Development of Low-Pressure Cold Spray Technique for Nuclear Piping Maintenance

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論文内容要約

Pipe damage would occur during nuclear power plant decommissioning due to corrosion, wear, fatigue, or other causes. To ensure the safe operation of the nuclear power plant, nuclear piping maintenance should be conducted. In this study, the low-pressure cold spray (LPCS) technique was proposed to maintain the nuclear piping. During LPCS, micro-sized particles (1–50 μm) are accelerated to a velocity of 300–600 m/s by a supersonic gas flow generated by a convergent-divergent nozzle (de Laval nozzle) to form a coating upon impact on the substrate surface. As the feedstock powder remains in a solid state throughout the process, unfavorable effects, such as high-temperature oxidation, thermal stresses, and phase transformation, observed in welding and thermal spray can be avoided. Additionally, the LPCS equipment is highly portable, making it ideal for on-site maintenance applications.

This thesis studied two prospective uses of LPCS in nuclear power plants that have previously received less attention, including active water leakage repair and underwater coating fabrication (chapters 2-3). These two investigations are involved in the water environment, which is a novel application of the LPCS technique. Additionally, the traditional LPCS system is difficult to spray stainless steel, the most common material for nuclear piping. Therefore, the LPCS nozzle was optimized for achieving a high-position efficiency of stainless steel (chapter 4). To prevent the inner wall of the pipe from corrosion, a nozzle of a spiral shape was designed to produce the fluoropolymer coating on the inner wall of the nuclear piping (chapter 5).

In chapter 1, the research background and objectives were introduced.

In chapter 2, the feasibility of applying LPCS to seal the active water leakage was explored. The feedstock used was mixed Sn/Zn powder. During repair, the spray gun was set above the water-leaking hole (diameter of 0.5 mm), and the water kept flowing inside the pipe. Several

influencing factors were studied, including powder mixing ratio, gas temperature, and gas pressure. Results demonstrated that the water-leaking hole could be sealed by the cold sprayed coatings within 10 s, although the water still flowed inside the pipe. Based on the results, the coating properties, including coating hardness, components, and thickness, have been detailly examined. To analyze the particle deposition behaviors, the velocity and temperature of the particles were calculated by computational fluid dynamics (CFD) simulations. Moreover, the microstructure of the interface between coating and substrate was observed using scanning electron microscopy to clarify the bonding mechanisms. Furthermore, the reliability of the repaired pipe was evaluated by the hydrostatic tests. The test pressure was 2.5 MPa, and the testing time was 24 hours. Results indicated that the water-leaking pipe repaired by LPCS could pass through the hydrostatic test. Therefore, the LPCS is a feasible technique for stopping leakage with high efficiency.

In chapter 3, the feasibility of using LPCS for manufacturing the Sn-Zn coating on the stainless steel substrates in the underwater environment was examined. Five influencing factors were investigated: water environment, traverse speed, gas pressure, temperature, and stand-off distance. Results demonstrated that the LPCS could be used to fabricate the Sn-Zn coating in the underwater environment. The water environment, traverse speed, gas temperature, and stand-off distance significantly influence the cold spray results. Particularly, the water-cooling effect and gas-water mixing medium generated during the spraying underwater hindered the particle deposition process, leading to a low deposition efficiency compared with the results in air condition. In addition, the coating properties, including the cross-sectional microstructure, deposition efficiency, surface roughness, and Zn ratio in the coating, were also analyzed. To investigate the influence of water film on the particle deposition process, the simulation of particle deposition with water film on the substrate surface was conducted. Results implied that particle size is another factor influencing the particle deposition process. This result demonstrated that LPCS is a feasible method for maintaining the nuclear piping underwater.

In chapter 4, to further improve the repairing strength, the LPCS nozzle was optimized for achieving a high-deposition efficiency of 304L stainless steel. The higher deposition efficiency could be obtained by increasing the particle velocity. Meanwhile, the ability of the LPCS system was confined by its low heater power. Therefore, the optimization strategy was constructed: increase the particle velocity under a certain power. The powder equation was derived from the one-dimensional isentropic analysis. Based on this equation, the throat diameter of the LPCS nozzle was optimized by

CFD simulations. Results demonstrated that reducing the throat diameter could significantly increase the particle velocity under a certain power until the powder feeding process was stopped. After that, the diameters of the transition section (between throat and outlet) and outlet were designed to increase the particle velocity further and guarantee the powder smoothly enters the nozzle. Results demonstrated that a proper transition section diameter could eliminate the main stream inflow into the power feeding pipe. At the same time, adjusting the outlet diameter could further increase the particle velocity. After optimization, the optimized nozzle was manufactured and compared with the conventional nozzle by cold spray experiments. Results show that the deposition efficiency of 304L stainless steel powder of the optimized nozzle is much higher than the conventional nozzle. Meanwhile, the power of the optimized nozzle is much lower than the conventional one. Therefore, the optimized nozzle is superior to the conventional nozzle, expanding the application range of the Dymet423 LPCS system.

In chapter 5, to prevent the inner wall from corrosion, the spiral nozzle was designed to coat the inner wall with Perfluoroalkoxy Alkane (PFA) coating by LPCS. The optimization goals were obtaining the maximum particle velocity under the premise of ensuring the particle could enter the nozzle through the Venturi effect. By just doing CFD simulation is challenging to realize these two goals simultaneously. As a result, the design method of combining CFD simulation with neural network (NN) was proposed to optimize the spiral nozzle. The influence of NN models and algorithms was studied. Results indicated that the NN with a minimum error was obtained when combining the *feedforwardnet* model with the *trainbr* algorithm (both *feedforwardnet* and *trainbr* are from MATLAB software). Meanwhile, the trained NN determined the relation between nozzle dimensions (i.e., mean coil diameter, spring lift angle, and expansion ratio) and performance (i.e., particle velocity and gas flux of the powder feeding pipe). Hence, the optimal spiral nozzle was achieved when inputting the design goals of maximum particle velocity and suitable gas flux of the powder feeding pipe into the trained NN. Furthermore, the effect of each nozzle dimension on the particle velocity and gas flux of the powder feeding pipe was systematically analyzed. The following cold spray experiment validated that PFA coating could be fabricated by the optimal spiral nozzle. This result demonstrated that a spiral nozzle is feasible for inner wall PFA coating fabrication.

In chapter 6, the conclusions of this thesis are summarized.

This thesis demonstrated that the LPCS could be used to seal the active water-leaking hole, fabricate the coating underwater environment, and coat the inner wall of the nuclear piping. It developed a new method for nuclear piping maintenance, expecting to facilitate the nuclear power plant decommissioning process.