Evaluation of Corrosion Resistance of Thermal-Sprayed Coated Materials for Molten Salt Reactors

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***Keywords :** Molten Salt Reactor, Structural Materials, Type 316H Stainless Steel, Thermal Spray, Cladding

1. Introduction

Currently, Type 316H austenitic stainless steel is a prominent candidate for MSR structural materials under development in South Korea. While this material possesses excellent high-temperature mechanical properties and a certain level of corrosion resistance, issues have been reported where corrosion progresses due to the selective leaching of major elements within the alloy, such as chromium (Cr) and molybdenum (Mo), in molten salt environments. In particular, in chloride-based molten salts, the leaching of metal atoms by chloride ions proceeds rapidly, which can cause serious damage during long-term operation[1].

Surface modification technology is garnering attention as a way to overcome these limitations; among these, thermal spray coating technology is evaluated as a promising approach to improve the corrosion resistance of structural materials in high-temperature, highly corrosive environments. Thermal spray coating is a technique that forms a film on the surface of a base material by spraying metal or ceramic powder at high speeds, increasing chemical stability by shielding the coating layer from the external corrosive environment. Specifically, when materials with excellent corrosion resistance, such as Ni-based or Inconel-based alloys, are used as coating materials, the corrosion rate can be significantly reduced by suppressing direct contact with the corrosive molten salt[2,3].

Although research on the molten salt corrosion behavior of various alloy-based coating materials is already underway both domestically and abroad, most studies remain limited to short-term test results or specific salt compositions. Furthermore, systematic evaluations regarding the differences in corrosion behavior based on coating layer adhesion, micro-structural characteristics, coating thickness, and process variables have not been sufficiently conducted. Therefore, research is needed to compare and evaluate the corrosion behavior of coating materials and base materials by simulating conditions similar to actual reactor operating environments (approximately 650°C, specific molten salt compositions).

Accordingly, this study aimed to quantitatively evaluate the corrosion resistance performance of thermal-sprayed metallic materials in a high-temperature chloride-based molten salt environment at 650°C.

2. Experimental

2.1 Materials

Thermal spray coating was performed on rectangular Type 316H stainless steel specimens with a hole using Ni-200/201 grade powder and Inconel 625 powder. The Ni powder was a Ni-200/201 grade nickel powder produced by Höganäs AB, Sweden, with a carbon content of 0.02 wt% and an oxygen content of 0.11 wt%. The particle size of both the Ni-200/201 and Inconel 625 powders ranged from 50 to 150 μm.

2.2 Thermal Spray Coating Process

Corrosion test specimens were fabricated by Sewon Hardfacing using the HVOF(High Velocity Oxygen Fuel) method to spray pure Ni and Inconel 625 alloy powders to a thickness of approximately 300 μm onto the entire surface of rectangular specimens measuring 4 mm (thickness) x 20 mm (length) x 10 mm (width). During this process, the powder feed rate was 70–80 g/min, and the spray distance was approximately 350 mm. Oxygen and kerosene were used as fuel, while argon was used as the powder carrier gas. The flame temperature was approximately 3,300°C

2.3 Immersion Corrosion Testing

A mixed salt was prepared by blending high-purity NaCl (99%, Thermo Scientific) and (99.9%, Kojundo Korea Co. Ltd). Salt mixing was performed in a glove box under a high-purity (99.9999%) argon (Ar) atmosphere equipped with a filtration system to control oxygen and moisture levels as shown in Fig. 1.

The 57 mol% NaCl – 43 mol% mixed salt was heated at 350°C for 48 hours, followed by a descaling process at 550°C for 2 hours using Mg chips to remove carbonates and moisture (i.e., and removal). During the test, the concentration was maintained below 20 ppm and the concentration below 2 ppm. After mirror-polishing the specimens, they were mounted in alumina crucibles suspended by alumina rods. The crucibles were sufficiently filled with the mixed salt powder to ensure the specimens remained completely submerged even if the salt melted or partially evaporated. Immersion corrosion tests were conducted in 57 mol% NaCl – 43 mol% molten salt at 650°C for durations of 100 and 700 hours. The weight change of the specimens was determined by the difference between the weight before immersion and the weight after removal from the molten salt and ultrasonic cleaning.

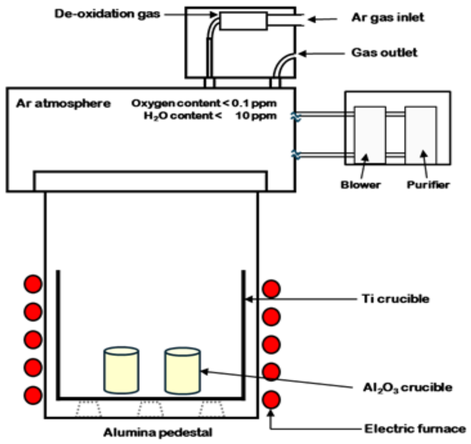

Fig. 1. Schematic of the molten salt immersion corrosion test apparatus.

3. Results and Discussion

The weight loss for the Type 316H stainless steel and the Inconel 625 coated specimens was 40.6 mg and 11.0 mg, respectively. However, the weight of the Ni-coated specimen actually increased after the corrosion test. This weight gain is presumed to be because the weight of solidified molten salt that remained on the surface despite cleaning was greater than the actual mass loss from corrosion.

When converting these results into corrosion rates, the rates for the Inconel 625 coated and uncoated specimens were approximately 0.18 mm/yr and 1 mm/yr, respectively as shown in Fig 2. Due to the weight gain, the corrosion rate for the pure Ni-coated specimen could not be measured. It was observed that the corrosion rate of Type 316H stainless steel was reduced to less than 1/5 due to the Inconel 625 coating, with a further reduction seen in the Ni coating.

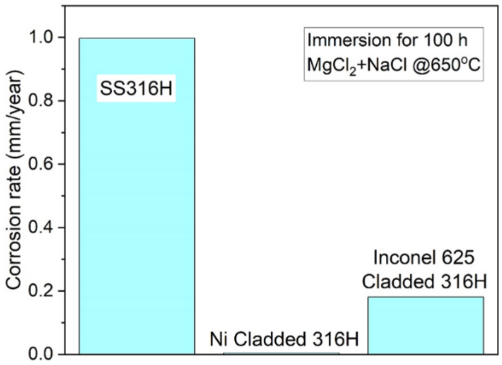

Fig. 2. Corrosion rate comparison after 100 h exposure.

The corrosion rates calculated after 700 hours of immersion are shown in Fig. 3. The corrosion rates for the Ni-sprayed specimen and the uncoated specimen were approximately 0.68 mm/yr and 1.2 mm/yr, respectively. The Inconel 625 coating was excluded from the 700-hour test because a visual inspection before the test revealed incomplete coating that exposed parts of the substrate. Notably, while no corrosion was observed on the Ni-coated specimen after 100 hours, it progressed during the 700-hour test to a rate more than half that of the uncoated specimen, though still slower.

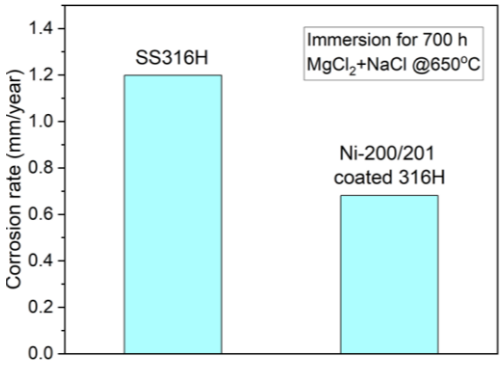

Fig. 3. Corrosion rate comparison after 100 h exposure.

Figures 4 and 5 show the cross-sections of the Ni and Inconel 625 coated specimens before the corrosion test. As seen in the figures, numerous voids were observed within the coating layers, and the interface between the coating and the substrate was significantly gapped. While the coating thickness was relatively uniform on the parallel sections, it was very thin—only a few tens of µm—at the corners.

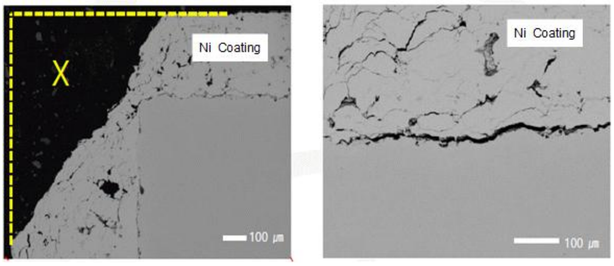

Fig. 4. Cross-sectional microstructure of Ni thermal-sprayed Type 316H stainless steel.

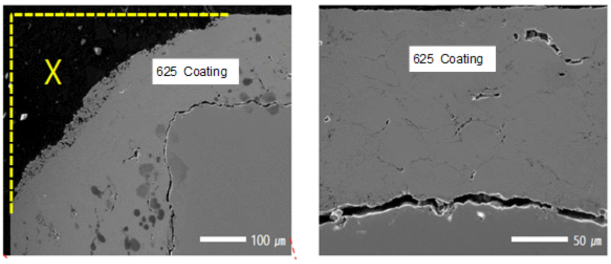

Fig. 5. Cross-sectional microstructure of Inconel 625 thermal-sprayed Type 316H stainless steel.

Based on these observations, it can be inferred that while the imperfect Ni coating layer successfully prevented corrosion for 100 hours, it gradually peeled off thereafter, largely losing its corrosion-reduction effect by the 700-hour exposure. In conclusion, these results indicate that when fabricating corrosion-resistant coatings using the HVOF process, precise spraying and optimization of process variables are required to form a dense coating layer free of internal defects for long-term effectiveness in molten salt environments.

4. Summary

The coated and uncoated Type 316H stainless steel specimens were subjected to immersion corrosion tests in a chloride-based mixed molten salt (57 mol% NaCl − 43 mol% $MgCl_2$) at 650°C for durations of 100 hours and 700 hours. The 100-hour short-term immersion test showed that the bare Type 316H stainless steel exhibited a corrosion rate of approximately 1 mm/yr, whereas the Inconel 625 coated specimen showed a significantly reduced rate of about 0.18 mm/yr. The pure Ni-coated specimen showed negligible weight change (or even a slight increase), confirming that the coating provides excellent short-term corrosion resistance. However, the 700-hour long-term immersion test revealed that the pure Ni-coated specimen's corrosion rate increased to approximately 0.68 mm/yr. Although slower than the bare specimen (approx. 1.2 mm/yr), this indicates substantial corrosion had occurred. Micro-structural analysis confirmed severe intergranular corrosion in the bare Type 316H stainless steel. While the Ni coating layer itself showed minimal corrosion, it was observed that molten salt penetrated the coating layer through multiple voids and imperfect adhesion at the coating/ substrate interface, leading to localized corrosion on the underlying Type 316H stainless steel substrate. The possibility of accelerated damage due to galvanic corrosion between the Ni coating and the substrate was also suggested.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (RS-2023-00261146).

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