ENHANCED CORROSION PERFORMANCE OF T91 AND 316L STEELS WITH COATINGS IN LIQUID LEAD UNDER CONTROLLED OXYGEN CONDITIONS

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Abstract

Small Modular Reactors (SMRs) based on Lead-cooled Fast Reactor (LFR) technology represent a promising option for future nuclear energy systems due to their enhanced safety features and efficient fuel utilization. A critical challenge for SMR-LFR deployment is the long-term compatibility of structural materials and key reactor components, such as primary circulation pumps, which are in direct contact with liquid lead coolant under high-temperature conditions and varying oxygen concentrations. Such a component exposure to demanding operating environments, lead to severe material degradation that can directly affect operational reliability and safety of the system.

This work presents a comparative investigation of the corrosion behaviour of two candidate structural materials, ferritic–martensitic steel T91 and austenitic stainless steel 316L. Both materials were studied in the as-received state to assess the corrosion performance of the reference materials. To enhance corrosion resistance, samples coated with a protective AlTi-based layer alloyed with tungsten were also examined. To simulate relevant operating regimes of SMR-LFR systems, exposure experiments were conducted in liquid lead at a temperature of 520 °C under controlled low-oxygen and high-oxygen concentrations in the melt.

Material degradation was evaluated in relation to corrosion mechanisms, formation and stability of protective oxide layers, dissolution phenomena, and coating integrity as a function of oxygen concentration in liquid lead. The results provide deeper insight into the performance of T91 and 316L steels, as well as the effectiveness of AlTi-W coatings under different oxygen conditions at elevated temperature. The presented findings support the optimization of material selection and surface protection strategies for structural components and pump systems operating in liquid lead-cooled SMRs.

Keywords: Small Modular Reactors, ferritic–martensitic steel T91, austenitic steel 316L, liquid lead, corrosion, coating

1. INTRODUCTION

Small modular reactors (SMRs) represent a promising advancement in nuclear energy systems due to their enhanced safety features, modular construction, and potential for cost-effective deployment [1,2]. Among the various SMR concepts, the lead-cooled fast reactor (LFR) has gained significant attention owing to its favourable neutronic properties, high boiling point of liquid lead, and inherent safety characteristics such as low operating pressure and chemical inertness with air and water [3,4]. These features make LFR-based SMRs an attractive option for future sustainable and flexible nuclear energy production.

A key challenge associated with the LFR concept is the long-term compatibility of structural materials with liquid lead, particularly under elevated temperatures relevant to reactor operation [5,6]. Ferritic–martensitic steel T91 and austenitic stainless steel 316L are among the candidate materials extensively considered for core and primary circuit components [7,8]. T91 is characterized by a good resistance to swelling and favourable mechanical properties at high temperatures, while 316L exhibits excellent fabricability and corrosion resistance in conventional reactor environments [9]. However, main drawback for both materials is their susceptibility to

degradation mechanisms such as dissolution corrosion, selective leaching of alloying elements, and oxidation when exposed to liquid lead or lead–bismuth eutectic [6,10].

To mitigate these corrosion-related issues, the application of protective surface coatings has emerged as a promising strategy [11,12]. Effective coatings can act as diffusion barriers leading to reduction of the interaction between the material and liquid lead and promote the formation of stable protective oxide layers [13]. The corrosion resistance of both bare and coated materials is strongly influenced by the concentration of dissolved oxygen in the liquid lead [6]. Controlled optimal oxygen levels are essential to enable the formation and maintenance of protective oxide scales, while deviations from the optimal oxygen window may lead to either excessive oxidation or accelerated dissolution of alloying elements [5,6]. Therefore, a comprehensive investigation of corrosion behaviour, considering both uncoated and coated T91 and 316L steels under well-controlled oxygen conditions, is crucial for assessing material corrosion performance and reliability in LFR-based SMR environments [6,11]. Such studies provide essential insights for material selection, surface modification strategies, and the overall feasibility of this advanced reactor concept.

2. EXPERIMENTAL

2.1 Materials, coating and specimens

The corrosion performance was investigated for two types of materials: ferritic – martensitic steel T91 and austenitic stainless steel 316L. Chemical composition of the reference materials is described in detail in [8,11]. Corrosion coupons with dimensions of 20 × 5 × 1.5 mm were prepared. Prior to exposure, all specimens were ultrasonically cleaned in acetone and subsequently dried.

The subject of the study were two types of specimens; uncoated specimens were studied to obtain the information about reference material corrosion behaviour and Al-based coated specimen (both T91 and 316L) were evaluated to assess the increase in corrosion resistance in an environment with a high lead content in the liquid.].

The Physical Vapour Deposition (PVD) method was used to apply Al-based coating. The coating was applied in a three-layer arrangement. The first, very thin layer deposited on the as-received material, was made of W. The second layer was an AlTi layer, and the third layer was made of W. The presented coating arrangement was designed based on experience gained from tests performed on various coatings in HLM environment [11].

Surface relief of the uncoated and coated specimen is documented in **Figure 1**.

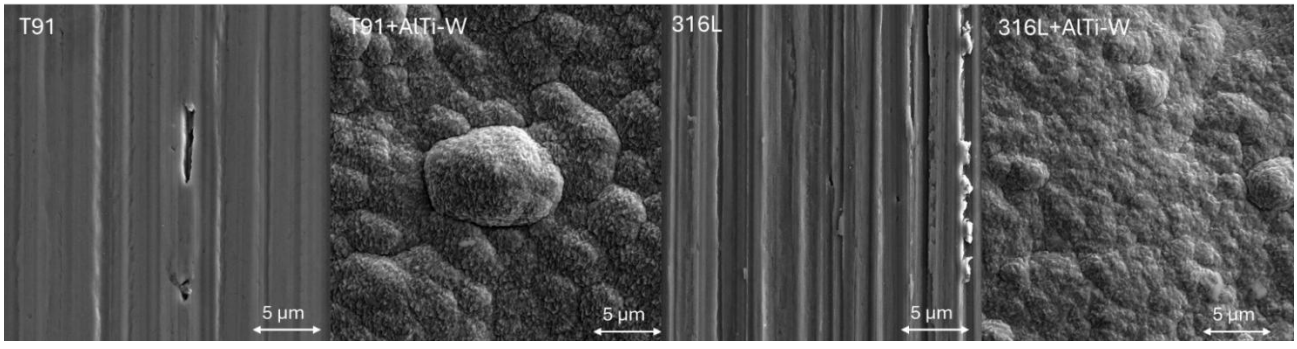

Figure 1 Surface morphology of the as received and coated specimen before exposure

2.2 Experimental procedure

The tests were performed in the static tanks Colonri, described in detail in [8,11].

The prepared specimens were exposed to liquid lead for 3500 hours at low (1×10^{-8} wt.%) and high (1×10^{-6} wt.%) oxygen concentrations at 520 °C.

2.3 Sample characterization

To assess the corrosion performance of the materials, metallographic cross-sections were prepared and analysed with a scanning electron microscope (SEM; LYRA3 and MIRA 3, TESCAN) equipped with Energy Dispersive Spectroscopy detector (EDS; Oxford Instruments X-Max^N 80). Based on the observation, the affected area was identified. The affected area included Pb penetration, inner and outer oxide layer.

3. RESULTS AND DISCUSSION

3.1 Corrosion performance - Low oxygen concentration experiment

Cross-sections of uncoated and coated T91 and 316L steels after 3500 h exposure are shown in **Figure 2 and Figure 3**, respectively. Corrosion characteristics determined from **Figure 2 and Figure 3** are summarized in **Table 1**.

Uncoated T91 showed localized lead penetration and inner oxidation with maximum depths of 6.31 µm affecting 88 % of the surface area (**Figure 2, Table 1**). Uncoated 316L was found to be even more degraded when compared to T91, with the affected surface area being 92 %. Observed Pb penetration, indicating deep grain-boundary-driven degradation, reached a maximum penetration depth of 68.98 µm (**Figure 2, Table 1**).

In contrast, the application of an AlTi–W coating significantly improved corrosion resistance in the case of both specimens. The affected surface area was reduced to 9 % for T91 and 14 % for 316L. Moreover, Pb penetration was completely suppressed, and inner oxidation was significantly reduced (**Figure 3, Table 1**). The coating effectively prevented direct contact between molten lead and the steel substrate material, demonstrating high protective efficiency under low oxygen conditions relevant to lead-cooled fast reactors and SMR applications.

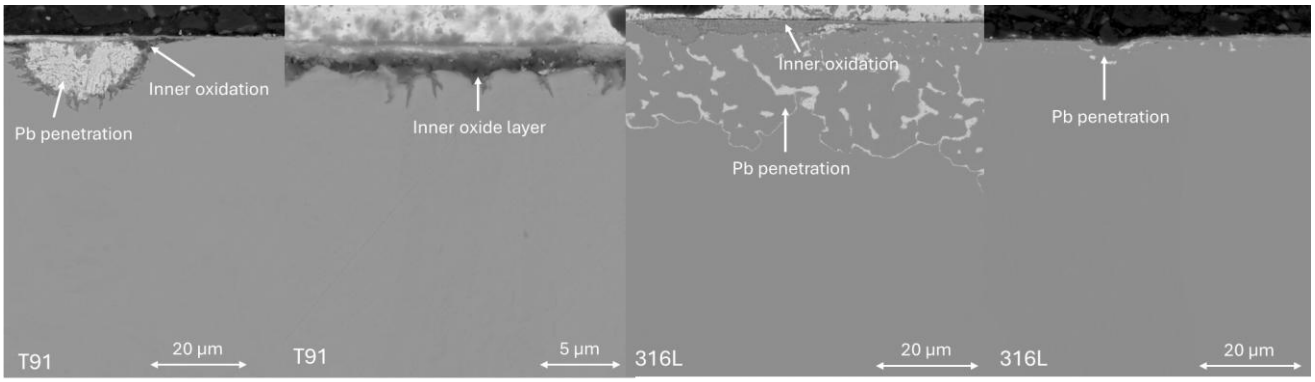

Figure 2 Cross-section of uncoated T91 and 316L specimens after the 3500 h of exposure: Corrosion damage at low oxygen concentration

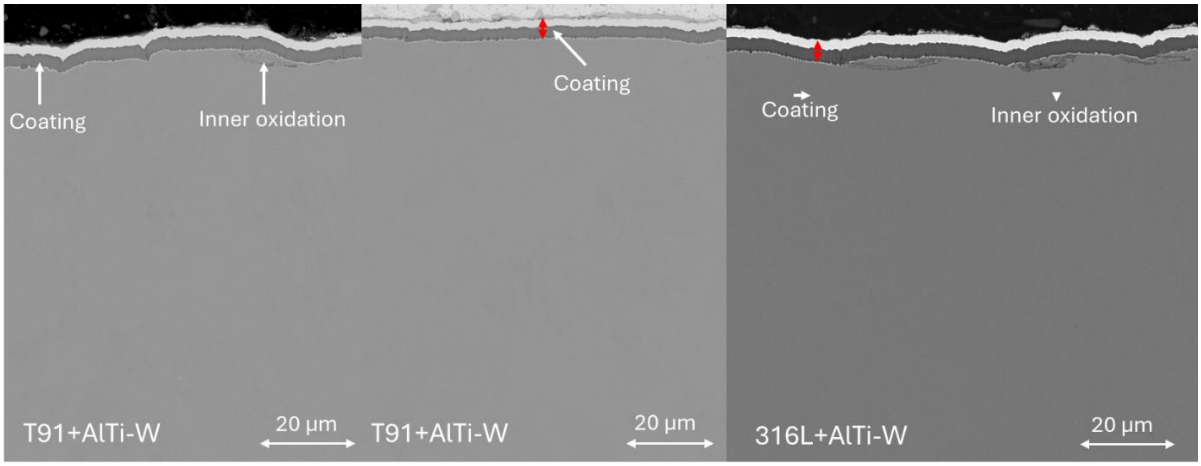

Figure 3 Cross-section of coated T91 and 316L specimens after the 3500 h of exposure: Corrosion damage at low oxygen concentration

Table 1 Corrosion characteristics of coated and uncoated specimen at low oxygen concentration

Specimen	Affected area (%)	Inner oxidation depth avg. / max. (µm)	Pb penetration depth avg. / max. (µm)
T91	88	0.90 / 6.31	0.64 / 6.31
T91+AlTi-W	9	0.16 / 5.28	0.00 / 0.00
316L	92	0.49 / 5.17	8.03 / 68.98
316L+AlTi-W	14	0.29 / 6.19	0.00 / 0.00

3.2 Corrosion performance - High oxygen concentration experiment

SEM image of cross-sections of uncoated and coated T91 and 316L steel after 3500 h exposure are shown in **Figure 4 and Figure 5**, respectively. Corrosion characteristics determined from **Figure 4 and Figure 5** are summarized in **Table 2**.

Evaluation of uncoated T91 revealed that the surface area was fully affected by liquid lead, where 100 % of the surface area was found to be degraded. Typically, extensive inner oxidation with an average depth of 15.55 µm and a maximum depth of 21.91 µm was identified (**Figure 4, Table 2**). Localized lead penetration was also observed, with maximum depth reaching up to 19.31 µm. Uncoated 316L exhibited a much lower affected surface area (48 %) compared to uncoated T91. In this case, it was found that pitting corrosion damage was prevalent, see Figure 4. Inner oxidation reached a maximum depth of 45.80 µm. Statistical evaluation revealed that Pb penetrated up to a depth of 47.10 µm (**Figure 4, Table 2**).

For coated T91 and 316L, the affected surface area was reduced to 12 % and 21 %, respectively. SEM observation revealed that protecting of the steel surface by the coating resulted in complete suppression of Pb penetration. (**Figures 5, Table 2**). Moreover, inner oxidation was limited to a shallow depth, not exceeding 2.93 µm in T91 and 5.75 µm in 316L, confirming the effective barrier function of the coating against both oxygen-induced oxidation and lead penetration.

Overall, these results showed that high oxygen concentration promoted extensive outer oxide growth and inner oxidation in uncoated steels, leading to severe local degradation. The AlTi–W coating effectively stabilized the corrosion resistance, significantly reduced the affected surface area and suppressed both solution-based attack and inner oxidation, thus providing robust protection under conditions relevant to lead-cooled fast reactors and SMR systems.

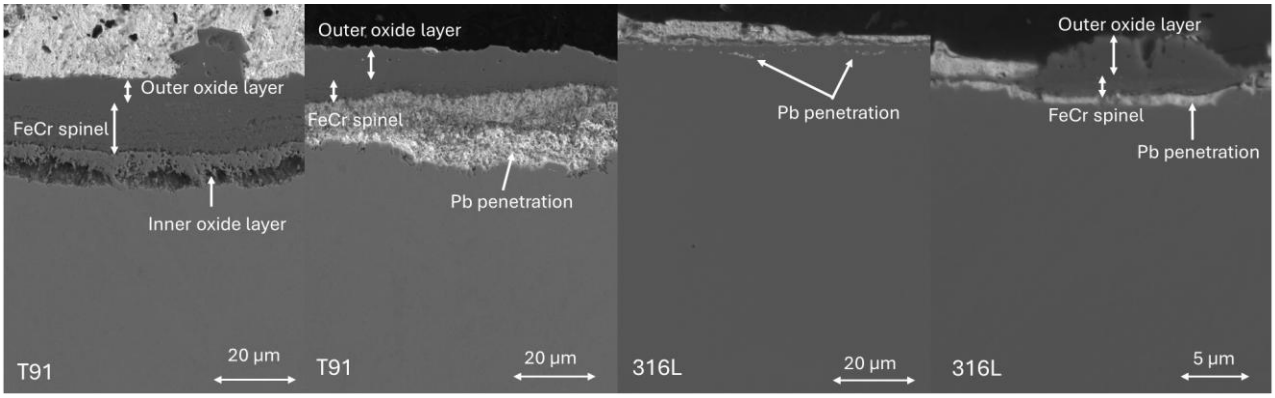

Figure 4 Cross-section of uncoated T91 and 316L specimen after the 3500 h of exposure: Corrosion damage at high oxygen concentration

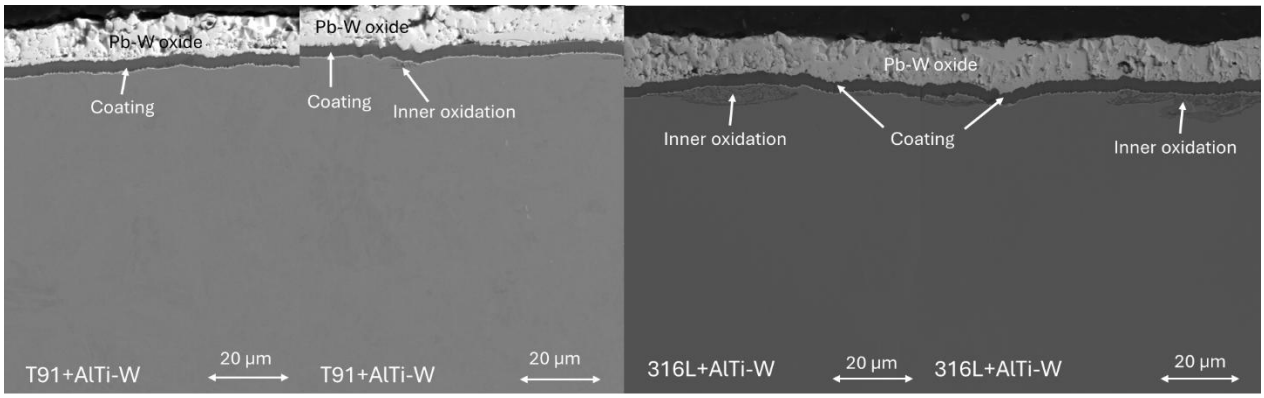

Figure 5 Cross-section of coated T91 and 316L specimen after the 3500 h of exposure: Corrosion damage at high oxygen concentration

Table 2 Corrosion characteristics of coated and uncoated specimen at high oxygen concentration

Specimen	Affected area (%)	Inner oxidation depth avg. / max. (µm)	Pb penetration depth avg. / max. (µm)
T91	100	15.55 / 21.91	1.48 / 19.31
T91+AlTi-W	12	0.13 / 2.93	0.00 / 0.00
316L	48	2.50 / 45.80	4.90 / 47.10
316L+AlTi-W	21	0.44 / 5.75	0.00 / 0.00

4. CONCLUSION

Corrosion experiments performed in molten lead for 3500 h under both low and high oxygen concentration conditions demonstrated that the oxygen has a huge impact on the degradation mechanisms of structural steels T91 and 316L.

Under low oxygen conditions, uncoated T91 suffered from localized lead penetration accompanied by internal oxidation, whereas uncoated 316L was primarily degraded by severe solution-based attack, leading to deep grain-boundary penetration of molten lead. In contrast, the high oxygen concentration promoted extensive outer oxide growth and inner oxidation in both uncoated specimens, resulting in pronounced local degradation despite partial surface coverage by oxide layers.

In both oxygen concentrations, the application of the AlTi–W coating led to a substantial improvement in corrosion resistance. The coating significantly reduced the affected surface area, completely suppressed solution-based attack, and significantly limited inner oxidation depths in both T91 and 316L. These results confirmed that the AlTi–W coating effectively acts as a diffusion barrier against both lead penetration and oxygen transport.

Overall, the study highlights that uncoated structural steels are highly susceptible to molten lead corrosion under both low and high oxygen concentration, though governed by different dominant mechanism. The AlTi–W coating provides significant protection across a wide oxygen concentration range, demonstrating high potential for application in lead-cooled fast reactors and advanced SMR systems.

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