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Recent Approaches for Mitigation and Repair of Chloride-Induced Stress Corrosion Cracking (CISCC) in Stainless-Steel Canisters for Spent Nuclear Fuel

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1. Introduction

As of 2023, twenty-five Nuclear Power Plants (NPPs) are operating in South Korea. In the first quarter of this year, 206 assemblies of spent nuclear fuels were produced from the light-water reactors. Furthermore, Korea Hydro & Nuclear Power Co., Inc. (KHNP) reported that 73.8% (22,033 of 29,872) of wet storage pool for light-water reactors are already occupied [1]. Since permanent geological disposal sites for spent nuclear fuel are not available in South Korea, the onsite dry cask storage facilities are required as a temporary solution.

Therefore, these systems need to ensure its integrity at least several decades. However, a type of corrosion mode called Chloride-Induced Stress Corrosion Cracking (CISCC) can severely deteriorate life expectancy of stainless-steel canisters in Dry Cask Storage System (DCSS).

2. Chloride-Induced Stress Corrosion Cracking (CISCC)

304/304L and 316/316L stainless steels have been used for the storage canisters. These materials were chosen due to its excellent corrosion resistance [2]. However, in combination of residual tensile stress, material sensitization, and corrosive environments, the corrosion resistance can be neutralized and vulnerable.

2.1 Effect of residual tensile stress

As manufacturing the storage canister in DCSS, a stainless-steel plate is usually rolled into cylindrical shape and then fusion welded. And the solidification-induced tensile stress remained around the welded regions. The residual tensile stress contributes to formation and propagation of CISCC.

2.2 Material sensitization

As mentioned, each edge of the cylindrical shaped stainless-steel plate is welded together after rolling. In the heat-affected zone (HAZ) around the welded area, the precipitation of Cr-rich carbides, by heat, is facilitated, particularly, on grain boundaries. This phenomenon is called sensitization. The sensitization depletes chromium in the vicinity of grain boundaries, making this material susceptible to CISCC.

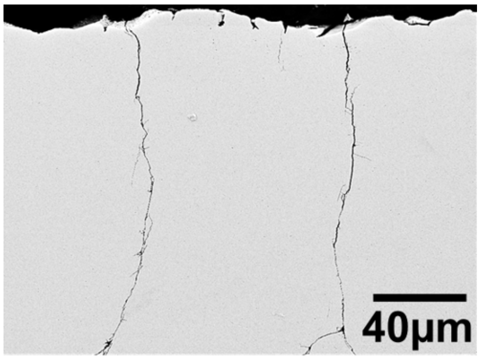

Fig. 1. CISCC in 304L Stainless Steel.

2.3 Corrosive environments

Chloride-rich environment can induce formation of pitting on surface of the sensitized stainless steels. Residual tensile stress provides driving force to develop pits into cracks.

Most nuclear power plants in South Korea were built in coastal regions where the high relative humidity and the chloride ion concentration level are prevalent. They are the main factors of pitting corrosion, higher than other inland areas.

3. Mitigation and Repair Technologies for CISCC

To mitigate, or repair cracks incurred by CISCC phenomena, it is necessary to suppress at least one of the three conditions for CISCC initiation and growth. Otherwise, for example, if the conventional fusion welding is used to repair cracks, another HAZ is formed again around the welded regions. It means residual tensile stress and corrosive environments are still remained, which warrants new sensitization occurred on the repaired area.

To mitigate/repair of potential CISCC on dry cask storage canisters, multiple surface engineering techniques are being investigated. The following approaches appear promising methods for mitigating, repairing, and preventing CISCC.

3.1 Surface Peening Techniques

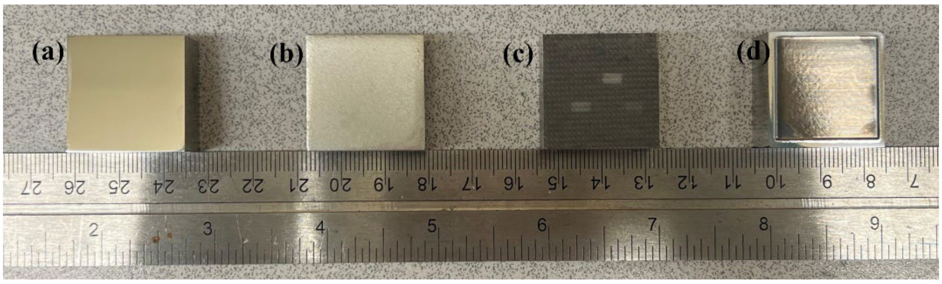

Fig. 2. Images of (a) Reference, (b) Pulsed Water Jet Peening (PWJP), (c) Laser Shock Peening (LSP), and (d) Ultrasonic Nanocrystalline Surface Modification (UNSM) processed stainless steel coupons. The processes were performed at the Univ. Wisconsin, Madison.

Surface peening for the storage canister includes Shot Peening, Water Jet Peening, Ultrasonic Impact Peening, Laser Shock Peening, and Ultrasonic Nanocrystalline Surface Modification.

The main principle of these surface peening methods is to provide compressive residual stress on the substrate surface. By impacting the surface of substrates with a high-energy medium (e.g., small pins or balls), it generates compressive stress in the materials, which compensates pre-existing tensile residual stress. However, these surface peening processes are not remedy to alleviate other two factors, such as sensitized microstructure and exposure to corrosive environments.

3.2 Cold Spray Deposition

Cold spray deposition is a coating process that can be used with various feedstock powders and substrates. In this process, feedstock powders are accelerated to supersonic velocity by inert gas (He, N_2), impacted and deposited on the substrate. This coated layer acts like a barrier layer that protects substrates from outer corrosive environments. Moreover, while feedstock powders impacting the substrate, compressive stress is also induced on the coated surface similar to surface peening techniques. As a result, cold spray deposition can mitigate both residual tensile stress and exposure to corrosive environments simultaneously.

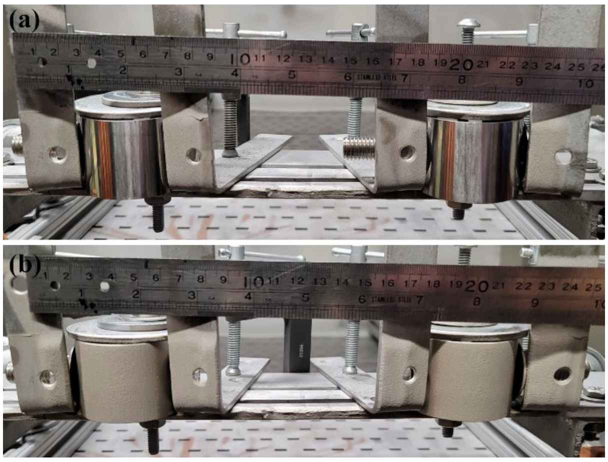

Fig. 3. (a) Before and (b) after stainless steel Cold Spray Deposition.

3.3 Burnishing

Burnishing is a type of mechanical surface modification, similar to surface peening. However, unlikely to surface peening, burnishing is conducted with balls or rollers, pressing the substrate surface constantly (without ultrasonic vibration or impact). By this process, plastic deformation of the near-surface of the substrate induces compressive stress, which counteracts the residual tensile stress of the material.

3.4 Other Methods

Material coating is also inclusive terminology, containing various types of coating materials. Polymers, ceramics, conversion coatings (e.g., Phosphate conversion, Chromate conversion), even the cold spray deposition described earlier can be regarded as material coating.

Material coating is based on keeping substrate from external corrosive environment, which is one of the conditions of CISCC. A. Knight et al. reported a summary of properties of various coating materials and potential implementation for in situ repair, ex situ repair, and ex situ prevention. In this report, various polymers like epoxy, polyvinylidene fluoride, rubber, etc., and ceramics like sol-gel, ion beam assisted or chemical vapor deposition methods, conversion coatings like phosphate and chromate conversion, and cold spray deposition methods are compared by a table. [3]

4. Conclusion

This article focused on the roots of CISCC phenomena and recent approaches to mitigate and repair it. Surface peening and burnishing are surface modification process that alleviate residual tensile stress, which is the one of the conditions of CISCC. Meanwhile, material coating is the method of forming a barrier layer, keeps substrate from corrosive solutions. These methods are mitigating only one of the conditions of CISCC, but cold spray deposition can alleviate both residual tensile stress and corrosive environments simultaneously.

Since there is no operating DCSS for light-water reactors in South Korea, KHNP is planning to build and operate dry storage facilities until 2030 [4]. However, there are few research activities on the corrosion of stainless-steel canisters for spent nuclear fuels in the domestic environment conditions. In the United States, Electric Power Research Institute (EPRI) reported that ASTM Ocean Water is generally composed of chloride, sulfate anions (88 wt.% and 12 wt.% of total anions, respectively) and sodium cations (84 wt.% of total cations), while Typical Inland Rainwater is composed of nitrate, sulfate anions (44 wt.% and 50 wt.% of total anions, respectively), ammonium and calcium cations (56 wt.% and 32 wt.% of total cations, respectively) [5]. Therefore, H.-G. Park et al. reported that sometimes rainwater can have a greater impact to corrosion than seawater, although the DCSSs are located at the coastal area in United States [6]. Like this, we need to investigate compositions and effects of rainwater and seawater on corrosion of stainless-steel canisters in South Korea.

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