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Surface Engineering Technologies to Mitigate Chloride-Induced Stress-Corrosion Cracking in Stainless Steel Dry Cask Storage Containments for Used Nuclear Fuel

Jinwook Choi[1], Kumar Sridharan[2], and Hwasung Yeom[1,*]
[1] *Pohang University of Science and Technology, 77, Cheongam-ro, Nam-gu, Pohang-si, Gyeongsangbuk-do 37673, Republic of Korea*
[2] *University of Wisconsin, Madison, 53705 USA*

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Interim dry cask storage systems comprising AISI 304 or 316 stainless steel canisters have become critical for the storage of spent nuclear fuel from light water reactors in the Republic of Korea. However, the combination of microstructural sensitization, residual tensile stress, and corrosive environments can induce chloride-induced stress corrosion cracking (CISCC) for stainless steel canisters. Suppressing one or more of these three variables can effectively mitigate CISCC initiation or propagation. Surface-modification technologies, such as surface peening and burnishing, focus on relieving residual tensile stress by introducing compressive stress to near-surface regions of materials. Overlay coating methods such as cold spray can serve as a barrier between the environment and the canister, while also inducing compressive stress similar to surface peening. This approach can both mitigate CISCC initiation and facilitate CISCC repair. Surface-painting methods can also be used to isolate materials from external corrosive environments. However, environmental variables, such as relative humidity, composition of surface deposits, and pH can affect the CISCC behavior. Therefore, in addition to research on surface modification and coating technologies, site-specific environmental investigations of various nuclear power plants are required.

Keywords: Dry cask storage system, Peening, Burnishing, Cold-spray coating

*Corresponding Author.
Hwasung Yeom, Pohang University of Science and Technology, E-mail: hyeom@postech.ac.kr, Tel: +82-54-279-9580

ORCID

Jinwook Choi	http://orcid.org/0009-0003-4454-3218	Kumar Sridharan	http://orcid.org/0009-0008-2237-1490
Hwasung Yeom	http://orcid.org/0000-0002-3798-2795		

1. Introduction

Management of spent nuclear fuel (SNF) is an increasingly important issue worldwide for the continued viability of nuclear power. Each year, a LWR generates several dozens of SNF assemblies, which contain radioactive elements. Many methods to recycle SNF or decrease their detrimental effects are being developed. Reprocessing is a common method to reuse SNFs by separating highly radioactive and useful materials. However, many of these reprocessing technologies have associated proliferation risks, and therefore most countries are forbidden to use these processes. Therefore, the proposed approach to reduce the hazards imposed by SNFs is interim storage in DCSS for a certain period and subsequently to store them in a hermetically-sealed, shielded containers for disposal in permanent geological repositories.

2. Status of SNF

2.1 Status of Domestic SNF

As of October 2023, twenty Nuclear Power Plants (NPPs) were operating and five NPPs were undergoing maintenance in the Republic of Korea. In the last quarter of 2023, 3,501 SNF assemblies were produced by light-water and heavy-water nuclear reactors. About 91% of light-water and heavy-water reactor wet pools (164,334 of 180,224) were occupied in 2023 [1]. Furthermore, permanent disposal facilities for SNFs are not even planned in the Republic of Korea, meaning that storage in wet pool and DCSS may have to occur for extended periods of time, perhaps decades.

Several attempts to reprocess or recycle SNF have been made in the Republic of Korea, but the Agreement for Cooperation Between the Government of the Republic of Korea and the Government of the United States of America Concerning Civil Uses of Atomic Energy limits any reprocessing or enriching of nuclear fuels without the discussion with the United States. As a result, all LWR SNFs in the Republic of Korea are still stored in wet-pool interim storage facilities.

2.2 Status of International SNF Management

Some nations that already possess nuclear weapons (e.g., France, Russia) have incorporated SNF reprocessing into this technology. The logic is that the risk of non-proliferation is a non-issue given that these nations already have nuclear weapons. However, for many countries such as Korea are not allowed to reprocess any SNF, so only available option is extended interim storage followed by permanent disposal in geologic repositories. No country is currently operating a permanent disposal site, but some have made significant advancements in this direction. For example, Finland [2] and Sweden [3] have made progress toward disposing of SNF. But for nations that are currently can neither reprocess nor permanently dispose of SNF, the only option is to keep the SNF in interim storage facilities for extended periods of time. On this account, most countries store SNFs in wet pools or in DCSS.

3. Interim Storage Systems

Typically, SNF is first stored in water pools until the SNF has sufficiently cooled, then moved to DCSS. This wet storage is accomplished in ‘wet pools,’ which are usually located at the nuclear power plant sites. In wet pools, light water is used to cool down the decay heat of SNFs. Wet pools have excellent cooling capacity due to the high specific heat of water. However, wet pools cannot be easily expanded to keep up with the continuous production of SNF. Furthermore, wet pools use liquid to cool the SNFs, so if the facility’s structure fails, it can lose its cooling capacity, resulting in attainment of criticality and severe accidents. Therefore, it is not feasible to store SNFs in wet pools until

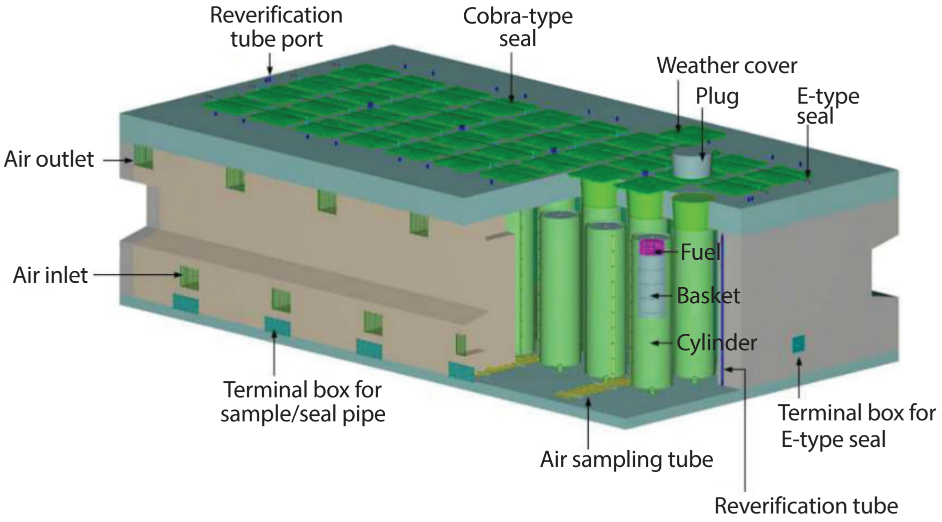

Fig. 1. MACSTOR/KN-400 dry storage module [28].

geologic disposal is available, but rather they should be moved to DCSS when the SNFs have cooled sufficiently to make this transition safely.

3.1 Dry Cask Storage System

DCSSs are cooled passively by natural air circulation, so storage safety is not at risk of any equipment failure. DCSSs for SNF storage have been used for several decades worldwide. In 2021, in the United States almost half of SNF was stored in dry inventory [4], and about 35% of all SNF storage worldwide is stored in dry casks [5]. In the Republic of Korea, since 2006, a high-density DCSS for pressurized heavy-water reactor (PHWR) called Modular Air-Cooled Storage (MACSTOR) has been in operation in addition to individual dry canisters. MACSTOR/KN-400 (21.9 m long × 12.9 m wide × 7.6 m tall) dry storage facility (Fig. 1) can store 24,000 CANDU SNF bundles (each 50 cm long × 10 cm in diameter) per module [6]. By contrast, a typical individual canister (3 m in diameter × 6.5 m high) in Wolsung NPPs can only hold 540 SNF bundles. The storing densities of these two types of systems are approximately similar when calculated as volumes, but canisters should be separated from each other by a minimum safe distance, and considering this distance, the total storage density is much higher in MACSTOR/KN-400 than in typical canisters. Currently, Doosan Enerbility and Korea Hydro and Nuclear Power (KHNP) are working on designing an on-site DCSS for light-water NPPs.

3.2 Characteristics of Dry Cask Storage Systems for LWR SNF

Numerous designs of dry storage casks have been used as shown in Fig. 2. A typical DCSS (e.g., VSC-24, HI-STORM 100, NAC-UMS, and MACSTOR) is composed of a stainless steel canister within a concrete overpack. SNFs are packed into the canister, which is then filled with a noble gas such as helium to expel water or oxygen which can cause corrosion, and also for transferring decay heat from SNFs to atmosphere efficiently. Cooling SNFs in these casks is achieved using air vents. The concrete overpack covering the stainless steel canister serves as an additional radiation shield and provides structural protection.

Some DCSSs (e.g., TN-24, MX-10, CASTOR V/21, and HI-STAR 100) are made completely of metal [7]. These metal casks can be used for transportation and storage (i.e., dual-purpose canister) and even sometimes for

Fig. 2. Schematic illustrations of various dry storage cask designs [29].

disposal (i.e., multi-purpose canister), without the need to move SNFs to other containers. However, cooling SNFs in metal casks are achieved using external cooling fins, which cannot sufficiently cool a large amount of SNF. Also, metallic casks are more expensive than to concrete casks [5].

Other cooling designs such as vaults and silos, are also being used. They are immobile, so they are used in centralized storage systems [8]. On the other hand, the casks are transportable, and therefore more amenable for on-site interim storage.

4. Chloride-Induced Stress Corrosion Cracking in Stainless Steel Canister

Most dry storage systems have an inner metal canister. To confine radioactive material over several decades, these canisters must maintain their structural integrity. The canisters are made of AISI 300-series stainless steels, which have high rigidity and good corrosion resistance. However, under certain conditions, these stainless steels can become susceptible to chloride-induced stress corrosion cracking

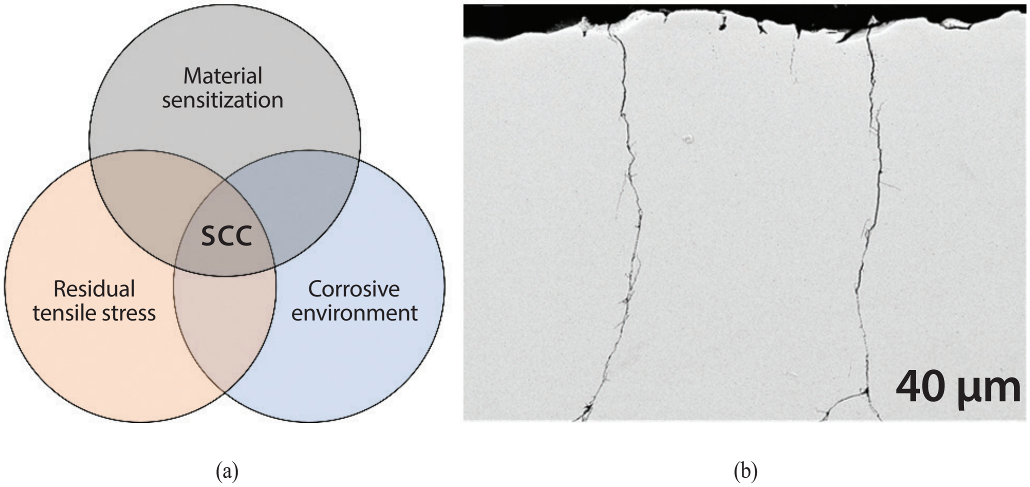

Fig. 3. (a) Three conditions of stress corrosion cracking, (b) CISCC on stainless steel 304 L [25].

(CISCC), which can compromise the integrity of the canisters due to the formation of through-cracks. These cracks typically initiate at corrosion pits, and they can greatly reduce the operational lifetime of DCSS. It should be noted here that CISCC have not been identified or detected in any of the operational canisters, but cautionary and remediation measures must be in place should it occur over the long-term storage.

CISCC can occur when three conditions are met: (1) the material and its microstructure are susceptible, (2) the environment is rich corrosive species such as chloride ion (Cl^-), and (3) the canister material is under tensile stress. The combination of these three preconditions can initiate CISCC as schematically illustrated in Fig. 3(a). Heat Affected Zone (HAZ) in welds created during fusion-welding processes in canister manufacture can yield both a susceptible microstructure and a region of tensile stress. Fig. 3(b) shows prototypical CISCC intentionally induced in a laboratory by imposing the three aforementioned conditions.

Susceptibility: Stainless steels 304/304 L and 316/316 L which contain ~18 to 20wt% or 16% to 18% chromium (Cr), respectively are widely used for manufacturing dry cask storage canisters. These stainless steels derive their inherent corrosion resistance from the formation of a thin passive film of chromium oxide on their surface. However, during fusion welding involved in the manufacture of canister, using processes such as the gas tungsten arc welding (GTAW), the heat affected zone (HAZ) in the vicinity of the weld pool gets sensitized [9]. Sensitization refers to segregation of Cr and carbon to the grain boundaries to form Cr-rich carbide phase, which leaves a Cr depleted region in the vicinity of the grain boundaries with substantially decreased corrosion resistance. This region becomes vulnerable to corrosion, particularly pitting corrosion, and eventually CISCC.

Corrosive environment: Various corrosive anion species in the environment can cause SCC, but the Cl^- ion is considered to be particularly destructive to the protective passive oxide film on the stainless steel surface. The Cl^- ion is of particular concern given its abundance owing to the vast oceanic coastline of Korea. Corrosion initiates at the anodic sites near the Cr-depleted regions in the vicinity of the grain boundaries while the rest of the surface becomes a cathode, creating the electrochemical cell required for corrosion. Corrosion due to Cl^- ions breaks through the passive oxide film leading to non-uniform corrosion or pitting, where cracks can potentially nucleate in the presence of tensile stress.

Tensile stress: The tensile stresses in the canister can originate from two sources. One contribution comes from the pressure (1 to 6 atm) within the canister. This pressure can cause development of hoop stress (tensile stress along circumferential direction) on the canister, but this stress is usually relatively small [10]. The second contribution is more significant, coming from the manufacturing process itself. During fabrication process of the canister, the stainless steel plates are cold-rolled into a cylindrical shape, followed by joining the welds longitudinally to form a cylinder. The circular end pieces are then welded circumferentially into the ends of the cylinder to make a container. During welding, at the shrinkage of the molten metal during solidification generates tensile stress between the two sides of the welded point, and this stress remains in the material even after the fabrication process is complete.

5. Mitigation and Repair Technologies for CISCC

CISCC initiation can be prevented by suppressing one or more of the three preconditions outlined above. If the material is not susceptible, the passive chromium oxide film effectively prevents the initiation of pitting corrosion on a substrate. If the environment is not rich in Cl^- (i.e., not corrosive), corrosion cannot occur. If residual tensile stress is not present, pits cannot transition to cracks and then propagate. Numerous techniques that are able to effectively mitigate CISCC initiation and propagation have been reported (Table 1). They suppress one or more of the three preconditions for CISCC. Research on some of these treatments for stainless steel canisters in DCSS is presently being conducted by Electric Power Research Institute (EPRI) in the United States [11].

5.1 Surface Peening

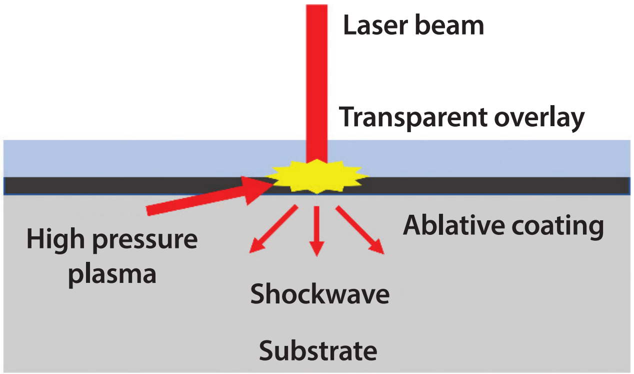

Fig. 4. Schematic illustration of laser shock peening.

Surface peening is a mechanical surface modification treatment that reduces the residual tensile stress or induces a net compressive stress in the substrate material. Many peening methods have been developed over the years and some of them are briefly outlined below.

5.1.1 Shot peening

In this method, small solid balls propelled by compressed air or a centrifugal blast wheel strike the substrate repeatedly. The impacts generate a thin layer of intense plastic deformation on material surface, and concurrently impose compressive stress that counteracts the residual tensile stress. As a result, the driving force for pit-to-crack transition is reduced. The process is quite simple and economical and amenable to onsite operation.

Shot peening with iron-based amorphous powder on cold-rolled, laser-welded AISI 304 L and AISI 316 L U-bend specimen can help to form dispersed micro-pits instead of large aligned corrosion pits, after 672 h of salt spray SCC test with 10% NaCl, at 80°C, based on ASTM E290 specification. The maximum residual stress of as-welded specimen was about 200 MPa in tension, at 0.02 mm depth. However, peak residual stress of the shot-peened specimen changed into over −800 MPa in compression for 316 sample and −1,100 MPa in compression for 304 sample [12].

5.1.2 Laser-shock peening

Laser-shock peening (LSP, Fig. 4) entails bombarding the substrate surface by using short pulses of coherent light, and no physical projectiles as in conventional shot peening are involved. Therefore, there are not only less mechanical damage to the surface, but also inducing deeper compressive stress. The substrate is usually first coated with a laser coupling ablative layer (e.g., carbon tape, paint) which decreases the damage that laser pulse heating can cause to the metal surface. Then a transparent overlayer (e.g., water, glass) is applied to cover the ablative layer to confine the plasma pressure during the process. When the surface of the substrate is subjected to a high-peak power laser pulse, it generates high-temperature plasma, which expands rapidly to form a shockwave. The transparent overlayer restrains outward expansion of plasma so that the shockwave is directed toward to the substrate. The shockwave introduces plastic deformation and compressive stress which is much higher than the shot peening in the near-surface region of material surface, and thus reduces the net residual tensile stress. Also, because the plasma is generated at the spot that the laser focused, the peening processing can be performed only at the desired point. So LSP has an advantage of selective, precise treatment on specific area, such as fatigue-intense region or HAZ over traditional mechanical peening techniques.

The improvement in SCC resistance of AISI 304 stainless steel by LSP was demonstrated in a couple of studies. The pitting potential increased from 222 mV to a maximum of 400 mV, and the average size of pits on the treated surface decreased as the pulse energy was increased from 0 J to 12 J [13]. In another study, U-bend SCC test based on ASTM G36 (42% $MgCl_2$ solution at boiling temperature of 155°C) and 65% HNO_3 immersion test at boiling point by modified ASTM A262, with GTAW welded AISI 304 L stainless steel and the sample with LSP. It showed that LSP can decrease the average grain size from 23.7 μm to 16.6 μm in base metal and 26.0 μm to 19.2 μm in HAZ, leading to a mitigation of total crack time from 3 h to 6 h. The crack propagation rate has decreased. However, unlike previous study, the pitting corrosion resistance (i.e., pitting potential) of the surface was decreased after the peening due to the surface roughness [14].

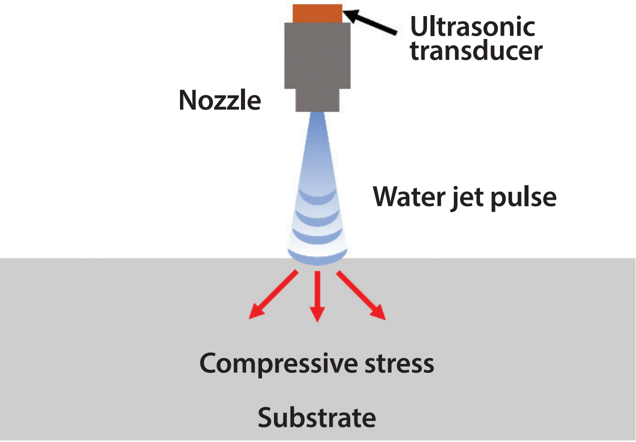

Fig. 5. Schematic illustration of pulsed water jet peening.

5.1.3 Pulsed water jet peening

Pulsed water jet peening (PWJP) is similar to shot peening, but uses water as a projectile. By combining a high-pressure water jet and ultrasonic transducer, the ultrasonic waves create cavitation in the water jet stream that make pulsated pressure wave of specific period. This pulsated water jet applies a hammering effect onto the material surface, inducing small plastic deformations which develop compressive stress counteracting to residual tensile stress (Fig. 5). As other peening methods, PWJP can improve corrosion, fatigue resistance and surface hardness. Also, PWJP has some economic and environmental advantages because it does not use other peening tools (e.g., pins, balls) but water. It has been shown that PWJP treatments on AISI 304 stainless steel welded joints can alleviate surface residual tensile stress, improve surface roughness, and increase surface hardness. However, because disintegration of the material at a very low traverse speed and lower relieving effect at higher pressure has been reported, maintaining major control variables such as water pressure, nozzle diameter, peening angle in appropriate range is important during PWJP [15].

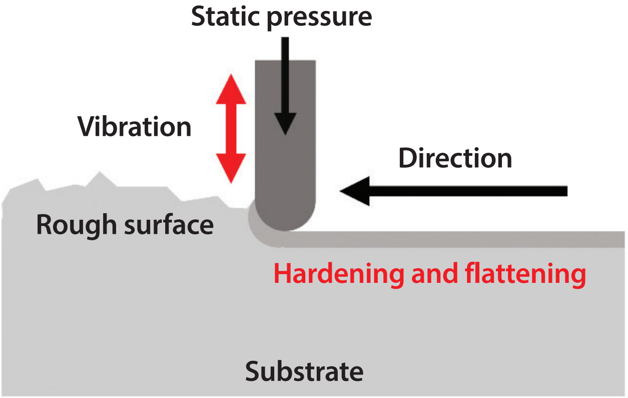

Fig. 6. Schematic illustration of ultrasonic nanocrystalline surface modification (UNSM).

5.1.4 Ultrasonic nanocrystalline surface modification (UNSM)

UNSM uses ultrasonic vibrations and static load simultaneously to introduce plastic deformation on in the near-surface regions of the materials [16]. While a static load is applied to the substrate, a high-frequency and low-amplitude ultrasonic vibration is applied using a tungsten carbide tip on the sample surface (Fig. 6). This arrangement causes severe plastic deformation of the material resulting in nanocrystalline structure [17]. These refined nanocrystalline structures act as obstacles of dislocation slip, improving surface strength, hardness, and fatigue resistance. It is shown in a study that UNSM treatment at room temperature can not only improve corrosion resistance, but also decrease roughness and increase hardness [18].

Previous research has shown that UNSM of 304 stainless steels increased pitting corrosion resistance. The UNSM-treated specimen showed higher pitting potential than untreated samples. Furthermore, the passivation film of the UNSM-treated specimen showed higher Cr concentration and lower Cl^- concentration than the untreated specimens [19]. On the other hand, another study performed combined slow strain rate test (SSRT) (ASTM G129-00 standard) and electrochemical test with 1 M H_2SO_4 (pH 0.2) electrolyte containing 5wt% NaCl to imitate harsh corrosive environment. This experiment showed that the corrosion current density of UNSM treated sample is 398 $\mu A \cdot cm^{-2}$, which is two orders of magnitude higher than the as-received sample, 3.94 $\mu A \cdot cm^{-2}$. It indicated the UNSM treated sample surface was more susceptible to pitting corrosion because the decrease of grain size (i.e., the increase of the grain boundary density) made the sample surface more active [20]. In short, the controversial results should be reexamined by additional experimental researches.

5.2 Burnishing

Burnishing is a type of surface mechanical treatment in which static load is applied to the metal's surface by balls or rollers. Burnishing uses only static load rather than a combination of ultrasonic vibration and static load as in the case of UNSM. Burnishing can induce severe plastic deformation of the surface, thereby creating a compressive stress that counteracts the tensile stress. Burnishing also uses uniform pressure and continuous plastic deformation with rotatable balls and rollers, so unlike many of the peening treatments, burnishing decreases surface roughness.

Research related to burnishing is being conducted at Korea Atomic Energy Research Institute (KAERI) [21]. Additionally, a study of turning with slide burnishing (TSB) on AISI 304 and 316 L demonstrated that the severe residual tensile stress, induced during the turning process (ranging from 288 MPa to 788 MPa in the machining direction and 245 MPa to 976 MPa in the perpendicular direction), can be effectively relieved. This relief is dependent on TSB parameters such as penetration depth, feed rate, and spindle speed. Furthermore, TSB could simultaneously develop higher surface hardness, lower surface roughness, grain refinement, and martensitic transformation [22].

5.3 Polymer or Ceramic Coatings

Coating with polymers such as epoxy, polyurethane, polyethylene (PE), and polyvinyl chloride (PVC) may be

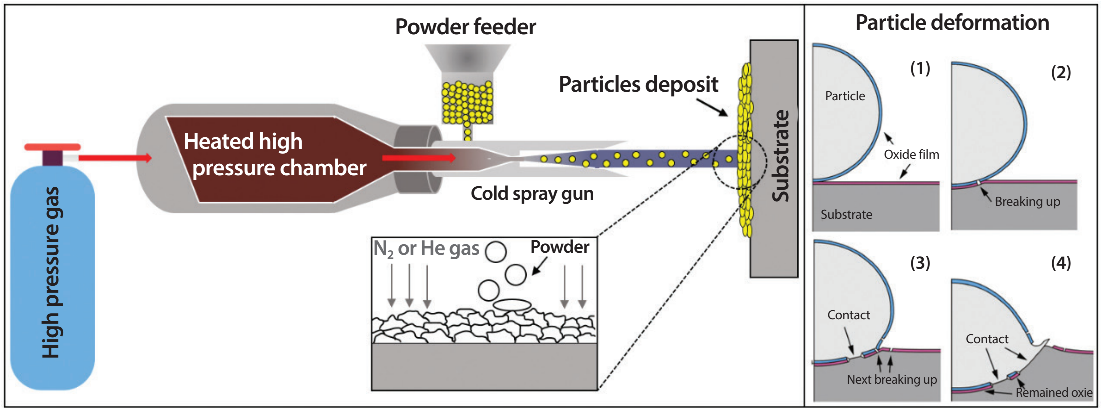

Fig. 7. Schematic diagram illustrating the cold spray coating process.

a way to prevent CISCC initiation [10]. These polymers develop effective, tough and high durability physical barriers composed of lengthy-chain molecules. A paint coating that contains reagent-grade polyaniline (PANI) on carbon steel can form a stable Fe_2O_3 layer between PANI coating and the surface of the substrate, and this coating can mitigate corrosion [23]. Nevertheless, polymer coatings are not preferred for DCSS because polymers can be degraded by radiation exposure (ultraviolet radiation and gamma-rays). Most DCSS are built outdoors, where they are exposed for several decades to sunlight and the radiation from the SNF itself. In this harsh environment, most polymers can decompose and lose its integrity.

Use of ceramic coatings can be an option. Oxide coatings produced by sol-gel methods can effectively prevent corrosion by restricting the interaction between the metal surface and corrosive ions. These coatings are also remarkably resistant to radiation. However, ceramics are brittle and have high melting temperature, so they cannot be easily deposited onto the surface of canister. Instead, special coating techniques like the sol-gel method, chemical vapor deposition or hydroxylation-condensation chemical reactions can be alternative options to develop ceramic coatings. However, these coating processes requires relatively high temperatures to initiate the chemical reactions, which would alter the microstructure of the substrate.

5.4 Cold-Spray Coating Deposition

Cold-spray deposition is a high-velocity, solid-state, powder spray coating technology where in powder particles of the coating material are propelled by a gas at supersonic velocities onto the surface of a substrates (the canister weld region in this case) via a specially designed nozzle, where upon impact the particles deform and form a coating. Coating formation occurs by high strain rate plastic deformation and associated adiabatic shear of the particles (Fig. 7). The process is conducted at ambient temperatures and pressures with not only high deposition rates, but also a low thermal input into the substrates. All of which are significant attributes of this technology for the DCSS application. Cold spray coatings are in a compressive stress state which is beneficial from the standpoint of CISCC initiation and propagation. Cold-spray coatings also provide a physical barrier that separates the substrate from the corrosive environment.

Cold spraying of SS304 L feedstock powder on SS304 L substrates welded using tungsten inert gas (TIG) and SS308 L filler yielded increase in the time required for through-cracking, from 17 hours in an uncoated sample to > 552 hours in accelerated tests [24]. Cold spraying of 20 – 45 μm sized 304 L feedstock powder onto 304 stainless steel substrates showed that cold-spray coatings

Table 1. Summary of recent research on surface-engineering methods relevant to DCSS

Method	Materials	Surface engineering condition	Findings	Ref.
SP	Stainless steel 304 L, 316 L	Shot-peened with iron-based amorphous powders under 200% surface coverage	Microcracks and pits are formed rather than coarse pits in the salt spray tests; maximum residual stress of sample changed from 200 MPa into −800 MPa for SS316, −1,100 MPa in compression for SS304	[12]
LSP	Stainless steel 304	Nd-YAG Laser (λ = 1,064 nm, *E* = 3, 6, or 12 J)	Pitting potential increased from 222 mV to 400 mV	[13]
	Stainless steel 304 L	Nd-YAG Laser (Energy *E* = 4.4 J)	Crack initiation time delayed from 1.5 h to 3 h	[14]
PWJP	Stainless steel 304 welded joints	Operating frequency = ~20 kHz, pressure and traverse speed (a) 20 MPa and 2 mm·s^{-1}; (b) 40 MPa and 4 mm·s^{-1}; (c) 60 MPa and 6 mm·s^{-1}	Enhancement of compressive residual stress by PWJP from initial maximum principal stress −67 MPa in welded region (WR) and −122 MPa in HAZ to (a) −332 MPa in WR, −449 MPa in HAZ; (b) −281 MPa in WR, −351 MPa in HAZ; (c) −301 MPa in WR, −397 MPa in HAZ	[15]
UNSM	Stainless steel 316 L	Vibration frequency = 20 kHz and amplitude = 30 μm; static load = 3 N. UNSM treatment with WC ball tip at 24 or 400℃	Toughness and hardness were improved, but corrosion resistance degraded when UNSM-treated at high temperature	[18]
	Stainless steel 304	Vibration frequency = 20 kHz and amplitude = 8 μm; static load = 2 kg. UNSM treatment with WC ball tip	UNSM-treated SS304 showed higher repassivation potential, and contained more Cr and less Cl^{-} in passive film	[19]
	Stainless steel 304	Amplitude = 16 μm and spacing = 10 μm; static load = 20 N; UNSM treatment with WC ball tip and no thermal treatment after UNSM	UNSM treated SS304 showed two orders of magnitude higher corrosion current density, but the corrosion potential did not change; UNSM treatment improved mechanical properties but allowing the higher corrosion susceptibility	[20]
Burnishing	Stainless steel 304 and 316 L	a) turning parameters: cutting speed, cutting depth, and cutting width b) TSB parameters: spindle speed, penetration depth, feed rate, and number of passes	The residual tensile stress ranged from 288 MPa to 788 MPa in the machining direction and 245 MPa to 976 MPa in the perpendicular direction.	[22]
Polymer coating	Carbon steel and Polyaniline (PANI)	Pickled and coated with PANI-containing paint, composed of vinyl resin binder and polyaniline pigment	Polyaniline aided ferrous oxidation to form stable Fe_2O_3 layer between PANI coating and steel surface	[23]
Cold spray coating	Stainless steel 304 L substrate and 16 to 44-μm commercial-grade gas-atomized SS304 L powder	Cold spray on TIG welded SS304 L substrate, with SS308 L filler, preheated to 430°C, propellant gas pure He at 3.62 MPa	Corrosion time before through-cracking improved from 17 h to > 552 h	[24]

Method	Materials	Surface engineering condition	Findings	Ref.
Cold spray coating	Stainless steel 304 substrate and 20–45 μm size stainless steel 304 L powder	Cold spray with propellant gas: pure N_2 at 750°C, 1:1 vol ratio N_2/He at 550°C or 1:3 vol ratio N_2/He at 550°C; all pressures 4 MPa	Increasing particle velocity reduced porosity levels, and cold spray coating could repair pre-existing cracks and mitigate further generation	[25]
	Carbon steel and commercial grade pure titanium feedstock powder	Cold spray with N_2 propellant gas at 600°C or 800°C and 4 MPa; comparison group heat treated at 1,050°C, 60 min	Higher spraying temperature showed less porosity and corrosion current density, and heat treatment could reduce interparticle voids and pore spheroidization	[26]
	5 mm thickness stainless steel 316 substrate and Inconel 718, stainless steel 410 mixed feedstock powder	Cold spray with N_2 propellant gas at 700°C and 4 MPa; comparison group heat treated at 1,200°C, 6 h	Even a large amount of SS410 particles was mixed with IN718 powder, SS410 did not deposit in the coating and rather coating porosity and microstructure defects were improved, and heat treatment reduced interparticle pores	[27]

repaired pre-existing cracks and mitigated crack growth in the underlying substrate [25]. This study also showed that the presence of a surface oxide layer on the substrate did not affect the efficacy of cold spray deposition. The cold spray process is considered as a promising measure for crack repair of the DCSS where thin oxide surface layers or other corrosion product layers may have developed on the canister surface after long term use. Cold spraying of pure titanium powder on carbon steel samples, using preheated N_2 gas achieved reduced porosity in coating layers when the gas was 800°C than when it was 600°C [26]. Also, the corrosion current density was an order of magnitude smaller when the titanium cold spray was at 800°C than at 600°C.

Cold spraying of a mixture of Inconel 718 powder (which has relatively high hardness) and stainless steel 410 powder on SS316 plates, using N_2 at 2.5 MPa as propellant gas that had been preheated to 700°C imparted an in-situ hammering and plastic deformation effect, which reduced the number and size of pores in the coating [27]. These experiments demonstrate the potential feasibility of dual metal cold spray coatings for CISCC mitigation.

Table 1 summarizes some of the recent surface modification and coating methods that have been investigated for DCSS application.

6. Conclusions

Since permanent geological repository for SNF has not been conclusively identified in the Republic of Korea, used nuclear fuel from the reactor will have to be stored in interim storage sites, predominantly in DCSS. DCSS consists of an inner 300-series stainless steel canister, being prone to CISCC in the HAZ of fusion welds due to its sensitized microstructure, the presence tensile residual stresses caused by weld solidification shrinkage, and corrosive environmental species such as Cl^- that is present in oceanic coastal areas. The paper has reviewed some key technologies that are at the forefront of investigation for the mitigation and repair of CISCC and identified their merits and drawbacks. These include peening technologies, such as shot peening, laser shock peening, pulsed water jet peening, and UNSM as well as the well-known cold spray technology. The technologies rely on inducing compressive stresses in the near surface regions of the canister to offset tensile stresses and/

or creating a physical barrier coating that seals the crack from the external corrosive environment, thereby preventing the progress of CISCC. It should be made clear that no CISCC events have been identified or detected in actual DCSS canisters, the long-term storage of SNF in DCSS warrants the development of these technologies as contingency measures to guard against occurrence of CISCC in the future.

Also, to apply the surface modification technologies or coatings to nuclear power plant components (or DCSS), its standard should be approved by the American Society of Mechanical Engineers (ASME) Code Case. The U.S. Nuclear Regulatory Commission (U.S. NRC) approved inspection relief of surface-modified facilities (according to ASME Code Case N-729-5, ASME Code Case N-770-4 and MRP-335-3A). While the technical basis and performance criteria and requirements (PCRs) are being developed for ASME Section III Code Case, the standard of material and mechanical properties after surface modification for DCSS has not been declared yet.

Finally, in the Republic of Korea, few studies of cold-spray and surface peening technologies have been performed for the DCSS application, so experimental data for their licensing and implementation are insufficient at present. Due to the urgency of deployment, Korea is planning to use AISI 304 L for DCSS canister (rather than AISI 316 L). Since AISI 304 L is more susceptible to CISCC than AISI 316 L, additional surface modification technologies are important to achieve a high reliability and safety. Cold spray deposition is one of the most promising technologies of surface modification because of its superior corrosion resistance and repairability, coming from suppressing residual tensile stress and forming solid, rigid coatings on the surface. Not only that, cold spray deposition can be applied to in-situ coat and repair since it does not require any high temperature.

In order to prepare for global competitiveness of the Korean DCSS, and to ensure the long-term viability of LWRs, societal acceptance, and effective management of SNF, it is crucial to support the Code Case establishment with our experimental data. This case should define standard properties for cold spray deposition coatings, including coating adhesive strength, coating density, minimum thickness, surface roughness, and pore density.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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