as well as the formation of hard alloys on the surface. It is clear that the wear resistance was improved obviously after ion implantation vie increase the surface hardness and reduce the wearing. For CC support, the plasma spray insulation coating was developed and introduced.

1，Introduction

Magnet supports is one of the key components to sustain all the magnet coils of ITER, including toroidal field（TF）coils, PF coils and correction coils(CC). The components in this system endure several large forces, such as dead weight of coils, thermal load during coil cooling down from room temperature to 4K, electromagnetic forces (TF coil operation, plasma burning, plasma disruptions (DIS) and vertical displacement events (VDE)), and seismic loads if they occur [1,2]. China signed the procurement arrangement with ITER international organization (IO) and promised to manufacture all the magnet supports for ITER construction. Therefore, the manufacturing-related R&D is a key step for the final components. In this report, we introduce our recent progress for the R&D work towards the ITER construction.

2，Material R&D

316LN austenitic stainless steel has been recommended in ITER structure components due to its excellent corrosion and fatigue resistance, high strength at low temperature and low creep rate. It is estimated that more than 2000 tons of various types of 316LN stainless steel are needed for all the magnet supports, including hot-rolled plate, forged blocks, and pipes. Until to now, both hot-rolled plate and forged block were developed. The chemical composition of the steels is similar with that of the steel developed by JAEA for TF case manufacturing[3]. The mechanical test results of these materials are summarized in Table 1. The plate and the forged block showed high strength and good elongation at both room temperature and a 4.2 K test temperature. In addition, almost no ferritic could be seen, and the Charpy absorbed energy is larger than 120 J for the Charpy impact test from 77 K to room temperature. Recently, the much larger forged block for semi prototype PF1 support (thickness: 500mm, length: 2600mm and width: 1100mm) is scheduled for fabrication, the fabrication processing control for this large-sized forged block with acceptable defects (micro-crack), uniform composition and microstructure is important.

Table 1 Mechanical properties of 316LN

samples	direction	Test temperature	Ultimate str (MPa)	Yield str (MPa) σ	elongation (%)
plate	L	4.2K	1	1191	43
	T		1	1170	39
forged			1	1267	35
FM316LNH			1	900	
plate	L	300K	6	352	66
	T		6	346	55
forged			7	436	37
FM316LNH			5	280	30

3，Manufacturing

3.1, TF support

Based on the ITER design report, the maximum displacement of the TF coils is estimated to be 32mm in radial direction during cooling down. The support has been designed using 21 flexible plates welded with upper and lower flanges (for each pedestal), through which the displacement along radial direction is possible. However, manufacturing the support need welding the flexible plates with both the upper and lower flanges, which is currently difficult. An alternative design for TFS manufacture without welding was carried out: that is using various connection bolts, short plates and shear keys to assemble all the flexible plates and flanges together to instead of welding the flexible plate with flanges. The static stress analysis using three-dimensional finite element model (FEM), was developed to analyze this structure. The preload on the bolts is up to 0.659 MN for each clamp bolt, and 2.06 MN for each connection bolt， respectively. Details of the analysis, conditions, and results could be found in [3]. Typical stress distribution of flexible plates and clamp bolts are shown in Fig. 1. It can be known that the stress in the present load condition/combination is under the stress limitation of the material. The flexible plates have no severe stress concentration under the normal operation, and even during accident, such as earth quake and VDE. The flexible plate should not only have enough strength to resist all kinds of loads, but also have enough buckling resistant to against the structure collapse, the GS stability analysis was also carried out. Detail of the method and result can be found elsewhere[4]. It seems that the structure is safe enough according to the ITER design criteria.

In order to further confirm this design with high reliability, a semi-prototype TFS test model with 5 flexible plates and all of the flanges and bolts will be experimentally tested to check the real deformation, stress distribution, buckling, slip moving between clamp block and plates, etc.

The schematic illustration of the TFS test set-up is shown in Fig. 2. This mock-up comprises four

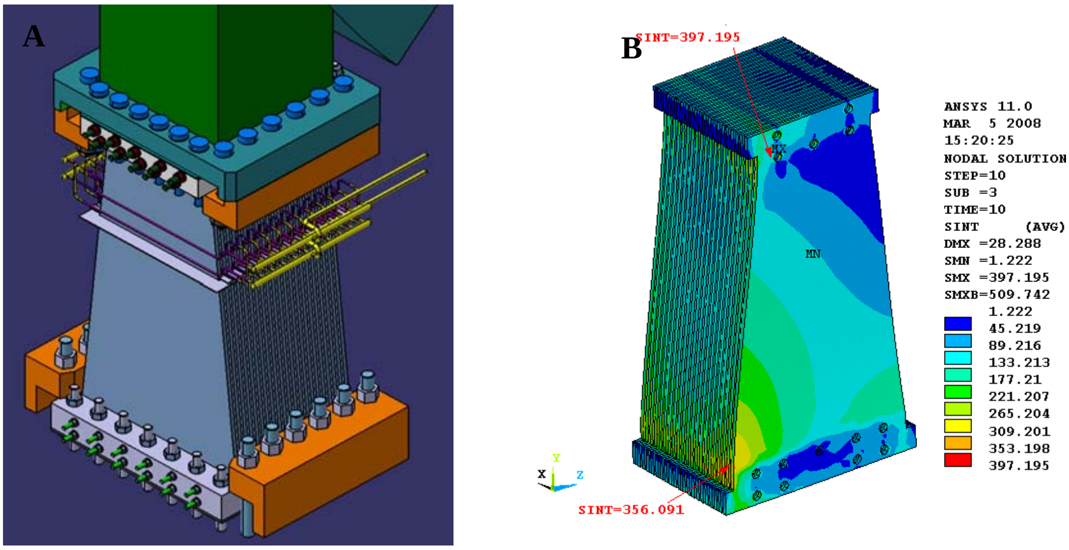

Fig. 1(A) Redesigned ITER TFS and (B) the typical stress distribution of flexible plates under DW+EOB+SL-1+VDEII load combination

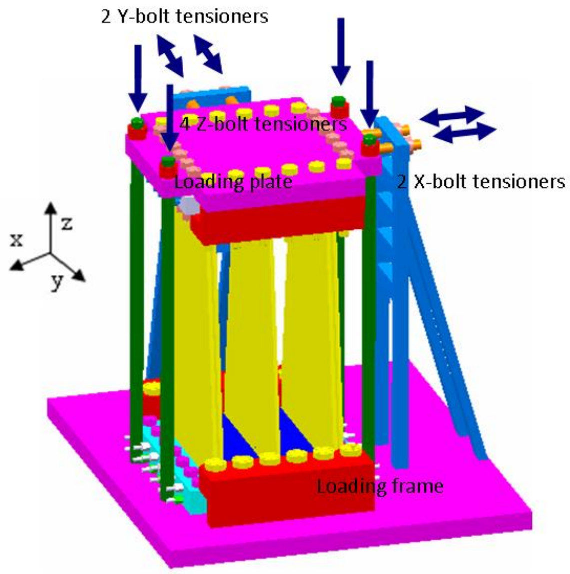

Fig. 2, schematic illustration of TFS semi-prototype test platform

outer plates – two on each side – and one central plate, the loads are scaled down from the TFS assembly design loads by a ratio of 5/21. In order to add the loads/load combinations onto the test mock up, a 8 hydraulic bolt tensioners in three directions has been applied to simulate various loads(forces and moments). The forces in the y-direction and x-direction of mock-up are applied byY-hydraulic bolt tensioners and X-hydraulic bolt tensioner, respectively. And the forces (including the forces converted into the moments M_x and M_y) in the Z-direction are applied by Z-hydraulic bolt tensioners. Through which, the deformation of the bolts, flexible plates and clamp blocks, the stress distribution in the flexible plates, the friction between the contact surface, could be monitored/tested. The structure stability test combined with the FEM analysis can guarantee the TF supports safe enough during 20 years (30000 times) operation.

3.2, PF support

In the ITER PF magnet system, totally 6 PF coils from top to bottom, in which PF3 and PF4 share the same support, which suspended by a strut dowel to the TF coil case, as shown in

Fig. 3A. The dead weight of PF coil combined with electromagnet force during discharge may enhance the movement of strut dowel. Therefore, the strut dowel need high wear resistance to against the friction wearing. The load from electromagnetic forces during discharge may not only enhance the load, but also cause the movement of the strut dowel. Therefore, the strut dowel needs high resistance against friction wearing. Ion implantation has been utilized in the strut dowel surface modification in this study to improve the wear resistance due to its non-boundary modification of the microstructure as well as the formation of hard alloys on the surface. Both nitrogen ions and nitrogen ions plus titanium ions, with the implantation dose of 2×10^{17} to 8×10^{17} ions/cm^2, were selected. After implantation, the friction wear resistance was checked via the surface hardness and weight loss. Typical wear resistance test sample after testing is shown in Fig. 3B,C. It is obvious that the wear resistance was increase after ion implantation. It seems that the ion implantation is an effective method for improving reliability for the strut dowel. However, according to the IO requirement, the further test of the wearing resistance with the enhanced load at low temperature (4-77K) is still essential and in work, the result will be give out in the near future.

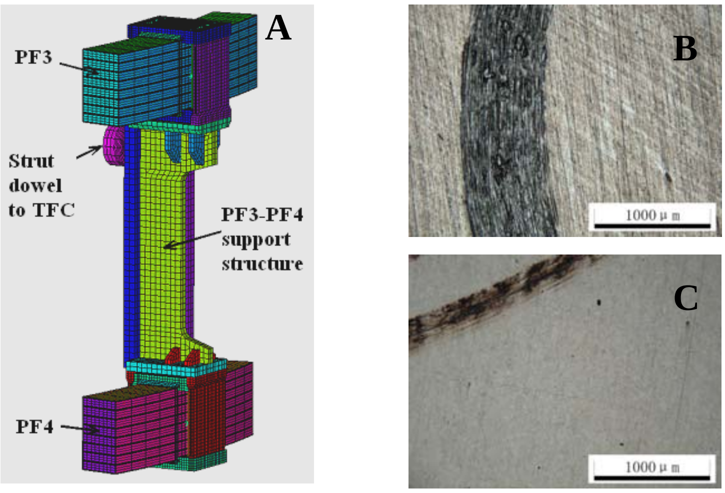

Fig. 3 (A) PF3-PF4 support structure, and Photograph of sample under the wear test with (B) non-implantation and (C) Ti^+/N^+ ion implantation

3.3, CC support

In the CC supports, the low voltage insulation coating on the shear pin was required. The same coating in the TF supports is also needed. Based on the ITER design, the plasma spray Al2O3+3% TiO2 coating with 0.3mm thickness should be developed. Because the coating withstand the strong shear force during operation, the high adhesion with matrix is expected. In this study, an advanced plasma spray system(GTV, Germany) was applied. In order to increase the bonding, the 0.1mm thick NiAl alloy interface was prepared before the plasma spray, which can be seen clearly in Fig.4A. The test result shows that the interface can improve the bonding strength of the coating with matrix: without interface, 33.4 MPa, with NiAl interface, about 40MPa. Further thermal shock test of the coated sample between 300K and 77 K for more than 50 times, no crack, debonding was found. The electrical resistance test shows that the resistance is 1.06×10^{10} Ωm, which can

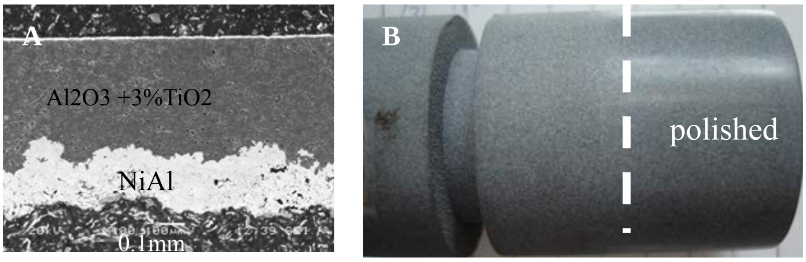

Fig. 4, (A), the microstructure of the coating. (B) the shear pin with Al2O3+3% TiO2 coating before/after polishing satisfy the ITER requirement. In addition, the coating can be polished to very well condition, as shown in Fig. 4B. However, the further 120000 cyclic shear loading test of the coating is still in performing.

3.4, Thermal anchor

Various cooling pipe is needed for maintaining the low temperature of the magnet supports, including TFS, PFS and CCS. The thermal anchor in TFS is shown in Fig. 1A. It is suggested to use brazing connection to attach the cooling pipe to support-plates. Hence, brazing filler with good strength, toughness and thermal conduction is required. In this investigation, three kinds of filler applied at low (200～300℃), intermediate(600～800℃) and high(900～1100℃) brazing

Table 2, wetting angle & mechanical property of different brazing fillers

NO.	Tensile Str(MPa)	Shear str(MPa)	Impact energy/J	Tensile str/MPa (at 77K)	Wetting angle /^{o}
Sn1	18	16	8.2	61	13.4
Sn2	17	14	7.7	58	9.7
Ag1	392	220	22	588	2.6
Ag2	370	209	20.5	414	3.2
Cu1	465	243	24.2	821	8
Cu2	354	201	18.7	609	11.8

temperature corresponding to Sn-Pb alloy, Ag alloy Cu alloy, respectively, were developed as candidates filler. The wetting angle to 316LN for both Sn-Pb and Cu alloy filler is almost the same, as shown in table2, but Ag based filler shows the most promise wettability with 316LN among the three kinds fillers due to it's obvious small wetting angle. Microstructures of some joints solders are shown in Fig.5. The obvious boundary layer was formed between the filler alloy matrix material means that the relatively high temperature is helpful for the connection of filler with matrix. The mechanical properties of the joints using different filler are also listed in Table2. In general, it is obvious that the strength of the joints increased with the increasing of brazing temperature. All the tested sample shows higher strength at 77K than that of tested at RT. The strength for one of the sample using Cu alloy as brazing filler at 77K is almost double of its RT strength, neither the strength nor the toughness of Sn-Pb alloy filler is good because the filler itself is very weak. For Ag-based filler, the tensile strength is up to 370 MPa at RT and more than 410MPa at 77K, microstructure of the Cu alloy brazed sample is shown in Fig. 5A. clear interface formed in the boundary. As an example, Φ12 pipe with 1.5 mm thickness brazed with a 30mm thickness plate using Cu alloy is shown in Fig.5B, completely filling up the space between pipe and plate by filler could be seen, which means very good moveability of the filler and helpful for heat exchange. In addition, no crack was found for all the joints after 20 times

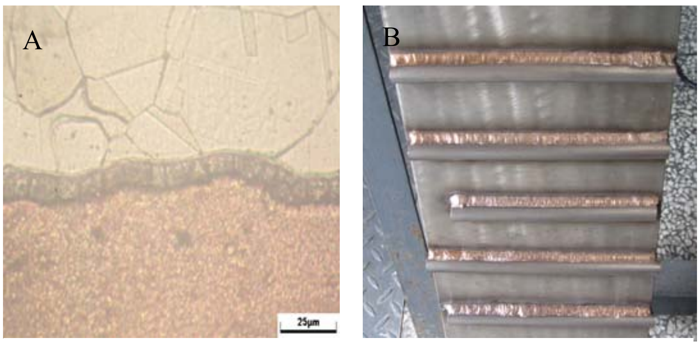

Fig. 5, (A)Microstructures of Cu joint solders boundary. (B) brazed pipe thermal shock.

4, Summaries

316LN stainless steel for magnet supports has been developed domestically. This material shows very good mechanical properties at both room temperature and low temperature (liquid nitrogen and liquid helium) and can satisfy the ITER construction requirements.

The redesign of TFS using pre-stressed bolted connections instead of welded connections is successful based on both static and stability FEM analysis. The new designed shows only local stress concentration and no large deformation would occur during all possible normal and abnormal load combinations. Therefore, it is safe and can satisfy the ITER operation requirement. Recently, this design has been approved for applied in the ITER construction by ITER/IO after the international review last year. However, the further engineering test is suggested to guarantee the safe operation, and will be finished in the near future.

Two different surface technologies have been developed for PFS and CCS. One is ion implantation to modify the strut dowel of PF3-4 to increase the wear resistance, another is plasma spray insulation coating for shear pin in CCS. Based on the test result, both of them can satisfy the ITER operation requirements.

Three type of brazing filler has been developed for magnet supports cooling pipe attachment. However, not only the brazing strength, but also the deformation, should be considered for the practical application. Therefore, the further work to select the suitable brazing method as well as the filler is needed.

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