

## Compatibility of CLAM steel weldments with static LiPb alloy at 550 °C

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### ABSTRACT

CLAM steel is considered as a structural material to be used in the Test Blanket Module as a barrier or blanket adjacent to liquid LiPb in fusion reactors. In this paper, CLAM steel is welded by tungsten inert gas (TIG) welding, and the compatibility of the weldment with liquid LiPb is tested. Specimens were corroded in static liquid LiPb, with corrosion times of 500 h and 1000 h, at 550 °C, and the corresponding weight losses are 0.272 mg/cm<sup>2</sup> and 0.403 mg/cm<sup>2</sup> respectively. Also the corrosion rate decreases with increased corrosion time. In the as-welded condition, corrosion resistance of the weld zone is higher than that of the HAZ (Heat Affected Zone). Likely, thick martensite lath and large residual stresses at the welding zone result in higher corrosion rates. The compatibility of CLAM steel weld joints with high temperature liquid LiPb can be improved to some extent through a post-weld tempering process. The surface of the as-welded CLAM steel is uniformly corroded and the concentration of Cr on the surface decreases by about 50% after corrosion. Penetration of LiPb into the matrix is observed for neither the as-welded nor the as-tempered conditions. Influenced by thick martensite lath and large residual stresses, the welded area, especially the weld zone, is easily corroded, therefore it is of primary importance to protect the welded area in the solid blanket of the fusion reactor.

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### 1. Introduction

In order to propel the safe application of fusion energy, a great amount of research on fusion reactor design and fabrication has been accomplished by many researchers. At present, the design of the blanket module using liquid LiPb is considered as one of the most promising concepts for fusion reactor designs in the world [1,2]. RAFM steel is used as the first solid blanket material for containing liquid LiPb and its compatibility with high temperature liquid LiPb has been deeply studied [3–7]. Research on the corrosion behavior of many kinds of RAFM steels produced by different countries shows that an incubation period appears during the early stage of corrosion due to the existence of a passivation layer and the corrosion rate increases with both increasing flow rate and temperature of liquid LiPb. Moreover, no penetration of LiPb into the matrix is observed after long corrosion times. In China, series of tests on the corrosion behavior of tempered China Low Activation Martensite (CLAM) steel, a type of RAFM steel, in liquid LiPb have been conducted by the FDS team [3,4]. At present, research on RAFM

steels is mainly focused on changing external operating conditions, such as temperature and flow rate of liquid LiPb, etc., to study the corrosion properties of CLAM steel.

Welding technology is indispensable in the manufacture of the fusion reactor blanket structure. However, the microstructure of the base metal and the distribution of stress are heavily modified during the solidification of fusion welded metals. Significant differences in microstructure and macroscopic properties are observed between the welds and the base metal in CLAM steel [8–11]. Thick martensite lath and large residual stress in welding zone make the weld zone at higher risk for corrosion than the base metal, and therefore the corrosion resistance of welded CLAM steel requires significant additional research. To date, more attention has been given to the compatibility of liquid LiPb alloy to unwelded compared to welded RAFM steel. TIG welding is widely used in the manufacture of the first solid blanket in fusion reactor designs. This article focuses on evaluating and validating the corrosion resistance of TIG welds in CLAM steel exposed to liquid LiPb at 550 °C, which is considered the highest operating temperature of CLAM steel.

### 2. Compatibility experiments

In this experiment, CLAM steel plates of 4 mm thickness, were chamfered to produce a V groove, then welded in two passes

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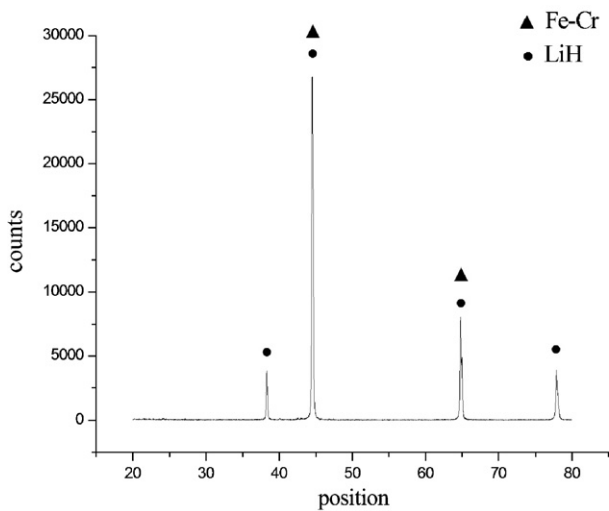


Fig. 1. The XRD composition plot of the specimen corrosion surface for 1000 h.

with a welding current of 96 A. The filler wire was of the same composition as the base metal. After welding, cross-section specimens of the welds including weld bead and HAZ (Heat Affected Zone) were obtained by machining. Before the corrosion experiments, the specimens were ground and polished to decrease the surface roughness, then ultrasonically cleaned and dried. The weights of the specimens before corrosion were recorded as  $W_0$ . The specimens were then put into a crucible made of 316L stainless steel and corroded in the thermal convection loop DRAGON-I [12]. After corroded for 500 h and 1000 h in static liquid LiPb at 550 °C, the specimens were washed repeatedly with a solution of  $\text{CH}_3\text{COOH}$ ,  $\text{H}_2\text{O}_2$  and  $\text{C}_2\text{H}_5\text{OH}$ , until the specimen weights remained constant. The weights of the specimens after corrosion were recorded as  $W_1$ . Thus the specimen weight loss is  $\Delta W = W_0 - W_1$ . The average corrosion rate is  $D = \Delta W / (\rho \times S)$ , where  $\rho = 7820 \text{ kg/cm}^3$  is the density of CLAM steel, and  $S$  is the weld zone area, which is determined by grid-area method due to its irregular shape.

### 3. Analysis of corrosion testing

The surfaces and cross-sections of the specimens were observed and analyzed with XRD, EDS and EDX.

#### 3.1. Composition analysis of corroded surfaces

After corrosion for 500 h and 1000 h, no significant changes in composition were observed on the surfaces according to XRD. The XRD composition plot of the specimen surface corroded for 1000 h is given in Fig. 1. Martensite and LiH can be observed on the surface. LiH may occur due to the possible existence of H in liquid LiPb [13,14]. In the welded area, the reaction  $\text{Li} + \text{H} + \Delta E \rightarrow \text{LiH}$  may take place on the corrosion surface, which is similar to the behavior of weldments in flowing liquid LiPb [14].

In many other studies on the compatibility of RAFM steels with liquid LiPb, the existence of a passivation layer is mentioned [15,16], and its functional mechanism is analyzed as well. Ref. [16] suggests that the corrosion rate during earlier stages can be decreased by delayed wetting of the passivation layer which protects the matrix effectively. By analyzing the delayed wetting theory, Protsenko et al. [17] found that the effect of surface passivation on wetting was not obvious, leading to the proposed theory of slow dissolution of the passivation layer. From the current research, the delayed corrosion behavior of CLAM steel may be explained more reasonably by the slow dissolution of the passivation layer

theory. In this test, the XRD analysis suggests that the surfaces of specimens contain few oxides of Fe and Cr. The experiments conducted here are typically much longer than the short incubation period. Thus overall passivation protection for weld area matrix is considered negligible.

EDS tests show that the main elements and their compositions on the corroded surface of the welded area are Fe (92.4%), Cr (5.61%), W (1.99%) after corrosion and washing, compared with that of the uncorroded base metal where the elements and compositions are Fe (90.5%), Cr (9.00%), W (1.50%). It is clear that the content of Cr reduces significantly.

#### 3.2. Corrosion metallographic analysis

##### 3.2.1. Surface corrosion analysis

The corrosion SEM pictures of CLAM steel welds completed by TIG welding after being corroded for 500 h and 1000 h are shown in Fig. 2. After 500 h, as shown in Fig. 2a–c, the surface is smooth with white granular attachments and pitting corrosion occurring locally on the surface with the diameter of the pits being about  $4 \mu\text{m}$  (Fig. 2a). The crucible used to hold the specimens during corrosion is made of 316L austenitic stainless steel, of which the main components are Fe–18Cr–12Ni–2Mo. The corrosion behaviors of 316L austenitic stainless steel and CLAM steel in high temperature liquid LiPb are considered a dynamic diffusion process, which can be divided into two dynamic sub-processes: the elements in the matrix of the specimens diffuse to the liquid LiPb and the elements in the liquid LiPb accumulate on the surfaces of the specimens. When the diffusion rate is faster than the accumulation rate, the specimen weight decreases, otherwise, the specimen weight increases. Under the same condition, the corrosion rate of 316L is ten times faster than that of CLAM steel. At the early stage of corrosion (small values of time), the liquid LiPb is static and has a high solubility for elements originating from the specimen and crucible. Thus, during the early stage of corrosion elemental Ni in the 316L austenitic stainless dissolves and diffuses preferentially [18]. At the same time, most of the specimen matrix is protected by the passivation layer and corrosion takes place only at the areas not covered with the thin passivation layer and at the grain boundary areas containing complex compositions [19]. Elemental Ni from the 316L austenitic stainless keeps dissolving and diffusing into liquid LiPb and then attaches to the surface of CLAM steel specimens, which can be seen in Fig. 2a–c as the white granular attachments. These behaviors are also observed in JLF-1 steel, which is another type of RAFM steels, under static LiPb condition with a corrosion time of 250 h, at 550 °C [20].

Fig. 2d and e shows the SEM pictures of specimens corroded for 1000 h. It is clear that the surface is corroded much more seriously compared with that corroded for 500 h. After corroded for 1000 h, the passivation layer on matrix surface is seriously damaged and the white granular attachments on the surface disappear by redissolution. No obvious large-diameter local pitting areas are found on specimen surface. Because of the loss of the protective passivation layer, corrosion has progressed to uniform attack corrosion in addition to small scale pitting corrosion. Cr depleted zones surrounding martensitic laths and at grain boundaries can be preferentially corroded which has been elaborated in the theory of easily corroded areas in Ref. [14]. Refs. [8–11] show that due to the welding process applied to CLAM steel, local areas with unbalanced structural stress are distributed uniformly along the weld seam and therefore the corrosion morphology of a CLAM steel weldment is manifested as what is shown in Fig. 2b. The integral damage of the passivation layer results in general corrosion of the specimen surface and destroys the early stage corrosive resistance condition. During general corrosion, the corrosion rate is increased by the larger interface between pitting area edges and liquid LiPb. A large wetting angle

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