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Chemical compatibility of Eurofer steel with sodium-potassium NaK-78 eutectic alloy

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HIGHLIGHTS

- Eurofer SSTT specimens were immersed in static NaK-78 for 6 months at 480–500 °C.
- The Eurofer steel did not suffer any degradation in its mechanical properties.
- The chemical interaction between Eurofer specimens and NaK-78 was minimal.
- Using NaK-78, with low oxygen content, is feasible for the IFMIF HFTM capsules.

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ABSTRACT

In the high flux area of the International Fusion Materials Irradiation Facility (IFMIF) neutron source, the capsules of the High Flux Test Module (HFTM) contain SSTT Eurofer specimens for fusion relevant irradiation at temperature up to 550 °C. Using the sodium potassium eutectic alloy NaK-78 to fill the gaps among the Eurofer specimens stacked inside the HFTM capsules was introduced in order to improve the thermal conduction among all specimens and have uniform and predictable temperature distribution. Therefore the objective of this study is to investigate the chemical compatibility between Eurofer steel and NaK-78 to evaluate the applicability of this concept. In the present experiment, the SSTT Eurofer specimens were immersed in static NaK-78 inside a capsule made of Eurofer and kept under IFMIF HFTM-relevant conditions including high temperature (cycling between 480 °C and 500 °C) and duration of six months. Following the experiment, mechanical tests (tensile and Charpy impact) of the Eurofer specimens were performed in addition to surface and microstructure analyses to detect any relevant corrosion or degradation. The mechanical tests revealed that the Eurofer specimens did not show any degradation in their mechanical properties. Also, the surface and microstructure analyses showed that the chemical interaction between the Eurofer steel and NaK-78 was minimal after six month of exposure at cyclic temperature between 480 and 500 °C.

1. Introduction

The structural materials of the fusion reactor in-vessel components including the first wall and blanket should cope with the severe working conditions without any degradation in their mechanical properties or dimensional stability beyond the allowable design limits. Selecting these structural materials requires a dedicated testing at fusion-relevant irradiation conditions. Therefore building the International Fusion Materials Irradiation Facility (IFMIF) has become an unavoidable step in the way to design and construct a fusion reactor. IFMIF is an accelerator-based neutron source that uses lithium-deuterium Li(d,xn) nuclear reactions to produce a neutron flux similar to that expected at the fusion reactor blanket. The task of IFMIF is to irradiate the fusion materials in irradiation conditions similar to those of the future fusion reactor DEMO in order to: (i) provide data for the engineering design of DEMO, (ii) contribute to the selection of candidate fusion materials, and (iii) validate the understanding of the irradiation effects on the

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fusion functional materials. Next to the IFMIF neutron source in the high flux region, the irradiation of the structural material (e.g. Eurofer steel) specimens will be performed in the High Flux Test Module (HFTM) [1]. Eurofer steel belongs to the group of the Reduced Activation Ferritic Martensitic (RAFM) steels that have swelling resistance and low activation properties. Therefore Eurofer steel has been developed and optimized to serve as a structural material for the fusion reactor blanket. The Eurofer specimens are stacked inside the HFTM capsules and should have a specific uniform temperature therefore the heat transfer, mainly conduction, should be well understood and predictable. The idea of using the sodium-potassium eutectic alloy NaK-78 (with 78 wt% K and 22 wt% Na) to fill the small gaps among the Eurofer specimens has been considered in order to: (i) improve the thermal conduction among all capsule parts and the heat transfer predictability, (ii) establish a uniform temperature distribution, and (iii) ensure that the thermocouples are in contact with NaK-78 or the specimens and not a gap to obtain accurate representative temperatures. However, the chemical compatibility of Eurofer with NaK-78 needs to be experimentally investigated to evaluate the applicability of this concept. For instance, the corrosion level and its influence on the mechanical properties and microstructure of the Eurofer specimens should be evaluated.

2. Literature review

When the steel is exposed to a liquid metal (e.g. NaK or Na), the corrosion possibly occurs due to: (i) a mass transfer of non-metallic elements such as oxygen, carbon, nitrogen, and hydrogen, and (ii) a mass transfer of metallic elements as some of the steel constituents may dissolve into the liquid metal and react with its impurities; therefore the solubility of the steel constituents in the liquid metal plays a significant role in the corrosion process. The mass transfer of non-metallic elements can change the microstructure and hence the mechanical properties of the steel on the long run. Hence, it is preferred to have low concentrations of the non-metallic elements in the liquid metal. The chemical reactions between the steel and the surrounding liquid metal with its impurities, in most cases oxidation of the steel, cause the corrosion process. The oxygen content in the liquid metal is an important factor that can accelerate the corrosion of the structural materials; therefore it should be minimized. A previous study [2] reported that the corrosion of metals by a liquid metal is affected by some parameters including system temperature, oscillation of cyclic temperature, ratio of exposed solid surface area to volume of liquid metal, impurities in the liquid metal, flow velocity of the liquid metal, conditions of the container, and composition and microstructure of the materials involved. For instance, increasing the system temperature leads to higher solubility of the steel constituents into the liquid metal, higher diffusion rates and smaller viscosities and consequently results in a higher corrosion rate. Also, the cyclic temperature oscillation is a catalytic factor; for example the corrosion rate of the Cu-Bi system at $500 \pm 5\,^{\circ}$C is several times higher than that at $500 \pm 0.5\,^{\circ}$C as reported in the literature [2]. Another previous work [3] studied the compatibility between the RAFM steel and sodium, where the data of sodium except for oxygen solubility were used to evaluate the NaK compatibility. A mass transfer of a metallic element between the RAFM steel specimens and the Na (or NaK) was observed. It was concluded that the corrosion depth of RAFM specimens, due to the dissolution of metallic elements into the liquid metal and the oxidation by oxygen present in the liquid metal, is less than 1 μm if the liquid metal is purified using the cold trap, and hence it is unlikely to affect the RAFM steel performance. It was stated in the literature [4] that the corrosive properties of sodium and NaK are similar and no distinction between the two liquid metals can be observed.

A fusion relevant study [5] presented an assessment of using alkali metals as a coolant for the ITER blanket. It was reported that the austenitic stainless steels did not produce iron or chromium oxides in the environments of liquid Na and NaK particularly at oxygen levels that correspond to a cold-trapped liquid. Hence, the corrosion rates of the steels are fairly low under the aforementioned conditions. In another study [6], the experimental results indicated that all stainless steels that were tested showed a good performance in static NaK capsules up to a temperature of 760 °C. For the stainless steel SS310 in a very pure NaK, there was very small initial weight loss, which decreased quickly with the increase of exposure time at 760 °C. The authors concluded that stainless steels are extremely resistant to a chemical attack by NaK at temperatures up to 760 °C. In addition, experimental examinations were performed [7] to evaluate the performance of a stainless steel 316 loop for circulating the NaK-78 at temperature of 760 °C for a long-term exposure of 32,600 h. It was concluded that the SS316 performed satisfactorily as a structural material for the loop and some changes in its mechanical properties and metallurgical effects occurred only when circulating non-isothermal NaK-78. However, these changes did not significantly affect the material properties in a way that can result in a material failure. At Oak Ridge National Laboratory, eleven experimental loops were built for the SNAP-8 corrosion program [8] to study the compatibility of NaK-78 with some structural materials including the nickel-based alloy Hastelloy N as well as the stainless steels 316 and 347. The loops were operated with a minimum NaK-78 temperature of 1100 °F and for a running time of about 2000 h. The metallurgical analyses showed that the deposits consisted mainly of nickel, chromium and manganese in the low oxygen loops while the deposits were basically iron and chromium in the high oxygen loops. It was concluded that the oxygen level in NaK-78 is the most important factor that affects the corrosion of steels. Also, it was noted that corrosion of stainless steels 316 and 347 was very low compared with that of Hastelloy N.

3. Experimental setup

The experimental setup, shown in Fig. 1, mainly consists of: (i) the capsule that contains the Eurofer specimens and NaK-78, (ii) two heaters, seven thermocouples, an insulation block, structural supports and a metallic base, and (iii) a gas-tight cylinder to contain most of the setup's components. The capsule has a shape of rectangular prism with inner and outer dimensions of 24 mm × 28 mm × 66 mm and 36 mm × 40 mm × 78 mm respectively. The capsule walls, cover, and base were welded together by electron beam welding because it is performed in vacuum; and hence it minimizes any contamination and produces consistent welds. The capsule has three tubes for filling, bleeding and pressurizing; and they penetrate from its cover and are used for the NaK filling process. Fig. 2 shows the capsule packed with the Eurofer specimens as well as its tubes and cover. The capsule, its tubes, and the Eurofer specimens were manufactured from the same Eurofer plate (Eurofer 97-2, batch 993391, thickness of 25 mm) and its properties are given elsewhere [9]. The capsule encloses 20 Eurofer specimens, similar to the IFMIF HFTM specimens, for post experiment mechanical tests. The Eurofer specimens were manufactured according to the Small Specimen Test Technology (SSTT) which was developed to investigate mechanical properties of nuclear materials taking into account the limited irradiation volumes in the test nuclear reactors and accelerator-based neutron sources. The tensile test specimen has a diameter of 2 mm and a gauge length of 7.6 mm. The Charpy impact specimen has dimensions of 27 mm × 4 mm × 3 mm with a v-notch depth of 1 mm, 60° notch angle, and 0.1 mm notch tip radius. In addition, the capsule contains two specimens, with a shape of rectangular prism