Corrosion compatibility of capillary-porous system solid base with low melting metals applied as plasma facing materials for tokamak

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Abstract. Capillary-porous systems (CPS) with liquid Li, Ga, Sn and Sn-Li alloy is considered as alternative decision under development of plasma facing elements (PFE) for DEMO-type fusion reactor and fusion neutron source. The estimation of considered liquid metals application is carried out on the analysis of their corrosion compatibility with potential base materials of CPS and PFE - W, Nb, Mo, V and stainless steels. The experimental study of corrosion resistance are performed in static isothermal conditions in the temperature range of 400-1400°C. It is shown, that the top temperature limit for operation of PFE based on the CPS with Ga does not exceed 400-500°C. Only the W is compatible with Ga at higher temperature level. The similar situation is detected for structural materials in liquid Sn. Stainless steels are resistant at the temperatures not above 400-500°C and only W and Mo are compatible with Sn at ≥1000°C. In a contrast with Ga and Sn the corrosive activity of Li is low and all considered structural materials are resistant at the temperatures of ≤1000°C. The refractory metals and alloys are resistant to Li at higher temperature level.

1. Introduction

Application of liquid metals in matrix of Capillary-Porous Systems (CPS) is encouraging idea to get over the difficulties generally erasing from the use of solid materials under development of plasma facing elements (PFE) for DEMO-type fusion reactor and fusion neutron source facility [1, 2]. Basic advantages of CPS with liquid metals are high resistance to property degradation, natural capability of their surface to self-renewal and stability under plasma effects during normal discharge, ELMs and disruptions owing to capillary forces. In the last time Li, Ga, Sn and Sn-Li alloy in CPS based PFE are intensively studied [3–6]. The well-grounded selection of liquid metal for tokomak application should follow from the analysis of many aspects of their use: assurance of good wetting of CPS material for self-renewal and surface stability; corrosion compatibility with materials of CPS base and PFE structure; technological features and safety of their use with respect to prospective design of the tokamak PFE; their maximum allowable content in plasma; interaction with hydrogen isotopes and residual gases; availability of extraction technology.

The compatibility of wide range of structural materials (stainless steels, refractory metals, etc.) is well studied in liquid Li [1] but lack of experimental data on corrosive activity of Ga and Sn is occurred. As follows from our experimental results, stainless steels are not compatible at the temperature higher 400°C with Ga and Sn [6]. Only W alloys are compatible with Ga at the temperature higher 500°C. In addition should be noted that for the most of structural materials the corrosive damage in Ga and Sn occurred just after its wetting (wetting angle $<\pi/2$). Nevertheless Sn is considered as one of the candidates for the CPS because it has a lower corrosivity comparing to Ga and a lower saturated vapor pressure comparing to Li. As it shown previously [6, 7], the only such refractory metals as W, Nb, Mo are compatible with Sn at high temperatures.

2. Experimental study of liquid Sn corrosivity

Corrosion of Nb, Mo and W was studied on the samples putted into the capsule made of Nb-2%Mo-0.1%Zr alloy and filled with liquid Sn. Capsules were exposed at 1400°C in vacuum for 1 hour.

No interaction was observed on the macrophotography of the Mo sample after corrosion test in Sn (Fig. 1). Changes in the near-surface layer of Mo sample were detected in more precise investigations (Fig. 2). The study of the elements (Mo, Sn, Nb) distribution in the Mo sample near-surface layer has shown the following (Fig. 3).

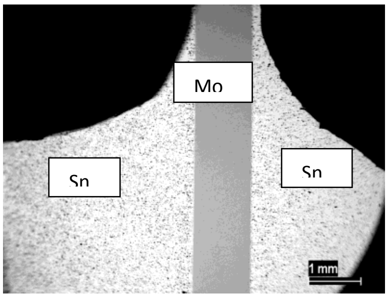


FIG. 1. Macrophotography of the Mo-Sn cross-section after corrosiveness experiments

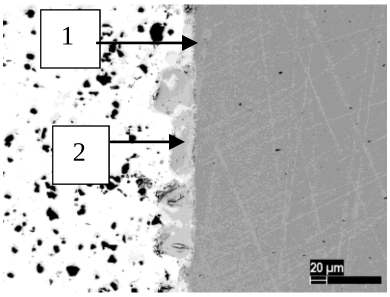


FIG. 2. SEM image of the Mo-Sn interaction zone. 1 – Nb-Sn interaction zone; 2 – Nb crystals

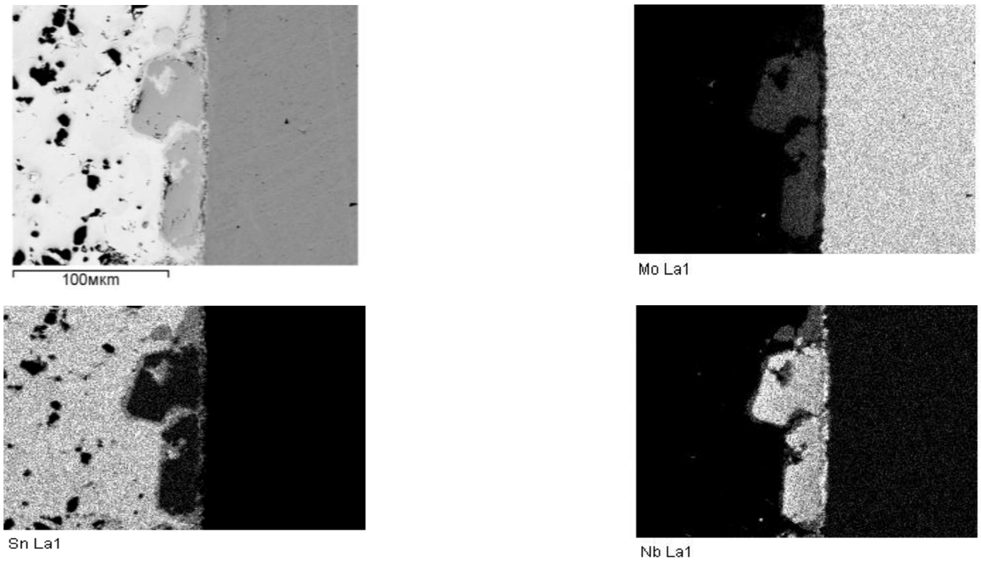


FIG. 3. Microstructure and element distribution maps in the Mo-Sn interaction zone

The enrichment of both Nb and Sn is observed on the Mo in the near surface layer with 2 μm thick. This is a result of the Nb dissolution in Sn and process of isothermal mass transfer from the surface of the Nb capsule to the Mo sample. Niobium crystals are observed on the surface of Mo (Fig. 2) which precipitated from the niobium solution in Sn (saturated concentration of Nb in Sn at 1400°is about 3%) during the cooling after tests. This results are in a good correspondence with Nb-Sn and Mo-Sn phase diagrams [8].

The interaction between the Nb alloy (structural material of capsule) and Sn was also studied to complete the research of the material interactions. The metallographic analysis of the capsule walls clearly shows (Fig. 4, 5) the formation of interaction zone with about 20-30 μm thick.

The study of element (Mo, Sn, Nb) distributions in the interaction zone on the surface of Nb capsule wall has shown the following (Fig. 6).

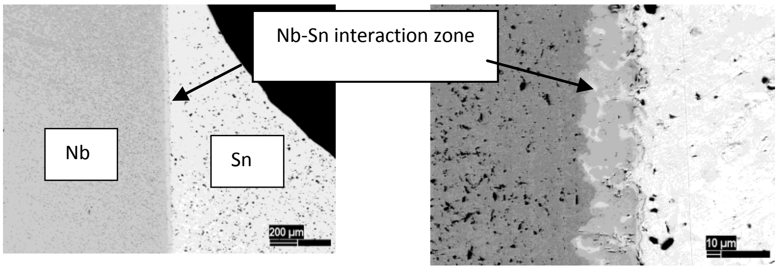


FIG. 4. Macrophotography of the Nb-Sn cross-section after corrosiveness tests

FIG. 5. Nb-Sn SEM image of the Nb-Sn interaction zone

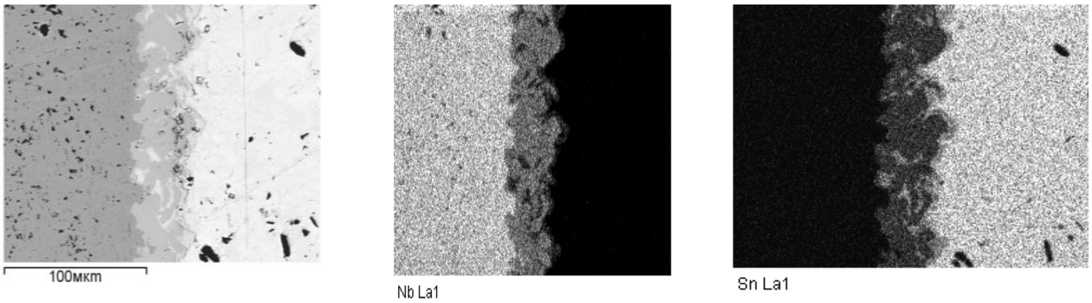


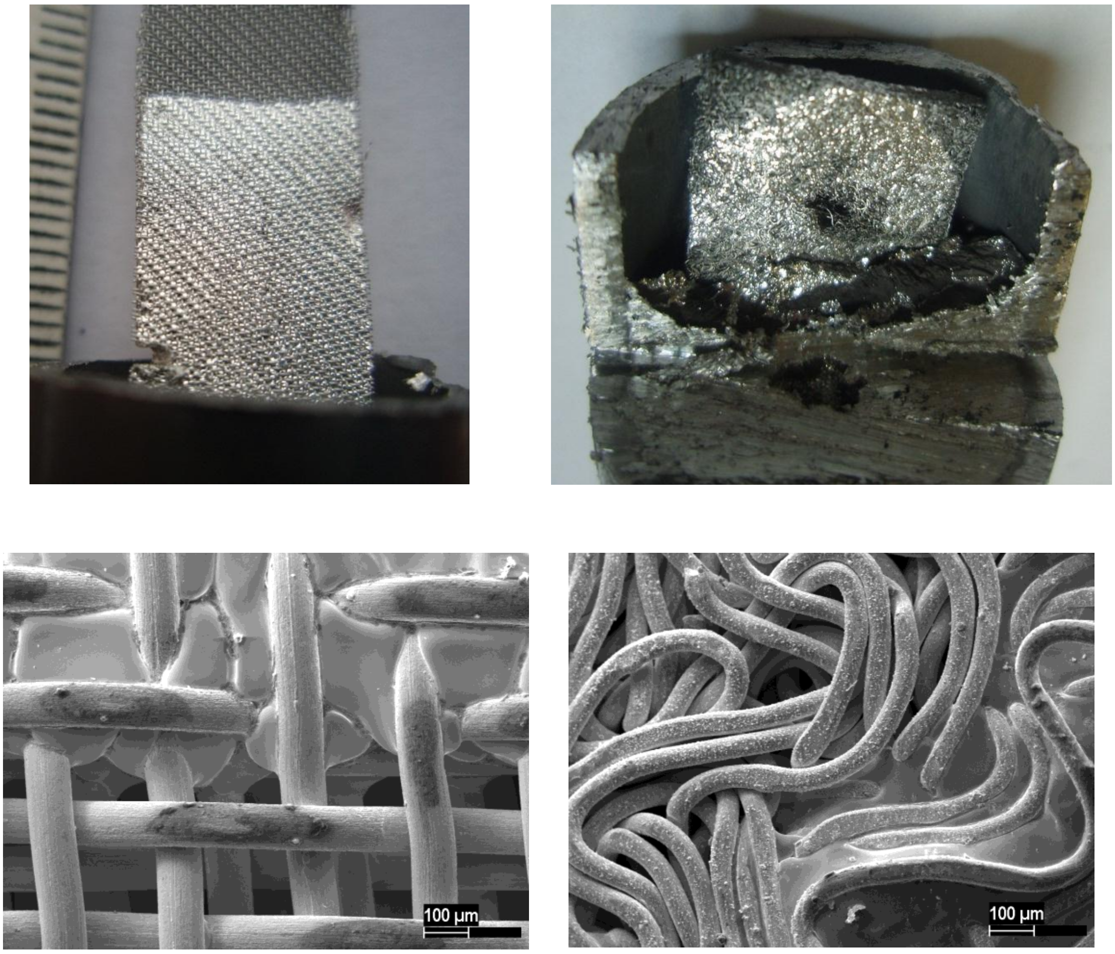
FIG. 6. Microstructure and element distribution maps in the interaction zone

The 20-30 μm thick interaction zone is enriched with both Nb and Sn. No significant amounts of molybdenum were found in that zone. The formation of Nb-Sn intermetallic compounds and very low Mo dissolution in Sn are expected on the base of the Nb-Sn and Mo-Sn phase diagrams consideration [8].

3. Experimental study of wetting in liquid Sn

The experimental study of the wettability process of Nb, Mo and W in Sn is the next important aspect in consideration of Sn application in PFC because it is the principal point in ensuring of capillary affect in CPS and good heat transfer thought PFE structure to cooling system. Series of experiments on wet with Sn for compact and porous (fig. 7) samples of Mo and W have been performed. It has been shown that a good developed wetting process should provide the polluted film removal from material surface (by chemical etching) and prevention of it formation during the process. Preliminary cleaned surface of W and Mo exposed in Sn pool at temperatures of 950-1050^{o}C during 1 hour demonstrates (fig.1, 4) a high scale of wetting (wetting angle less than 30^o and full filling of CPS structure). It has been shown that wetting temperature for Mo is ~100^{o}C lower then for W.

In addition the high corrosion resistance of W in molten Sn has been confirmed in the experiments on wetting of W based CPS. No interaction of W wire with Sn has detected at the temperatures up to 1050^{o}C.



a b

FIG. 7. The wettability of metals by liquid tin in vacuum
a – Mo mesh, 950°C, 1 hour; b – W felt, 1050°C, 0.6 hours

Conclusion

As a result of the corrosion study it was found that Mo and W do not corrode in liquid Sn, in a contrast with Nb, and are compatible with liquid Sn at temperatures of up to 1000°C. This allows consider Mo and W for an alloy base material of the PFE of tokamak based on liquid Sn capillary pore systems.

Good developed wetting process for W and Mo ensure capillary effect for surface self-renewal of PFE and liquid metal surface stability under tokamak conditions. The wetting of clean surface of Mo and W is achieved at the temperatures of 950 and 1050°C respectively.

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