

Materials Corrosion in Fast Reactor Environment

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Abstract. This paper gives an overview of materials corrosion in fast reactor environments. The focus is on fast reactors using liquid metals as heat removal fluids, in particular liquid sodium and lead / lead-bismuth. This overview recalls parameters affecting materials corrosion and highlights materials corrosion mechanism and corrosion rate. Moreover, the impact of the liquid metal on the mechanical properties of materials will be also summarized. Finally, corrosion mitigation options will be briefly discussed.

Key Words: liquid metal, corrosion, mechanical properties degradation, oxidation.

1. Introduction

An overview of liquid metal corrosion of reference structural materials in relevant Fast Reactor (FR) environments is herein reported. Within the Generation IV initiatives two classes of liquid metal fast reactors are under consideration, i.e. the Sodium cooled Fast Reactors (SFR) and the Lead cooled Fast Reactors (LFR) [1]. Moreover, outside the Generation IV initiative Lead-Bismuth cooled systems as the subcritical accelerator driven systems (ADS) [2] and the Russian Fast Reactor SVBR are also considered [3].

The design objectives of the Generation IV FRs are related to sustainability and economics while keeping high safety standards. To reach these objectives numerous design options are under development [1]. However, for all options an important aspect is the selection and characterisation of the structural and fuel clad materials. Current development and assessment of structural materials for Generation IV reactors are given in a recently published monograph [4].

Phenomena that degrade the structural materials in the liquid metal FR environment are related to irradiation damages, mechanical stresses, thermal aging and corrosion. In the present work the focus is on liquid metal corrosion and irradiation as well as mechanical stresses combined effects. The understanding of corrosion phenomena and of the combined effects is relevant at the design phase of the reactor components as well as for their performance assessments. In the following paragraphs the corrosion of the reference materials (austenitic and ferritic/martensitic steels and their Oxide Dispersion Strengthened (ODS) variants) as well as corrosion mitigation means under investigation are presented.

2. Corrosion in liquid metals

The parameters affecting the corrosion of steels in the liquid metals are mainly the temperature, the temperature differences in non-isothermal systems (as reactor systems are), the flow velocity of the liquid metal and the impurities dissolved into the liquid metal.

In particular, for what concerns the impurities dissolved in the liquid metals a key role in determining the corrosion mechanism is given by the dissolved oxygen. Indeed, depending on the oxidizing potential of the liquid metal oxidation or dissolution of the steel elements might occur. In case of onset of dissolution processes, the amplitude of the corrosion process is

dependent from the solubility of the steel elements in the liquid metal. The higher the solubility is the more severe the corrosive attack can be. A detailed description of the impact of solubility of metallic and non-metallic elements in the liquid metal is given in [5].

2.1. Corrosion in liquid Sodium

The corrosion of Fe-9Cr in liquid sodium with low oxygen concentration corresponds to homogeneous dissolution of the steel elements. The corrosion rate (V_{cor}) of steels specified for the prototype fast reactor Monju, [6] in the temperature (T) range of 400-650 °C, and a Na flow velocity of 2-4 m/s, and an oxygen concentration (C_{O}) of 5-25 ppm is given by the correlation: $\log V_{\text{cor}} = 0.85 + 1.5 \log C_{\text{O}} - (3.9 \cdot 10^{-3}/(T+273))$.

As shown by this correlation, the corrosion rate of ferritic-martensitic steels in sodium increases with temperature and dissolved oxygen concentration. Experimental corrosion rates measured on Fe-9Cr steels in static sodium containing 10 wppm dissolved oxygen at 500 °C, are around a few microns per year [7]. With the expression above, the calculated corrosion rate is 2 $\mu\text{m}/\text{year}$, which is in the same order of magnitude.

The corrosion of austenitic steel in liquid sodium and low oxygen potential, corresponds to an heterogeneous dissolution. Indeed, selective dissolution of chromium, nickel, and manganese occurs and a ferritic layer develops on the steel surface (see Fig. 1). The thickness of the corrosion layer remains more or less constant, since dissolution at the surface removes the ferrite, while at the interface with the austenitic matrix, diffusion removes nickel, chromium, and manganese so that ferrite becomes stable [8].

The dissolution kinetics of austenitic steels in sodium is linear. As for ferritic-martensitic steels, dissolution rates increase with temperature but also with the dissolved oxygen concentration. The specific influence of the dissolved oxygen concentration on the corrosion rate of iron base alloys in liquid sodium has to be noted. Indeed, in liquid sodium, when the oxygen concentration increases, an increase in the dissolution rate is also observed [9]. It is assumed that the formation of compounds between the dissolved metal species and Na_2O leads to an increase in the corrosion rate. The precise mechanism is still not clearly understood, however the influence of double oxides like $\text{Na}_2\text{O} \cdot \text{FeO}$ is mentioned but the dissolution of chromium seems to be more influenced by the formation of the ternary oxide NaCrO_2 , which is experimentally observed [6, 8, 10-13]. This oxide is lifted away by the flowing sodium. The stability of the sodium chromite in contact with liquid sodium depends on temperature and on the oxygen concentration in the liquid metal. The empirical correlation for the corrosion rate of austenitic steels is:

$\log V_{\text{cor}} = 2.44 + 1.5 \cdot \log C_{\text{O}} - (18000/2.3RT)$, with V_{cor} , corrosion rate (mil/year)¹; C_{O} , concentration of dissolved oxygen in sodium (wppm); R, perfect gas constant ($\text{J}/\text{mol}/\text{K}$); T, temperature (K).

The corrosion rate of austenitic steels immersed in liquid sodium at low oxygen concentration (10 wppm) at 500 °C is around 1 $\mu\text{m}/\text{year}$. This low corrosion rate has been also testified through post-operational experiences collected on components of earlier fast reactors [47, 48]

Finally, if the dissolved oxygen concentration in liquid sodium is maintained to a level as low as possible, ferritic-martensitic steels as well as austenitic steels can be used in the usual temperature range of a sodium-cooled fast reactor.

¹ (1 mil = 25 μm)

In addition to the impact of dissolved Oxygen in liquid Sodium on the corrosion of steels, dissolved Carbon also shows some effects [8, 10]. Since the solubility of carbon in sodium is lower than that of most metals, sources for dissolved carbon are carbon-containing compounds or alloys in contact with sodium in which the chemical activity of carbon is relatively high. Generally, carbon activity in a 2.25Cr-1Mo ferritic steels is higher than that of austenitic 18Cr-8Ni steels [14]. Therefore, in a sodium system containing both austenitic and ferritic steels, carbon would transfer from the ferritic steel to the austenitic steel leading to carburization of the austenitic steel. If the dissolved carbon concentration in sodium is higher than its activity in austenitic and ferritic steels, general carburization of the system is expected. On the other hand, in sodium with very low carbon concentrations in which the chemical activity of carbon is lower than in the steels, decarburization of the steels can occur. This process may even decompose chromium carbides and thus enhance the dissolution of chromium out of the surface layers.

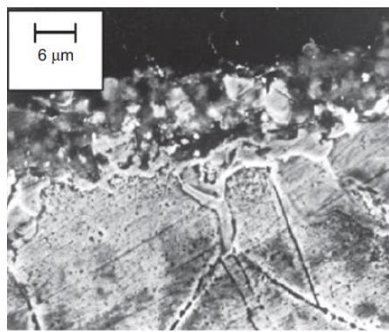


FIG. 1: Microscopic observation of a cross-section of 304 austenitic stainless steel after 60,000 h at 550 °C and 20,000 h at 600 °C in sodium (CREVONA loop of FZK) [15].

As reported in Fig. 2, specific studies on the impact of flow velocity with low oxygen Sodium have been performed and have shown that:

- at low velocity the diffusion of dissolved elements in the liquid metal boundary layer controls the corrosion rate and increases with increasing velocity
- at intermediated velocity the rate controlling step is the reaction at the interface between the liquid metal and the steel and the corrosion does not depend from the flow velocity
- at high velocity erosion corrosion occurs and the corrosion rate increases considerably (not observed for liquid Na up to 8 – 10 m/s).

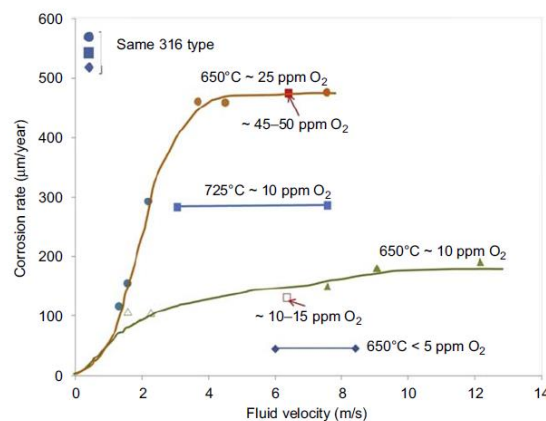


FIG. 2: Influence of the sodium velocity and of the oxygen concentration on the corrosion rate of various austenitic steels in liquid sodium at 650 °C and 725 °C [9].

2.2. Corrosion in liquid Lead and Lead-Bismuth Eutectic

In the case of lead alloys, for oxygen potential lower than a potential close to the magnetite formation (Fe_3O_4), corrosion of steels (Fe-Cr or Fe-Cr-Ni steels) proceeds by dissolution [16]. Dissolution of ferritic-martensitic steels such as Fe-9Cr in lead alloys is homogeneous, as shown in Fig. 3 and the dissolution kinetics is linear. However, no empirical correlation is available due to a large scatter of experimental results, making it difficult to develop a global empirical correlation. In spite of these uncertainties, an average corrosion rate of $\sim 100 \mu\text{m}/\text{year}$ can be estimated for Fe-9Cr steels in lead alloys for temperatures up to 400-450 °C and a moderate hydrodynamic regimen (fluid velocities lower than 2-3 m/s). For temperatures around 550 °C, the dissolution rate varies from a few hundred $\mu\text{m}/\text{year}$ up to a few mm/year, which is extremely high and forbids the use of such materials at these temperatures and with low oxygen potential in the liquid metal [17].

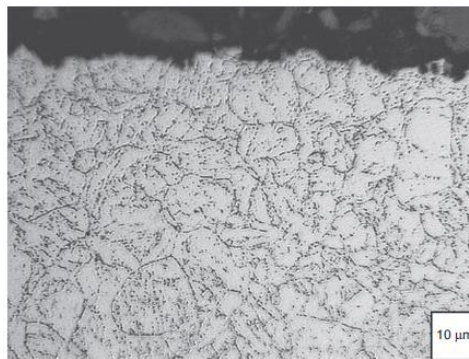


FIG 3: Microscopic observation of a cross-section of T91 immersed 1200 h in liquid Pb-Bi at 470 °C for $[O] = 10^{-11} - 10^{-12}$ wt % and $V_{\text{Pb-Bi}} = 0.075$ m/s. [17]

Fe-Cr-Ni steels show heterogeneous dissolution processes in lead alloys. A preferential dissolution of chromium and nickel is observed, where the preferential dissolution of nickel is explained by its very high solubility limit [5]. The corrosion layer is completely depleted in nickel and strongly depleted in chromium. In lead alloys, the corrosion kinetics of austenitic steels is linear and the dissolution rate increases with temperature and seems independent of the dissolved oxygen concentration and the liquid metal or alloy velocity in a low fluid velocity range. Empirical correlations have been established to express the corrosion rate [18]:

For a liquid metal velocity between 0 and 1.3 m/s, the corrosion rate can be estimated according to: $\log V_{\text{cor}}(\mu\text{m}/\text{year}) = 5.3 - 2447/T$ (K)

For a liquid metal velocity higher than 2 m/s, the corrosion rate can be estimated according to: $\log V_{\text{cor}}(\mu\text{m}/\text{year}) = 3.8 - 852/T$ (K)

Therefore, using these correlations, for low fluid velocities, the corrosion rate at 500 °C is $\sim 140 \mu\text{m}/\text{year}$, and for high fluid velocities, it is $\sim 500 \mu\text{m}/\text{year}$. Therefore, Austenitic steels should not be used in lead alloys having a low oxidizing potential and for temperatures above 350-400 °C [17].

In the case of pure lead or Pb-Bi eutectic alloy, for oxygen concentrations higher than the one necessary for the magnetite formation, an oxide layer can form at the surface of both ferritic martensitic steels with a chromium concentration below or equal to 12 wt% and for austenitic steels (304, 316SS). This oxide scale is duplex and is constituted of a Fe-Cr spinel oxide layer in the case of Fe-Cr steels and a Fe-Cr-Ni spinel oxide layer in the case of Fe-Cr-Ni steels

which is in contact with the steel [19-28]. Above this layer, a porous magnetite layer is observed which is in contact with the liquid alloy. For Fe-9Cr steel, the nature of these layers remains identical regardless of the test temperatures between 470 °C up to 8000 h and 600 °C for durations shorter than 1000 h. However for T91 and 316 type steels, after 2800 h in oxygen-saturated Pb-Bi at 560 °C, Pb diffuses in the external magnetite layer to form plumboferrite, which is a mixed oxide containing Pb-O-Fe [28]. For T91, when the temperature is above 550 °C, internal oxidation occurs with chromium-rich oxide precipitates localized along the grain boundaries. For austenitic steels, a pronounced intergranular oxidation is observed.

Similar oxidation kinetics are observed for lead and lead-bismuth eutectic for the same dissolved oxygen concentrations. Moreover, at 500 °C and up to 10,000 h the thicknesses of the oxide layers grow according to a parabolic law. It has been also observed that the oxidation rates are higher for ferritic-martensitic steels than for austenitic steels [19]. However, for aluminized 316L and for ferritic-martensitic steels, with silicon (e.g., the Russian steel named EP823 which contains 1.3% Si) very low oxidation kinetics have been experimentally measured.

In this oxidation mode, austenitic steels can be used as structural material up to temperatures around 400-450 °C and martensitic steels up to 450-500 °C.

Finally, tests performed with PM2000 ODS steel (containing 5.5 wt% Al) showed excellent corrosion resistance results after immersion for 600 h in flowing liquid lead-bismuth at 535 °C with an oxygen concentration of 10^{-6} wt% [29].

3. Impact of liquid metals on mechanical properties

Liquid metal fast reactors normally operate at temperatures higher than light water reactors and at much lower pressures (except for the steam generator); moreover due to the excellent heat transfer properties of the liquid metals, fast temperature changes are produced in the metal structures when the reactor system is subject to transients. As consequences on most reactor components, the primary stresses are lower with respect to the secondary stresses and proper materials with high-temperature strength (creep) and structural stability are required.

The effect that liquid metals can have on the mechanical properties of the reference steels needs to be carefully evaluated since this can have an impact on the assessment of the specific component.

3.1 Mechanical properties of materials in liquid Sodium

Liquid Na itself does not impact the mechanical properties of both austenitic and ferritic/martensitic steels [30-32]. However, in presence of carbon or oxygen dissolved in liquid Na the mechanical properties of the steels can be deteriorated.

As discussed previously carburization/decarburization processes can occur depending from the carbon activity in the reference material and in the liquid metal at the given temperature.

Carburization of austenitic steels exposed to liquid sodium can be summarized as follows: it causes an increase of yield strength and a decrease of ductility as well as an increase of stress-to-rupture and a decrease of elongation-to-rupture. In a pure creep regimen, a reduction of ductility has been observed, as well as a shortening of the tertiary creep regimen and the occurrence of fine cracking. Liquid sodium carburization affects fatigue lifetime, which is higher than in air, showing a beneficial effect of Na. However, the fatigue lifetime is reduced when holding time is superimposed; this has been attributed to creep-damage.

Even if liquid sodium carburization impacts the mechanical properties, the observed effects are in general negligible on the austenitic steel AISI 316 L up to a temperature of 650 °C [6, 30-36].

For what concerns the decarburization of austenitic steels in liquid Na, this might induce the formation of delta phases (Fe-Cr intermetallics with 45% Cr) which could induce embrittlement effects and a reduction of the creep-rupture strength [32]. However, decarburization of AISI 316L steel is less likely, most probably due to the formation of fine Mo carbides, thus reducing the carbon activity in the steel.

The impact of decarburization of ferritic (mainly on 2.25Cr-1Mo type) and ferritic/martensitic steels (mainly on 9Cr-1Mo type) exposed to liquid sodium can be summarized as follows [6, 30-31, 33]:

- Tensile and yield strength of ferritic steels are reduced while the tensile properties of ferritic/martensitic steel seem to be not affected.
- The creep-rupture strength of ferritic steels is reduced. However, 9Cr ferritic/martensitic steels did not show the same effect.
- Similarly to the austenitic steels, the fatigue lifetime of both ferritic and ferritic/martensitic steels, is higher than in air, showing a beneficial effect of Na and the fatigue lifetime is reduced when holding times are superimposed, due most probably to creep-damage.

Prevention and mitigation of the mechanical degradation process involving carbon can be done keeping the carbon activity in liquid sodium low (below ~ 20 wppm) and selecting reference materials with low carbon activity with respect to liquid Na such as to prevent material decarburization.

The effect of oxygen dissolved in liquid sodium on the mechanical properties of austenitic and ferritic/martensitic steels has been thoroughly investigated and recently summarized in Ref. [37]. It has been shown that negligible degradation of the mechanical properties of steels occurs when the amount of oxygen dissolved in liquid sodium is maintained at very low level. While in oxygen polluted sodium (higher than 100 wppm) degradation of mechanical properties may occur. This finding is valid for both austenitic and ferritic/ martensitic steels. [37-38].

Due to the low impact of liquid Na on the degradation of the mechanical properties of structural materials, in particular when the oxygen and carbon activities are kept low, synergetic effects with neutron irradiation might be less relevant. No data are available concerning the effects on materials exposed to liquid sodium having high oxygen activity in combination with neutron irradiation. On the contrary, the behavior of materials exposed to carbon containing liquid sodium in combination with neutron irradiation has been discussed in a relatively recent experimental study on in-reactor creep rupture properties of austenitic steels [39]. These studies showed that in-reactor creep rupture times of 20% cold worked modified AISI 316 stainless steel are shorter when compared to the results of out-of-reactor creep rupture tests.

Finally, some preliminary results of 9Cr and 12Cr ODS alloys developed and mechanically tested in liquid Na in Japan have shown that the mechanical properties of these alloys are not affected [34].

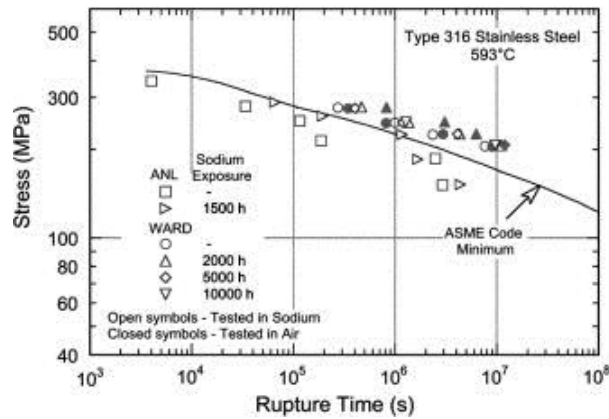


FIG. 4: Creep-to-rupture of AISI 316 in Na and air. The effect of Na is very low [31]

3.1 Mechanical properties of materials in liquid Lead and Lead-Bismuth Eutectic

A comprehensive literature review on the degradation of mechanical properties of structural materials exposed to liquid Pb and Pb-Bi is given in reference [16]. As reported in this reference most of the experiments have been performed in liquid Pb-Bi and the extension of these experimental findings to pure Pb could lead to incorrect estimations, since liquid Pb-Bi seems to be more aggressive than liquid Pb. Moreover, the main structural materials tested were the 9Cr ferritic/martensitic steel "T91" and the austenitic steel AISI 316. However, a generalisation of the results obtained in order to predict the behaviour of other 9Cr ferritic/martensitic and austenitic steels is not possible, since as for instance minor alloying elements in the steel impact the materials behaviour in these liquid metals.

Since the only non-metallic element dissolved in the liquid metal that has an influence on the mechanical properties of the steel, is oxygen, this paragraph will summarise the experimental findings on tensile, creep and fatigue properties and synergetic effects with neutron irradiation fields of the tested steels in Pb-Bi and oxidising or reducing environments. Where available, results in Pb will be mentioned as well.

In general, from the experiments performed, it has been shown that low oxygen promotes wetting of the steel surface and accelerates degradation of the steels' mechanical properties. A high oxygen potential slows the wetting of the steel surface due to the growth of oxide layer. However, the kinetics of the two processes depend on the temperature, and at high temperatures the two processes can compete. When a native oxide scale grows on the structural material, in general no degradation due to liquid metal can be observed, unless inhomogeneity, flaws and cracks in the oxide allows contact between the steel and the liquid metal

The austenitic steel did not show any modification of its tensile properties when in contact with the liquid metal regardless of the oxygen content in the Pb-Bi. On the contrary, the T91 steel under certain circumstances shows a reduction of the total elongation and a mixed ductile / brittle fracture mode. A continuous oxide layer without defects is considered as protective and hinders the direct contact between the bare T91 steel and the liquid metal, therefore reducing the risk for a degradation of the mechanical properties of the steel.

For what concerns tensile properties degradation in liquid Pb, from the few literature data available it can be assumed that the austenitic and ferritic/martensitic steels show the same trends as in liquid Pb-Bi.

Creep and Creep-to-rupture tests performed and published in the open literature are relatively scarce and mainly focused on 9Cr ferritic/martensitic steels exposed to Pb-Bi [40]. From the Russian literature also creep test on Russian versions of austenitic and ferritic/martensitic steels in liquid Pb are reported [24]. The tests in Pb-Bi and Pb have been performed at 550°C

in oxygen controlled environment, to allow for the development of an oxide layer. These tests have shown that ferritic/martensitic steels in liquid Pb-Bi and Pb exhibit a lower time-to-rupture with respect to air. This behaviour has been ascribed to the fact that at high stress level, the creep mechanism is faster than the oxide formation on the steel surface thus the oxide scale is not fully developed and the crack propagation process is mostly controlled by the reduction of the surface energy due to Pb and Bi adsorption directly on the steel surface.

The Low Cycle Fatigue (LCF) tests on AISI 316L steel have been performed in a temperature range between 300°C and 500°C. The results have shown that at high total strain range the number of cycle to failure in Pb-Bi is lower with respect to that in air. On the other hand, introducing hold-time did not change the LCF behaviour of the austenitic steel in Pb-Bi with respect to its behaviour in air [42]. Even pre-corroding the austenitic steel in Pb-Bi with low oxygen content did not impact the steel behaviour in LCF mode [43].

As reviewed in reference [44] the impact of Pb-Bi on LCF behavior of T91 steel is much more pronounced. First, T91 suffers cyclic softening in air and Pb-Bi at 300°C, indicating that the effect of Pb-Bi must be a surface effect, and not a bulk effect. Moreover, at this temperature the number of cycle to failure decreases over the full strain range when testing T91 in Pb-Bi with respect to testing in air. A further reduction of the number of cycles to failure is observed when the LCF tests are done with hold-time. Finally, a reduction of number of cycle to failure has been also observed on T91 steel pre-corroded in low oxygen Pb-Bi (causing surface defects at inter-granular level) with respect to T91 not pre-corroded or pre-oxidised in high oxygen Pb-Bi.

The potentialities of synergetic effects between neutron irradiation and the heavy liquid metals have been investigated mainly within two irradiation campaigns i.e. ASTIR at BR2 reactor [45] LEXUR-II at BOR60 reactor [46]. Very first results have shown that the tensile properties of the austenitic steel both irradiated in the ASTIR and the LEXUR-II experiments are not impacted by neutron irradiation and liquid metal synergetic effects in the temperature range investigated. On the contrary the ferritic/martensitic steel exhibited in the low temperature range (up to about 450°C) a synergetic effect of the tensile properties degradation (mainly hardening and reduction of elongation); however, when increasing the temperature above 450°C this effect seems less evident.

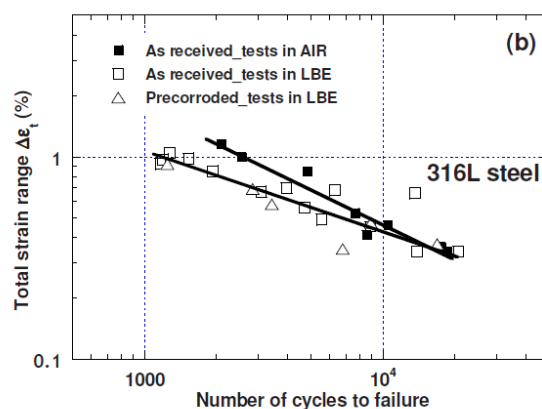


FIG. 5: LCF of AISI 316L steel tested in Pb-Bi eutectic at 300°C. [43]

4. Corrosion Mitigation

As already mentioned, structural materials used in liquid sodium, such as austenitic and ferritic/martensitic steels, are unlikely to corrode significantly in the normal operation

conditions. However, in transient conditions, for which an increased oxygen concentration can be encountered, corrosion can no longer be neglected. For this reason, the oxygen concentration has to be controlled (below 3 wppm), for instance through the use of cold traps. While maintaining sodium at high purity is favourable to suppress the corrosion of material, it plays a role in increasing friction and wear because the oxide layer formed at the surface of the material is reduced [6]. For reactor components subjected to repeated friction and wear due to the direct contact of materials in sodium at all times during steady state operations, it is standard to use hard facing materials. Generally, cobalt containing materials such as Stellite are used, however due to the activation of cobalt in nuclear reactor; cobalt free materials are evaluated as e.g. Ni based alloys. However, due to their high nickel content which is prone to dissolution in sodium, their corrosion behaviour has to be evaluated. Triballoy 700 which contains 30 wt% Mo has corrosion resistance equivalent to that of Stellite n°6 up to 700 °C, which is lower than 1 µm/year [6].

In liquid Lead and Lead-Bismuth eutectic the mitigation of structural materials corrosion and its mechanical properties degradation can be done through the control of the oxygen potential in the liquid metal, resulting in the growth of a native oxide layer on the steel surface. An issue of the native oxide layer growth method is the high thickness that it can reach in a relatively low time frame (particularly at high temperature), with consequences on its stability and integrity. Therefore, alternative corrosion protection methods have been studied which involve the modification of the steel surface. These methods are thoroughly described in reference [16] and here a brief summary is given.

The most promising alternative corrosion protection methods are the coating or the alloying in the steel surface, elements that forms thin oxides as for instance Al, Si and FeCrAlY. The resulting modified surface still require an active oxygen control in order to promote the building up of the protective oxide scale, but the protectiveness in the long-term behaviour and at higher temperatures is of a better quality than that of the steel native oxide layer.

There have also been studies which consider the coating of the steel surface with refractory metals (W, Mo, Nb, Ta) and their carbides and nitrides. Generally, these coatings have a very low solubility limit in liquid Pb, but they are easily oxidised. Therefore, this type of modification would require a very low oxygen potential in the liquid metal.

Other methods as e.g. the alloying of Si and Al in the steel or the use of so-called "inhibitors" have been also studied.

Regardless of the technique used to protect the structural material from corrosion and mechanical properties degradation, it is necessary that the methods comply with some basic requirements, as e.g. feasibility at industrial scale, applicability on the selected structural material without changing its properties, specifications, quality assurance procedures, etc.

5. Conclusions

Corrosion phenomena and potential mechanical properties degradation of reference structural materials when in contact with liquid Na and Pb / Pb-Bi have been discussed. As shown in the previous paragraphs, these issues are more important in Pb/Pb-Bi environment than in sodium environment.

In the operational conditions of the SFR, it has been shown that corrosion rate is negligible if the oxygen concentration is below ~ 3 wppm and carbon below ~ 20 wppm.

Furthermore, it has to be pointed out that the conditions, for which the corrosion rates of steels in liquid Na are mitigated, are also favourable conditions to impede their mechanical properties degradation. However, the correlations to estimate corrosion rate have all an

empirical character and are poorly related to chemical and physical phenomena. Therefore it is still important to perform experimental programs to generate data for newly developed materials and for validating models that should be based on first principles in order to improve the reliability of predictive capabilities.

In liquid Pb/Pb-Bi for certain testing conditions multiple corrosion mechanisms can be activated, making the assessment of steel corrosion in these liquid metals more complex.

The very high solubility of the steel alloying elements as e.g. Ni in de-oxidized liquid Pb or liquid Pb-Bi, makes the use of austenitic and to a certain extent ferritic/martensitic steels in relatively high temperature range and for long-term exposure, quite prohibitive. Similarly, the mechanical properties are severely degraded when a direct contact or wetting between the liquid Pb and Pb-Bi and the steel surface occurs. It should be highlighted that the degradation of the mechanical properties, which can be in some cases explained through liquid metal embrittlement mechanism of ferritic/martensitic steels are much more pronounced than what is observed in austenitic steels.

In oxidizing liquid Pb and Pb-Bi both austenitic and ferritic/martensitic steel develop an oxide layer. Even if the oxide layer protects the steel from corrosive attack the low thermal conductivity of the oxide layer needs to be considered in case of the fuel cladding or heat-exchanger tubes design. Moreover, for being protective the oxide layer should grow uniformly on the steel surface without exhibiting damages even over time. However, experimental evidence has shown that thick oxide layers can spall-off and allowing for a direct contact between the steel substrate and the liquid metal. The oxide layer can also mitigate the degradation of the mechanical properties of the reference steels (as already mentioned before, the mechanical degradation of ferritic/martensitic steels is more pronounced than that of austenitic steels) given that the applied stresses or the strains stay below certain values. Above 500°C the corrosion mechanisms changes again. It seems that above this temperature, even in oxidising conditions, there is the onset of competing dissolution and oxidation processes resulting in steel surfaces partially oxidised and partially corroded.

Corrosion mitigation methods foresee the surface alloying of for instance Fe-Al or FeCrAlY showing an improvement of the materials behaviour; however for their full application in the reactor environment a characterisation and validation program needs to be performed.

Finally, corrosion studies in liquid Pb and liquid Pb-Bi could benefit from a mixed approach, were traditional experiments are blended with first principle modelling and validation, to improve physical understanding of the phenomena and develop reliable predictive tools.

When evaluating the technological readiness of Na and Pb/Pb-Bi coolant technologies from a corrosion point of view, it can be claimed that Na shows a higher level of readiness with respect to the heavy metals.

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