Welding techniques development of CLAM steel for Test Blanket Module

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**A B S T R A C T**

Fabrication techniques for Test Blanket Module (TBM) with CLAM are being under development. Effect of surface preparation on the HIP diffusion bonding joints was studied and good joints with Charpy impact absorbed energy close to that of base metal have been obtained. The mechanical properties test showed that effect of HIP process on the mechanical properties of base metal was little. Uniaxial diffusion bonding experiments were carried out to study the effect of temperature on microstructure and mechanical properties. And preliminary experiments on Electron Beam Welding (EBW), Tungsten Inert Gas (TIG) Welding and Laser Beam Welding (LBW) were performed to find proper welding techniques to assemble the TBM. In addition, the thermal processes assessed with a Gleeble thermal-mechanical machine were carried out as well to assist the fusion welding research.

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**1. Introduction**

The China Low Activation Martensitic (CLAM) steel\textsuperscript{[1,2]} based on the nominal compositions of 9Cr–1.5W–0.45Mn–0.2V–0.15Ta, one of the Reduced Activation Ferritic/Martensitic steels (RAFM)s\textsuperscript{[3]} and under development in China, is chosen as the primary candidate structural material in the designs of FDS series LiPb blankets\textsuperscript{[4–7]} for ITER in China. So the fabrication techniques for DFLL-TBM with CLAM need to be studied in detail.

Blanket components in fusion DEMO reactors will receive a neutron wall load for more than 3–5 MW/m\textsuperscript{2} and a surface heat flux for more than 0.5 MW/m\textsuperscript{2}. And blankers should have sufficient cooling capability against high thermal loads from plasmas and enough mechanical stiffness against large electromagnetic loads during plasma disruptions, which is a great challenge on fabrication techniques of the blanket as well as the structural material. The fabrication of DFLL-TBM mainly includes the manufacturing of the First Wall (FW), the Cooling Plates (CP) and the assembly of these components. And Hot Isostatic Pressing (HIP) and uniaxial diffusion bonding are the most promising candidate fabrication techniques for the FW and CPs\textsuperscript{[10]}. Experiments of HIP diffusion bonding of CLAM/CLAM were performed and effect of surface preparation on the joints was studied\textsuperscript{[11]}. Effect of HIP process on the mechanical properties of base metal was also investigated. Experiments on uniaxial diffusion bonding were performed to study the temperature effect on the microstructure and mechanical properties of the joint. Electron Beam Welding (EBW), Tungsten Inert Gas (TIG) welding and Laser Beam Welding (LBW) are candidate welding techniques for the joining of FW and CPs. Some preliminary experiments on these fusion welding techniques were performed. In addition, simulation of these thermal processes with the Gleeble thermal-mechanical system was carried out as well to assist the fusion welding research. Results of these experiments and simulations are summarized in this paper.

**2. Diffusion bonding**

2.1. HIP diffusion bonding

Surface preparation is one step of pre-HIP treatment and an important factor for getting good joints. HIP diffusion bonding experiments on CLAM steel was performed to study the effect of surface preparation and good joints with high Charpy impact absorbed energy have been obtained. Also, mechanical properties of base metal before and after HIP diffusion bonding were tested to study the influence of HIP process.
2.1.1. Effect of surface preparation on joint quality

The faying surfaces were machined by high speed dry milling, dry grinding without coolant and hand lapping, respectively. The hand lapping procedure is that specimen is ground by grinding machine and then lapped on a large flat plate with alumina grits. Then the specimens were washed in ultrasonic bath with mixture of alcohol and acetone which was followed by outgassing in vacuum furnace under 1000 °C and vacuum sealing. The HIP parameters are 1100 °C/150 MPa/3 h. The post HIP heat treatment (PHHT) was 955 °C/60 min/air and 755 °C/90 min/air to regain martensite phase. And the faying surfaces after machining were inspected by optical microscopy and the photos are shown in Fig. 1. The surface roughness of faying surfaces and mechanical properties test results of the joints by standard samples are shown in Table 1. In spite of comparable values of surface roughness by difference machining methods, the structures revealed significant differences. The surface by high speed dry milling was rather smooth with fine-structured lines. The surface by dry grinding had small cavities which might contain contaminations difficult to be clean thoroughly. Although the surface by hand lapping had lowest roughness, it was gray in eye-view and showed irregular structure under optical microscopy. The tensile test and Charpy impact test were performed according to the corresponding ISO standards. The diffusion bonding line located at middle of the gauge part of the tensile specimen and right bottom of the notch of the Charpy impact test. All the tensile specimens did not break at the bonding line. Although ultimate tensile stress (UTS) is comparable, the Charpy results show great difference as shown in Table 1. Fracture surface of the joint by hand lapping was rather smooth and just like original faying surface. It was inspected by Scanning Electron Microscopy (SEM) and analyzed by Energy Diffraction Spectrum (EDS). There is a very high Al-Kα peak in EDS results of many grits as shown in Fig. 2 which means aluminium is a main composition of them. They are possibly the abrasive material used in hand lapping. This is one of the possible reasons for low Charpy absorbed energy. These results show that neat and fine-structured surface without apparent defects containing contaminations is very important for the HIP diffusion bonding. High speed dry milling is a very good choice and hand lapping is not suitable because the grinding grits can be easily embedded in the surface. And for the grinding, the parameters may be optimized to get better surface. Based on these results, a small FW module will be fabricated.

2.1.2. Properties before and after HIP diffusion bonding

Tensile and creep test of the bulk material before and after HIP diffusion bonding were performed with small specimens. The gauge size of the tensile specimens was 5 mm × 1.2 mm × 0.25 mm, which is the same to the Ref. [12]. And the bonding line did not locate on the tensile sample. Tensile tests were conducted at room temperature (RT), 400 °C, 500 °C and 600 °C at an initial strain rate of 6.67 × 10⁻⁴ s⁻¹. The RT test was conducted in air, while the tests at elevated temperatures were carried out in a vacuum of 10⁻³ Pa. The same kind of specimen was used for creep test. The ultimate tensile stress and creep test results are shown in Figs. 3 and 4. As shown in these figures, the UTS and creep rupture time decrease a little after
HIP diffusion bonding. Considering the data dispersion by small specimen, the decrease is not obvious. However, further research on the influence of HIP diffusion bonding on the bulk material should be carried out to push work on TBM and fusion blanket designs.

2.2. Uniaxial diffusion bonding

Uniaxial diffusion bonding experiments were performed and the effect of temperature on microstructure and mechanical properties was studied. The pressure and holding time were 10 MPa and 60 min, respectively. The temperatures of 920 °C, 940 °C, 1000 °C, 1050 °C and 1100 °C were chosen for the experiments. After bonding, microstructure of the joints was inspected by optical microscopy and SEM and the shearing strength was assessed. The results are shown in Fig. 5. As it can be seen, the bonding ratio and shearing strength increase quickly with temperature up to 1050 °C. The shearing stress reaches 648 MPa at 1050 °C. However, the increase of bonding ratio is small and shearing strength even reduces from 1050 °C to 1100 °C. These results can be explained as follows. Increase of temperature can significantly enhance the diffusion and speed the vanishment of the voids along the bonding line. At the same time, it can coarsen the grain and speed the carbides precipitating and growing, which reduces the shearing stress of bulk material and the joint. Further study on bonding pressure and post bonding heat treatment will continue to get better joints.

3. Fusion welding techniques

3.1. Fusion welding experiments

EBW of CLAM plates with 11 mm wall thickness were performed with the welding parameters of 60 kV, 70 mA and 600 mm/min. No preheating and post-welding heat treatment were done in this experiment. Good penetration joints were obtained and no pore was found in the joint. And mechanical properties were tested following the corresponding ISO standards. The UTS of the joint was 655 MPa which was 91% of base metal and Charpy impact absorbed energy was 168 J which was 82% of base metal. However, the maximum hardness was HV453 and located in the center of fusion zone. And it is too high compared to HV220 of base metal. Further experiment and research will be carried out in order to reduce the hardness of weld center.

Two manual TIG welding experiments on plates of 4 mm wall thickness were performed. A chamfer was filled with a 2 mm filler wire extracted from the CLAM plate. The welding grooves were V-type with 60° angle. Weld preheating of 150 °C was carried out in one weld and no preheating for the other. And these double-bead lap joints were tempered under 760 °C/30 min to enhance the mechanical properties. The results are as follows. (1) X-ray detection showed that they were good joints without significant defects. (2) Metallographical inspection showed microstructure of the joints was lath martensite. The grain of fusion zone was coarsened obviously, especially for the joint without preheating. (3) SEM observation showed that a lot of carbides precipitate along grain boundary and lath packet at fusion zone and heat affected zone for both joints as in the base metal. The carbides in fusion zone were relatively small and mainly bar-type as in the base metal. However, the carbides in heating affected zone were relatively large and mainly grit-type.

And a preliminary LBW experiment on CLAM plates of 12 mm wall thickness with YAG laser was done. The power and welding speed were 3 kW and 0.010 m/s, respectively. The visual control did not reveal any defect. Further inspection of the joint is being carried out.

3.2. Simulation of thermal process

Simulation of thermal experiments of CLAM fusion welding by Gleeble were carried out. Hannerz method was used to control heating and cooling process of CLAM sample. Setting parameters include maximum temperature of 1350 °C, preheating temperature of 100 °C and cooling time from 800 °C to 500 °C (i.e. t8/5 for short). Series t8/5 of 300 s, 200 s, 100 s, 50 s, 20 s and 8 s were chosen in
the experiments. Hardness and microstructure of the samples were inspected. Microstructure of all the samples was lath martensite. Fig. 6 shows the graph of grain size and hardness versus $t_{8/5}$. It is clear that the grain size increases with $t_{8/5}$, and the hardness decreases first and increases after 50 s. This phenomena possibly owes to the competitive relation of carbide precipitating and grain coarsening on hardness of martensitic steel. When $t_{8/5}$ is smaller than 50 s, the grain size coarsening plays the main role on hardness change. When $t_{8/5}$ is larger than 50 s, a lot of carbides precipitate, which strengthens grain boundary greatly and results in the hardness increase.

4. Summary

CLAM steel is chosen as the primary candidate structural material in FDS series LiPb blanket designs and DFLL-TBM in China. Diffusion bonding and fusion welding techniques of CLAM are being under development.

Good HIP diffusion bonding joints with Charpy impact absorbed energy close to that of base metal have been obtained. The results showed that neat and fine-structured surface without apparent defects containing contaminations was very important for the HIP diffusion bonding as well as surface roughness. And the mechanical properties of base metal before and after HIP were comparable. A small FW module by HIP diffusion bonding is in plan. Uniaxial diffusion bonding experiments showed that bonding ratio and shearing stress increased with temperature before 1050 °C, but grain coarsening and carbides growth decreased the bulk material and joint from 1050 °C to 1100 °C. Further research on bonding pressure and post bonding heat treatment will be carried out to get better joint.

Preliminary EBW, TIG and LBW experiments were performed and further research will be carried out to meet the requirement of TBM assembly. Simulation of thermal experiments of fusion welding process with a Gleeble machine showed that grain size increased with $t_{8/5}$ and the hardness decreased first and increases after 50 s. The hardness change may owe to the competitive effect of carbide precipitating and grain coarsening on hardness of martensitic steel.

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