



Corrosion experiment in the first liquid metal LiPb loop of China

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Abstract

The liquid metal LiPb blanket design is one of the most promising designs for future fusion power reactors and under wide research in the world. The first liquid metal LiPb loop in China named DRAGON-I was built in 2005 in order to do research on characteristics of liquid metal LiPb such as its corrosion to structural materials of the blankets and so on. The first corrosion experiment in flowing LiPb with a speed of 0.08 m/s at 480 °C for 500 h was done in October 2005 on CLAM (China low activation martensitic) steel and 316L stainless steel for comparison. The weights and compositions, etc. of the specimens before and after corrosion experiment were tested and analyzed, the microstructures of the specimens were also inspected by SEM. The results show that the corrosion of CLAM steel is relatively slight, while that for 316L is obvious and very serious. Further study on corrosion behavior of CLAM for longer time experiment in liquid LiPb at different temperatures and flow speeds will be carried out in the near future.

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1. Introduction

The liquid metal LiPb blanket design is one of the most promising designs for future fusion power reactors and under wide research in the world. EU, US, China and other members of ITER (international ther-

monuclear experimental reactor) all pay much attention to the R&D of the liquid LiPb blankets. LiPb is considered widely as the most suitable tritium breeder, neutron multiplier and coolant with attractive nuclear properties and steady chemical properties with air and water. Compared with the solid blankets, the liquid metal LiPb blanket has the following characteristics [1]: (1) Pb has higher neutron economy, it can enhance the tritium breeding performance, and then no additional neutron multiplier such as Be is needed; (2) liquid

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LiPb eutectic fits tokamak's geometry well; (3) it is easy to extract tritium from liquid LiPb eutectic online. Therefore, the liquid LiPb TBM (test blanket module) with RAFMs (Reduced Activation Ferritic/Martensitic steel) as the structural material becomes one of the most attractive designs for ITER TBM.

In China, among the series fusion-driven system designs by the FDS Team of ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences) [2], the DFLL (dual functional lithium lead) TBM design for ITER is a preferential design for liquid metal blanket [1,3], it can demonstrate the technologies of DLL (dual-coolant lithium lead) and SLL (single-coolant lithium lead). The candidate structural material for the TBM is CLAM (China low activation martensitic) steel, which is under development by the FDS Team with wide collaborations in domestic and overseas [4].

RAFM is considered as one of the candidate structural materials for DEMO and the first fusion power plant, and the compatibility of RAFMs with liquid LiPb is a typical issue for the liquid LiPb blanket concepts and its corrosion behavior in liquid LiPb needs to be studied in detail because of the potentially significant effect on the reliability and safety of the blanket. Therefore, two kinds of cylindrical specimens made of martensitic steel CLAM and austenitic stainless steel 316L were exposed to the flowing LiPb with a speed of 0.08 m/s at 480 °C for 500 h corrosion experiment in the first liquid metal LiPb loop DRAGON-I in China, which was built in 2005 at ASIPP.

2. Experimental procedures

2.1. Main features of the DRAGON-I loop

The first liquid metal LiPb loop in China named DRAGON-I is a thermal convection loop used for corrosion experiments for structural materials in flowing LiPb. It is made of austenitic stainless steel 316L pipes with 22 mm inner diameter and with a 0.5 m × 0.5 m shape, as shown in Fig. 1. It consists of a test section (i.e. hot leg) and a cold leg. The electrical heaters will heat the liquid metal to the desired temperatures of 480 °C in the test section and 420 °C in the cold leg, respectively, in order to make liquid metal LiPb flow in the loop due to the temperature difference. The temperatures of the loop are measured by thermocouples

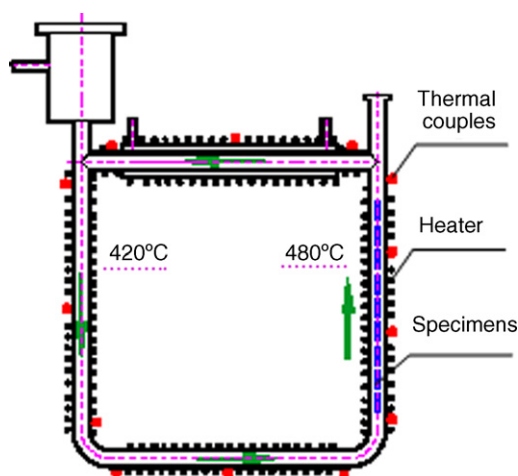


Fig. 1. The scheme of DRAGON-I thermal convection loop.

fixed along the pipe. The left top of the circuit was connected to an expansion tank which is made of austenitic stainless steel and heated by electrical heater, too.

The tested chemical composition of LiPb eutectic contains Li 0.71, Al 0.004, Cd 0.0003, Cr 0.0005, Cu 0.0013, Fe 0.0284, Hg 0.0037, Mg 0.0105 wt.%. Sum content of the other elements is less than 0.0003 wt.%. The LiPb was molten and filled into the loop from the expansion tank at the beginning of the corrosion experiment.

2.2. Specimens and corrosion experiment

The thermal treatment of CLAM steel were normalized at the temperature 980 °C for 30 min, cooled to room temperature (RT) in air, and tempered at 760 °C for 90 min, then cooled to RT in air. Cylindrical specimens (31 mm in length and 10 mm in outer diameter) of martensitic steel CLAM and austenitic steel 316L were prepared. The chemical compositions of them are listed in Table 1.

After machining, the cylindrical specimens were polished mechanically by grinding paper (until 1200 grade) to reduce the roughness of the original surface of the specimens. Then they were cleaned in an acetone ultrasonic bath and dried for some time and then put into the hot leg of the loop to do corrosion experiment at 480 °C for 500 h.

After that, the specimens were taken out of the loop, and some were washed by flowing water for a very

Table 1
Chemical compositions of the two steels (wt.%)

	Cr	Ni	Mn	C	S	Si	W	V	Ta	Mo	N	P	Fe
CLAM	8.91	–	0.49	0.12	0.003	–	1.44	0.20	0.15	–	0.0084	–	Balance
316L	17.4	11.1	1.11	0.018	0.001	0.53	–	–	–	2.16	0.04	0.026	Balance

short time to achieve clean but less destroyed surfaces. Then they were immersed into a solution mixture by CH_3COOH , H_2O_2 and $\text{C}_2\text{H}_5\text{OH}$ in a ratio of 1:1:1, with the cleaning procedure performed until the weight of the specimens remained constant [5,6], and the weight losses of post-test specimens were tested after cleaning. While the other corrosion specimens were not treated with the cleaning solution for comparison and used for metallographic analysis directly.

3. Results

The corrosion behavior of these specimens was characterized and analyzed by weight change, observation of corroded surfaces, and measurements of LiPb-environment-induced composition changes, respectively. The metallographic analyses were performed by optical microscope and scanning electron microscope (SEM). The chemical compositions of the corroded layers were evaluated by means of energy dispersive X-ray spectroscopy (EDX).

3.1. Weight change

After exposed to the flowing LiPb at 480°C for 500 h, the weight loss for CLAM specimen was about 0.17 mg/cm^2 . While the 316L specimen exhibited obvious differences in weight changes, i.e. the weight loss of it was about 1.7 mg/cm^2 , which was 10 times higher than that of CLAM specimen. So the corrosion of 316L in liquid LiPb was much more serious than that of CLAM.

3.2. Surface investigation

The cross-section morphologies of the specimens' interface between liquid metal and base materials after cleaned by SEM are shown in Figs. 2 and 3. It's clear that the surface defects on the corroded layer of CLAM specimen were much more shallow compared with that

of 316L specimen, and most area of the surface kept unaffected. But the 316L specimen was corroded obviously, it looked like saw-teeth on the surface and there were lots of small irregular holes on the substrate which were easy to fall off the steel matrix.

In addition, two specimens were not washed with water or the chemical mixture in order to avoid destroying the specimen surfaces. The thickness and compositions of their layer were achieved by EDX line-scan analysis on the cross-sections of the specimens in

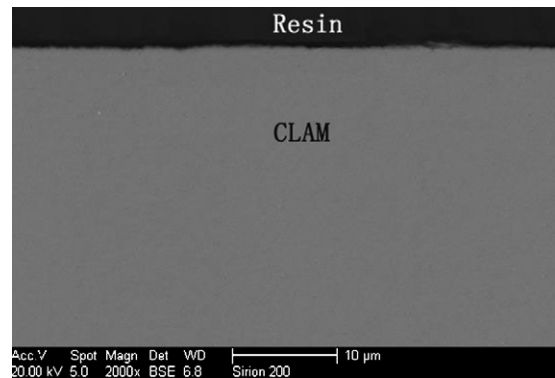


Fig. 2. Cross-section of CLAM specimen after exposure (after cleaned).

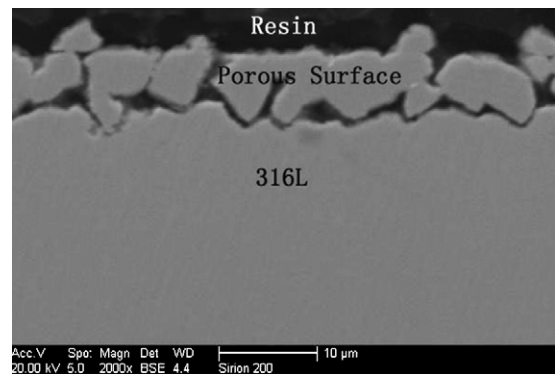


Fig. 3. Cross-section of 316L specimen after exposure (after cleaned).

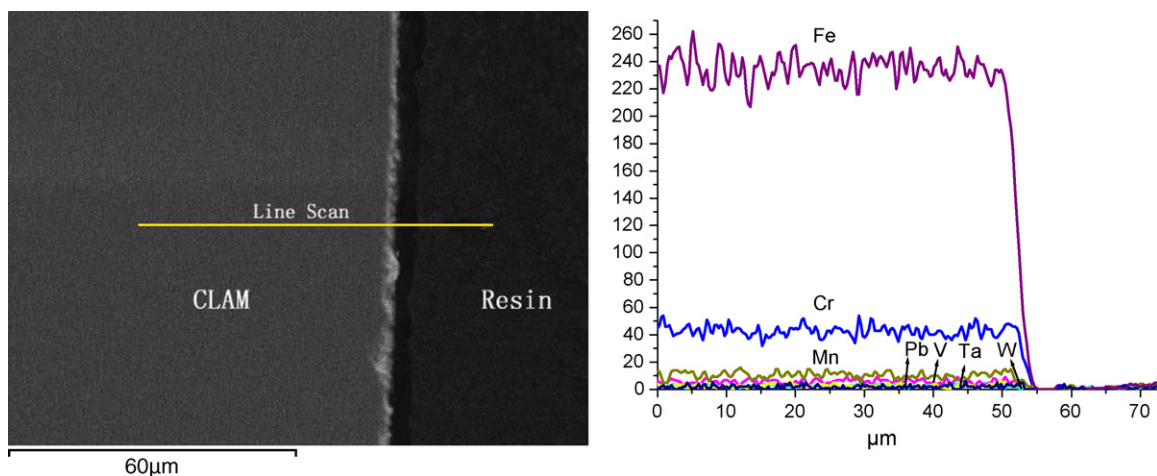


Fig. 4. EDX line scan on cross-section of CLAM specimen after exposure (before cleaned).

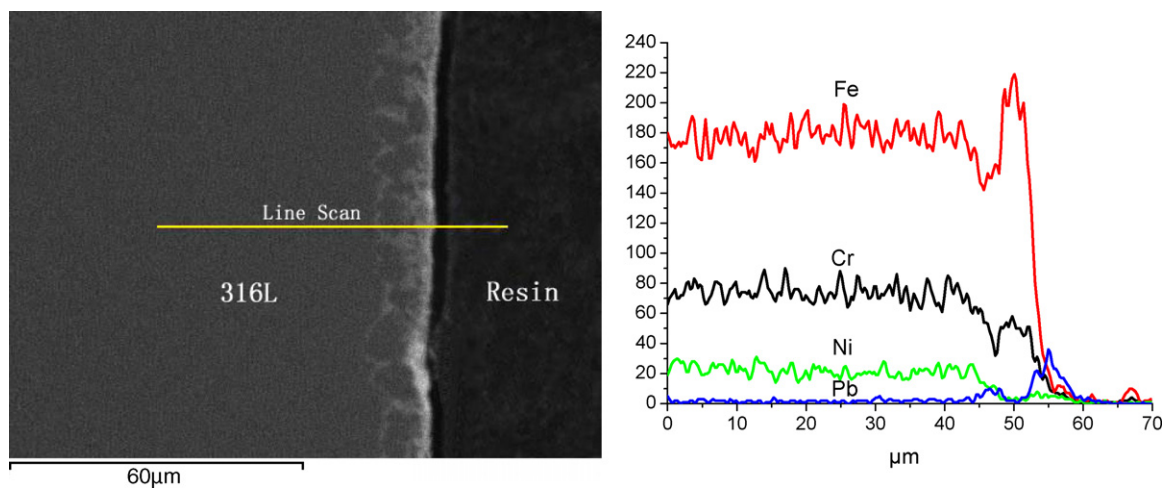


Fig. 5. EDX line scan on cross-section of 316L specimen after exposure (before cleaned).

the range of about 70 μm showed in Figs. 4 and 5, respectively. In Fig. 4, a very thin LiPb layer was covered on the surface of CLAM, the concentration profiles of specimen surface exhibited little changes for its main compositions of Cr and Fe contents after 500 h exposure.

As to the corrosion layer of 316L specimen in Fig. 5, it is clear that LiPb had penetrated into the matrix from the surface and all the small holes showed in Fig. 3 were filled with LiPb. The concentration of chromium changed from the normal level as the base material to low value, and nickel existed with very low content in

the porous layer, while iron decreased apparently compared with the base material. The thickness of corrosion layers for 316L was about 8 μm by EDX.

4. Discussion

As the conclusion made from the work done on the other RAFMs, such as EUROFER97, MANET I, Optifer IVa and F82H-mod. etc. [5–9], the corrosive attack follows a two-step process: first, the dissolution of the passivated oxides occurs during the so-called

incubation period, the surface layers do not suffer from a direct attack by the LiPb eutectic. After the incubation period and then last for a longer exposure time, these layers disappear gradually, and then followed the dissolution of the steel matrix. The incubation period is not only dependent on the temperature but also on the flow velocity of LiPb [6].

Under our experimental conditions, the less weight loss for CLAM specimens can be explained to a longer incubation time for it; while for 316L specimen, the corrosion attack by the flowing LiPb is obvious and significant. The SEM observation and EDX analysis are in good agreement with those mentioned in Ref. [10]. It can be conclude that the dissolution of high solubility elements Ni and Cr in LiPb from the matrix resulted in a porous corrosion layer. This layer became very weak in the LiPb, and it might fall off from the matrix in the flowing LiPb during longer experimental time.

5. Summary

The specimens of CLAM and 316L were exposed to liquid metal LiPb at 480 °C for more than 500 h in the first LiPb loop DRAGON-I in China. Results showed that the severe and non-uniform attack to the austenitic steel 316L specimen resulted in the formation of extensive porous corrosion layers on the surface. In contrast, from the SEM observation and EDX analysis, there was almost no change in the morphology and composition of the martensitic steel CLAM. However, it is necessary to do longer time corrosion experiment to evaluate the corrosion behavior of the CLAM. Further study will focus on the quantities of metallic element dissolved and transferred by liquid LiPb and on corrosion behavior of CLAM for longer time experiment in liquid LiPb at different temperatures and flow speeds.

Acknowledgements

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