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Article

The Code Case N-931 and Ultrasonic Nanocrystal Surface Modification Technology for Improving Service Life and Safety of Nuclear Power Plant

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Abstract: We are trying to apply surface stress improvement process (SSIP) to the repair and maintenance of nuclear power components, mainly in the United States and Japan. A representative example is applying water jet peening (WJP) and laser peening (LP) technology to parts to extend their lifespan. The biggest problem with the lifespan of nuclear power equipment is the occurrence of stress corrosion cracking (SCC), which is directly related to safety. The SSIP is one of the good ways to mitigate SCC. The Code Case N-931 "Performance and Qualification Criteria for Mitigation of Stress Corrosion Cracking by Surface Stress Improvement: Section III, Division 1 and 3' was developed since 2017 by the task group "Advanced Surface Stress Improvement Technology" in Korea International Working Group (KIWG) of the American Society of Mechanical Engineers (ASME). This case provides performance and qualification criteria for the pre-service application of a SSIP to items potentially susceptible to SCC, as a means to prevent crack initiation. Mitigation of items to the requirements of this case does not modify or change the in-service inspection (ISI) requirements for those items. This Code Case is to be used for SSIP such as ultrasonic nanocrystal surface modification (UNSM), WJP, LP that satisfy the performance criteria and qualification criteria defined in this case. Two major technical bases for this Code Case are "PVP2022-85151" and "EPRI Report 3002018458". Brief summary of UNSM technology and two technical bases is introduced.

Keywords: ASME Code Case, surface stress improvement process (SSIP), ultrasonic nanocrystal surface modification (UNSM), stress corrosion cracking (SCC), small modular reactor (SMR)

1. Introduction

ASME, as the American Society of Mechanical Engineers, is a certification body for standardization in the mechanical field. ASME Code Cases is a certification procedure for early implementation of approved code revisions or urgent replacement rules for materials, construction, or in-use inspections that are not covered by the existing boiler and pressure vessel code regulations. ASME Code cases are effective upon ASME approval [1].

SMR stands for small modular reactor, a type of advanced nuclear-fission reactor that has a power generation capacity of up to 300MW per unit. SMRs are considered as a promising technology for providing low-carbon energy in remote areas or off-grid applications [2]. SMRs have gained significant attention in recent years due to several compelling reasons: SMRs can provide flexible and sustainable solutions to a changing world through flexibility and scalability, enhanced safety, reduced capital costs, market diversity, hybrid applications, etc. [3]. However, SMRs have several challenges that can hinder its development and deployment. There are issues such as licensing and regulation, economics and finance, nuclear waste and proliferation, etc. [4]. Also, SMRs present unique challenges related to materials due to their compact design and specific operating conditions. In order to improve the lifespan and ensure reliability of SMRs, material properties such as heat resistance, excellent radiation resistance, and corrosion resistance are required [5].

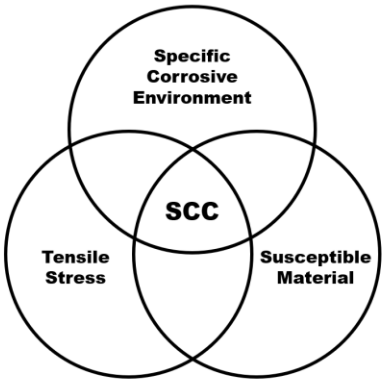

Figure 1. Stress Corrosion Cracking Venn Diagram.

Stress corrosion cracking (SCC), as shown in Figure 1, is the most vulnerable part for the life of nuclear power plant equipment. SCC occurs only when these three conditions are satisfied simultaneously: 1) susceptible material, 2) tensile stress, and 3) corrosive environment [6]. Work to apply surface stress improvement processes (SSIP) to mitigate SCC started from Korea International Working Group (KIWG) in 2017. Ultrasonic nanocrystal surface modification (UNSM) technology is one of the SSIP technologies, and the SSIP technology meets the performance and qualification criteria for SCC mitigation, and ASME Code Case N-931 has been approved. This code example is based on PVP2022-85151 [6] and EPRI Report 3002018458 [7] and introduces this underlying technology and UNSM technology.

2. Surface Stress Improvement Processes

The SSIP available for ASME Code Case N-931 are UNSM, water jet peening (WJP), laser peening (LP) technologies, and characteristics of the technologies are shown in Table 1 [8-12].

Table 1. Characteristics of SSIP available in ASME Code Case N-931

Contents	WJP	LP	UNSM
Mechanism	Shockwave		Resonance/Continuous Contact
Source of Impact	Cavitation Bubble	Laser Ablation	Solid Ball/Tip
Source of Energy	Water Jet	Pulse Laser	Ultrasonic Vibration
Contact Pressure and Impulse	~10 GPa Kinetic	~12 GPa Kinetic	~30 GPa Static and Dynamic
Contact Numbers Controllability	Random Process		Deterministic Control
Surface Compressive Residual Stress (CRS)	~1.0 GPa		~2.0 GPa
Effective Depth of CRS	More than 1 mm		
Surface Hardness	Increase The effective depth is shallower than the effective depth of CRS		
Surface Roughness	Rougher		Smoother
Nano Structure Nano Twin	Nano Grain Refinement		

2.1. UNSM technology

The main concept and mechanism of UNSM technique are shown in Figure 2 [13]. A tungsten carbide ball attached to an ultrasonic device that strikes the surface of a work-piece 20,000 or more times per second with 1,000 to 100,000 shots per square millimeter. These strikes, which can be described as micro cold-forging, bring severe plastic deformation (SPD) and elastic deformation to surface layers and thus generate nano-crystalline structure. This nano-structural modification of the surface layer can improve both the strength (hardness) and ductility (toughness) of the work-piece simultaneously according to the well-known Hall-Petch theory [14, 15]. This process also improves surface integrity, increases surface hardness, produces micro-dimples, and induces compressive residual stress in surface layers. The UNSM effects and their anticipated benefits are summarized in Table 2 [13, 16, 17].

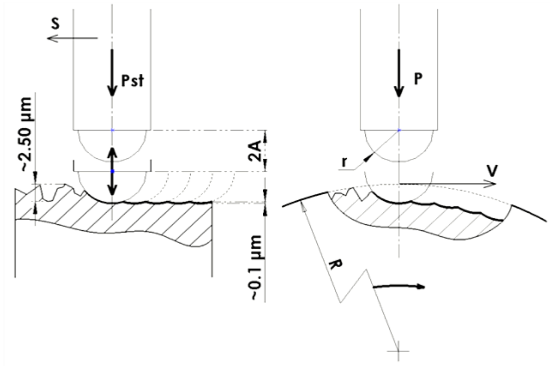

Figure 2. Mechanism of ultrasonic nanocrystal surface modification.

Table 2. The effects of UNSM treatment and their anticipated benefits

Effects of UNSM treatment	Anticipated benefits
Deep compressive residual stresses (Greater than 1,000MPa into depths of more than 2,000μm)	Improved LCF and HCF endurance limit Improved rolling contact fatigue strength Improved stress corrosion cracking resistance
Micro dimples surface (Area: 1-2μm^2, Depth: submicron, Pattern pitch: few μm)	Reduced surface roughness Decreased friction coefficient Reduced wear rate
Increased hardness (into depths of more than 1,500μm)	Reduced wear rate Improved LCF and HCF endurance limit
Nano-crystalline structure (Grain sizes of 50-200nm into depths of 100μm)	Increased tensile strength and hardness Increased fatigue strength Increased wear resistance

2.2. WJP technology

The WJP process utilizes cavitation bubbles to produce a shockwave which is generated in a submerged water jet as shown in Figure 3 [18, 19]. The cavitation bubbles are produced by the strong shear force that acts on the boundary between the high-speed jet and the surrounding stationary water, and the bubbles are carried by the high-speed water jet to the material surface. The collapse of the cavitation bubbles generates a large shock pressure more than 1 GPa that causes local plastic deformation.

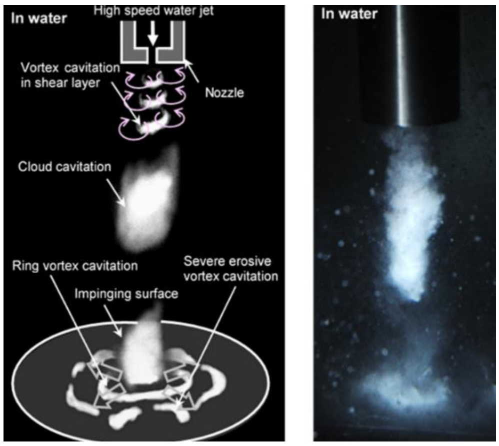

Figure 3. Mechanism and actual operation of water jet peening.

2.3. LP technology

The physical principle involved in laser peening treatment (also known as laser shock peening (LSP)) is considered to be an energy conversion procedure from a laser to shock wave that results in material plastic deformation by pressure of several GPa. After the passage of the shockwave, the permanent strain remains and the surrounding metal material constrains the strained region as a reaction to elastic strain, thus forming a compressive residual stress on the metal surface [20, 21].

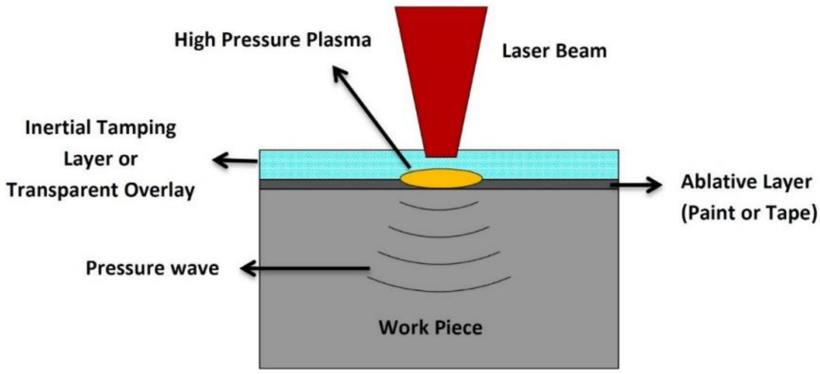

Figure 4. Mechanism of laser shock peening.

3. Development of a ASME Code Case for Application of SSIP

The detail contents of this ASME Code Case had been developed by the task group "Advanced Surface Stress Improvement" in KIWG of ASME from 2018 to 2023. The detailed history of this development was recorded in record number 19-1510 of ASME Codes and Standards connect in ASME. The contents of the developed ASME Code Case N-931 are shown in Table 3 [22].

Table 3. ASME Code Case N-931

ASME Code Case N-931: Performance and Qualification Criteria for Mitigation of Stress Corrosion Cracking by Surface Stress Improvement: Section III, Division 1 and 3	
Inquiry: What requirements may be used for performance and qualification criteria of surface stress improvement processes (SSIP) to mitigate the potential for stress corrosion cracking (SCC) for Section III, Division 1 and 3 items? **Reply**: It is the opinion of the Committee that the following requirements may be used to qualify surface stress improvement processes used to mitigate stress corrosion cracking for Section III, Division 1 and Division 3 items.	
1000 Scope	This Case provides performance and qualification criteria for the pre-service application of a surface stress improvement process (SSIP) to Section III Division 1 and 3 items potentially susceptible to SCC, as a means to prevent crack initiation. Mitigation of items to the requirements of this Case does not modify or change the in-service inspection (ISI) requirements for those items.
1100 Item Applicability	The following items may be subject to application of a SSIP a) Items with base material potentially susceptible to SCC due to environmental conditions that have been identified in the Design Specification, as required by NCA-3211.19(b) (Division 1) or by WA-3351.2 (Division 3). b) Items with weld material potentially susceptible to SCC due to tensile residual stresses caused by weld repairs at the wetted surface. Paragraphs NB-4451, NCD-4451, and NG-4451 prohibit weld repairs on the wetted surface of items susceptible to SCC unless a mitigation action is applied.
1200 Surface Stress Improvement Processes	This Case may be used for surface stress improvement processes such as ultrasonic nanocrystal surface modification, water jet peening, or laser peening that satisfy the performance criteria and qualification criteria defined in this Case.
1300 Examination Sequence	The provisions of NB-4422(b), NCD-4423.3(b), and NG-4422(b) state that surface stress improvements shall be performed after examinations required by NB/NCD/NG-5000 are completed. However, the required preservice examinations/ inspections (PSI) specified by Section III shall be performed after application of the SSIP. A surface examination shall be completed after surface stress improvement when not required by PSI or when there is no PSI. The acceptance criteria for surface examinations shall be either NB-5340 or NB-5350.

2000 Surface Stress Improvement Process Performance Criteria	To minimize the likelihood of crack initiation, the process shall have resulted in a mitigated stress state in the susceptible material along the entire wetted or susceptible surface under steady state operating conditions (i.e., item subject to operating pressure while at operating temperature). Susceptible material includes the weld, butter, and base material, as applicable. The residual stress plus normal operating stress shall be included in the evaluation.
2100 Coverage, Depth, And Stress Criteria	A combination of demonstration testing and analysis shall be performed to demonstrate the required capability of the SSIP to produce the required post-mitigation stress state. A demonstration test shall be performed to confirm the post mitigation stress state exclusive of normal operating stresses. The testing shall be used to demonstrate the critical process parameters and define acceptable ranges of the parameters needed to ensure that the required residual stress field (exclusive of operating stresses) has been produced on the mitigated surface. Specimens representative of the geometry, materials, accessibility, and surface condition of the item to be mitigated by a SSIP shall be used for the testing. The nominal wall thickness of the specimen shall be no greater than that of the item to be mitigated by a SSIP. An analysis shall be performed to determine the effect of normal operating loads on the steady-state operating stresses at the surfaces required to be mitigated by a SSIP. The uncertainty in measurement of the surface residual stress shall be considered in the analysis to determine the surface stress including operating and residual stress.
2110 Item Weld Material Susceptible to SCC	a) To ensure full coverage of the susceptible material, the SSIP application shall extend at least 0.25 in. (6 mm) beyond the edge of welds or weld repair areas on the wetted surface. b) The nominal compressive residual stress field shall extend to a minimum depth of 0.04 in. (1.0 mm). c) The effect produced by the SSIP shall result in a mitigated surface stress state no greater than +0 ksi (+0 MPa) including residual and operating stresses.
2120 Vessel Penetrations, With Partial Penetration Welds, Susceptible to SCC	a) To ensure full coverage of the susceptible material, the SSIP application shall extend at least 0.25 in. (6 mm) beyond the edge of welded areas. b) The nominal compressive residual stress field shall extend to a minimum depth of 0.04 in. (1.0 mm) on the outside surface of the penetration nozzle and attachment weld surface. c) The nominal compressive residual stress field shall extend to a minimum depth of 0.01 in. (0.25 mm) on the inside surface of the penetration nozzle in areas adjacent to the attachment weld. d) The effect produced by the SSIP shall result in a mitigated surface stress state no greater than +0 ksi (+0 MPa) including residual and operating stresses.
2130 Item Base Material Susceptible to SCC	a) The SSIP coverage shall extend at least 2 in. (50 mm) from each side of each weld centerline or at least 1 in. (25 mm) from the weld edge, whichever is larger. b) The nominal compressive residual stress field shall extend to a minimum depth of 0.04 in. (1.0 mm). c) The effect produced by the SSIP shall result in a mitigated surface stress state no greater than +0 ksi (+0 MPa) including residual and operating stresses.
2140 Nominal Depth of Compressive Residual Stress	The nominal depth of the compressive residual stress field is the depth of the compressive residual stress that is reliably obtained in demonstration testing, i.e., for at least 90% of the locations measured.
3000 Mitigation Effects Sustainability Criteria	The effect produced by the mitigation process shall remain effective for the design life of the item. Analysis or testing shall be performed to verify that the mitigation process maintains the surface stress condition identified in -2110(c) -2120(d), and -2130(c), under normal operating plus residual stress, for at least the design life of the item. The analysis or demonstration test plan shall include startup and shutdown stresses, normal operating pressure stress, thermal cyclic stresses, transient stresses, and residual stresses. The analysis or demonstration test shall account for: a) load combinations that could relieve stress due to shakedown b) any material properties related to stress relaxation over time
4000 Examination Capability Criteria	
4100 Volumetric Examination Qualification Criteria	The capability to perform volumetric examinations, as required by the applicable ISI requirements for the relevant volume of the item, shall not be adversely affected.

4200 Surface and Eddy Current Examination Qualification Criteria	The capability to perform surface and eddy current examinations, as required by the applicable ISI requirements for the relevant inspection area of the item, shall not be adversely affected.
4300 Visual Examination Qualification Criteria	The capability to perform visual examinations of the accessible surface on the item shall not have been adversely affected.
5000 Adverse Effects Criteria	The SSIP, including vibration effects during application, shall not degrade the item or adversely affect other items in the system, including generation of new flaws.
5100 Geometry Effects Criteria	An analysis or testing shall be performed to verify that the SSIP does not result in changes to the item geometry that exceed Section III design criteria.
5200 Surface Effects Criteria	Analysis or testing shall be performed to verify that the SSIP does not cause erosion of surfaces, undesirable surface roughening, or detrimental effects in the transition regions adjacent to the regions mitigated by the SSIP. The SSIP shall not reduce wall thickness of the item below minimum design thickness.
6000 Inspectability Criteria	The mitigated item, including the weld and weld repair in the repaired region, shall be inspectable by the required ISI examination method(s). Examination coverage of 100% shall be achieved for the required volume and surface area mitigated by SSIP.
7000 Documentation	This Case number shall be identified on the Data Report.

4. Conclusions

The SMR is attracting attention as a future energy source, and is being developed in the United States with the goal of commercialization in 2027. SCC prevention will be a very important factor in the lifespan of nuclear power plants currently in use and future SMR devices. The most efficient way to prevent SCC is to increase device life through surface modification rather than expensive material development. However, there is no standard to apply so far, so new ASME Code Case N-931 “Performance and Qualification Criteria for Mitigation of Stress Corrosion Cracking by Surface Stress Improvement: Section III, Division 1 and 3" was developed. The SSIPs can be applied to parts where SCC is expected to occur in newly manufactured nuclear power plants through this standard. Currently, a UNSM device for application to SMR parts is being developed, and it will be possible to mount and apply it to devices such as robots and manipulators in the future.

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