Structural Repair of Degraded Process Piping By In-Situ Deposition of Nanostructured Materials

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Many process components, particularly tubes and pipes, are prone to failure via mechanisms such as localized, general and flow-assisted corrosion, as well as stress corrosion cracking and fatigue. In some cases, "cut and replace" techniques for damaged sections of piping can be applied; however, in many cases, accessibility to the degraded pipe section is hindered and these procedures can become far more onerous from both a tactical and cost-perspective. In all "cut & replace" scenarios, significant plant downtime can be experienced as a result of the tasks required to isolate the degraded sections from process fluids prior to repair. In order to minimize downtime and address accessibility issues, a proprietary electrodeposition process has been developed which applies an OD reinforcement to degraded sections of pipe. A fully bonded nanocrystalline microalloy is produced, such as previously utilized in the electrosleeve repair of the ID of nuclear steam generator tubing. This nano-material provides superior mechanical properties and thus allows for design/operating load conditions to be accommodated with significantly less material build-up than would normally be required if using a conventional material. In this presentation an overview of the OD piping repair technology will be presented and discussed.

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Many process components, particularly tubes and pipes, are prone to failure via mechanisms such as localized, general and flow-assisted corrosion, as well as stress corrosion cracking and fatigue. Commercially pure Ni has long been recognized as an ideal corrosion–resistant material for typical boiler and other process environments and has been used extensively in Europe, for instance, as a protective coating on the inside of steam generator tubes[1]. However, its relatively poor mechanical strength has precluded its use as a structural repair. Nanocrystalline Ni, on the other hand, possesses the mechanical strength required for both structural and preventative repair applications as a direct result of the Hall-Petch grain size strengthening effect. By careful manipulation of the electrodeposited Ni microstructure, important material properties such as strength, ductility, fatigue resistance, thermal stability, and corrosion resistance can be optimized.

Steam Generator Tube Repair

In the early 1990's, an electrodeposition process for nuclear steam generator repair using nanocrystalline nickel was developed[2]. Degraded steam generator tubes were ID-coated in-situ; this 'electrosleeving' process has been successfully used in both CANDU and PWR systems. In this process, an electroplating cell is created between the host steam generator tube and a positioned probe comprised of a rigid central tubular non-consumable anode and sealing modules at both ends of the anode; the region between modules defining the length of the sleeved region (see Figure 1). A polymeric conduit connected to the probe delivers both power and process chemicals from a remote chemical process station. Process chemicals are delivered at a controlled flow rate and temperature through the annulus defined by the anode and the inside surface of the steam generator tube, and are circulated back through the central tubular member. Upon application of an electric field between the central electrode (anode) and the inside surface of the steam generator tube (cathode), electrodeposition occurs on the inside surface of the tube, the desired thickness being accurately controlled by charge integration (current-time). Strong adhesion of the electrodeposited sleeve to the host tubing is ensured by the proper application of suitable surface activation and prefilming procedures. As previously outlined by Erb and co-workers[3], the deposit grain size is controlled by appropriate selection of current density, solution ionic strength, temperature and pulsed current waveform.

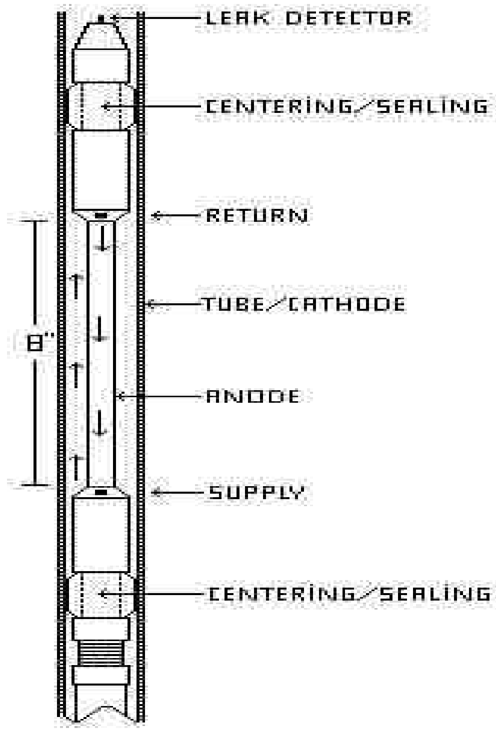

Fig. 1 – Electrosleeve probe for in-situ structural repair of degraded steam generator tubing.

Material Properties

The electrodeposited nanostructured material is >99.5% nickel containing microalloyed phosphorus (<3000ppm by weight). This electrosleeve material is generally free of macroscopic defects (e.g., voids) and porosity, and possesses a microstructure not resolvable by optical microscopy. The average grain size of the material is approximately 50nm.

Thermal Stability

Thermal stability of the electrosleeve material is a major concern since many process components are subjected to long-term thermal exposure at operating temperatures as high as 350°C (660°F) or greater. Moreover, previous studies[4] have shown that nanocrystalline Ni possesses a driving force for grain growth that is several orders of magnitude higher than that for conventional coarse-grained polycrystalline materials. Figure 2 shows the effect of annealing time at 343°C (650°F) on the Vickers microhardness of (1) nanocrystalline Ni and (2) Ni containing 1500ppm P; both materials having an as-plated hardness of approximately 400VHN[5]. As shown in this figure, the pure Ni shows a rapid decay in hardness to below 150VHN within the first few hours of annealing, this being representative of rapid grain growth leading to a resultant grain size consistent with that of conventional polycrystals (i.e., 10-30micrometers (~0.5-1mils)). The nanocrystalline Ni containing 1500ppm (by wt.) phosphorus shows no evidence of hardness decay within the total test period evaluated (approximately 10 months). The influence of minor solute additions on retarding grain growth in nanostructured Ni has been previously documented[4,6] and attributed to (1) solute drag effects on the grain boundaries, (2) reduction in grain boundary energy from solute segregation, and (3) Zener drag effects associated with the possible formation of 'nano-precipitates'[4,6].

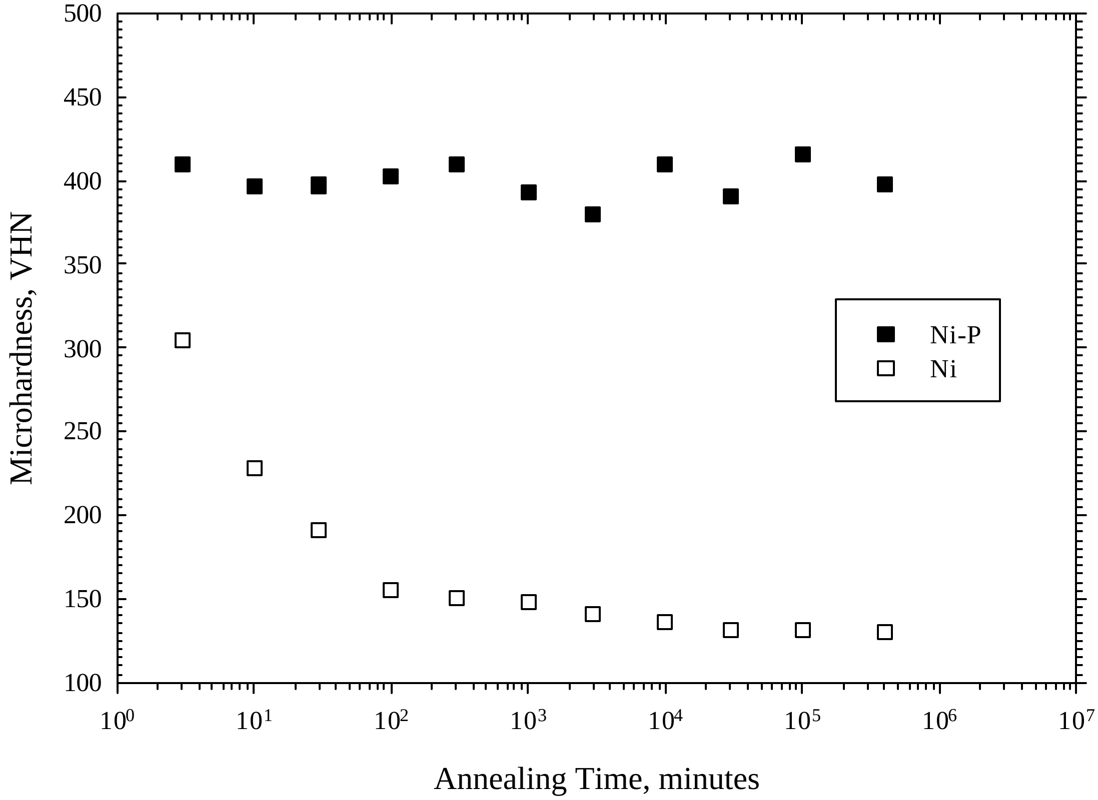

Fig. 2 – Vickers hardness as a function of annealing time at 343°C (650°F) for nanocrystalline (1) Ni and (2) Ni-1500P[5].

Thermal Expansion Coefficient

The most common electroplated substrate material is carbon steel. Since the nanocrystalline materials discussed here are intended as structural repair coatings on carbon steel components exposed to temperatures up to 343°C (649°F), the coefficient of thermal expansion of the Ni microalloy relative to carbon steel is of interest. Linear thermal expansion measurements were carried out for SA106 Gr.B carbon steel and nanocrystalline Ni-P from 100°C (212°F) to 343°C (649°F) and the results are presented in Table 1 below. It can be seen that the thermal expansion coefficient for nanocrystalline Ni-P is marginally higher than that for SA106 Gr.B carbon steel. However, the relative difference between the two materials at temperatures between 100°C (212°F) to 343°C (649°F) is only 8% to 6%, respectively.

Table 1 – Summary of Thermal Expansion Coefficient Test Results (units: 10^{-6} in/in·°C)

Temperature	SA106 Gr.B	Conventional Ni[7]	Electrosleeve
100°C (212°F)	12.2	12.96	13.2
265°C (509°F)	13.0	14.22	13.9
343°C (649°F)	13.5	14.58	14.4

Mechanical Properties

Table 2 summarizes the mechanical properties of the nanostructured Ni electrosleeve. It can be seen that the material demonstrates a desirable combination of strength and ductility both at room temperature and elevated temperature. The values of yield strength and tensile strength are shown to be significantly greater than that of conventional commercially pure Ni (e.g., Ni201)[8], while the modulus of elasticity is approximately the same. The electrosleeve material displays room temperature elongations to failure in excess of 15% in tension and somewhat greater ductility (i.e., >25%) is observed in bending (180° reverse U-bends). Tensile tests were also carried out at a number of different strain rates and the value of the electrosleeve strain rate sensitivity was found to be –0.003, indicating that strain rate has no effect on the flow properties of this material.

Table 2 – Summary of the Mechanical Properties of Electrosleeve Ni

Property	Conventional Ni[8]	Electrosleeve
Yield Strength, 25°C (77°F)	103MPa (14.9Kpsi)	667MPa (96.7Kpsi)
Yield Strength, 350°C (662°F)	-	492MPa (71.3Kpsi)
Ultimate Tensile Strength, 25°C (77°F)	403MPa (58.5Kpsi)	855MPa (124.0Kpsi)
Ultimate Tensile Strength, 350°C (662°F)	-	714MPa (103.5Kpsi)
Elongation, 25°C (77°F)	50%	15-23%
Modulus of Elasticity, 25°C (77°F)	207GPa (30.0Mpsi)	204GPa (29.6Mpsi)
Modulus of Elasticity, 350°C (662°F)	-	179GPa (26.0Mpsi)

In addition to tensile testing, the fatigue performance of the Ni electrosleeve material has been evaluated in air, both at room temperature and elevated temperature (300°C / 572°F). The tests were performed in fully reversed bending (R=-1) at frequencies in the range 0.5-25Hz[5]. It was found that the electrosleeve fatigue performance is generally consistent with that of conventional coarse-grained Ni and this performance was not compromised at elevated temperature. Furthermore, experimentally determined room temperature fatigue data was compared to the ASME design and mean fatigue curves for austenitic stainless steels and nickel-based alloys[9]. This is represented graphically in Figure 3 below. The test data is shown to be above the ASME SC III design and within the bounds of the calculated mean fatigue curves for austenitic stainless steel and nickel-based alloys.

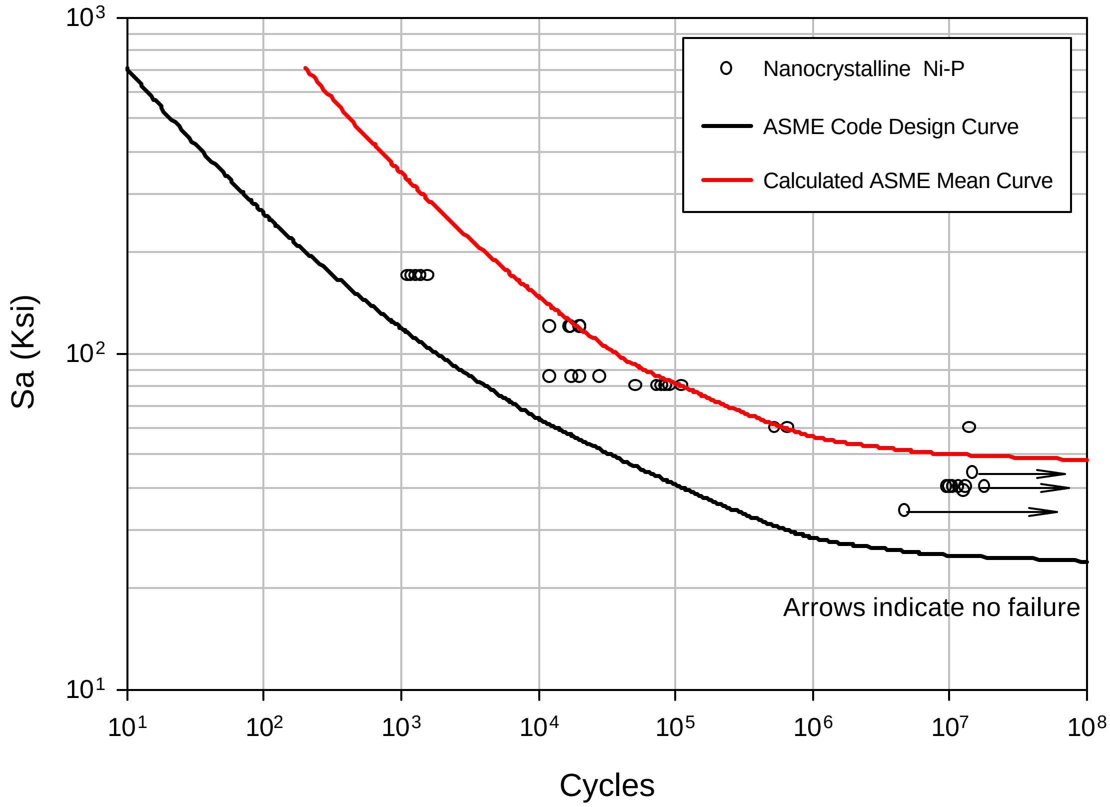

Fig. 3 – Comparison of nanocrystalline Ni-P fatigue test data to the ASME fatigue design[9] and mean curve for austenitic stainless steels and nickel-based alloys (Tests were performed in fully reversed bending (R=-1)). Arrows denote no sample failure.

OD Tube Repair

Based upon the favourable properties of the nanocrystalline microalloyed Ni, it is apparent that this material could serve as an effective structural repair that can be applied not only to the ID of process tubing (as was the case for the steam generator tubing repair), but also to the OD surface of various other process piping components. The motivation for this lies in the difficulty in carrying out conventional "cut and replace" repairs when accessibility to the degraded component is limited and/or when the piping contains hazardous process fluids. In addition, OD plating does not require any plant shutdown. The OD technique may also be used to create high strength coatings on the outside of degraded tubes in industrial plants, above ground and underground pipelines, pipe systems and related applications.

Carbon steel (e.g., ASME SA106 Gr. B) is frequently used in process piping. Table 3 shows the mechanical properties of the Nanoplate material relative to carbon steel. The superior mechanical properties of the nanocrystalline materials could thus be used as a 'thin-wall' structural repair to be applied in selected critical locations.

Table 3 – Replace / Repair Material Selection

Property	SA106 Gr. B	Nanoplate
Yield Strength, 25°C (77°F)	241MPa (35Kpsi)	667MPa (96.7Kpsi)
Ultimate Tensile Strength, 25°C (77°F)	414MPa (60Kpsi)	855MPa (124.0Kpsi)

Tooling

In order to perform an OD pipe repair, a concentric jacket is positioned and sealed to the pipe at the required location, creating a local electrochemical (plating) cell which is used to electrodeposit a fully bonded 360° OD sleeve on the pipe. The plating cell includes a housing that is configured so that it may be clamped around the pipe in order to provide a leak tight volume between the pipe and the housing for the circulation of electrolyte or plating solution through the volume within the plating cell. An anode is provided within this housing and is located in the vicinity of the degraded portion of the pipe within the housing. The plating cell also includes appropriate electrical wiring and electrical connections for connection to the current source required for plating. The housing of the plating cell further includes fluid supply inlets and outlets through which solution is circulated. Two end-tooling options are available: 1) a flexible jacket, or 2) a split-mold cell. A drawing of the flexible jacket concept is presented in Figure 4. This approach offers the obvious advantage of flexibility in pipe geometry that can be coated and because a non-consumable anode is employed, severe space restraints between pipes can be accommodated. Alternatively, a cell consisting of two halves that are positioned in order to conform to the pipe geometry can be employed in a similar fashion. The selection of plating cell is dependent upon factors such as pipe geometry, configuration and accessibility.

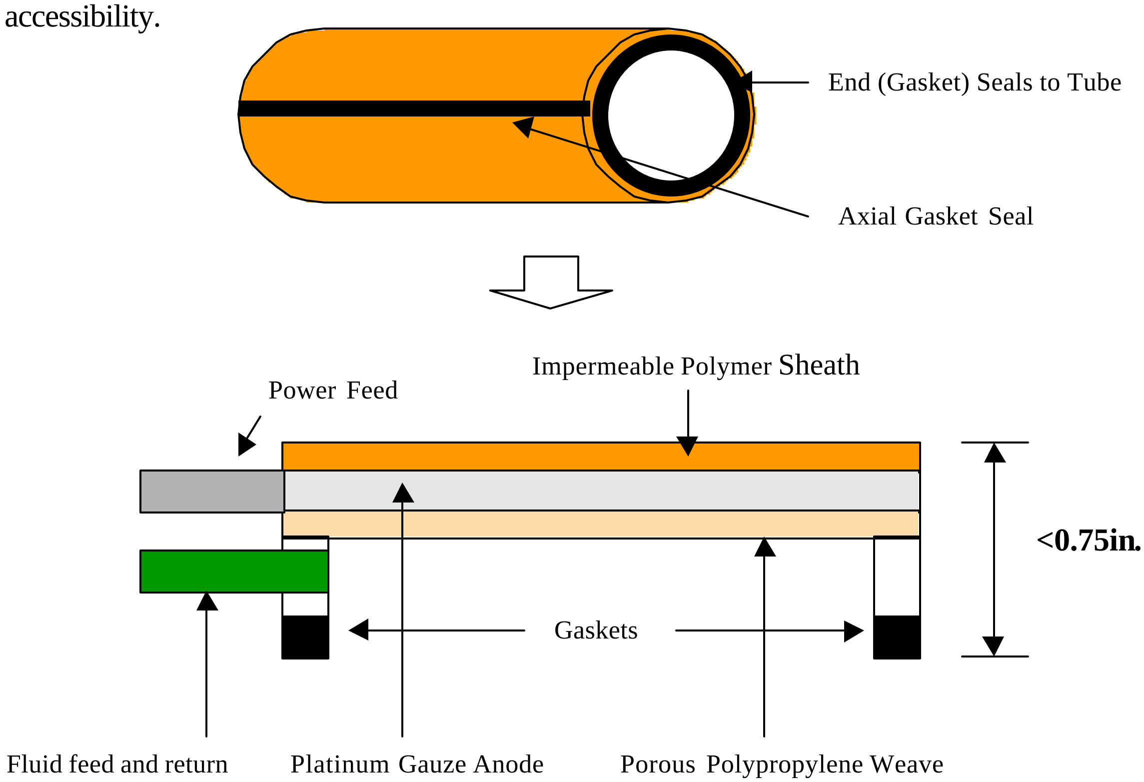

Fig. 4 – OD pipe plating cell – flexible jacket concept

A portable rig is used for all plating work (see Figure 5). This rig was designed to be modular and compact for access to restricted plant locations. The dimensions are 9ft x 3ft x 6ft and its weight is approximately 1000lb (empty) or 1500lb (fully loaded). Generally speaking, this rig consists of a series of tanks that hold the cleaning, activation, strike, plating and rinse solutions, along with the necessary plumbing to permit these fluids to be pumped to and from the plating cell. For the purposes of OD pipe plating process development, a small plating cell was used for much of the initial work, and this cell can be seen in the bottom left corner inset of the figure.

Fig.5 – Photograph of the portable plating rig along with an early plating cell prototype (inset).

Summary

A novel repair technique that can be applied to industrial process piping degraded through failure mechanisms such as localized, general and flow-assisted corrosion, as well as stress corrosion cracking and fatigue, has been presented. Emphasis is placed on the unique properties of the nanostructured sleeve repair material, i.e., microstructure, mechanical strength, corrosion resistance, thermal stability, etc. Based upon extensive experience gained during ID steam generator tubing repair campaigns, an OD pipe repair technique has been developed in a similar fashion. Currently, this process is in the 'pilot-plant' stage of development for application to degraded piping systems in industrial plants.

References

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