UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

FEB 1 2 1987

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Eric S. Beckjord, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER NO. 149, "EVALUATION OF THE MECHANICAL STRESS IMPROVEMENT PROCESS"

This Research Information Letter transmits the attached results of a study conducted by the Argonne National Laboratory (ANL) to evaluate the "Mechanical Stress Improvement Process" (MSIP) being proposed by several utilities as a remedy to mitigate intergranular stress corrosion cracking of stainless steel piping in BWR's. The evaluation was requested by the staff of the Engineering Branch of the Division of BWR Licensing who are reviewing licensee proposals to use the process.

The MSIP, like the Induction Heating Stress Improvement process (IHSI), is intended to produce a more favorable state of residual stress on the inner surface of piping in the vicinity of weldments. These processes convert the stress state at the inside surface of a pipe weldment from tensile to compressive which results in significant improvement in the resistance to intergranular stress corrosion cracking of BWR piping. Although the MSIP and IHSI have similar objectives the MSIP is purely a mechanical process and has the advantage of being simpler to perform and is less costly.

In this study, ANL reviewed information on MSIP submitted to the NRC by O'Donnell & Associates, Inc. and Westinghouse Electric Corporation, the developers of the process. Also, ANL performed analysis and tests to determine the residual stress state changes using two MSIP treated, large diameter pipe sections supplied by Vermont Yankee.

The experimental work from this study found that the residual stresses due to the MSIP treatment generated the desired compressive stresses on the inside surface of pipe in both the axial and hoop directions at all locations. Throughwall axial residual stress measurements in the regions near the HAZ showed the distribution to be almost linear across the thickness and similar to the distributions in weldments treated by IHSI. The compressive stresses produced by the MSIP in the HAZ persist through a substantial (50%) portion of the pipe wall. This indicates that the process can provide significant benefits, even in the presence of small flaws that may not be detected by non destructive testing. Experimental results agreed with the finite element analysis performed. No evidence of brittle phases like martensite that increase susceptibility to stress corrosion cracking were observed as a result of MSIP treatment.

This research has concluded that the basic concept of MSIP is valid and sound. Analysis and test results establish that the process is an effective means of improving the residual stress state of piping at weldments. The process was found to be equivalent to IHSI in terms of mitigating the susceptibility of pipes to stress corrosion cracking, and was found as effective for large diameter piping as it was for small piping.

Eric S. Beckjord, Director
Office of Nuclear Regulatory Research

# EVALUATION OF THE MECHANICAL STRESS IMPROVEMENT PROCESS

## Introduction

The Mechanical Stress Improvement Process (MSIP) is a development of O'Donnell and Associates, Inc. (OAI). Like Induction Heating Stress Improvement (IHSI) it is intended to produce a more favorable state of residual stress on the inner surface of piping weldments especially in the vicinity of heat-affected-zones (HAZs) and thereby mitigate stress corrosion cracking in BWR piping. Although the two processes have similar objectives, MSIP is a purely mechanical process. The favorable residual stresses are induced by the plastic compression of the weldment produced by a split-ring-like tool mounted on the pipe. The plastic strain imposed on the pipe is controlled by the opening between the split-rings, which is adjusted by inserting appropriate shims. Unlike IHSI there is no reversed plastic flow (i.e., plastic tension then plastic compression) in a weld treated by MSIP; the weldment undergoes monotonic compressive loading. However, the final stress state in the HAZs appear similar for the two processes.

## Technical Results

Two weldment specimens prepared by Vermont Yankee Nuclear Power Corp. and treated by MSIP have been examined to: (1) determine the residual stress state produced by the process, (2) compare the results of the measurements with the stresses predicted by finite-element analysis, and (3) investigate the possibility of undesirable side-effects associated with the process. One specimen was fabricated from 12-inch-diameter pipe and contained two pipe-to-pipe welds as shown in Figure 1. Only one of these welds was treated by MSIP according to the process specifications. The second specimen was a 28-inch-diameter pipe-to-pipe weldment. Detailed descriptions of the experimental procedures and results are given in [1,2].

The basic process specifications are proprietary. However, the critical process parameters can be verified by post-test measurements and inspection and are summarized in Table I for the 12-inch-diameter test specimen and in Table II for the 28-inch- diameter specimen. The measured parameters for the 12-inch-diameter specimen are consistent with those given in proprietary engineering procedure (Westinghouse Nuclear Services Integration Division Document Number SE-PP-85-277 Rev. 2). The measured contraction for the 28-inch-diameter specimen slightly exceeds the maximum value given in the procedure (2.0%). This was done intentionally to obtain a "worst case" degree of plastic cold work.

The 12-inch-diameter specimen had been tested in boiling $MgCl_2$ at the J. A. Jones Applied Research Center (JAJ) in Charlotte before shipment to Argonne. In this environment any portion of the weldment under significant (~5 ksi) tensile stresses will usually crack. No cracks in the vicinity of the test welds were observed by the staff at JAJ either in the baseline examination of the specimen or in the posttest examination. To obtain more quantitative results, strain gage residual stress measurements were made at Argonne.

The residual stresses on the inner surface of the MSIP treated weld in the 12-inch-diameter specimen were measured at two azimuthal locations. The location of the stress measurements are indicated in Figure 2. The stresses at the two azimuths did not differ significantly and the average stresses for a given axial position are summarized in Table III. Both the axial and hoop stresses are compressive at all locations. No control welds were prepared, but calculations and measurements suggest that the axial stresses in the HAZs of such welds will typically be tensile with a magnitude of -20-30 ksi [3,4]. Finite-element analyses by OAI predict tensile stress regions on the portion of the inner surface directly beneath the tool after MSIP. However, in this case the measured stresses are compressive in this region.

The measured residual stresses near the lower weld are summarized in Table IV. Although the edge of the MSIP tool is ~5 in. from the weld and hence well outside the distance specified in the application procedure, the measured stresses are compressive, although not as strongly compressive as in the actual treated weld.

Throughwall axial residual stress measurements were made at one azimuth for the MSIP treated weld [2]. In the regions near the HAZs, the stress distributions are almost linear across the thickness except near the outer surface and are similar to the distributions in weldments treated by IHSI [4]. In the region directly under the tool, the profiles are more nonlinear. The compressive stresses produced by MSIP in the HAZs persist through a substantial portion (~50%) of the pipe wall. This indicates that the process can provide significant benefits even in the presence of small flaws that may not be detected by nondestructive examination.

The results of the strain-gage residual stress measurements on the 28-inch-diameter weldment are summarized in Table V. There are high compressive stresses in the regions near the weld and heat-affected zones. The stresses do become tensile on the inner surface in the region under the tool (i.e., 3-8 in. from the weld centerline) in agreement with the finite-element analyses performed by OAI, but the magnitudes of the stresses are relatively low (~5-10 ksi) compared to the analytical predictions. Although this region of tensile stress is well outside the heat-affected-zone and hence any region of sensitization produced by welding, it is desirable to try to keep tensile stresses as low as possible everywhere on the inner surface. To minimize these tensile stresses it may be desirable to restrict the maximum deformations permitted under current procedures (2.0%) to slightly lower levels.

Throughwall residual stress measurements were performed at one azimuth on the 28-inch-diameter. As in the case of the 12-in-diameter weldment, the compressive stresses produced by MSIP in the HAZs persist through a substantial portion (~50%) of the pipe wall.

Plastic cold work is known to promote susceptibility to stress corrosion cracking. One mechanism by which this occurs in Type 304 stainless steel is martensite formation (Type 316 with Mo additions is much more resistant to martensite formation). The martensite is brittle and cracks easily under applied loads. These mechanical cracks provide excellent sites for the initiation of stress corrosion cracks. The plastic strains associated with the MSIP process are much less than those needed to induce martensite formation, and are much less than the local plastic strains routinely introduced by machining. No evidence of martensite formation was noted in the treated weldments. Lower levels of bulk plastic work also promote stress corrosion cracking by mechanisms that are not well understood. However, the strain levels needed to produce susceptibility to cracking appear to be 5% or more [5]. The plastic strains on the inner surface of the piping induced by MSIP (~1.5%) are somewhat larger than those associated with IHSI (~0.5%), but they do not appear to pose a significant problem.

## Metallurgical Results

Dye penetrant tests and metallographic examination revealed some irrelevant cracking on the inner surface of the 12-inch-diameter specimen away from the MISP treated weld. Numerous fine circumferential cracks up to 120 μm deep and 1-3 mm long were observed in the fillet regions at the ends of the counterbores. A long (~70 mm), relatively deep ( 3mm) longitudinal crack was also found on the inner surface of the pipe along the weld fusion line of a seam weld in the region almost directly under the MSIP tool. The remainder of the seam weld appears free of cracking. Relatively deep (5.4 mm, 35% throughwall) circumferential cracks were also found in the heat-affected zone (HAZ) of the second circumferential weld that was not MSIP treated. The crack morphologies in all of these cases were branched and transgranular and appear consistent with those observed for chloride-induced stress corrosion cracking. The only cracks near the treated weld are the short, shallow cracks in the fillets at the ends of the counterbores.

The areas in which the cracks were found had been checked by dye penetrant tests both before and after the $MgCl_2$ tests, and no indications were observed. It appears that the compressive residual stresses induced by MSIP had to be relieved before the cracks could open sufficiently to permit subsequent entry of the dye penetrant. Since both the dye penetrant test and the strain gage measurements show that the inner surface was under high compressive stresses, very local regions of tensile stress that produced the $MgCl_2$ cracking must have existed. In the case of the crack in the fusion line of the seam weld, there appears to have been a preexisting weld fusion flaw that could have provided a local stress riser. In the case of the cracks in the fillet regions, the extreme tightness of these cracks suggests that the tensile stresses associated with them are highly localized with very steep throughwall gradients, which is characteristic of residual stresses produced by rough machining. In the case of the crack in the lower circumferential weld, the weld was ~13 cm from the tool, and the induced stresses were not as compressive as in the treated weldment.

Although the existence of local zones of tensile stress cannot be conclusively demonstrated, it is almost certain that the cracks in the 12-inch specimen were due to chloride stress corrosion cracking, and were not induced by MSIP and that the favorable residual stress state produced by MSIP greatly reduced the amount of cracking that would have been observed in a corresponding untreated weldment subject to a $MgCl_2$ test. This conclusion that the cracking observed in the 12-inch diameter specimen was induced by the $MgCl_2$ and not the MSIP process is supported by the results of detailed dye penetrant and metallurgical examination of the 28-inch-diameter weldment. This weldment was not exposed to $MgCl_2$, and did not show any cracking in either the circumferential butt weld or the longitudinal seam weld even though it was subjected to a larger plastic strain than the 12-inch-diameter weldment.

## Conclusions and Recommendations

Based on the results of our research work and the data and analysis provided by O'Donnell and Associates, Inc., MSIP is judged to be an effective means of improving the residual stress state of piping system weldments and should be considered as equivalent to IHSI in terms of mitigating susceptibility to stress corrosion cracking. Unlike other residual stress improvement techniques it is as effective for large diameter piping as small diameter piping. The associated plastic strains are unlikely to have detrimental effects either through the production of brittle phases like martensite or other mechanisms that increase susceptibility to stress corrosion cracking.

## References


1. W. J. Shack et al., Environmentally Assisted Cracking in Light Water Reactors: Semiannual Report October 1985 - March 1986, NUREG/CR-4667, Vol. II, ANL-86-37 (July 1986).

2. W. J. Shack et al., Environmentally Assisted Cracking in Light Water Reactors: Semiannual Report April - October 1986, NUREG/CR-4667, Vol. III to be issued.

3. W. J. Shack, W. A. Ellingson, L. E. Pahis, Measurement of Residual Stresses in Type-304 Stainless Steel Piping Butt Weldments, EPRI NP-1413, Electric Power Research Institute, June 1980.

4. E. F. Rybicki et al., Computational Residual Stress Analysis for Induction of Welded BWR Pipes, EPRI NP-2662-LD, Electric Power Research Institute, December 1982.

5. J. E. Alexander et al., Alternative Alloys for BWR Pipe Applications, EPRI NP-2671-LD, Electric Power Research Institute, October 1982.

Table I. MSIP Application Parameters for the 12-inch-diameter Weld Test Specimen

| | |
|---|---|
| Tool Width | 2.25 in. |
| Axial Distance From Weld Centerline to Tool Midplane | 2.37 in. |
| Radial Contraction at Midplane of Tool | 1.4% |

Table II. MSIP Application Parameters for the 28-inch-diameter Weld Test Specimen

| | |
|---|---|
| Tool Width | 6.50 in. |
| Axial Distance From Weld Centerline to Tool Midplane | 5.25 in. |
| Radial Contraction at Midplane of Tool | 2.27% |

Table III. Average Measured Residual Stresses on the Inner Surface for a 12-inch-diameter Pipe Weldment Treated by the Mechanical Stress Improvement Process

| Location | Gage Position | Distance From Weld Centerline (in.) | Axial Stress (ksi) | Hoop Stress (ksi) |
|---|---|---|---|---|
| Tool Side | | | | |
| HAZ | 1 | -0.20 | -31 | -34 |
| | 2 | -0.59 | -35 | -33 |
| | 3 | -0.99 | -26 | -13 |
| | 4 | -1.77 | -16 | -17 |
| Under Tool | 5 | -2.57 | -15 | -17 |
| | 6 | -3.35 | -14 | -15 |
| | 7 | -4.14 | -17 | -13 |
| Across Weld HAZ | 8 | 0.20 | -34 | -36 |
| | 9 | 0.59 | -48 | -31 |

Table IV. Average Measured Residual Stresses at the Lower Weldment ~5 in. From the MSIP Tool

| Location | Gage Position | Distance From Weld Centerline (in.) | Axial Stress (ksi) | Hoop Stress (ksi) |
|---|---|---|---|---|
| Closest | 1 | -0.20 | -8 | -9 |
| HAZ | 2 | -0.59 | -19 | -5 |
| Across Weld | 3 | 0.20 | -8 | -15 |
| HAZ | 4 | 0.59 | -13 | -15 |

Table V. Average Measured Residual Stresses on the Inner Surface for a 28-inch-diameter Pipe Weldment Treated by the Mechanical Stress Improvement Process

| Location | Gage Position | Distance From Weld Centerline (in.) | Axial Stress (ksi) | Hoop Stress (ksi) |
|---|---|---|---|---|
| Tool Side | | | | |
| HAZ | 1 | -0.08 | -24 | -53 |
| | 2 | -0.55 | -36 | -30 |
| | 3 | -1.34 | -22 | -15 |
| Under Tool | 4 | -2.52 | -12 | 2 |
| | 5 | -3.70 | -1 | 8 |
| | 6 | -6.06 | 6 | 8 |
| | 7 | -8.42 | -6 | -15 |
| Across Weld HAZ | 1 | 0.08 | -22 | -50 |
| | 2 | 0.55 | -36 | -36 |
| | 3 | 1.34 | -40 | -25 |

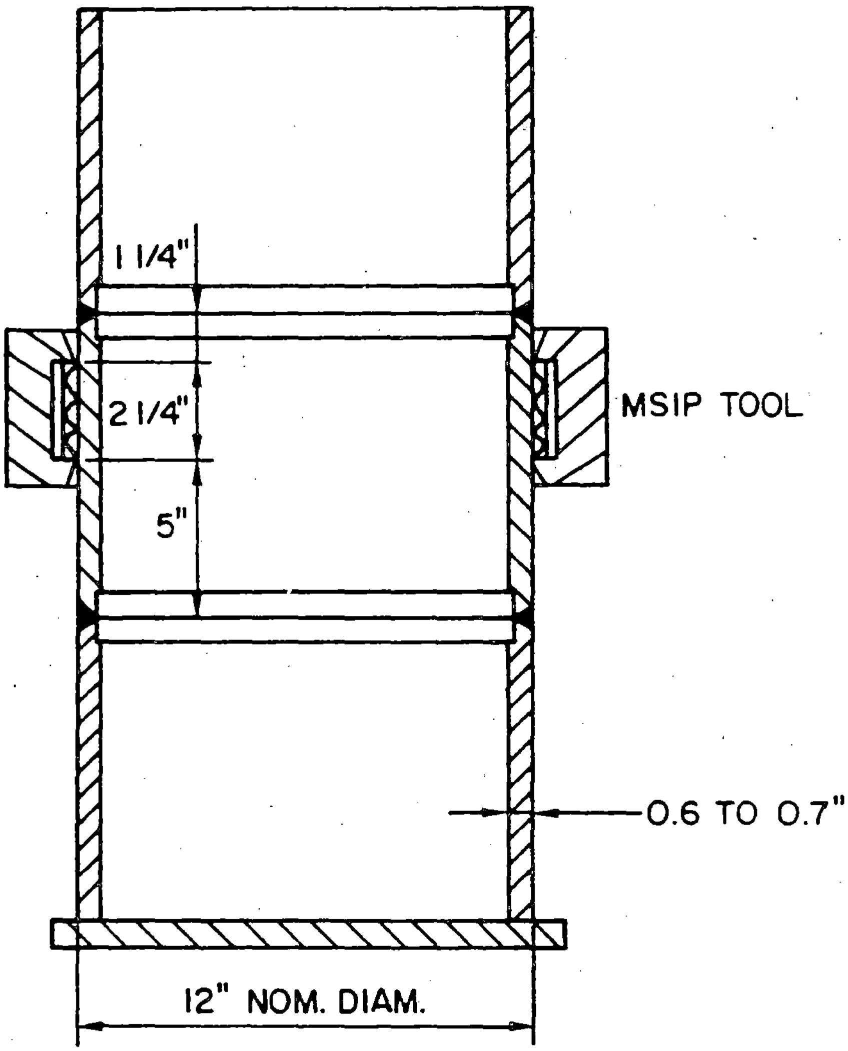


Fig. 1. Vermont Yankee 12-in.-diameter Specimen Treated by MSIP.

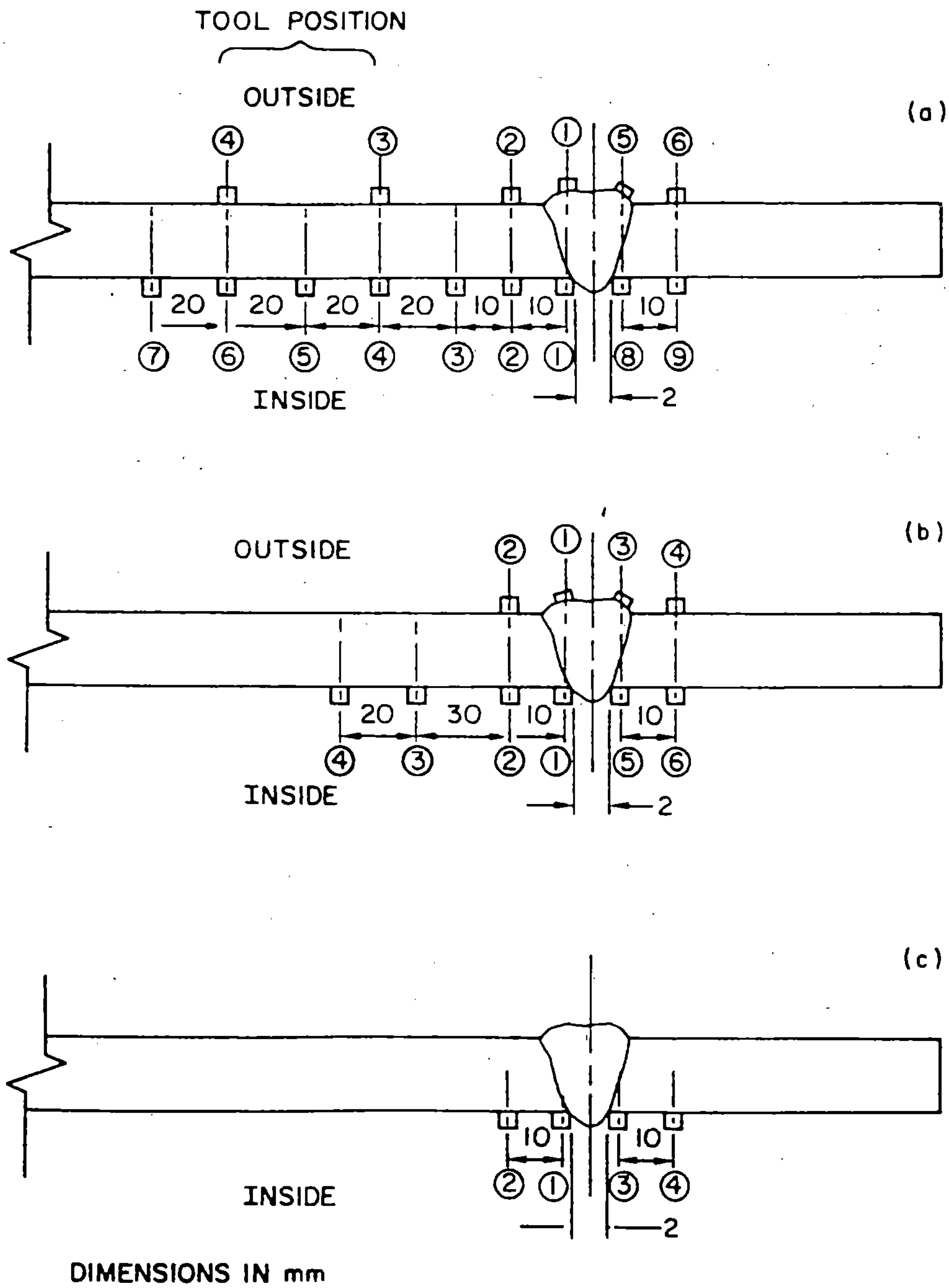


Fig. 2 Strain Gage Locations on the 12-in.-diameter MSIP Weldment. (a) 0° Azimuth Upper MSIP-treated Weld, (b) 90° Azimuth Upper MSIP-treated Weld, (c) 0° Azimuth Untreated Lower Weld.