SHOT PEENING TO PREVENT THE CORROSION CRACKING OF AUSTENITIC STAINLESS STEELS

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ABSTRACT

A joint test program to develop shot peening as a technique for preventing corrosion cracking in austenitic stainless steels has been conducted.[1] Laboratory-scale scoping tests demonstrated the feasibility of preventing stress corrosion cracking by shot peening. Conventional U-bend test specimens, when peened, survived 1000-h tests in the boiling 42% magnesium chloride stress corrosion test. Unpeened reference specimens commonly fractured within 1 or 2 hours in this test. Component tests demonstrated the practicality of the peening process for sizes and shapes that typify components in a reactor piping system. Pipe sections and cold-worked hexagonal tubes were tested. In all components, unpeened sections developed stress corrosion cracks within a few hours in the magnesium chloride test; in contrast, the shot-peened surfaces survived hundreds of hours. Intergranular corrosion can be prevented in austenitic stainless steels by severe shot peening prior to exposure to sensitizing temperatures.[2] For this purpose, the surfaces must be severely cold worked by the shot peening to break up surface grains and grain boundaries. Two nondestructive testing techniques show promise for measuring the stresses or cold work imparted on the surface of the workpiece by peening.

KEYWORDS

Shot peening; stress corrosion; intergranular corrosion; stainless steels.

INTRODUCTION AND BACKGROUND

One of the few shortcomings of the 18-8 type of austenitic stainless steels is their susceptibility to stress corrosion cracking and intergranular corrosion. It has long been known that a proper cold working surface treatment could be a preventative control measure for both of these modes of corrosion. Stress corrosion cracking (SCC) can occur only in the presence of a tensile stress; therefore, it

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[1] By Rockwell International and Metal Improvement Company

[2] U.S. Patent No. 3,844,846, Metal Improvement Company, Paramus, New Jersey, Licensee

can be prevented by imposing a compressive stress on the surface exposed to the corrosive environment. Nevertheless, the application of this principle for controlling SCC is not widely practiced in industry, at least not for the stainless steels. With respect to intergranular corrosion (IGC), Bain, Aborn, and Rutherford (1933) demonstrated some 40 years ago that cold working of austenitic stainless steels by cold rolling greatly reduced their susceptibility to intergranular attack if they were subsequently exposed to sensitizing temperatures. However, because the entire bulk of the alloy had to be treated, excessive work hardening occurred. Thus, as late as 1967 it was still being published that cold working for this purpose was not a recommended or practical procedure (Fontana and Green, 1967). The preferred methods of corrosion control have been and continue to be (1) heat treatments to relieve residual stresses and to minimize the risk of SCC, (2) solution annealing to eliminate chromium-depleted zones and remove grain boundary carbides, and (3) stringent control of the environments to minimize the contamination that can promote either or both of these corrosion modes.

This report addresses the application of one specific cold working procedure, controlled shot peening, as a practical method of preventing both SCC and IGC. First, shot peening imposes a compressive stress on the surface that can negate the tensile stresses, residual or applied, that are required for SCC. Second, shot peening uniformly cold works the surface of the workpiece; therefore, it can effectively reduce susceptibility to IGC. Third, the controlled shot-peening process is adaptable to most wrought or cast products or fabricated components, regardless of size and shape.

MATERIALS AND PROCEDURES

The materials covered in this study were the austenitic stainless steel Types 304, 316, 321, and 347. Conventional U-bend specimens used in the SCC scoping tests were of Type 304 stainless steel strip, 0.090-in. (0.23-cm) or 0.125-in. (0.32-cm) thickness. The coupons used for intergranular corrosion tests were of Type 304 stainless steel, 1/4-in.-thick (0.64-cm) plate. The scale-up welded pipe specimens were of Types 321 or 347 stainless steel, while the hexagonal tube was Type 316 stainless steel. The 8-ft (244-cm) length of 6-in.-diameter (15.2-cm) pipe was Type 304 stainless steel. Except for the Type 316 stainless steel hexagonal tube, which was 20% cold worked, all material was in the solution-annealed condition.

Peening was done using commercial peening equipment and procedures. All test specimens were peened manually except the 8-ft-long (244-cm) pipe section, which was peened by a fully automated process on both outside and inside diameters.

The conventional peening material was cast steel shot, Grade 230 or Grade 280 conforming to MIL-S-851. The peening of the pipe section was with a smaller size, Grade 170. For some experimental peening studies, specimens were peened with glass beads or ceramic beads.

The effectiveness of the peening processes was evaluated by conventional tests for stress corrosion cracking or intergranular corrosion. For SCC, the specimens were immersed in boiling 42% magnesium chloride. The evaluation criteria were the time to initiate stress corrosion cracks and/or time to failure of the specimen. In this test, cracks commonly initiated in about 1/2 h in unpeened U-bend specimens (used for control purposes), with full failure generally occurring within 2 h. For IGC, the specimens were immersed in a 10% HNO_3-3% HF solution at 70°C and examined metallographically for intergranular attack.

TEST RESULTS

Scoping Tests

The scoping phase of the study was intended to establish the feasibility of the shot-peening process to prevent the stress corrosion cracking and intergranular corrosion of austenitic stainless steels. The factors evaluated included such process variables as peening intensity, shot material and size, and coverage; the effects of elevated temperatures on the decay of the compressive stresses imposed by shot peening and the concomitant effects of resistance to SCC; the effects of exposures at sensitizing temperature with respect to intergranular attack; and the effectiveness of shot peening in preventing SCC due to residual stresses in weldments. The results of these scoping tests are summarized in Table 1.

TABLE 1 Shot Peening — Scoping Tests Summary

Parameter	Comments
Peening Intensity	Unpeened U-bend specimens stress-corrosion-cracked in 1 to 2 h in boiling $MgCl_2$ test; specimens peened over a wide range of peening intensities survived 1000 h without cracking.
Shot Material	Effective with steel, glass, or ceramic beads.
Stress Decay	Effective after thermal soaking at 1050°F (566°C).
Sensitization (Stress Corrosion)	Peening is effective on sensitized material.
Sensitization (Intergranular Corrosion)	Peening may prevent intergranular corrosion.
Weld Stresses	Stresses induced by welding are sufficient to cause stress corrosion cracking; peened welds did not crack.
Peening Defects	Process control required to assure 100% coverage.

Component Tests

This phase of the study was conducted to establish the practicality of the peening process for sizes and shapes that typify components in a reactor piping system. The scale-up tests were conducted on (1) weldments of a heavy-wall boss to a 7-1/2-in. (19-cm) OD, Type 321 stainless steel pipe; (2) circumferential butt welds in a 5-1/2-in. (14-cm) OD, Type 347 stainless steel pipe; (3) a 4-1/2-in. (11.4-cm) Type 316 stainless steel, hexagonal-shaped tube with 20% cold work; and (4) a 6-in. (15.2-cm) OD, Type 304 stainless steel pipe, 8 ft (244 cm) in length.

One weldment from the Type 321 stainless steel pipe section was unpeened, while the second specimen was peened on all surfaces at 0.011A Almen Intensity. The unpeened specimen cracked severely in the $MgCl_2$ test after immersion for ~22 h. In contrast, the peened specimen was tested for a total of 264 h without visible stress corrosion cracks in the peened surfaces.

Three similar circumferential weldments from the Type 347 stainless steel pipe were tested. Figure 1 shows the cracks that developed adjacent to the weld of the unpeened specimen during 23-h immersion in $MgCl_2$. Note that the stress pattern indicated by the crack is circumferential and parallel to the weld on one side of the weld bead and radial on the other side. In contrast, no cracks developed in 120 h of testing on the specimen which was peened on both outside-diameter and inside-diameter surfaces. The third specimen was peened around one-half of its circumference on both OD and ID surfaces. No cracks were detectable in the peened half-section after a 22-h exposure in $MgCl_2$; however, cracking was readily visible in the unpeened half-section. The cracks propagated until they terminated at the interface with the peened surface as shown in Fig. 2.

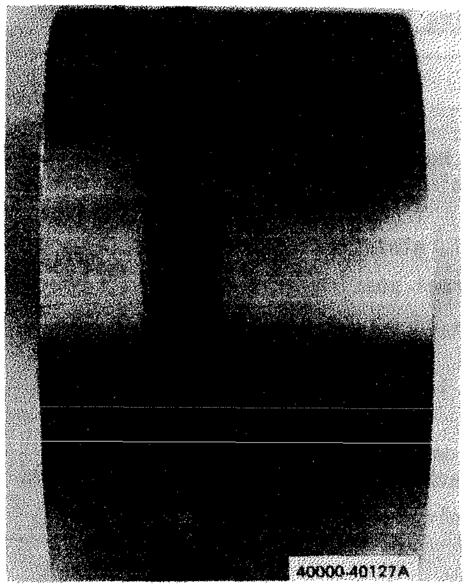

Fig. 1 Stress corrosion cracks in unpeened Type 347 stainless steel pipe weld.

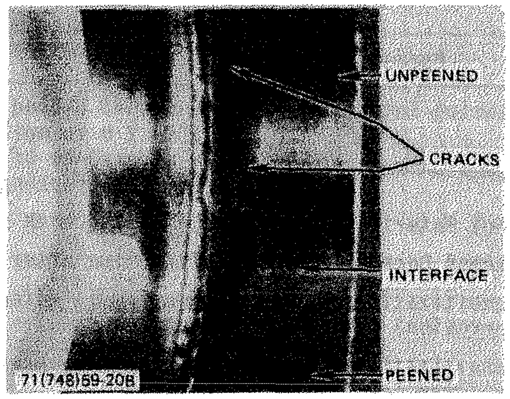

Fig. 2 Stress corrosion cracks in unpeened Type 347 stainless steel pipe weld surface. There are no cracks in the peened surface.

A section of a hexagonal Type 316 stainless steel pressure tube that had a 15 to 20% reduction in wall thickness in its final processing operation was tested after peening one-half of the surface. Cracks were detected in one inside-diameter corner of the unpeened section after only 3 h of testing. After testing for 22 h, cracks were present in the flats as well as in the corners of the unpeened section on both inside-diameter and outside-diameter surfaces. In contrast, no cracks developed in the peened surfaces during this test. Figure 3 shows the interface between the peened and unpeened surfaces and the stress corrosion cracks present near the corners of the hexagonal tube. The major crack shown in the corner was a through-crack.

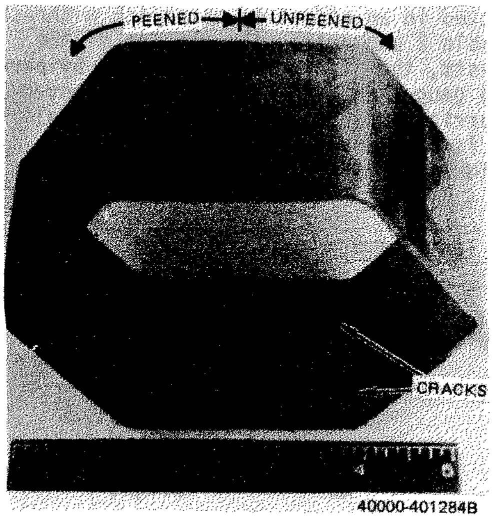

Fig. 3 Stress corrosion cracks in unpeened surface of Type 316 stainless steel hexagonal tube (20% C.W.).

Intergranular Corrosion Prevention Tests

The efficacy of severe shot peening to suppress IGC is illustrated in Fig. 4. The microstructures shown are typical of peened and unpeened Type 304 stainless steel surfaces after being "sensitized" and tested for intergranular attack in an HNO_3-HF solution. The cold-worked surface of the peened specimen is completely free from attack; in contrast, the unpeened surface is severely and uniformly attacked at the grain boundaries.

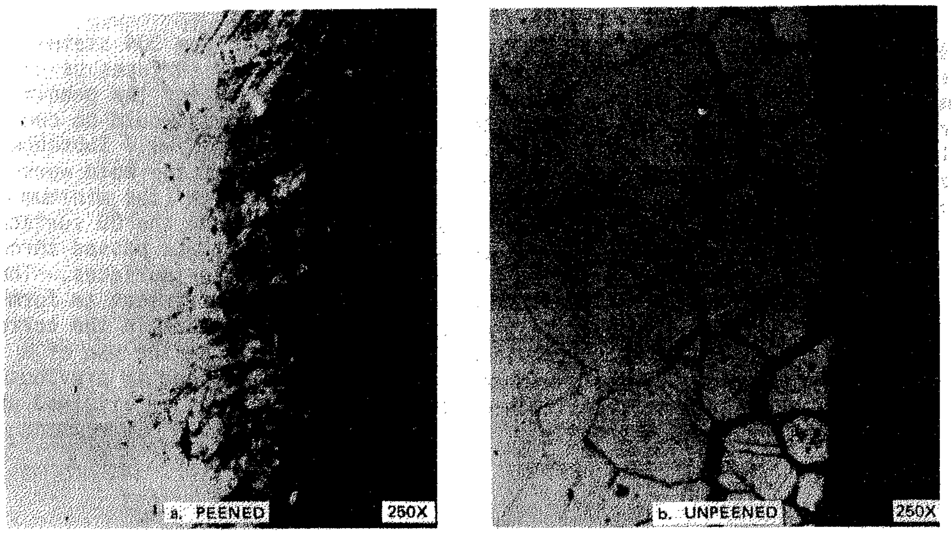

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Fig. 4 Photomicrographs of peened and unpeened Type 304 stainless steel plate surfaces sensitized at 1200°F (649°C) 1 h and tested for intergranular corrosion in HNO_3-HF.

Several series of peening tests were conducted in an effort to establish a threshold level of cold work by shot peening. Table 2 summarizes the results of the final series of peening tests. In these tests, the peening was monitored by percent coverage, up to 400%, and by a ferrite gauge, an instrument that is conventionally used to determine the amount of ferrite in austenitic stainless steel weld metal. The indicated threshold level is 300% coverage or 0.5% ferrite. Using the eddy current method, the threshold level is 43.

TABLE 2 Peening Test Summary

Specimen Number	Peening Coverage (%)	Ferrite Gauge (%)	Reading - Eddy Current Gauge	Intergranular Corrosion
Reference	Unpeened	<0.5	40	Severe
1	100%	<0.5	40	Moderate
2	200%	<0.5	40	Slight
3	300%	~0.5	43	None
4	400%	0.5 - 1.0	46	None
5	-	1.0 - 1.5	48	None
6	-	1.5 - 2.0	51	None
7	-	2.5 - 3.5	73	None
8	-	4.0 - 5.0	85	None

Note. All specimens were peened with 390-grade ceramic beads at 80-psig pressure. The Almen Intensity was 0.024A.

An 8-ft (244-cm) length of 6-in. (15.2-cm) OD, Schedule 40, Type 304 stainless steel pipe was peened on outside-diameter and inside-diameter surfaces using commercial automated equipment. The measured Almen Intensity for the peening operation was 0.012A. It was intended that the peening process would be controlled with the ferrite gauge, but this proved to be unsuccessful. Subsequent metallographic examinations and corrosion tests indicated that the cold working induced by the peening was insufficient to produce 0.5% ferrite (the minimum readout on the ferrite gauge) or to prevent intergranular attack on the OD surface. The inside-diameter surface, which was peened via a wand that was passed through the pipe, was more highly cold worked than the outside-diameter surfaces. The amount of cold work on the inside-diameter surface was not sufficient to form 0.5% ferrite, but it was severe enough to prevent intergranular attack in the corrosion tests. This deficiency of cold work is attributed, in part, to the use of a smaller size (170-grade) of shot instead of the larger sizes used in previous tests. It is believed that acceptable cold-worked surfaces can be attained using larger shot and increased intensity.

DISCUSSION

This investigation demonstrated the feasibility of preventing stress corrosion cracking and intergranular corrosion in Type 304 stainless steel and probably in any similar austenitic stainless steel. It was found that resistance to SCC is: (1) achieved over a wide range of shot peening conditions, shot sizes, and materials, (2) effective on sensitized as well as unsensitized material, and (3) not negated by prolonged (144-h) heating at temperatures to 1050°F (566°C). The effectiveness of shot peening for preventing this type of corrosion is probably dependent, in the main, on achieving complete surface coverage rather than on any particular processing parameter. This is illustrated by the fact that there were no failures due to stress corrosion cracking in any peened surface, regardless of the peening condition.

With respect to preventing intergranular corrosion, it is necessary to control the peening process by means other than the conventional peening intensity and coverage. The surface grains must be cold worked sufficiently to prevent the precipitation of carbides along continuous paths if the surface grains are subsequently exposed to sensitizing temperatures.

The feasibility of both magnetic and eddy current techniques for controlling the amount of cold work on a peened workpiece has been demonstrated; however, further work is required to define their full capabilities and limitations. The ferrite gauge uses a series of magnets that are calibrated in "% ferrite" and is conventionally used to determine the amount of ferrite in austenitic stainless steel weld metal. This principle can be applied to monitor peening since ferrite may be formed by a martensitic reaction during the cold working of the surface grains. Using the ferrite gauge, it was shown that peening developed up to 7.5% ferrite in Type 304 stainless steel. Development tests also demonstrated that the presence of 0.5% ferrite in a peened surface is indicative of sufficient cold work to prevent intergranular attack in Type 304 stainless steel. This approach has its limitations in that (1) it will also respond to the ferrite in any peened welds and (2) it cannot be applied to alloys other than the 18-8 types of stainless steels that are subject to the martensitic reaction. The eddy current technique can be adapted to monitor shot peening since it responds to changes in electrical properties. Using an unpeened standard of the same material and thickness, an eddy current instrument will indicate changes in the electrical properties induced by the cold-worked surface grains. For this technique, a new calibration curve has to be developed for each material and condition. Tests to date have indicated that the eddy current is very sensitive to local variations in the peened surface and, as such, considerable judgment must be exercised in interpretation of results.

CONCLUSIONS

Shot peening can prevent stress corrosion cracking by imposing compressive stresses on the surface of the workpiece. In general, adequate compressive stress levels were attained by 200% surface coverage.

Controlled shot peening can prevent intergranular corrosion due to sensitization. Peening must be sufficient to severely cold work the surface grains.

The feasibility of shot peening to prevent corrosion of austenitic stainless steels has been established. The practicality of shot-peening processes, equipment, and control techniques needs to be demonstrated for industrial applications.

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