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Measured Residual Stresses in Overlay Pipe Weldments Removed from Service

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Abstract

Surface and throughwall residual stresses were measured on an elbow-to-pipe weldment that had been removed from the Hatch-2 reactor about a year after the application of a weld overlay. The results were compared with experimental measurements on three mock-up weldments and with finite-element calculations. The comparison shows that there are significant differences in the form and magnitude of the residual stress distributions. However, even after more than a year of service, the residual stresses over most of the inner surface of the actual plant weldment with an overlay were strongly compressive.

1. Introduction

Because of the severe economic consequences of long forced outages for replacement of cracked piping due to intergranular stress corrosion cracking (IGSCC) in boiling water reactors (BWRs), a weld overlay technique has been developed by the industry for short-term repairs. Weld overlays provide structural reinforcement, and calculations have shown that the radial shrinkage induced by the overlay produces compressive residual stresses on the inner surface of the weldment. To provide experimental verification of these results, surface and throughwall residual stresses were measured on an elbow-to-pipe weldment that had been removed from the Hatch-2 reactor about a year after the application of a weld overlay. The results were compared with experimental measurements on three mock-up weldments and with finite-element calculations.

2. Specimens and Experimental Procedures

The three mock-up weldments, supplied by Georgia Power and NUTECH, were fabricated from 12-in. Schedule 100 pipe. One side of each weldment had a long, smooth weld prep geometry typical of that used in the Hatch-1 reactor, while the other side of each weldment had a short, more abrupt weld prep geometry typical of that used in the Hatch-2 reactor. Last-Pass Heat Sink Welding (LPHSW) was used for one of the mock-up weldments. The other two were fabricated by conventional butt welding procedures, followed by the application of weld overlays. The two overlays

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are similar to those actually applied to the recirculation piping in the Hatch reactors. They were fabricated by identical procedures, but they are slightly different in size. One, which will be referred to as the minioverlay, is ∿100 mm (4 in.) long and ∿5 mm thick. The other, which will be referred to as the standard overlay, is ∿118 mm (4.7 in.) long and ∿5 mm thick.

On each of the three mock-up weldments, four azimuths (45°, 135°, 225°, and 315°) were instrumented with strain gages. Micro-Measurements EA-09-030YB-120 miniature 60° strain-gage rosettes, with an active length of 0.76 mm (30 mils), were used. The azimuths were taken with respect to an origin established by Georgia Power and NUTECH during fabrication. For the overlay weldments, measurements were made at seven axial positions on the side with the long weld prep geometry and at six axial positions on the side with the short weld prep geometry. For the LPHSW weldment, measurements were made at six axial positions, three on each side of the weld.

After the complete weldment was instrumented, full-thickness specimens were cut from the weldment at the four azimuthal positions where the strain gages were mounted. For the overlay weldments, the bars were ∿63 mm wide and ∿340 mm long. For the LPHSW weldment, in which the weld area is relatively narrow, the bars were ∿63 mm wide and ∿100 mm long. The stress changes on the inner and outer surfaces during the parting out of the full-thickness bars can be used to calculate the net forces and moments acting on the bars before they were cut from the complete weldment. However, these stress changes are not accurate measures of the actual stresses on the inner and outer surfaces, since substantial self-equilibrating stresses remain in the full-thickness specimens. To determine the actual stresses on the inner surface, a thin slab (3 mm thick) was removed from the inner surface of each specimen by electrical discharge machining. This provided almost complete stress relief for the gages on the inner surface.

To determine the throughwall distribution of stresses in the weldment, thin layers of material were removed from the inner surface by milling. The resultant strain relief was measured by the gages mounted on the outer surface of the weldment and used to compute the throughwall stress distribution. A detailed discussion of the experimental procedures and analysis used has been given by Shack [1].

3. Results

The inner-surface stresses were measured at four azimuths for the minioverlay. The axial and circumferential stresses on the inner surface are shown in Fig. 1. Since both these stresses and the parting-out stresses were axisymmetric, the inner-surface stresses were determined at only one azimuth for the other two weldments. The inner-surface stresses for the standard overlay and the LPHSW weldment are shown in Fig. 2.

Throughwall axial and circumferential residual stresses in the minioverlay mock-up ∿8 mm from the weld centerline are shown in Fig. 3. The corresponding results for the standard overlay and the LPHSW mock-ups are shown in Figs. 4 and 5, respectively. As expected, both the axial and circumferential throughwall stresses are strongly compressive on the inner portion of the wall and tensile on the outer portion. There is relatively little axial variation in stress in the regions under the overlays for the two overlay weldments.

In addition to the measurements on the mock-up weldments, residual stresses were also measured on an actual elbow-to-pipe weld overlay removed from the Hatch-2 reactor (weld 2B31-1RC-12BR-C3). Strain gage rosettes were laid on the inner and outer surface of the weldment at four azimuthal positions. The 0° position is at the extrados of the elbow. The 90° and 270° positions are on the midplane of the elbow. The measured stresses are shown in Table I.

4. Discussion

At least near the weld, the residual stresses measured for the LPHSW mock-up are similar to those obtained for the minioverlay and the standard overlay. The differences in the stresses produced by the different procedures are small and appear to be within the variations that might be expected from weld to weld with a single procedure. The overlay procedures probably produce larger plastic strains and deformations, but since the stress is a relatively weak function of plastic strain, the corresponding stresses produced by the different procedures do not differ too greatly.

The throughwall distributions shown in Figs. 3-5 should not be interpreted to indicate that overlays will be effective for cracks roughly halfway through the wall and ineffective for deeper cracks, since the presence of a crack strongly perturbs the stresses produced by the overlay process. Stress distributions [2] for a complete circumferential crack, 60% throughwall, are shown in Fig. 6. These results, which were obtained by finite-element calculations, indicate that owing to the residual stresses, the stresses at the crack tip remain compressive even under substantial applied loads.

It is impossible to directly measure the stresses at the tip of a crack in a pipe weldment that has been repaired by a weld overlay and is acted on by axial and circumferential loads characteristic of reactor piping systems. However, the experimental measurements on the uncracked weldments can be used to benchmark the finite-element techniques. A comparison of the residual stresses predicted by finite-element techniques with measured axial residual stresses [3] is shown in Fig. 7. The figure compares the predicted stresses at the centerline of the overlay with the measured residual stresses at four different axial positions for both the minioverlay and the standard overlay.

The measured stresses on the weldment removed from service are much less axisymmetric than those measured in the companion mock-up weldments; the asymmetry seems stronger on the elbow side, as might be expected. The stresses on the inner surface are compressive, although not as compressive as the stresses measured on the mock-up weldments. This is consistent with the increased flexibility due to the elbow, which could accommodate the shrinkage due to the overlay; but other explanations are also possible.

References

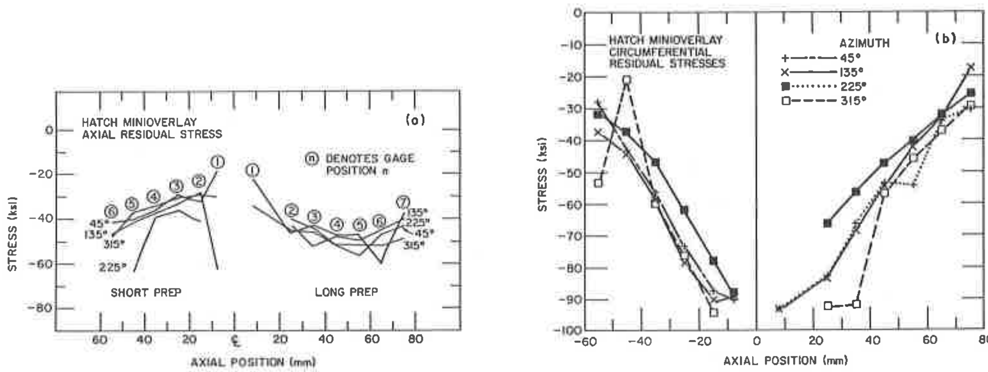
1. SHACK, W. J., "Measurement of Throughwall Residual Stresses in Large-Diameter Type 304 Stainless Steel Piping Butt Weldments," ANL-82-15, Argonne National Laboratory (1982).
2. "Materials Science and Technology Division Light-Water-Reactor Safety Research Program: Quarterly Progress Report, October-December 1983," NUREG/CR-3689 Vol. IV, ANL-83-85 Vol. IV (August, 1984).
3. "Light-Water-Reactor Safety Materials Engineering Research Programs: Quarterly Progress Report, January-March 1984," NUREG/CR-3998 Vol. I, ANL-84-60 Vol. I (September, 1984).

Table I. Measured Residual Stresses[a] on a Hatch 12-in. Elbow-to-Pipe Overlay Weldment

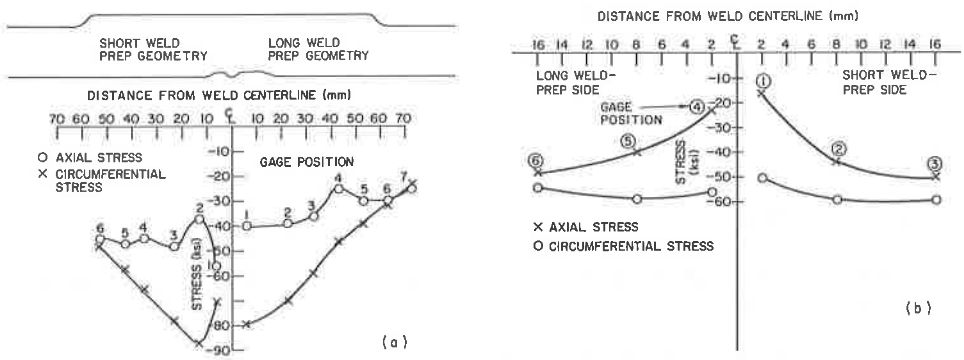
	Azimuth			
	0°	90°	180°	270°
	Inner Surface, Pipe Side			
Axial Stress	-15 (-105)	-10 (-70)	-21 (-147)	-15 (-105)
Hoop Stress	-37 (-259)	-27 (-189)	-66 (-462)	-45 (-315)
	Inner Surface, Elbow Side			
Axial Stress	-31 (-217)	-11 (-77)	-60 (-420)	b
Hoop Stress	-42 (-294)	-29 (-203)	-55 (-385)	
	Outer Surface, Pipe Side			
Axial Stress	25 (175)	32 (224)		
Hoop Stress	5 (35)	10 (70)		
	Outer Surface, Elbow Side			
Axial Stress	0 (0)			
Hoop Stress	-15 (-105)			

[a]Values in ksi (MPa).

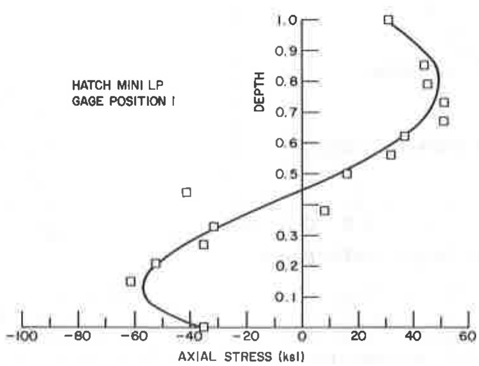
[b]A number of rosettes were lost during the stress relief machining operations; consequently, measurements were not obtained at all the intended positions.



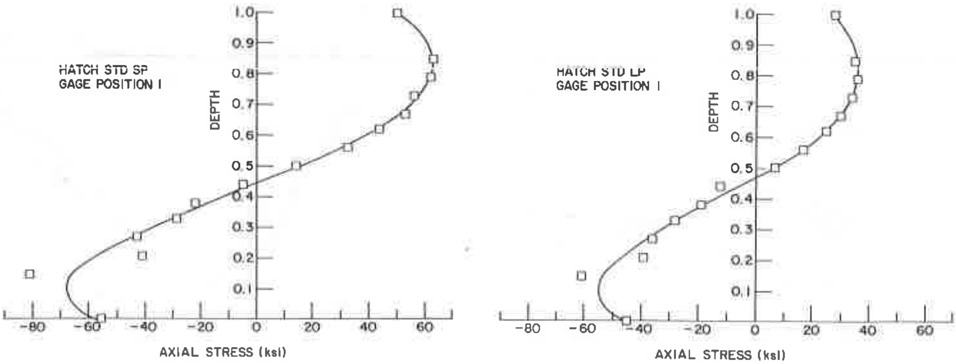
1. Axial (a) and Circumferential (b) Stresses on the Inner Surface of the Minioverlay Mock-up.



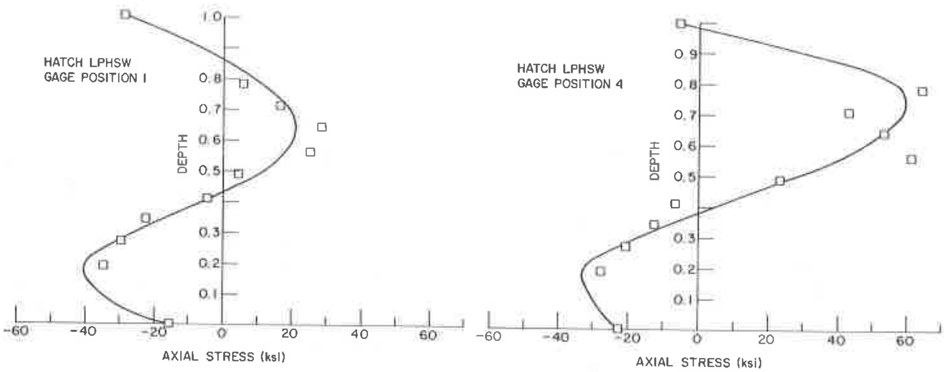
2. Axial and Circumferential Residual Stresses and Strain Gage Locations on the Inner Surface of the Hatch Standard Overlay (a) and LPHSW (b) Mock-ups.



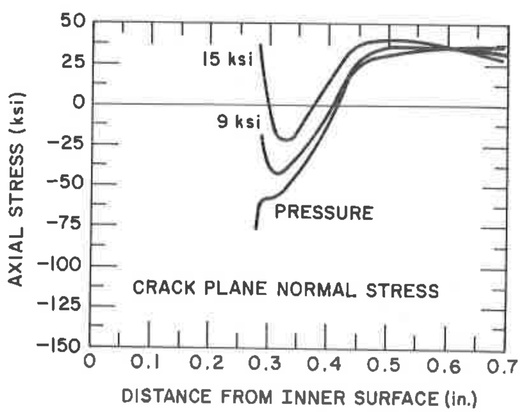
3. Throughwall Axial Residual Stresses for the Hatch Minioverlay Mock-up ~8 mm from the Weld Centerline on the Side of the Weldment with the Long Weld Prep.



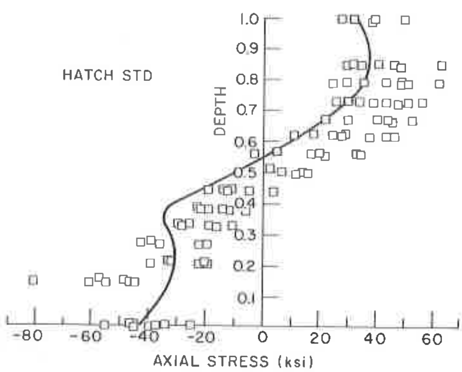
4. Throughwall Axial Residual Stresses for the Hatch Standard Overlay Mock-up ∿8 mm on Either Side of the Weld Centerline.



5. Throughwall Axial Residual Stresses for the Hatch LPHSW Mock-up ∿2 mm on Either Side of the Weld Centerline.



6. Predicted Crack Plane Normal Stress for Various Applied Axial Stresses (15 ksi, 9 ksi, or Internal Pressure Alone) in a Weldment with a Complete Circumferential Crack, 60% Throughwall, After an Overlay Repair.



7. Comparison of Axial Residual Stresses Predicted by Finite-Element Techniques (Curve) with Measured Axial Residual Stresses on the Hatch Mock-up Weldments (Symbols).