

A Review of Hydriding Mitigation of Cr coatings for Zirconium-alloy Cladding

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1. Introduction

Chromium (Cr) coatings have been extensively studied as one of the promising Accident Tolerant Fuel (ATF) cladding concepts for Light Water Reactor (LWR) zirconium (Zr) alloy fuel cladding. Since the hydrogen pickup resistance of Cr-coated cladding has received relatively limited attention to date, this paper aims to bridge that gap by reviewing literature on hydrogen pickup and permeation in Cr-coated Zr alloys to evaluate and understand the mitigation performance across coating deposition methods.

2. Hydrogen pick-up performance of Cr coatings

2.1 Hydrogen pick-up mitigation by Cr coatings

Previous studies reported that Cr coatings effectively suppress hydrogen pickup in zirconium-alloy cladding under both water-side exposure and gaseous charging conditions. In long-term autoclave tests under VVER water chemistry, uncoated Zr-1Nb reached 75 ppm after 700 days, whereas Cr-coated specimens remained at 21 ppm after the test [1]. Additionally, a hydrogen charging of E110 upset welds at a constant H₂ pressure of 2 bar, uncoated specimens reached 890 ppm, while Cr-coated specimens recorded 64 ppm, indicating substantial mitigation even in the weld-affected regions [2].

Furthermore, the hydrogen pickup fraction—the ratio of hydrogen absorbed by the sample to the total hydrogen initially introduced into the quartz tube—varies across the coating fabrication methods shown in Fig. 1. Walters reported that Cr coatings reduce hydrogen pickup fraction by 15–59% relative to uncoated cladding, with the largest reductions were observed for He cold spray (59%) and pulsed magnetron-sputtered PVD (53%), and a smaller but still meaningful reduction for N₂ cold spray (15%). In addition, the experimental data showed that the coating provided tolerance to localized damage; through-coating scratch defects increased the hydrogen pickup fraction only modestly (1–2% for cold-sprayed coatings), although larger increases (up to 10%) were observed when the multiple scratches exposed [3].

Collectively, these results suggest that Cr coatings are not perfectly impermeable; rather, they functioned as effective transport barriers that substantially delayed hydrogen permeation, with performance governed by fabrication process and microstructure.

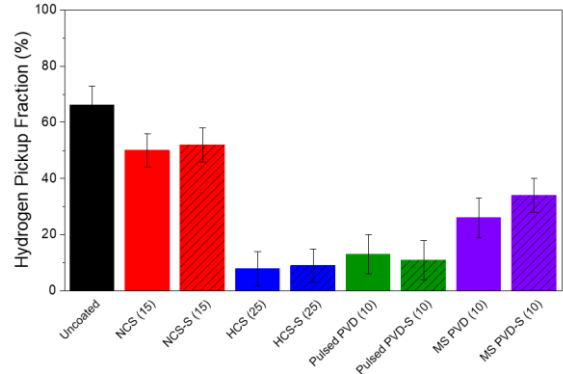


Fig. 1. Hydrogen pickup fraction by fabrication method

2.2 Hydrogen permeation of the Cr coatings

Permeation analysis reveals that the Cr₂O₃ layer played a dominant role in hydrogen transport: at 430 °C, metallic Cr exhibited a hydrogen permeability on the order of 10⁻¹⁵–10⁻¹², whereas Cr₂O₃ provided substantially higher transport resistance, with permeability typically reported to be between 10⁻²⁰ and 10⁻¹⁶. Accordingly, formation of a Cr₂O₃ layer on the coating can further strengthen the barrier performance and thereby mitigate hydrogen ingress beyond that provided by the metallic Cr alone.

Table I: Hydrogen permeability of oxide layer

Material	Permeability at 430°C (mol H ₂ /m/s/Pa ^{0.5})	Reference
ZrO ₂	5.0×10 ⁻¹⁵	Walters [3]
	10 ⁻¹⁷	Walters et al. [6]
	5.3×10 ⁻¹⁷	Smith et al. [5]
	10 ⁻¹⁸ - 10 ⁻¹⁶	Viands [4]
Cr ₂ O ₃	10 ⁻¹⁷ - 10 ⁻¹⁶	Walters [3]
	10 ⁻¹⁹ - 10 ⁻¹⁸	Walters [6]
	10 ⁻²⁰ - 10 ⁻¹⁹	Nemanic et al. [7]
	1.5×10 ⁻¹⁷	He et al. [8]
	10 ⁻¹⁷ - 10 ⁻¹⁶	Viands [4]

Interestingly, the reported values for hydrogen permeability through Zr and Cr oxides vary throughout the literature (Table 1). This may be due to different oxide growth mechanisms and corresponding microstructure. While oxidation in pressurized-water

autoclave generally produces robust, high-density oxide layers, air-grown counterparts are often characterized as increased porosity, which serves to enhanced effective transport pathways. In addition, hydrogen transport is influenced by pre-oxidation surface preparations, including mechanical polishing and finishing, which dictate initial surface roughness and defect density. These factors, combined with the specific chemical environment of the oxidation process, such as the distinction between pure gaseous O₂ and aqueous autoclave conditions, collectively alter the defect populations and microstructural integrity of the oxide.

3. Conclusions

The hydrogen mitigation of Cr coatings on Zr-alloy cladding is characterized not as absolute impermeability, but by a substantial delay in hydrogen transport, which is influenced by the coating microstructure, and process-dependent features. Specifically, permeation analysis indicates that the primary resistance to hydrogen ingress is provided by the oxide layer. Finally, the reported permeability values of oxide layers were scattered across the studies, suggesting that measured values are sensitive to experimental factors including oxidation conditions.

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