Review on The Compatibility of Fusion Reactor Structural Materials with High-temperature Liquid Metals

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Abstract. This paper aims at the current candidate structure materials for fusion reactors such as RAFM (Reduced Activated Ferritic / Martensitic) steel, SiCf / SiC composites and V alloy, summarizing and analyzing the research progress of their corrosion compatibility in the liquid metal Li and LiPb, which includes static corrosion and dynamic corrosion research such as circuit corrosion and rotary corrosion. The review in this paper hopes to provide a reference for corrosion compatibility for the development of fusion reactor structural materials.

1. Introduction
Nuclear fusion energy is one of the feasible ways to solve the energy and environmental problems in the future. Currently, fusion energy commercialization faces three important problems, plasma steady-state operation, material neutron irradiation and corrosion damage, and tritium self-sustainability. The blanket serves as the core component of the fusion reactor, and its main functions are tritium proliferation, energy proliferation and radiation shielding. It can be seen that the blanket material is the key proliferation material and energy conversion component of the fusion reactor, so the material problem is one of the key problems restricting the development of nuclear fusion. Owning to good thermal conductivity, radiation resistance and flexible extraction, Liquid lithium and its alloys (LiPb, etc.) are regarded as candidate materials for the coolant of the blanket module and tritium proliferations [1-3].

Fusion structural materials currently under extensive research include RAFM steel, SiCf / SiC composites, and V alloys. Compared with other materials, RAFM steels (such as CLAM, EUROFER and F82H) are generally considered to be the first choice of structural materials for future fusion demonstration reactors due to their mature technology and low industrial production costs [4]. Because of its good compatibility with Li, V alloy is usually the first choice for Li self-cooling blanket system. SiCf/ SiC composite material has obvious advantages in high temperature resistance and radiation resistance, and it is the main candidate material for advanced blanket design in the future.

The realization of long-term steady-state operation of fusion reactors is an important goal of current scientific research experiments. Therefore, in complex working environments, the compatibility of liquid metals with structural materials is very important, which is directly related to the stability and safety of fusion reactor operation.

2. Research Progress of Liquid Metal Corrosion
Current candidates for fusion structure materials include RAFM steel, SiCf / SiC composites, V alloys, etc. They have their own advantages and disadvantages in terms of liquid metal compatibility, operating temperature, radiation resistance, etc.
2.1. Research on Static Corrosion of Liquid Metals

The main liquid metal blankets currently designed internationally are shown in the table 1. Li or Li alloys are generally used as coolants and tritium proliferations.

| Blanket(Reactor) Name | Country | Coolant |
|-----------------------|---------|---------|
| FDS-DWT               | China   | LiPb    |
| SLL                   | China   | LiPb    |
| DLL                   | China   | He/LiPb |
| ARIES-RS              | US      | Li      |
| ARIES-II              | US      | Li      |
| TAURO                 | EU      | LiPb    |
| ARIES-ST              | US      | He/LiPb |
| ARIES-AT              | US      | LiPb    |
| Li/TBM                | Russia  | Li      |

2.1.1. RAFM steel

Li [5] et al conducted a corrosion test of 9Cr-ODS and CLAM (China Low Activation Martensitic) steel in 873K static LiPb for 250 h. Both steels showed weight loss and softening near the surface after exposure. The tensile properties of 9Cr-ODS steel did not change, and the creep properties decreased slightly. In contrast, CLAM steel shows hardening through the increase in tensile strength and creep rupture time, the decrease in minimum creep rate and area. Analysis shows that both steels are subject to uneven corrosion with preferential corrosion at grain and subgrain boundaries. Near the surface, Cr depletion of 9Cr-ODS is more severe than CLAM. The corrosion mechanism is that the substrate loses the protective oxide layer, and then Cr is dissolved in the liquid Pb-Li. The corrosion effect of LiPb on 9Cr-ODS is more obvious than that on CLAM, which may be due to the finer grains and sub-grains of 9Cr-ODS, which enhances the preferential corrosion of LiPb at the boundary, or the lack of Mn in 9Cr-ODS,because Mn can form a protective layer of CLAM.

In response to the corrosion mechanism of the Indian RAFM steel (IN RAFMS) during the short-term exposure (ie, incubation period) with protective oxide layer on the surface, Chakraborty [6] et al. conducted a corrosion experiment with total duration of 1000h in liquid Pb-Li under 773K and static conditions. Studies have shown that the corrosion of RAFM steel by Pb-Li is related to the uneven dissolution of the oxide layer and the infiltration of the grain boundary, which may also cause the carbide of the grain boundary to fall off. In addition, the study found that the dissolution of the oxide layer is the main factor for material mitigation after short-term corrosion. Research by Atchutuni [7] et al. showed that the corrosion rate of static Pb-16Li to IN-RAFM steel at 550°C is about 38μm / year. Particles, nodules and pebble-like structures can be observed in the surface micrographs. However, the tensile strength of the material is not significantly reduced. The Japanese Institute of Nuclear Fusion has studied the corrosion behavior of JLF-1 (Fe–9Cr–2W) steel at 600°C in static N-containing Li (0.5wt% N) for up to 750h[8]. Significant weight loss was shown within hours. Corrosion eroded along the previous austenite grains, forming an embossed surface and a porous and softened Cr-poor ferrite region below the surface. The transformation of martensite to ferrite occurs in this area. In addition, the weight loss of JLF-1 in nitrogen-containing lithium is about 25 times that in pure lithium. At the same time, Xu[9] et al. obtained similar results in the static and dynamic corrosion tests of liquid Li at 500°C for 250h.

According to the above research, under static corrosion conditions, RAFM steel exhibits better corrosion resistance in liquid LiPb compared to ordinary austenitic steel. The corrosion on its surface is generally non-uniform corrosion, so it will appear uneven and the degree of corrosion will increase with the increase of corrosion time. Generally, preferential corrosion occurs easily at the grain boundaries. During this corrosion process, the oxide film with a certain protective effect on the surface of RAFM steel will be first peeled off by corrosion, and then the liquid metal penetrates into the material matrix and further corrosion occurs. In terms of mechanical properties, the tensile properties
of RAFM steel are less affected by LiPb corrosion. In addition, research shows that ODS steel also exhibits certain corrosion resistance in liquid LiPb. The ODS process can significantly improve the mechanical properties of RAFM steel, but a lot of research shows that the type of RAFM steel (Eurofer, CLAM steel, ODS-Eurofer, etc.) has no or little effect on corrosion because they have similar microstructures and composition. However, their corrosion behavior may change under varying test / application conditions (eg. laminar flow, reflow) or varying impurity levels.

2.1.2. SiC and SiC / SiC composite materials
Continuous silicon carbide (SiC) fiber-reinforced SiC-based composites (SiC / SiC) have good prospects in nuclear fusion applications [10,11], and are expected to achieve high operating temperatures up to 1000°C (to achieve high energy conversion efficiency) and low activation of the blanket system. Since SiC materials have a rich performance database[12,13], researchers have evaluated the structural application of SiC / SiC composites in fusion reactors.

Pint [14] et al. conducted a corrosion study on β-SiC in liquid LiPb. After 800°C at 5000h, the content of Si in LiPb solution did not change significantly. The temperature was further increased to 1000°C. After that, the Si content increases significantly, so it is considered that the critical temperature of β-SiC for LiPb corrosion resistance is less than 1100°C. Barbier[15] et al. soaked CerasepN3-1SiC / SiC in static LiPb at 800 °C for 3000h. The experiment proved that no reaction occurred, but there was LiPb flowing into the pores of SiC / SiC, because SiC / SiC has porosity and low density. Holes of SiC / SiC will appear after mechanical processing. Ling [16] et al. conducted an experimental on the compatibility of SiC and SiC / SiC composites with liquid LiPb. It can be seen that CVD-SiC has excellent corrosion resistance in high temperature liquid LiPb. Simultaneous corrosion of SiC fiber and SiC ceramic matrix of RS-SiC / SiC appeared.

Compared with metal-based blanket, SiC / SiC composites have unique advantages, but also face huge challenges, including how to manufacture large and complex shaped components, lacking practicality structural application experience and how to maintain tightness in the working environment. China’s research on SiC / SiC composites started late, and industrial preparation needs to be improved. It is necessary to further explore efficient and mature preparation techniques in order to obtain SiC / SiC composites that have good compatibility with high-temperature LiPb under large-scale preparation conditions, and carry out more corrosion tests under complex conditions.

2.1.3. V alloy
Since the 1980s, vanadium alloys are considered to be an attractive candidate for fusion reactor blanket structural materials due to their good compatibility with liquid lithium, low activity, resistance to neutron radiation, and high temperature strength. At 600°C, their radiation life is still more than 200dpa, and their thermal stress is smaller than ferritic steels, but they have poor solderability, high tritium permeability, and poor compatibility with helium. The helium gas with 100ppm water is enough to significantly oxidize the vanadium-based alloy above 450°C[17]. The vanadium alloys currently used in fusion blanket structural materials are mainly V- (4-5) Cr- (4-5) Ti series vanadium alloys.

2.2. Research on Dynamic Corrosion of Liquid Metals
In addition to corrosive action with structural materials, flowing liquid metals may also damage materials due to friction. Taking liquid lithium as an example, research shows that when the flow rate of liquid lithium is too large, the shear stress on the surface of the strong liquid will peel off the protective layer on the surface of the solid material, causing abrasive or gas attacks and accelerating corrosion of solid surfaces. Studies have found that [18,19], at 500°C and 600°C, the mass loss of JLF-1 in static liquid lithium changes linearly with time, while the mass loss in flowing liquid lithium is much greater than that in static lithium, and it changes linearly with time as well. Aiming at the dynamic corrosion of liquid metals, varieties of experimental platforms were built to carry out relevant research. At present, there are mainly two types of devices for dynamic corrosion experiments of liquid metals, one is liquid metal circuit corrosion device, and the other is rotary corrosion device.
2.2.1. Circuit corrosion device

The circuit corrosion device uses external driving force to form liquid metal convection in the circuit system and fix the sample in the circuit pipe. Non-isothermal, forced convection and other complex environments can simulate the process of dynamic corrosion of structural materials in the actual cooling pipe by liquid metal, which is closest to the actual operating conditions of the fusion reactor, but also has the following shortcomings: it can not carry out corrosion experiments at different flow rates in a uniform corrosion environment; circuit joints are susceptible to corrosion; migration corrosion and physical phase deposition are prone to occur in the circuit; the device is large and complicated to build.

Atchutuni[20] et al. exposed IN-RAFMS samples to lead-lithium Pb-16Li in the pump drive circuit. The liquid flow rate is 10 cm / s and maintained at (465 ± 30) ° C. The corrosion rate obtained by weightlessness is about 44 μm / year below 2500 h, and decreases to 31 μm / year after 5000 h exposure. After 5000 h, the tensile strength and elongation did not decrease significantly. Chakraborty [21] et al. conducted a corrosion test with a duration of 5000h and a flow rate of 0.6–1.5 m / s under 773K. The results show that the corrosion rate of RAFM steel is 47-50μm / year, and the corrosion rate depends on the local flow rate on the exposed sample. The corrosion attack of liquid Pb-16Li is inherently non-uniform, resulting in the formation of undulations on the exposed RAFMS surface.

Konyš[22] et al. tested EUROFER and CLAM steel of China on KIT's Pb-15.7Li corrosion test circuit PICOLO. Both steels were simultaneously exposed in PICOLO at a flow rate of 0.1 m / s with time up to 12,000 h. Experiments show that both EUROFER and CLAM steels exhibit similar corrosion behavior throughout the test range. The corrosion attack has little dependence on radial and axial positions. The corrosion velocity observed in the experiment is close to 220μm / year, which is very suitable for the prediction of low flow velocity in the turbulent system by MATLIM modeling.

Due to the similar microstructure and composition under the same test conditions (such as impurity levels), the type of FM steel has no or little effect on corrosion.

The FDS team first proposed the concept of a series of liquid LiPb experimental circuit in China [23] and constructed a Chinese liquid LiPb blanket research technology platform, which can comprehensively evaluate candidate structural materials(such as CLAM), SiC / SiC composites and functional materials etc. in liquid LiPb, in order to provide theoretical guidance and experimental basis to optimize the material composition and preparation process, which improves the service performance of materials, promotes the development of related technologies of blanket materials for fusion reactors in China, and promotes their application in fusion reactors.

2.2.2. Rotary corrosion device

This type of device drives the impeller to rotate by a motor, so that the liquid metal rotates in the test container and moves relative to the sample. The sample can be fixed in the container or fixed on the impeller, which can simulate the structure of the actual working environment by creating relative movement between the material and the liquid metal. Compared with the circuit corrosion device, it has the advantages of small volume, good air tightness, and simultaneous corrosion experiments with different flow rates in a uniform environment.

Chakraborty [24] et al. used a rotating disc corrosion test equipment to perform a 3000 h Pb-17Li and IN RAFMS compatibility experiment at 773 K and 360 rpm. The results show that the rate of mass reduction is 1.02 μg / cm² h. Corrosion depends on the dissolution of alloy elements from the sample surface and the penetration of Pb-17Li into the IN RAFMS matrix. As the linear velocity along the radial direction of the IN RAFMS disk increases, the depth of Pb-17Li erosion also increases. Kondo [25] et al. conducted static and dynamic corrosion experiments on RAFM and JLF-1 steels in Li, Pb-17Li at 600°C, and the effect of different experimental parameters (such as flow conditions, exposure time and geometric conditions) on the corrosion behavior was studied. The results show that the fluid promotes the dissolution of metal elements from the steel.

Based on the above dynamic corrosion research, it can be seen that the mechanism of corrosion of structural materials in flowing liquid LiPb is basically the same as that of static corrosion, which is represented by the shedding of surface oxide layer, the penetration of liquid metal, the fluctuation of surface morphology and the change of microstructure. However, the corrosion rate and degree are
directly affected by the flow rate. The faster the liquid flow rate, the greater the corrosion rate, and the flowing liquid metal itself will also cause erosion and wear on the material. In the application of liquid metals in fusion reactors, the choice of flow rate is also critical. The flow rate is too low to achieve mass transfer and cooling effects; the flow rate is too high, which shortens the service life of structural materials. Therefore, the dynamic corrosion research has very profound application value.

3. Summary and Outlook
This paper reviews and analyzes the domestic and foreign research results on the resistance of liquid metal corrosion of fusion reactor structural materials. RAFM steel is currently the preferred candidate structural material for fusion reactors due to its good compatibility with LiPb, high thermal conductivity, and radiation resistance. SiC/SiC composites have the advantages of high strength, low activation, and high temperature resistance, but the compatibility with liquid LiPb at high temperature needs to be further studied and improved. V alloy has good compatibility with Li, low radiation swelling, and high operating temperature (700°C).

For now, the corrosion research carried out at home and abroad includes static and dynamic corrosion research, and the experimental data of simulating actual operation of the fusion reactor needs to be further supplemented and improved. At present, the problems in the research of liquid metal corrosion are as follows:

(1) The actual working environment of structural materials is much more complicated than the experimental conditions, and more experimental factors need to be considered in the future.

(2) In the Tokamak fusion experiment, it is inevitable of impurities entering the liquid metal. It is necessary to consider the influence of impurities on the compatibility of the structural material with liquid metal.

(3) Accurate determination and adjustment of oxygen content in liquid metals and its effect on the corrosion resistance of materials.

(4) Synthesize the advantages of candidate materials and explore new component structure materials to obtain better compatibility with liquid blanket.

4. Acknowledgments
This work is sponsored by the National Key R&D Program of China (2017YFE0300603), the National Natural Science Foundation of China with grant No. 11975022, 51576208.

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