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α-Alumina Synthesis at Room Temperature Using a Plasma Focus Device for Fusion Blankets

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α-Alumina (α-Al_2O_3) is a highly promising candidate for tritium permeation barriers (TPBs) in fusion blanket modules due to its excellent permeation reduction factor, superior thermal stability, corrosion resistance, and high melting point[1]. Among the various alumina polymorphs such as γ, κ, θ, and β, α-alumina represents the most thermodynamically stable phase, ensuring long-term structural and chemical integrity under the extreme operating conditions of fusion reactors[2]. In contrast, metastable phases like γ-Al_2O_3 and θ-Al_2O_3 are prone to phase transformations and microstructural degradation when exposed to elevated temperatures, leading to deterioration in barrier performance over time. The robust properties of α-alumina, including its dense crystalline structure and chemical inertness, make it particularly effective in mitigating tritium permeation, preventing hydrogen embrittlement of structural materials, and reducing radioactive inventory within the reactor environment.

Extensive research by ITER collaborators across Europe, China, and India has highlighted the potential of α-alumina coatings as effective tritium permeation barriers. Conventional synthesis methods such as hot-dipping, pack cementation, electrochemical deposition (ECD), and chemical vapor deposition (CVD) have been widely used to fabricate alumina coatings on candidate structural materials, including Eurofer 97[3], MANET steels[4], and SS-316L[5]. However, these techniques typically require processing temperatures exceeding 900°C, which can induce adverse microstructural changes, grain coarsening, and thermal stress in the substrate, ultimately compromising mechanical properties and reactor component lifetime[6] .

To overcome these limitations, a dense plasma focus (DPF) device is being employed to synthesize α-Al_2O_3 coatings under near-room-temperature conditions. The DPF is a pulsed plasma device capable of generating transient high-density (10^{18}–10^{20} cm^{-3}), high-temperature (1–3 keV) plasmas in the pinch region[7]. Operationally, it consists of coaxial electrodes connected to a capacitor bank, which upon discharge forms an axially moving plasma sheath. This sheath accelerates towards the open end of the anode and undergoes radial compression to form a dense pinch with intense X-ray emission, energetic ions, and localized electromagnetic fields. These energetic plasma species facilitate efficient ablation of the aluminum target in an oxygen environment, leading to the formation of reactive Al–O species. Due to the nanosecond to microsecond pulse duration, there is minimal heat transfer to the substrate, enabling rapid nucleation and crystallization of α-alumina while preserving substrate microstructure.

In the present study, initial deposition trials using the DPF device have successfully demonstrated the formation of α-alumina coatings on SS 316 substrates. X-ray diffraction (XRD) analysis confirmed the presence of characteristic α-Al_2O_3 peaks at 2θ = 25.6°, 35.1°, 37.8°, 43.4°, 52.6°, and 57.5°, corresponding to (012), (104), (110), (113), (024), and (116) planes respectively, indicating a well-crystallized α-phase structure. X-ray photoelectron spectroscopy (XPS) analysis revealed strong Al 2p peaks at ~74.2 eV and O 1s peaks at ~531.4 eV, consistent with stoichiometric Al_2O_3, further confirming the chemical composition and oxidation state of the deposited coatings. Scanning electron microscopy (SEM) analysis showed a globular surface morphology typical of plasma-assisted α-alumina deposition, with dense and uniform coverage across the substrate. Transmission electron microscopy (TEM) characterization is currently ongoing to examine the nanoscale crystallinity, grain size distribution, and interfacial structure between the coating and the SS 316 substrate.

Overall, this innovative room-temperature deposition approach leveraging the unique physics of dense plasma focus plasmas presents a significant advancement in tritium permeation barrier fabrication. The process enables the synthesis of thermodynamically stable α-alumina coatings without thermal degradation of the substrate, offering a promising route to enhance the durability, safety, and performance of fusion blanket modules in future commercial fusion reactors. Further optimization of process parameters and detailed microstructural analysis will be pursued to fully establish its applicability in fusion energy systems.

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