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Effect of preheating on welding cold crack sensitivity of China low activation martensitic steel

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ABSTRACT

The China low activation martensitic (CLAM) steel has been chosen as the primary structure material in Chinese series PbLi blankets for fusion reactors. The assembly preparation of the blanket would be seriously influenced by the weld performance of the CLAM steel. In this study, the welding cold crack sensitivity index of the CLAM steel was analyzed, then the maximum hardness in weld heat-affected zone (HAZ) and y-groove tests were performed. Based on the analysis to the maximum hardness in weld HAZ and the cracking rate of y-groove test at different preheating conditions, the results indicated that the HAZ maximum hardness of CLAM increased at firstly and then decreased with the increase of the preheating temperature (PT). The cracking rate of y-groove test reduced with the increase of the PT, and the crack rate maintained at a relative stable stage when the PT exceeded 250 °C. It revealed high welding crack tendency of the CLAM steel. Thus, the preheating before welding should be applied, and a PT at about 250 °C was proposed in order to prevent welding cracking.

1. Introduction

China low activation martensitic (CLAM) steel is one of three primary kinds of reduced Activation Ferritic/Martensitic (RAFM) steel, which is developed in the Institute of Nuclear Energy Safety Technology (INEST), Chinese Academy of Sciences for about fifteen years [1–3]. It has been chosen as the primary structure material of China series blanket for fusion reactors [4,5], CN helium cooled ceramic breeder (HCCB) test blanket module (TBM) for ITER and the blanket of China fusion engineering test reactor (CFETR) [6–8].

Due to the structural complexity of the blanket, it is difficult to fabricate the blanket by casting and one-off molding, and welding is considered as a flexible way to assemble the blanket [9–13]. However, the fabrication would be seriously influenced by the weld performance of the CLAM steel because the martensitic steel is sensitive to cracking in welding for its obvious hardenability [14]. Thus, it is crucial to investigate the weldability of CLAM steels as it will be applied in the blanket fabrication by welding [15–18].

The cold cracking tests for weldments are designed to assess the cold cracking sensitivity of the parent materials. And the cold cracking sensitivity is one of most important contents to evaluate the procedure weldability of the structure materials. The study of the procedure weldability has important value to the development of the welding process. As mentioned above, the CLAM steel has been chosen as the primary structure material of China series fusion blanket. To ensure the welding precedure of the CLAM steel available and reliable, it should be qualified by the nuclear safety regulator before the engineering applications. Therefore, the cold cracking sensitivity of the CLAM steel, as one of the most important contents of the weldability, it must be clarified before the qualification and engineering applications.

In this paper, the study was focused on the welding cold crack sensitivity of CLAM steel. On the one hand, the welding cold crack sensitivity index of the CLAM steel was analyzed based on empirical formula [19]. On the other hand, the cracking tendency was investigated by maximum hardness in weld heat-affected zone (HAZ) test. Meanwhile, the critical preheating temperature (PT) to improve the cracking tendency of CLAM was obtained by calculating the crack rate in the y-groove test at different PTs [19–21]. Based on the study on the weld crack sensitivity of CLAM, it will provide essential guidance and reference on the welding procedure establishing of the CLAM steel.

2. Experiment

2.1. Materials

The material used in this research is 16 mm HEAT 1105 CLAM steel plate, which was normalized at 980 °C/30 min, air cooling and tempered at 760 °C/90 min, air cooling [14,22]. Its chemical composition was listed in Table 1. The welding was performed by tungsten inert gas (TIG), and the filler wires were cut from the 16 mm thick CLAM plate.

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Table 1
Chemical compositions of CLAM (HEAT 1105) in wt.%.

Cr	C	W	V	Ta	Mn	Si	Ti
8.73	0.08	1.34	0.21	0.15	0.43	0.14	0.01
O	N	S	Al	Cu	Ni	Nb	Fe
0.004	0.004	0.004	0.02	0.01	0.01	0.01	Bal.

2.2. Weld crack sensitivity index

Hardenability and crack tendency in weld HAZ is closely related to the chemical composition of steels. Therefore, the crack sensitivity could be evaluated by chemical composition. Based on the results of extensive experiments, Doctor Ito proposed the cold crack sensitivity index [19], which was related to chemical composition, thickness and diffusion hydrogen, as shown in formulas (1)-(3). The PT could be calculated according to the crack sensitivity index, and the formulas could be used in the high-strength low alloy steels with the tensile strength of 400–1000 MPa.

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (1)$$

$$P_c = P_{cm} + [H]/60 + t/600 \quad (2)$$

$$T_0 = 1440P_c - 392°C \quad (3)$$

In the formulas, P_{cm} – carbon equivalent of low carbon steel; t – plate thickness, [H] – diffusion hydrogen in weld metal according to Japanese standard JIS Z3118 (ml/100 g) [23], T_0 - lowest preheating temperature before welding, °C.

According to the chemical compositions of CLAM in Table 1, the P_{cm} of CLAM is about 0.59, and P_c is 0.61, while diffusion hydrogen in the weld wires is usually considered as $[H] \leq 0.02$ ml/g [23]. Then, the critical PT (T_0) is calculated as 486 °C. It was shown that the hardenability and crack tendency of CLAM steel is obvious, and it has poor resistance to crack in welding.

2.3. Maximum hardness in weld HAZ test

Maximum hardness in weld HAZ test was performed according to the standard ISO 6507 [24]. The standard specification test plates were prepared by quenched and tempered CLAM plate retained the rolling surface as shown in Table 2. The 1# plate was welded at room temperature (RT), and the 2#–5# plates were welded in different PTs, as seen in Table 3.

The filler material was CLAM wires with diameter of 2*2 mm, and it was cut from the CLAM steel plate (the same to the test plate) with the method of wire electric discharge (WED). Before the welding, it was dried at 75 °C for 2 h. The welding was performed on the rolling surface by manual at the environment of 25 °C × 39% relative humidity (RH). The post weld plates were cooled naturally in the air without any other heat treatment. The hardness tests were performed on the samples, which were machined from the plates after 12 h of placement, as shown in Fig. 1.

The inspection surface of the samples was etched with 20% $FeCl_3$ for 30 s after grinding. The hardness tests were conducted as Fig. 2 shown. The test line was parallel to the rolling surface and tangent to the bottom of the fuse line. The hardness test points were located on the tangent point and more than 7 points on each side of the tangent point in the test line with the interval of 0.5 mm and load of 10 kg. The tests were performed at RT according to ref. [24].

Table 2
Sizes of testing plate for maximum hardness in weld HAZ tests.

Test plate number	L (Length), mm	B (Width), mm	I (Seam length), mm
1#	200	75	125 ± 10
2# ~ 5#	200	150	125 ± 10

Table 3
PTs of maximum hardness in weld HAZ tests.

No.	1	2	3	4	5
PT (°C)	RT	100	200	250	300

2.4. Y-groove cracking test

The y-groove cracking test relates to more stringent test conditions and is recommended for parent material testing. The dimensions of the test pieces shall be in accordance with Fig. 3 based on the standard of ISO 17642-2 [21].

Key: a-test welding, b-anchor weld, t-thickness of the test plate, g-root gap 2.0 mm ± 0.2 mm.

The test pieces were machined by sawing, milling and grinding. Ensure that surfaces to be welded are milled or ground finish. Where the principal rolling direction of the plate can be determined, arrange the rolling directions of the plates to be the same and parallel to the welding direction. Ensure that the surfaces to be welded are ground smooth and free from scale, rust, oil, grease and other contaminants.

The anchor welds (shown in Fig. 3 b-area) with a welding consumable with a yield strength equal to or greater than the yield strength of the material under test. Deposit the welds with a procedure to avoid hydrogen cracking, using preheat, interpass and post-heating control. Dry all consumables used for anchor welds in accordance with manufacturers' recommendations to give the lowest possible hydrogen levels.

The filler material was also CLAM wires with diameter of 2*2 mm, and dried at 75 °C for 2 h, and the welding was performed by manual at the environment of 25 °C × 39% RH. The tests were executed on 12 test plates for 6 PTs, as shown in Table 4. In order to reduce the accidental and statistical error, 2 prototypes were prepared and the results of the crack rate at one condition were averaged.

The welding temperature in the test section was strictly controlled in ± 3 °C of preheating temperature. The welding was started when the temperature of the whole test plate has reached the specified preheating temperature. And the welding arc started and ended outside the test section. The test bead was welded with the method of tungsten inert gas (TIG) welding with argon (Ar) protection and the welding process was listed in Table 5 [25–28].

After 48 h of placement, samples were prepared for crack observation in surface, cross section and root of the weld joints, and the positions of the 5 sectioning cuts at the positions nearest to the starting point where the width of bead becomes constant and the centre of the bead crater, and the positions quartering the distance there of as shown in Fig. 4.

Key: 1-Cutting in the width direction, 2-Examining section position

The length and height of the cracks were measured according to Fig. 5. The crack length was measured following the strait line even the crack was curve, as Fig. 5(a) shown. When the cracks overlapped, the length was measured as one crack.

1) The surface crack rate was calculated by the formula (4):

$$C_f = \frac{\sum l_f}{L} \times 100\% \quad (4)$$

2) In the formula, C_f is the surface crack rate, %; Σl_f is the total length of the surface crack, mm; L is the weld length, mm.
3) Test pieces were snapped or bent to fracture after dyeing with appropriate methods, then the root crack could be measured according to Fig. 5(b), and calculated by formula (5):