ABSTRACT

The primary concern for hydrogen permeation barriers can prevent hydrogen entry into the materials that could degrade due to hydrogen intake. In a fusion reactor, it has demonstrated in a deuterium or tritium buildup in structural steels that are inadmissibly high or permeation into steel structures through liquid coolants that are too high. As a result, the need for development and advancement of permeation barriers arise from these twin concerns: (i) decreasing H (hydrogen) intake into the steel to avoid deterioration and (ii) restricting T (tritium) permeation into the steel structures to attain maximum yield for the tritium produced in the breeder during reactor cycle. The idea of reproducing tritium during the reactor cycle arise due to its limited availability and also for the future needs of a large-scale fusion power plant.

Hydrogen isotope permeation barriers have considered as external coatings on most of the active fusion reactor components to reduce hydrogen permeation. In certain instances, exposure-treatments found to form an oxide layer on the steel structures that also serve this purpose.

Typically, the most efficient method appears to be the development of an appropriate surface barrier coat having low hydrogen permeability, diffusivity and solubility. Certain metals on its own had low hydrogen permeation characteristics as equal to many nitrides, oxides and carbides. Whereas the later one having beneficial intrinsic properties compare to pure metals such as high-temperature phase stability, corrosion and wear resistance.
The current study plans to develop a dual layer ($\text{Al}_2\text{O}_3$/Fe-Al) coating on RAFM steel (low or reduced activation ferritic/martensitic steel) for fusion reactor application. Permeation barrier required on the tritium breeding blanket modules (TBMs) made up of RAFM steel to minimize the escape of tritium by diffusion into the structural material. Among the various methods used to form alumina coating on the steel, HDA (hot-dip aluminizing), high-temperature annealing and thermal oxidation techniques have used in this work due to its simplicity and low cost and also its ability to coat complex, intricate part geometries of any material including nonconductive materials etc.

However, in the view of preparing $\text{Al}_2\text{O}_3$/Fe-Al permeation barrier, the effects of preparation techniques and alloying additions on the performance of barrier coatings are still lagging. Also, the work done so far does not reveal a systematic approach or theory, thus limiting the advancement in the application of permeation barriers. Moreover, addressing this issue will help the real-time development and implementation of hot-dip coatings simpler. Therefore, analysis of various alloys and its addition on the performance of $\text{Al}_2\text{O}_3$/Fe-Al permeation barriers are necessary. It makes the HDA a promising engineering preparation technique for the development of high-quality permeation barriers.

Hot dipping was employed to deposit Al/Fe-Al layer on the RAFM steel directly by dipping into superheated Al melts. Annealing serves to increase the adherence of the deposited layer with the steel either by the formation of an intermetallic compound (Fe-Al) compatible with both the Fe and Al or by reducing the gradient of thermal expansion coefficient between them.
High-temperature oxidation was employed to convert the aluminium (Al) into alumina (Al₂O₃). In this study, two different HDA melts having Al; an Al-Si alloy has selected for depositing barrier coatings (Al/Fe-Al and Al-Si/Fe-Al-Si) on RAFM steel.

The diverse composition of Si (1, 6, 11, and 11.7 in wt. %) along with other elements including rare earth (Zr) have used for understanding the influence of alloy composition and superheat on the microstructural features (morphology, microstructure, crystal structure, microhardness, hydrogen permeation, scratch and corrosion resistance) of the permeation barriers developed on reduced activation steel (RAFM) by hot-dipping, annealing and oxidation processes.

Additionally, the RAFM steel samples of varying surface roughness (Ra) 3.5μm, 4.5μm and 7.5μm obtained by mechanical grinding, milling and shot blasting processes has aluminized in Al-Si (11.7%) alloy melt for understanding the influence of surface roughness on the microstructural features of barrier formed by HDA, annealing and oxidation processes have also investigated.

Standard characterization equipment’s such as high-resolution SEM (Scanning Electron Microscope) provided with EDS (Energy Dispersive Spectroscopy), optical microscope, XRD (X-ray diffraction), microhardness (Vickers hardness) and linear scratch test (for adhesion strength) instruments have used to characterize the nature of coating formed on reduced activation steel (RAFM) by hot-dipping, annealing and thermal oxidation processes.
The experimental results confirmed the samples prepared by shot blasting process (Ra:7.5μm) and aluminized in Al-Si alloy melts of Si concentration 11% and 11.7% exhibited better morphology and microstructural features compared to all other samples.

The crystal structure of alumina formed after oxidation has mainly consist of theta (θ) phase with a small fraction of alpha (α) phases in it. The microhardness of the coating was found to vary across its thickness, which includes an oxide layer, solidified Al-Si alloy layer (coating layer) and intermetallic layers. Details of the optical, SEM and EDS analysis reveals the diffusion of Al into the RAFM steel is minimal in these samples compared to the rest of the samples even after oxidation.

Hydrogen permeation resistance of the barrier coat (Al2O3/Fe-Al-Si) developed on RAFM steel was evaluated qualitatively by measuring the hydrogen adsorption/desorption kinetics with the help of TDS (thermal desorption spectrometry) and electrochemical techniques.

The outcome of the measurement proved a 5 times improvement in permeation resistance of RAFM steel with the barrier coating in comparison to without barrier coating.

The corrosion resistance of the samples evaluated by electrochemical polarization technique also confirm 4 times increase in corrosion resistance of RAFM steel with barrier coating in comparison to without barrier coating.