

**RESIDUAL STRESSES AND STRESS CORROSION
CRACKING IN PIPE FITTINGS**

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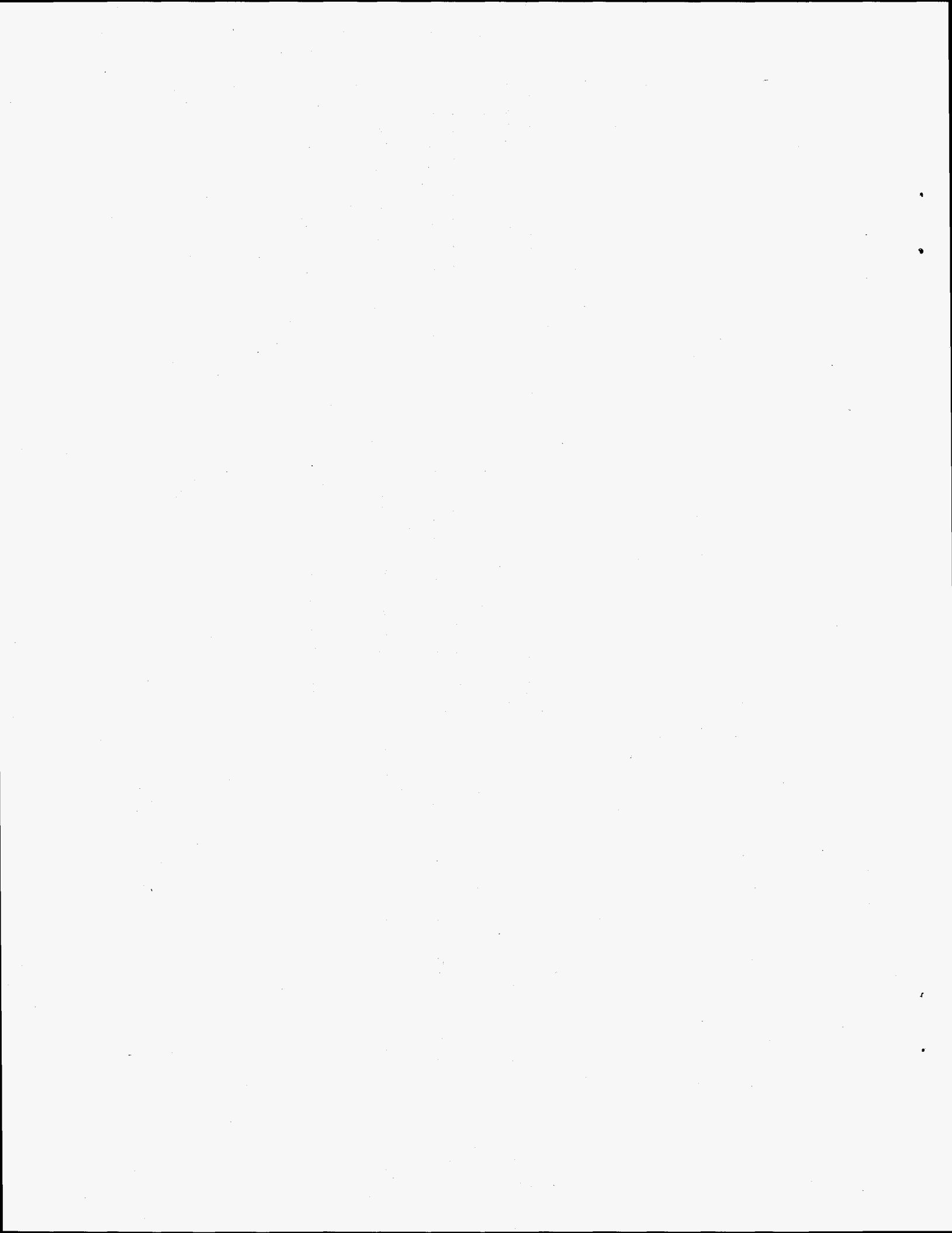
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RESIDUAL STRESSES AND STRESS CORROSION CRACKING IN PIPE FITTINGS

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Residual stresses in as-fabricated pipe fittings are sufficient to induce stress corrosion cracking (SCC) in susceptible materials exposed to 400°C steam environments. This has been demonstrated qualitatively for Alloy 600 fittings by testing in high purity 400°C steam and for stainless steel fittings by testing in boiling magnesium chloride. Quantitative residual stress measurements were performed on Alloy 600 elbows using the section and layer removal technique (SLR). Fittings manufactured from several fabricators were evaluated. Significant differences were observed suggesting that vendor manufacturing methods can significantly influence SCC susceptibility of fittings.

Fourteen Alloy 600 elbows from four different fabricators were tested in 400°C steam with 0.07 MPa hydrogen. SCC on the inside surfaces was observed in as early as 6 weeks. Only fittings made by one fabricator have cracked. The time for SCC initiation decreases with decreasing fitting diameter and increasing wall thickness.

Thirty-six Type 304 stainless steel elbows from four different fabricators were tested in boiling magnesium chloride. The results suggest strong fabricator-to-fabricator differences in residual stresses. Specific cracking patterns can be attributed to bending, ball sizing and the use of expandable tapered plugs. A fabricator ranking based on testing stainless steel fittings in magnesium chloride is consistent with the ranking obtained from testing Alloy 600 fittings in 400°C steam.

Two 7.6 cm schedule 160 Alloy 600 elbows from two fabricators were destructively evaluated for residual stress using the SLR technique in which the fittings are strain-gauged and then sectioned, followed by layer removal. Stresses relieved at each step are recorded by the strain gauges and used to analyze the residual stresses. Stresses as high as 620 MPa were measured and, consistent with 400°C steam and boiling magnesium chloride testing, as-fabricated stresses were twice as high in one fabricator's elbow.

INTRODUCTION

Residual stresses can play a key role in the SCC performance of susceptible materials in PWR primary water applications. Residual stresses are stresses stored within the metal that develop during deformation and persist in the absence of external forces or temperature gradients. Sources of residual stresses in pipe fittings include fabrication processes, installation and welding.

There are a number of methods to characterize the magnitude and orientation of residual stresses. These include numerical analysis, chemical cracking tests, and measurement (e.g., X-ray diffraction, neutron diffraction, strain gage/hole drilling, strain gage/trepanning, strain gage/section and layer removal, and acoustics).

This paper presents 400°C steam SCC test results demonstrating that residual stresses in as-fabricated Alloy 600 pipe fittings are sufficient to induce SCC. Residual stresses present in as-fabricated pipe fittings are characterized by chemical cracking tests (stainless steel fittings tested in boiling magnesium chloride solution) and by the sectioning and layer removal (SLR) technique.

EXPERIMENTAL PROCEDURE

400°C Steam Test

Fourteen Alloy 600 elbows from four different fabricators were tested in 400°C steam. Testing in this environment is believed to provide accelerated SCC data for nickel base alloys applicable to PWR primary water environments. The test specimen matrix is shown in Table 1. With the exception of elbows A-10w and A-12w, which were welded to short pipe segments at both ends, all elbows were tested in the as-fabricated, unloaded condition.

400°C steam testing was performed in a 60-liter autoclave with system modifications to permit hydrogen and pH control. Monitoring and

control of hydrogen were achieved through a single Ag/Pd transfer tube penetrating the autoclave head. The desired hydrogen concentration (0.07 +/- 0.01 MPa)

Fitting		Run1	Run2	Run3	Run4	Run5	Run6	Run7	Run8
B-1	5.1 cm sch 160 elb (Tube)	7 wks	13 wks	19 wks	32 wks	45 wks	58 wks		
B-4	5.1 cm sch 160 elb (Bar)		7 wks	13 wks	19 wks	32 wks	45 wks	58 wks	
C-1	5.1 cm sch 160 elb (Tube)	7 wks	13 wks	19 wks	32 wks	45 wks	58 wks		
C-2	7.6 cm sch 160 elb (Tube)	7 wks	13 wks	19 wks	32 wks	45 wks	58 wks		
A-1	7.6 cm sch 160 elb (Tube)	<u>7 wks</u>	13 wks	19 wks	25 wks	31 wks	37 wks		
A-4	10.2 cm sch 120 elb (45°-Bar)	6 wks	12 wks	18 wks	24 wks	<u>30 wks</u>	36 wks	42 wks	
A-5	10.2 cm sch 120 elb (45°-Tube)	6 wks	12 wks	18 wks	24 wks	30 wks	36 wks	42 wks	
A-6	10.2 cm sch 120 elb (90°-Bar)	13 wks	26 wks	39 wks					
A-8	10.2 cm sch 120 elb (90°-Tube)	6 wks	12 wks	18 wks	24 wks	30 wks	36 wks	42 wks	
A-9	5.1 cm sch 80 elb (Bar)	7 wks	<u>13 wks</u>	19 wks	25 wks	31 wks	37 wks	43 wks	49 wks
A-10	5.1 cm sch 80 elb (Tube)	<u>6 wks</u>	12 wks	18 wks	24 wks				
A-12	5.1 cm sch 160 elb (Tube)	<u>6 wks</u>	12 wks						
A-10w	7.6 cm sch 160 weld/elb (Tube)	6 wks	12 wks	18 wks	24 wks	30 wks			
A-12w	7.6 cm sch 160 weld/elb (Tube)	6 wks	<u>12 wks</u>	18 wks	24 wks	30 wks			

Underline = Crack initiated during this cycle
 Tube/Bar = Starting stock material
 LD. Prefix (A, B, C) = Fabricator

TABLE 1 - ALLOY 600 ELBOWS IN 400°C STEAM AUTOCLAVE TESTING

was established with a hydrogen-argon mixed gas. A system pressure of 19.3 +/- 0.3 MPa was maintained. The test facility was designed to permit the addition of makeup water at high temperature and pressure. Proper water chemistry was achieved by degassing the initial steam test environment to a low pressure (~0.7 MPa) and then adding high purity water (pH of 10.0 to 10.3, oxygen less than 10 ppb, and resistivity of 0.012 to 0.058 meg ohm-cm) until the desired system pressure is reached. Test temperature was controlled at 400°C +3/-6°C.

Pipe fittings tested in 400°C steam were removed from test periodically and inspected visually and ultrasonically for crack indications. Upon test completion, nondestructive inspection of pipe fittings was followed by destructive, metallographic examination. Only one elbow (A-1) has been terminated and destructively evaluated, to date.

Boiling Magnesium Chloride Test

Thirty-six Type 304 stainless steel elbows from four different fabricators were tested in boiling magnesium chloride solution. Boiling magnesium chloride induces cracking in stainless steel under tensile stress and was employed as a chemical cracking test to characterize residual stresses. The location and orientation of tensile residual stresses are revealed by the location and orientation of chloride induced cracking. A semi-quantitative estimate of the magnitude of residual stresses can be made based on the Reference (1) correlation of tensile stress magnitude to time to crack initiation (Figure 1). The test specimen matrix is shown in Table 2.

Testing was performed in accordance with ASTM G36 - "Standard Practice for Performing Stress-Corrosion Cracking Tests in a Boiling Magnesium Chloride Solution". The bench top test setup consisted of a large glass vessel equipped with a heating jacket, reflux column and an alarm for out-of-specification thermal excursions.

Pipe fittings were tested in boiling magnesium chloride for times ranging from 0.5 to 22 hours. Following test exposure, the pipe fittings were sectioned longitudinally and fluorescent penetrant inspected. Metallographic examination was also performed in some instances.

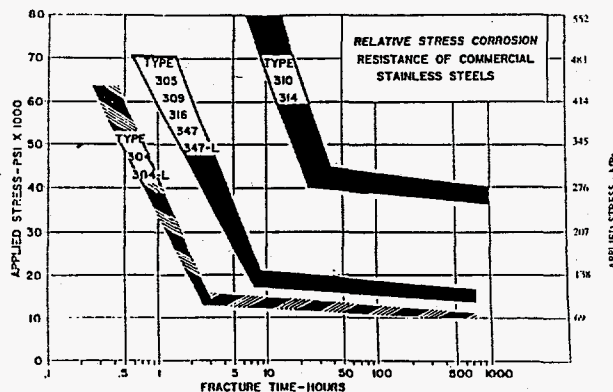


FIGURE 1 - DENHARD CURVE OF STRESS LEVEL AS A FUNCTION OF FRACTURE TIME

Section and Layer Removal (SLR) Measurements

Two 7.6 cm schedule 160 Alloy 600 elbows from different fabricators were destructively evaluated for residual stress using the SLR technique.

Fabricator a	TIME	DEPTH	EXTENT	DESCRIPTION
5.1 cm sch 80	0.5 hrs	20%	■■■■■■■■■■	Highly networked, tight cracking (spider web). Bony and polygonal near elbow ends and along sidewall. Highly circumferential at intrados center and extrados. Axially elongated strips along sidewall. Only intrados and extrados cracking, greatest at low exposures. 5.1 cm sch 160 and 7.6 cm sch 160 showed similar patterns - but more severe in 5.1 cm.
	1.0	20%	■■■■■■■■■■	
	2.0	25%	■■■■■■■■■■	
	22	20%	■■■■■■■■■■	
5.1 cm sch 160	1.0	20%	■■■■■■■■■■	Highly branched, river delta type cracking. More axial than circumferential. Cracking also not as interconnected as Fabricator a. Axial cracking along counterbore where exterior was masked off. Only cracking at intrados and extrados present after exposure < 20 hrs. Cracking for 5.1 cm sch 160 and 7.6 cm sch 160 was similar in pattern and extent, though deeper and slightly more circumferential than 5.1 cm. 7.6 cm and 10.2 cm tested similarly to each other.
	2.0	25%	■■■■■■■■■■	
	22	20%	■■■■■■■■■■	
	22	20%	■■■■■■■■■■	
7.6 cm sch 160	1.0	20%	■■■■■■■■■■	Short, isolated patches of highly axial cracking located primarily along sidewalls. Cracking was very tight and clustered, regardless of size. Crack extent was slightly more pronounced for thicker walled elbows and fairly deep.
	2.0	20%	■■■■■■■■■■	
	22	20%	■■■■■■■■■■	
	22	20%	■■■■■■■■■■	
10.2 cm sch 120	1.0	20%	■■■■■■■■■■	Extremely isolated, axial cracks that were longer than Fabricator c. Cracks were preferentially located towards the ends of the elbows. Cracks were fairly deep, but extremely rare. 5.1 cm sch 160 elbows cracked more frequently and deeply than 5.1 cm sch 80 elbows.
	2.0	20%	■■■■■■■■■■	
	22	20%	■■■■■■■■■■	
	22	20%	■■■■■■■■■■	
Fabricator b	0.5 hrs	0%	■■■■■■■■■■	Extremely isolated, axial cracks that were longer than Fabricator c. Cracks were preferentially located towards the ends of the elbows. Cracks were fairly deep, but extremely rare. 5.1 cm sch 160 elbows cracked more frequently and deeply than 5.1 cm sch 80 elbows.
	1.0	0%	■■■■■■■■■■	
	2.0	<5%	■■■■■■■■■■	
	22	10%	■■■■■■■■■■	
Fabricator c	0.5 hrs	0%	■■■■■■■■■■	Extremely isolated, axial cracks that were longer than Fabricator c. Cracks were preferentially located towards the ends of the elbows. Cracks were fairly deep, but extremely rare. 5.1 cm sch 160 elbows cracked more frequently and deeply than 5.1 cm sch 80 elbows.
	1.0	0%	■■■■■■■■■■	
	2.0	<5%	■■■■■■■■■■	
	22	10%	■■■■■■■■■■	
Fabricator d	0.5 hrs	0%	■■■■■■■■■■	Extremely isolated, axial cracks that were longer than Fabricator c. Cracks were preferentially located towards the ends of the elbows. Cracks were fairly deep, but extremely rare. 5.1 cm sch 160 elbows cracked more frequently and deeply than 5.1 cm sch 80 elbows.
	1.0	0%	■■■■■■■■■■	
	2.0	<5%	■■■■■■■■■■	
	22	10%	■■■■■■■■■■	

TABLE 2 - RESULTS OF MgCl₂ TESTING OF UNLOADED STAINLESS STEEL ELBOWS

These measurements were performed by Prosig, Inc. The SLR technique involves placing strain gauges on the surfaces of the elbows and machining out pieces to be evaluated. Next, layers are removed from the inner surface of each piece. Changes in the strain gauge readings are recorded after each machining and layer removal step. Residual stress changes are evaluated for each machining and layer removal step and accumulated to obtain a throughwall residual stress distribution.

Twenty-four 90° biaxial strain gauge rosettes were mounted on each elbow, 12 on the interior surface and 12 on the exterior surface. The two axes of the strain gauges were aligned with the axial and hoop directions of the elbows. The locations of the strain gauges are portrayed in Figure 2.

After initial strain readings were recorded, the elbows were cut into twelve pieces (Figure 2), each piece containing strain gauges on the inner and outer surface. Strain changes during sectioning were recorded. Next, the pieces were trimmed to nominal dimensions of 3.22 cm wide (hoop direction) and 3.05 cm long. Strain changes due to trimming were

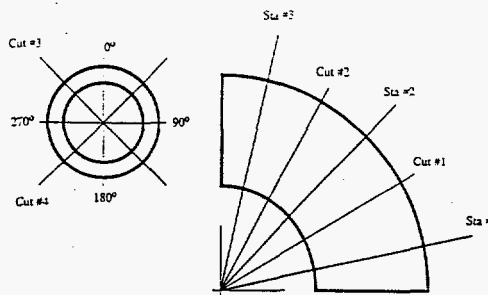


FIGURE 2

Strain Gauge Locations (2 for each location - inner and outer surfaces; 24 gauges total)			
Station 1	0°	90°	180° 270°
Station 2	0°	90°	180° 270°
Station 3	0°	90°	180° 270°

recorded. The final machining step involved removing layers from the inner surface of each piece to obtain data points at 0 (inner surface), 9, 25, 38, 50, 75 and 100% throughwall thickness locations. Strain changes were recorded for each removed layer.

The residual stresses present in the as-fabricated elbows prior to any sectioning were computed from the recorded strain changes.

TEST RESULTS

400°C Steam Test

Table 1 presents the 400°C steam SCC test results. To date, only elbows made by one of the four fabricators have cracked. No elbows made by the other three fabricators have cracked after test exposures up to 58 weeks.

SCC in Fabricator "a" elbows was observed in as early as 6 weeks. Cracking on all elbows was located primarily on the intrados of the elbow and ran circumferentially within 0-15° off axis. Furthermore, with the exception of the cracked 10.2 cm schedule 120 elbow, all cracks propagated during subsequent test exposures. Destructive evaluation has revealed the cracking to be intergranular. The circumferential extent and depth of cracking was significant. Elbow A-1 exhibited cracking that extended 360° and up to 90% throughwall depth.

For data plotting purposes, independent cracks on the same elbow are plotted as unique points. Figure 3 shows a clear correlation of crack initiation time to the wall thickness-to-diameter ratio. The thicker the wall and the smaller the diameter, the shorter the crack initiation time. Also, thicker walled and smaller diameter elbows generally propagate cracks deeper and more extensively through the elbows (Figure 4).

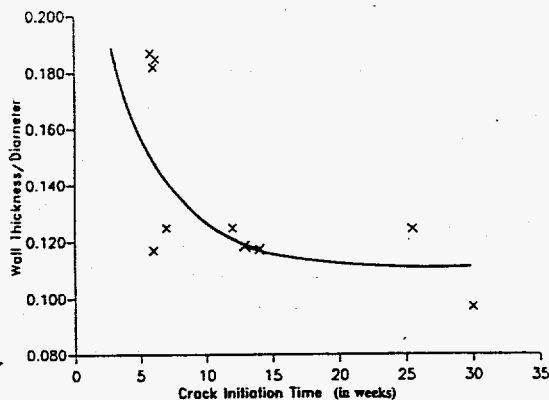


FIGURE 3 - GEOMETRY INFLUENCE ON CRACK INITIATION TIME IN 400° C STEAM

Boiling Magnesium Chloride Test

The results of testing stainless steel pipe fittings in boiling magnesium chloride solution are summarized in Table 2. Transgranular cracking was observed in elbows from all fabricators and of all sizes. Differences in crack initiation, crack depth and the extent of cracking were observed between elbow fabricators and elbow sizes.

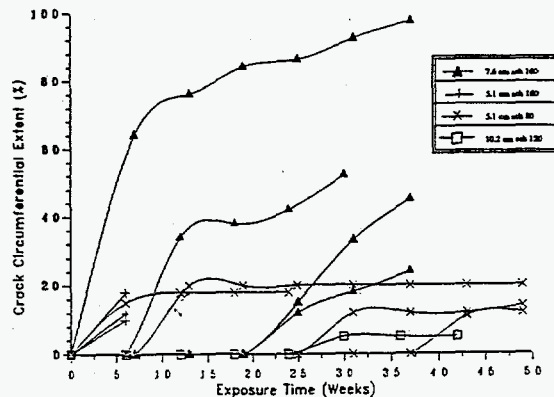


FIGURE 4 - CRACKING EXTENT AS A FUNCTION OF EXPOSURE TIME IN 400° C STEAM (MULTIPLE CURVES MAY REPRESENT MULTIPLE CRACKS IN THE SAME ELBOW)

Based on testing four 5.1 cm schedule 80 elbows from each fabricator for test exposures ranging from 0.5 to 22 hours, the fabricators are ranked in descending order of residual stress levels as follows: a, b, c and d. Fabricator "a" elbows cracked in as early as 0.5 hours, indicative of stresses exceeding about 330-410 MPa (Figure 1). No cracks developed in fabricator "b"- "d" elbows in test times less than 2 hours, indicative of stresses less than approximately 140 MPa. The residual stress ranking of fabricators "b"- "d" was based primarily on differences in the depth and extent of cracking as described in Table 2.

Testing of several different size and schedule elbows from a given fabricator demonstrated residual stress levels to generally increase as diameter decreases and wall thickness increases. This observation is based on crack depths, initiation times, and judgement of sometimes subtle differences in crack extent and appearance. Magnesium chloride testing ranked the geometry of different elbows in order of decreasing residual stress as: 5.1 cm schedule 160, 7.6 cm schedule 160, 5.1 cm schedule 80, and 10.2 cm schedule 120.

Section and Layer Removal (SLR) Measurements

SLR residual stress measurements provide a more quantitative estimate of residual stress levels than does magnesium chloride testing. Figures 5 and 6 compare the measured axial residual stresses on the intrados of 7.6 cm schedule 160 Alloy 600 elbows made by Fabricators "a" and "e". Axial stresses on the intrados are shown because cracking in 400°C steam and boiling magnesium chloride tests was predominantly circumferentially oriented and located on the elbow intrados. However, the distribution of residual stresses shown in Figures 5 and 6 is similar to the distribution at other locations measured on the elbows. The

Fabricator "a" elbow exhibited much higher (greater than 2X) tensile residual stresses than the Fabricator "e" elbow. The maximum measured residual tensile stress was ~620 MPa and the maximum stress on the inner surface, where SCC initiates, was ~350 MPa.

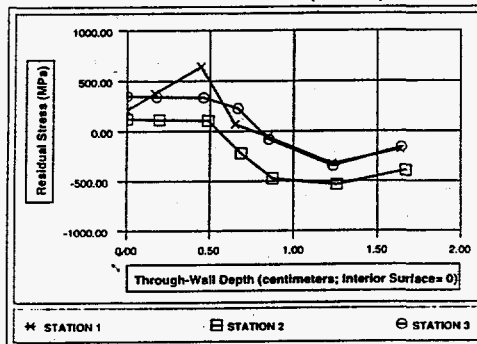
DISCUSSION

400°C steam test results of Alloy 600 elbows demonstrate that SCC can occur in the absence of applied tensile stress under the sole influence of as-fabricated residual stresses. Residual stress characterization of Fabricator "a" elbows using boiling magnesium chloride testing and the SLR measurement technique confirm the presence of high (330-620 MPa) tensile residual stresses.

Large differences in as-fabricated residual stress levels are attributed to the differences in fabrication processes. Table 3 summarizes the fabrication processes of the elbows tested. The bending process appears to be the most influential in imparting residual stresses since the region of maximum cracking, the center of the intrados and extrados, also experiences the maximum bending stress. Fabricators "a" and "b" employed the most severe bending process (cold pressed through a die) and exhibited the highest residual stresses. Somewhat higher

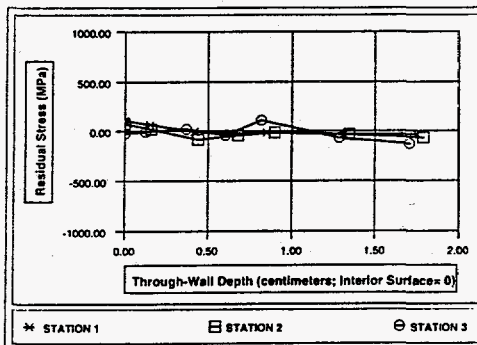
residual stresses observed in Fabricator "a" elbows versus Fabricator "b", although both employ the same bending process, are probably due to subtle differences such as grip

Figure 5: Fabricator A - Alloy 600 Elbow
Axial Residual Stresses (intrados)



For Measurement Locations See Figure 2

Figure 6: Fabricator E - Alloy 600 Elbow
Axial Residual Stresses (intrados)



For Measurement Locations See Figure 2

TABLE 3 - ELBOW FABRICATION PROCESSES

Fabricator a	Fabricator b	Fabricator c	Fabricator d	Fabricator e
TUBE OR BAR	TUBE OR BAR	TUBE OR BAR	TUBE OR BAR	TUBE OR BAR
COLD PRESSED THROUGH DIE	COLD PRESSED THROUGH DIE	HOT FORMED AT 955° C	COLD FORMED OVER HORN MOLD	COLD FORMED THROUGH DIE
CAUSTIC CLEAN (NaOH)	CAUSTIC CLEAN (NaOH)	ACETONE AND TRICHLORO CLEAN	ACETONE CLEAN	TRICHLORO CLEAN
1010° C/20 MINUTES	1010° C/30 MINUTES	900° C/30 MINUTES	1010° C/30 MINUTES	900° C/60 MINUTES
WATER QUENCH	WATER QUENCH	AIR COOL	WATER QUENCH	AIR COOL
BALL SIZING/ TAPERED PLUGS	HYDRAULICALLY EXPANDING PLUGS	FINAL GRINDING	FINAL GRINDING	GRINDING/ TAPERED PLUGS

location, speed of bending, and pipe supports. The observed size/schedule dependence provides further support for bending being the major contributor to the residual stress state. Bending thick-walled, small diameter pipe requires more bulk material deformation per volume of material than bending thin-walled, larger diameter pipe.

Other fabrication processes also appear to affect residual stresses based on the magnesium chloride test results. Fabricator "a" used ball sizing and Fabricator "b" used expanding tapered plugs to meet final waterway opening tolerances. Distinctive axial strips of circumferentially oriented cracking were observed along the sidewalls of Fabricator "a" elbows and attributed to ball sizing. The presence of axial cracks near the counterbores of Fabricator "b" elbows were attributed to the use of hydraulically expanding tapered plugs. Stresses due to ball sizing and expanding plugs are judged to be lower than stresses induced by bending, because only cracks attributed to bending were present after low magnesium chloride test exposure times (<2 hours).

Based on this testing, pipe fittings with lower as-fabricated residual stresses and, hence, improved SCC performance can be made by better controlling the fabrication process. Some possible controls include specifying the method and parameters for bending and specifying allowable final sizing processes.

CONCLUSIONS

1. SCC can occur in pipe fittings without applied stresses. As-fabricated tensile residual stresses can be as high as ~330 MPa on fitting surfaces.
2. Significant fabricator-to-fabricator differences exist in the as-fabricated residual stresses present in pipe fittings.
3. The bending process is dominant in influencing the residual stress state, although evidence of other residual stress inducing fabrication techniques is observable.
4. Smaller fitting diameters and larger wall thicknesses lead to higher tensile residual stresses and shorter SCC initiation times.

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