MEASURED RESIDUAL STRESSES
IN
TYPE 304 STAINLESS STEEL PIPING BUTT WELDMENTS

MASTER

by

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Seminar on

Countermeasures for BWR Pipe Cracking

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ABSTRACT

Residual-stress measurements on Type 304 stainless steel Schedule 80 4-, 10-, and 26-in. pipe weldments are presented. Both strain-gauge and x-ray diffraction techniques have been used. The bulk of the measurements have been made on the inner surface, since these stress levels presumably control the initiation of intergranular stress-corrosion cracking. Complete stress profiles have also been obtained through the thickness of the pipe wall, since the throughwall distribution controls the growth of a crack once it has initiated.

Both azimuthal and axial variations in the residual-stress distributions have been considered, but the strongest emphasis has been given to the measurement of the peak tensile axial stresses in the region 2-3 mm from the weld fusion line on the inner surface where peak sensitization levels generally occur.

Of the weldments examined, the 26-in. weldment had the lowest peak stress on the inner surface. However, the 10-in. weldment had the highest peak stress, and thus no clear trend in the variation of the peak residual-stress level on the inner surface with pipe size is evident. On the other hand, there appear to be significant differences in the distributions of throughwall residual stress in the 4- and 10-in. weldments as compared with the 26-in. weldment. At least at certain azimuthal positions, not only are there large tensile stresses on the inner surface of the 4- and 10-in. weldments, but also the throughwall residual stresses remain tensile through a large part (∿50-75%) of the wall thickness. This is not true for the 26-in. weldment. Although there may be significant residual tensile stresses on the inner surface, the residual stresses become strongly compressive at a depth >15% of the wall thickness.

CONTENTS

Section 1

INTRODUCTION

Failure analyses of Boiling Water Reactor (BWR) piping cracks at Argonne National Laboratory (ANL) (1,2) and elsewhere (3) have shown that the cracks developed through intergranular stress-corrosion cracking (ISCC). Austenitic stainless steels become susceptible to ISCC in a BWR environment in the presence of microstructural changes, commonly called sensitization, and high stresses. It is well known that sensitization frequently occurs in the heat-affected zone of austenitic stainless steel pipe weldments. Since BWR piping systems have been designed in conformance with all applicable codes, the source of the high stresses usually associated with ISCC is thought to be the residual stresses associated with welding.

Most measurements of residual stress near weldments have been made on butt-welded flat plates, and residual stress distributions are reasonably well characterized in this case (4). The stress parallel to the weld direction is tensile in a region that may extend to several times the plate thickness on either side of the weld centerline. Close to the weld, stresses approaching yield may be expected. The stresses transverse to the weld are generally small compared to those parallel to the weld, unless the outside edges of the plate are constrained during welding.

Some preliminary measurements of the residual stress distributions near butt welds in cylinders are available (5-7), but only weldments between thin-walled cylinders ($t/R < 0.6$, where t is the wall thickness and R is the radius of the cylinder) were considered. Analytical models which attempt to predict residual stresses near butt weldments have been developed (5-10). However, in order to reduce the computational effort to reasonable levels these models have assumed that the residual stress distribution is axisymmetric. The experimental results in Refs. 5 and 6 indicate that this is a reasonable assumption for thin-walled cylinders; however, its validity for heavy-walled, multipass pipe weldments has not been demonstrated.

The residual stresses in the weldment are due primarily to the thermomechanical deformations occurring during the welding process and the pre- and postweld surface treatments. The stresses due to the surface treatments are significant only in a shallow surface layer, typically 0.25 mm thick. Their contribution to the net force and bending moment acting on a section through the pipe wall is very small. Strain-gauge techniques measure changes in strain due to the relief of the net force and moment when the section parts out. The stress redistribution due to the removal of the force and moment is indicated schematically in Fig. 1-1. The initial residual-stress distribution is shown in Fig. 1-1(a). There is a smoothly varying distribution through the wall of the pipe and a sharp spike, which represents the surface stresses produced by surface treatment. The unloading that occurs during the parting-out process is illustrated in Fig. 1-1(b). Although the initial stress redistribution may be highly nonlinear, the elastic unloading produces a linear redistribution, since the specimen is basically a beam. The change in stress $\Delta\sigma_1$ is detected by strain-gauge measurements

$$\Delta\sigma_1 = \sigma_R - \sigma_L \quad ,$$

where σ_R denotes the actual residual stress and σ_L denotes the contribution from the linear distribution relieved during the parting-out process. Because of the nonlinearity of the initial stress distribution, $\Delta\sigma_1$ is not equal to the actual stress at the inner surface. The stress changes corresponding to $\Delta\sigma_1$, i.e., data obtained from full-thickness specimens, are identified in later discussion and figures as "bar data."

Because the stresses are not completely relieved by parting out the specimen, the full-wall-thickness specimen must be cut again using a 1.5-mm-dia wire electrode to produce a final 1.5-mm-thick specimen. The stress redistribution that occurs is shown in Fig. 1-1(c). This section is sufficiently thin that all the stresses except those in a surface layer are relieved, and the actual stress at the inner surface is approximately

$$\sigma = \Delta\sigma_1 + \Delta\sigma_2 \quad .$$

The stress changes $\sigma = \Delta\sigma_1 + \Delta\sigma_2$ (i.e., data obtained from the 1.5-mm-thick specimens) are identified in later discussion and figures as "strip data."

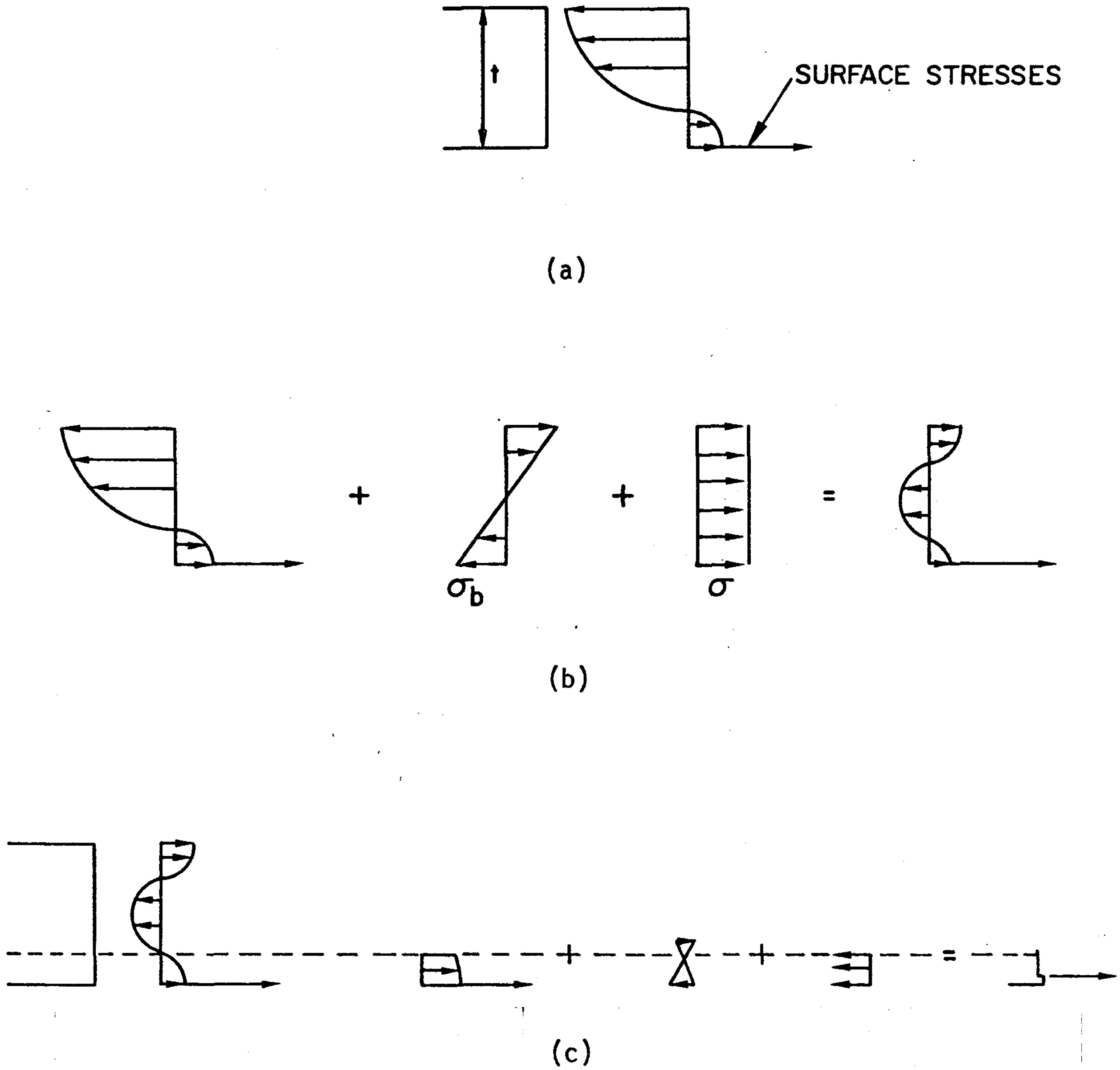


Fig. 1-1. Schematic of Residual-stress Redistribution During Stress-relief Operations. (a) Residual stress distribution through the wall for a thick-walled Pipe weldment. (b) Stress redistribution as a specimen is parted out from the weldment. (c) Stress Redistribution as a thin "strip" is cut from the full-wall-thickness specimen. ANL Neg. No. 306-78-693.

Detailed measurements of the residual-stress distributions (11) indicate that, except for the rapidly varying surface stresses, the distribution of residual stress through the thickness of the 4-in. weldments in reasonably linear in most cases. For a linear distribution, the "bulk" residual stress as measured by strain gauges on the inner and outer surfaces of full-wall-thickness specimens gives a good measure of the stress available to drive the crack. The "bulk" stress on the inner surface obtained from the strip specimens is a better measure of the actual stress at the inner surface, although there may still be significant unrelieved surface stresses. The difference between the "bulk" residual-stress values obtained from the bar and strip specimens is due to the nonlinearity of the residual-stress distribution and the relief of the surface stresses. Rough estimates indicate that a significant portion of any observed stress differences between the bar and strip specimens from 4-in. weldments may be attributed to the stresses induced by surface treatments (11). A significant nonlinear residual-stress distribution remains in the thick 26-in. weldment after the specimen is parted out, and hence the meaningfulness of "bulk" residual stresses obtained from full-thickness specimens is difficult to evaluate.

To predict crack propagation through the wall, the complete throughwall distribution of stress must be known. To obtain this information for the 4- and 10-in. weldments, a full-thickness specimen was cut from a weldment and successive thin (0.4 mm) layers were removed from the inner surface. To ensure the removal of a uniform thickness of material, a special electric-discharge machining (EDM) apparatus was built. After each layer was removed, strain gauges mounted on the outer surface were read, and the strain relief due to the removal of each layer was recorded. Since the removal of each layer produces a redistribution of stress in the rest of the specimen, the measured strain relief cannot be used to directly calculate the residual-stress distribution in the undisturbed weldment. However, an analysis that accounts for the redistribution of stress was developed (11).

It is impractical to remove layers thicker than 0.6 mm by this EDM technique. Thus, use of this technique to analyze the throughwall residual stresses in the 26-in. weldment, which is $\sim$33 mm thick, becomes prohibitively expensive, and an alternative technique was used. Strain gauges were laid on the inner and outer surfaces of the specimen. The specimen was then cut into two equal-thickness parts by EDM with a 0.7-mm-dia wire electrode. The axial stress changes on the inner and outer surfaces (denoted σ_x^i and σ_x^o, respectively) can be measured directly. A piece-wise linear distribution of stress is assumed over each half; the slopes and intercepts of these distributions can be determined from the measured stresses σ_x^i and σ_x^o and the condition that the net force and moment on the specimen must vanish (11). By repeating the process for the two halves of the specimen a better approximation can be obtained and the process can obviously be continued if necessary.

Section 2

RESULTS ON 4-, 10-, AND 26-IN.-DIAMETER PIPING

Experimental residual-stress measurements on Type 304 stainless steel Schedule 80 4-, 10-, and 26-in. pipe weldments have been made by ANL (11) and the General Electric Company (GE) (3,14) using both strain-gauge and x-ray diffraction techniques. Some of these weldments are from autopsy pipes, i.e., pipes that have seen actual field service. Others are mock-ups that have been fabricated following standard nuclear-industry welding practices, but which have not been in actual reactor service.

Both azimuthal and axial variations of the residual-stress distributions have been considered, but the strongest emphasis has been given to the measurement of the peak tensile axial stresses on the inner surface and through the wall in the region 2-3 mm from the weld fusion line where the peak sensitization levels generally occur.

The test matrix for the ANL residual-stress program is shown in Table 2-1. The mock-up weldments, provided to ANL by the Nuclear Energy Division of GE, were seven-pass 2G welds; the first pass was made with a consumable Grinnell insert. The basic geometry of the weld preparation is shown in Fig. 2-1. Details of the weld heat input for each mock-up weld are given in Ref. 11. The placement of strain gauges on each weldment is also described in detail in Ref. 11. Surface roughness dictated minor variations in placement for each weldment; the general pattern, however, is shown schematically in Fig. 2-2.

Detailed residual-stress measurements from one 4-in. weldment (identified in Ref. 11 as weldment 27A) are presented in Figs. 2-3 to 2-5. Figure 2-3 shows the aximuthal distribution of bulk residual stress on the inner surface at gauge positions 1 to 3 (2.4, 7.9, and 18.2 mm from the edge of the weld fusion line, respectively; see Fig. 1-1). The solid lines indicate data obtained from the thin (1.5-mm) strip specimens, and the dashed lines indicate data obtained from

Table 2-1

RESIDUAL-STRESS TEST MATRIX FOR 4- AND 10-IN. TYPE 304 STAINLESS STEEL PIPE WELDMENTS

Weld Preparation	Pipe Diameter, in.	Fabricator	Weld Position	Strain-gauge Positions	Weld Identification
Light Grinding (63 rms Finish)/Heavy Grinding (125 rms Finish)	4	GE	2G	ID: 2 axial, 4 azimuthal	W27B
Light Machining (63 rms Finish)/ Heavy Machining (125 rms Finish)	4	GE	2G	ID: 2 axial, 4 azimuthal OD: 1 axial, 4 azimuthal	W27C
Standard Machining (125 rms Finish)/ Standard Grinding (125 rms Finish)	4	GE	2G	Six axial positions across weld at 45° intervals around weld	W27A
Standard Grinding, Both Sides	4	Field Weld from Dresden-2	2G	Same as W27A but one side of weld only (three axial positions)	Either PD21/ 1DIA or PD23/ PD10A
Standard Machining, Both Sides	4	Field Weld from Monticello	2G	Same as W27A but one side of weld only (three axial positions)	-
Standard Machining, Both Sides	10	Field Weld from Dresden-2	2G--to be verified	Three axial positions normal to weld at 45° intervals around weld	-

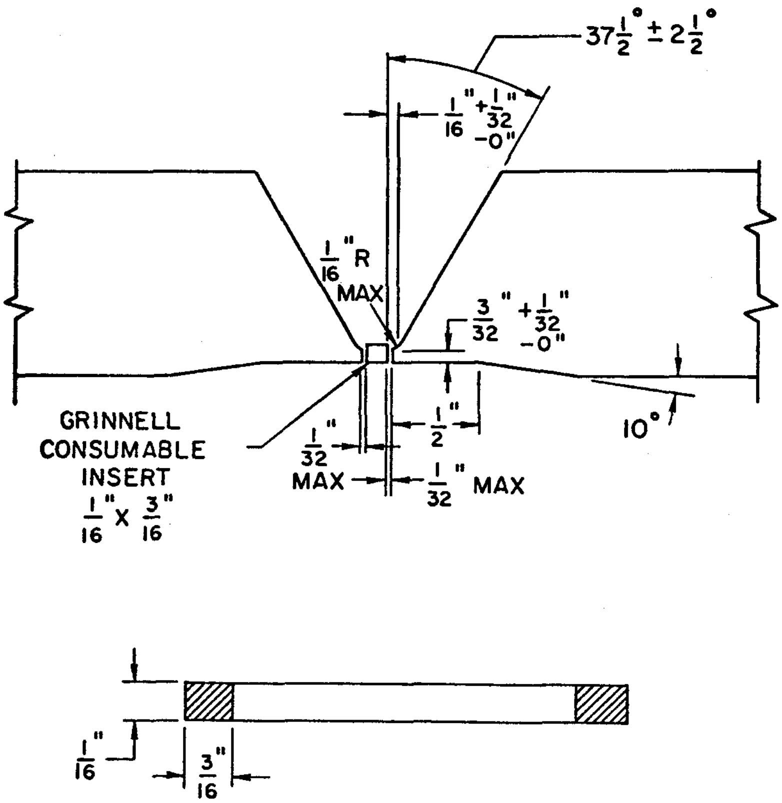


Fig. 2-1. Weld-prep Geometry. To convert dimensions to mm, multiply by 25.4. Neg. No. MSD-63927.

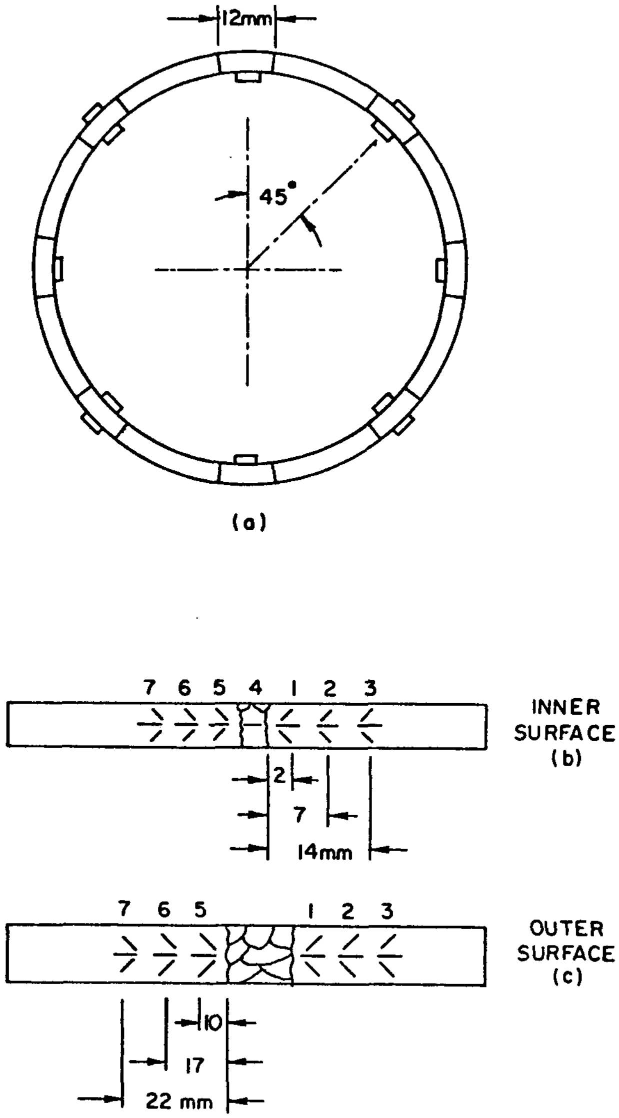


Fig. 2-2. Schematic Diagram of Azimuthal and Axial Placement of Strain Gauges. Neg. No. MSD-63928.

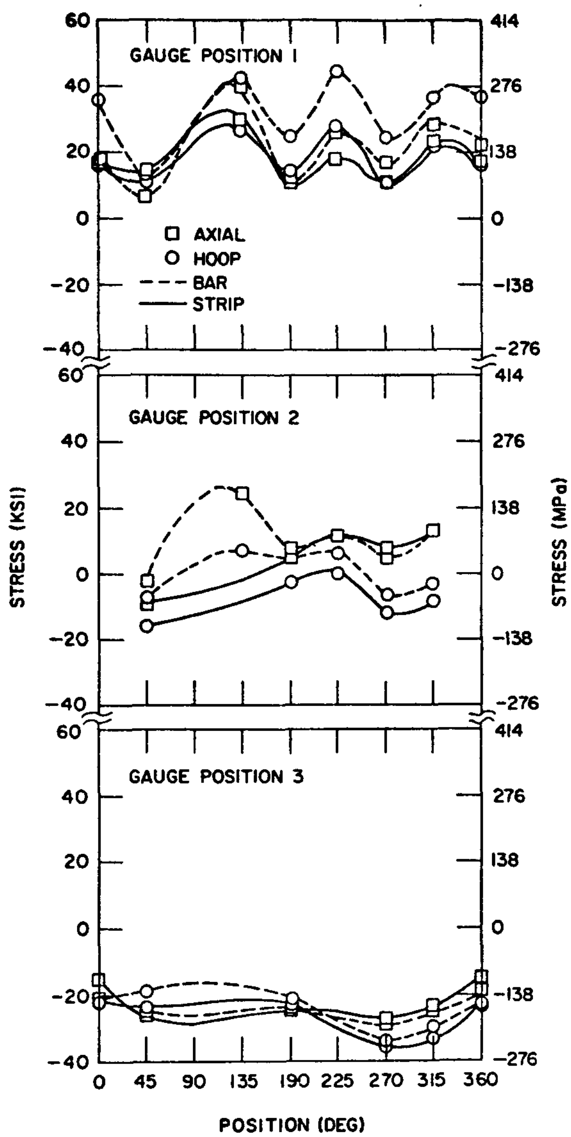


Fig. 2-3. Azimuthal Distribution of Axial and Hoop Stresses at Gauge Positions 1 to 3 for Weldment W27A. Neg. No. MSD-64055.

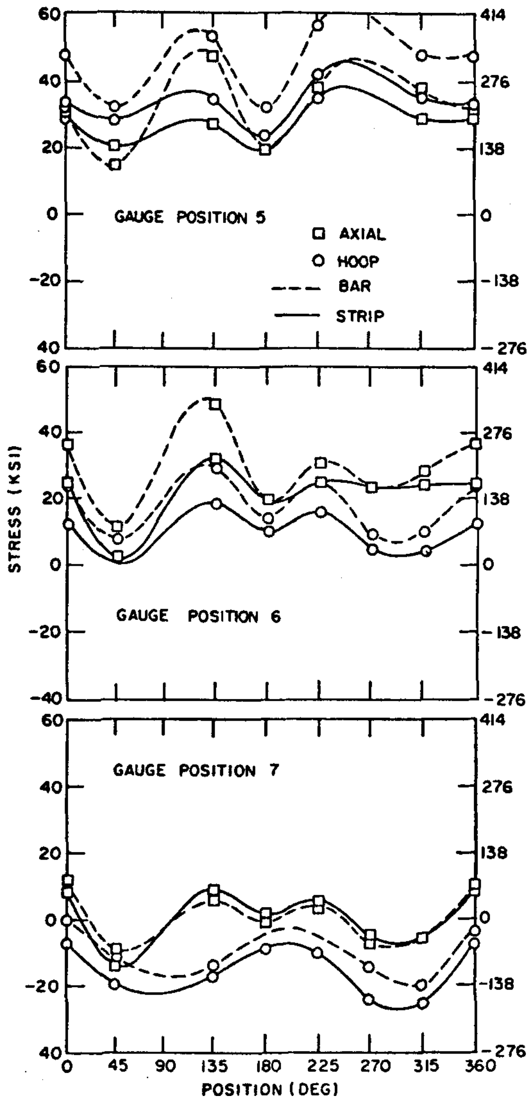


Fig. 2-4. Azimuthal Distribution of Axial and Hoop Stresses at Gauge Positions 5 to 7 for Weldment W27A. Neg. No. MSD-63925.

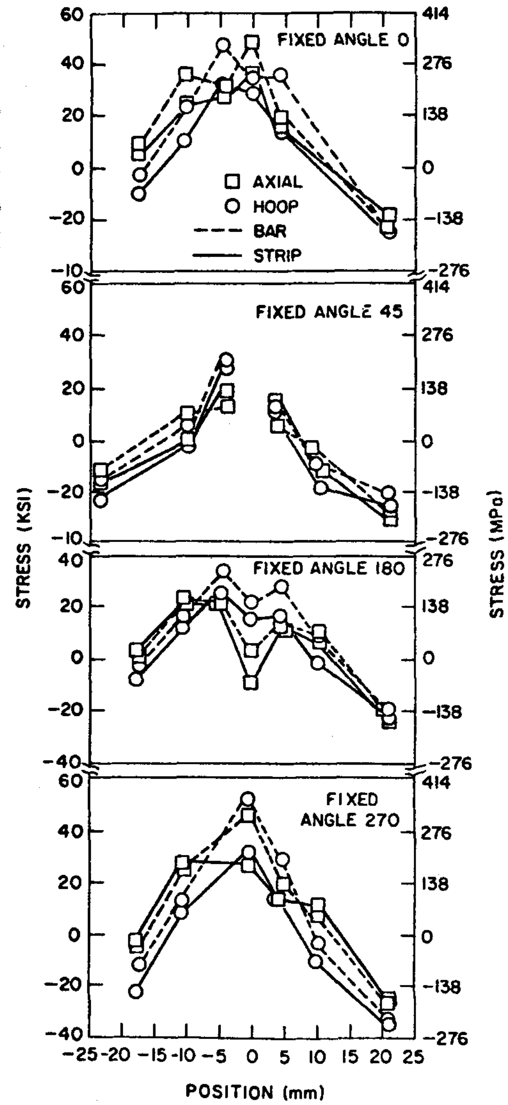


Fig. 2-5. Axial Variation of Hoop and Axial Stresses Across the Weld for Weldment W27A. Neg. No. MSD-64071.

the full-thickness (8.6-mm) bar specimens. Figure 2-4 presents the same information at gauge positions 5 to 7.

The stresses at most gauge positions show a periodic oscillation, and to accurately map the residual welding stresses, gauges must be placed at no greater than 45° intervals. However, the peak-to-peak variations at each gauge position are modest compared with the magnitude of the peak stress at each position. Since the yield strength at the service temperature of 280°C (540°F) is 160 MPa (22 ksi), Figs. 2-3 and 2-4 show that at gauge positions 1 and 5, 2.4 mm from the weld fusion line, significant portions of the inner surface are stressed beyond the nominal initial yield strength of the material.

Axial stress distributions normal to the weld at 45, 90, 180, and 270° are presented in Fig. 2-5. They conform to the expected bell-shaped distribution (3-5). The results of the bulk residual-stress measurements are summarized in Table 2-2, which shows the average stresses, peak stresses, and peak-to-peak variations at each gauge position. These results are in reasonably good agreement with analytical calculations presented in Ref. 10. The bulk residual stresses in the other mock-up weldments examined in the ANL study are presented in Tables 2-3 and 2-4. Detailed discussions of these results are available in Ref. 11.

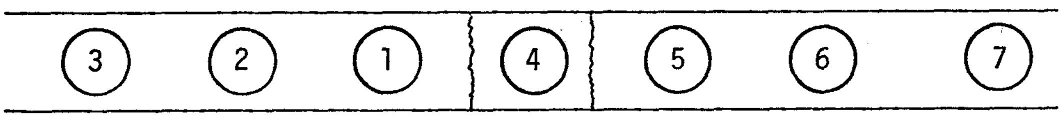
The 10-in. pipe weldment examined at ANL is a field-welded piece from the Dresden-2 BWR. It was taken from the Loop A emergency core-spray line just ahead of a check valve on the pump side.

Figure 2-6 presents the azimuthal distribution of bulk residual stress on the inner surface at gauge positions 1 and 2 (2 and 14 mm from the edge of the weld fusion line, respectively). The solid lines indicate data obtained from thin (1.5-mm) strip specimens, and the dashed lines indicate data obtained from the full-thickness (8.6-mm) bar specimens. Figure 2-7 presents the same information for gauge positions 4 and 5 (same positions as 1 and 2 but on the opposite side of the weld).

Table 2-2

SUMMARY OF BULK RESIDUAL STRESSES FOR WELDMENT W27A

	ROSETTE POSITION						
	3	2	1	4	5	6	7
Average Axial Stress	-164 -23	93 13	136 19	236 33	193 27	157 22	0 MPa 0 ksi
Average Hoop Stress	-164 -23	21 3	143 20	242 34	250 35	71 10	-79 MPa -11 ksi
Peak Axial Stress	-107 -15	96 13	170 24	273 38	249 35	234 33	64 MPa 9 ksi
Peak Hoop Stress	-151 -21	0 0	202 28	219 31	296 41	137 19	-51 MPa -7 ksi
Axial Peak-to-Peak Variation	87 12	159 22	89 13	347 48	112 16	218 31	164 MPa 23 ksi
Hoop Peak-to-Peak Variation	105 15	118 16	122 17	122 17	130 18	132 18	127 MPa 18 ksi

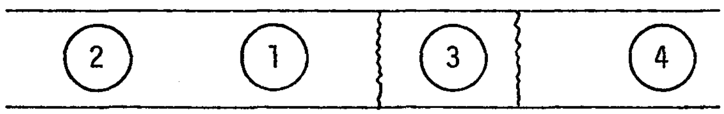


Weld

Table 2-3

SUMMARY OF BULK RESIDUAL STRESSES FOR WELDMENT W27B

	ROSETTE POSITION				
	2	1	3	4	
Average Axial Stress	14	83	84	141	MPa
	2	12	12	20	ksi
Average Hoop Stress	-55	104	114	219	MPa
	-8	15	16	30	ksi
Peak Axial Stress	159	352	347	367	MPa
	22	49	49	51	ksi
Peak Hoop Stress	59	364	301	413	MPa
	8	51	42	58	ksi
Axial Peak-to-Peak Variation	409	317	387	464	MPa
	57	44	55	65	ksi
Hoop Peak-to-Peak Variation	272	451	301	377	MPa
	38	63	42	53	ksi



Weld

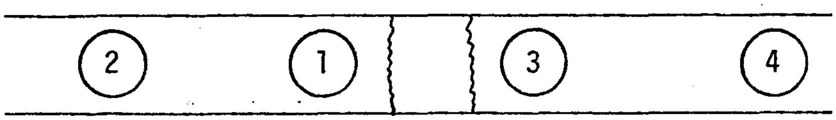
Light Grinding

Heavy Grinding

Table 2-4

SUMMARY OF BULK RESIDUAL STRESSES FOR WELDMENT W27C

	ROSETTE POSITION				
	2	1	3	4	
Average Axial Stress	140	229	220	234	MPa
	20	32	31	33	ksi
Average Hoop Stress	21	186	250	236	MPa
	3	26	35	33	ksi
Peak Axial Stress	199	315	256	326	MPa
	28	44	36	46	ksi
Peak Hoop Stress	52	270	401	346	MPa
	17	38	56	48	ksi
Axial Peak-to-Peak Variation	113	158	97	304	MPa
	16	22	14	25	ksi
Hoop Peak-to-Peak Variation	70	147	235	211	MPa
	10	21	33	29	ksi



Weld

Heavy Machining Light Machining

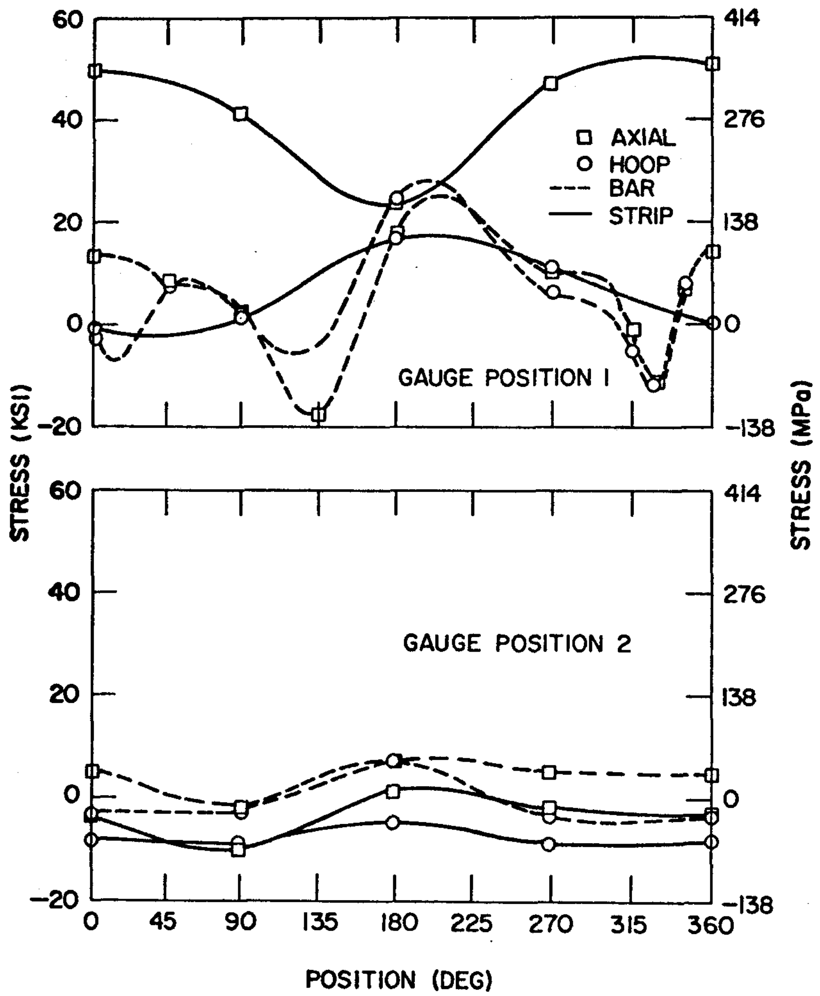


Fig. 2-6. Azimuthal Variation of Axial and Hoop Stresses at Gauge Positions 1 and 2 for the 10-in. Dresden 2 Weldment. Neg. No. MSD-64069.

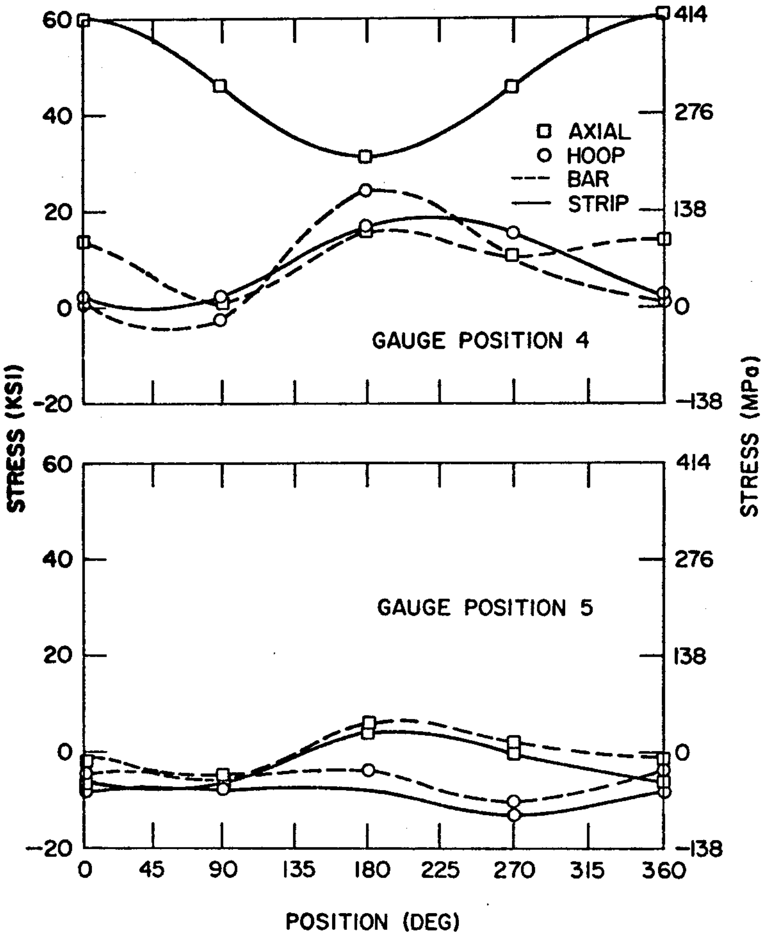


Fig. 2-7. Azimuthal Variation of Axial and Hoop Stresses at Gauge Positions 4 and 5 for the 10-in. Dresden 2 Weldment. Neg. No. MSD-64065.

Unlike the 4-in. weldments, large differences exist between the stress values obtained from the bar specimens and those from the strip specimens, at least for gauge positions close to the weld. For example, the axial stress at position 1 obtained from the strip specimens has a peak value of 360 MPa (50 ksi); the peak axial stress at position 1 obtained from the bar specimen is only 215 MPa (30 ksi).

Two striking qualitative differences exist between the stress distributions shown in Figs. 2-6 through 2-8 for a 10-in. weld and those typical of the 4-in. pipe weldments. First, although the hoop and axial stresses were virtually equal for all the 4-in. weldments examined, large differences in magnitude exist between the axial and hoop stresses for the 10-in. weldment, with the axial stress generally much larger than the hoop stress. A difference is also observable in the axial distribution of stress at fixed azimuthal angles shown in Fig. 2-8. The hoop stresses follow the expected bell-shaped distribution (e.g., see Refs. 4 and 5), with the peak stresses occurring on the weld; however, the axial stresses follow a bimodal "rabbit-ear" distribution with the peak stresses occurring on either side of the weld. Similar results have been observed in other investigations (12-13), and several explanations of the phenomenon have been proposed. Computer simulation of the welding process using an elastic-plastic finite-element model also predicts a bimodal distribution (3).

The results of the bulk residual-stress measurements are summarized in Table 2-5, which shows the average stresses, peak stresses, and peak-to-peak variation at each gauge position.

To assess the importance of preweld surface treatment on the final postweld distribution of residual stress, x-ray diffraction techniques were used in the ANL study (11) to measure surface residual stresses on specimens from the mock-up weldments W27A, W27B, and W27C. As shown in Table 2-3, the two halves of each weldment received different preweld surface treatments. During the parting-out process, the thermomechanically induced welding stresses are almost completely relieved. Thus the surface stresses on the specimens are due solely to the surface treatment.

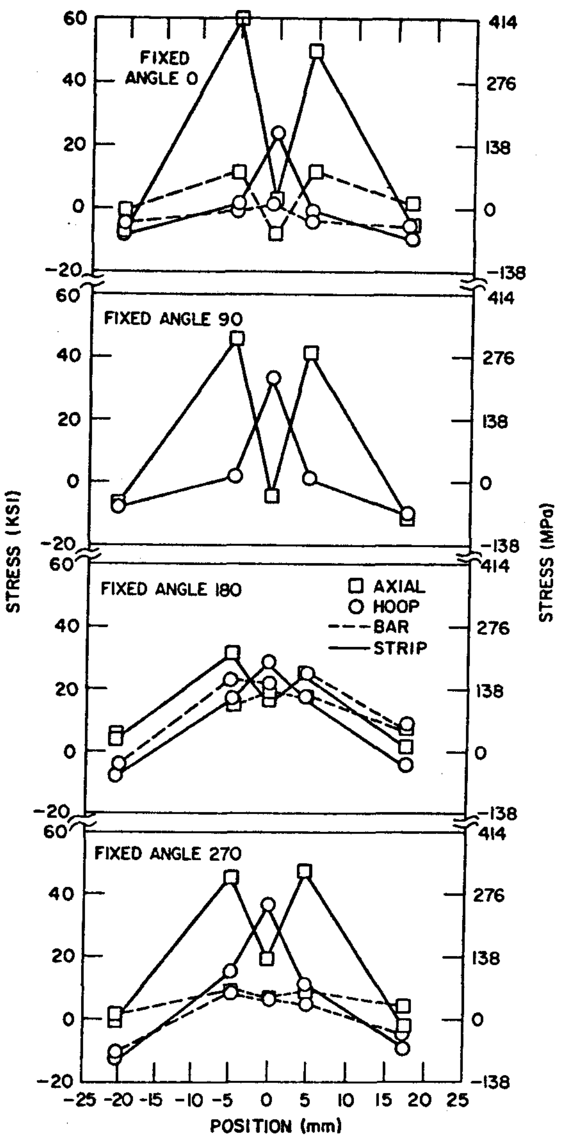


Fig. 2-8. Axial Variation of Hoop and Axial Stresses Across the Weld for the 10-in. Dresden 2 Weldment. Neg. No. MSD-64064.

Table 2-5

SUMMARY OF INNER-SURFACE BULK RESIDUAL STRESSES FOR THE 10-IN. DRESDEN 2 WELDMENT

	ROSETTE POSITION					
	2	1	3	4	5	
Average Axial Stress	-29	293	62	325	-16	MPa
	-4	41	9	45	-2	ksi
Average Hoop Stress	-57	54	220	62	-66	MPa
	-8	8	31	9	-9	ksi
Peak Axial Stress	7	361	138	430	28	MPa
	1	51	19	60	4	ksi
Peak Hoop Stress	36	121	261	117	-55	MPa
	-5	17	37	16	-8	ksi
Axial Peak-to-Peak Variation	82	190	167	209	77	MPa
	11	26	23	29	11	ksi
Hoop Peak-to-Peak Variation	30	121	86	102	38	MPa
	4	17	12	14	5	ksi

The results shown in Fig. 2-9 from the weldment identified as W27A are typical of the measurements obtained on all the weldments examined. As Fig. 2-9(a) shows, at axial locations far from the weld-fusion lines, the various preweld surface treatments induce very large residual stresses. At most of the measurement locations, these very large stresses are compressive; however, other studies have shown that these stresses can vary widely, with small regions exhibiting tensile stresses in the midst of relatively large regions exhibiting compressive stresses.

Near the weld fusion line, the high surface residual stresses induced by the preweld treatments seem to be modestly compressive. However, to obtain the actual surface stresses on a weldment, the stresses relieved during the parting-out process, which are presumably due to the welding process, must be added to the stresses due to the surface treatment. The total stresses on the inner surfaces, shown in Fig. 2-9(b), are highly tensile. These results suggest that, at least for regions <5 mm from the weld-fusion line, the effect of the preweld surface treatment is not particularly important. The treatments do induce high residual surface stresses, but these are largely relieved during welding. Even if the preweld surface treatment produces a compressive residual stress, the shrinkage and thermomechanical history associated with the welding process can produce high tensile residual stresses on the inner surface of the weldments, and attempts to obtain favorable residual-stress states must involve changes in the welding process itself, not just in the preweld surface treatment. In contrast, postweld mechanical treatments, such as grinding, are extremely detrimental and greatly increase susceptibility to ISCC.

Measurement of throughwall residual stresses in 4-, 10-, and 26-in. weldments were also carried out.* The distribution of throughwall residual stress in the 4-in. weldments appears to differ significantly from that in the 26-in. weldment. At some azimuthal positions, not only are there large tensile stresses on the

*The specimen from the 26-in. weldment used in the ANL study was cut from a quadrant of a 26-in. weldment supplied by GE as part of the work supported by EPRI. An ∿35° azimuthal portion of the circumference of the entire weldment was cut from the weldment and sent to ANL. X-ray and stress-relief measurements by GE indicated that only minor amounts of bulk stress relief occurred when the quadrant was cut from the complete weldment.

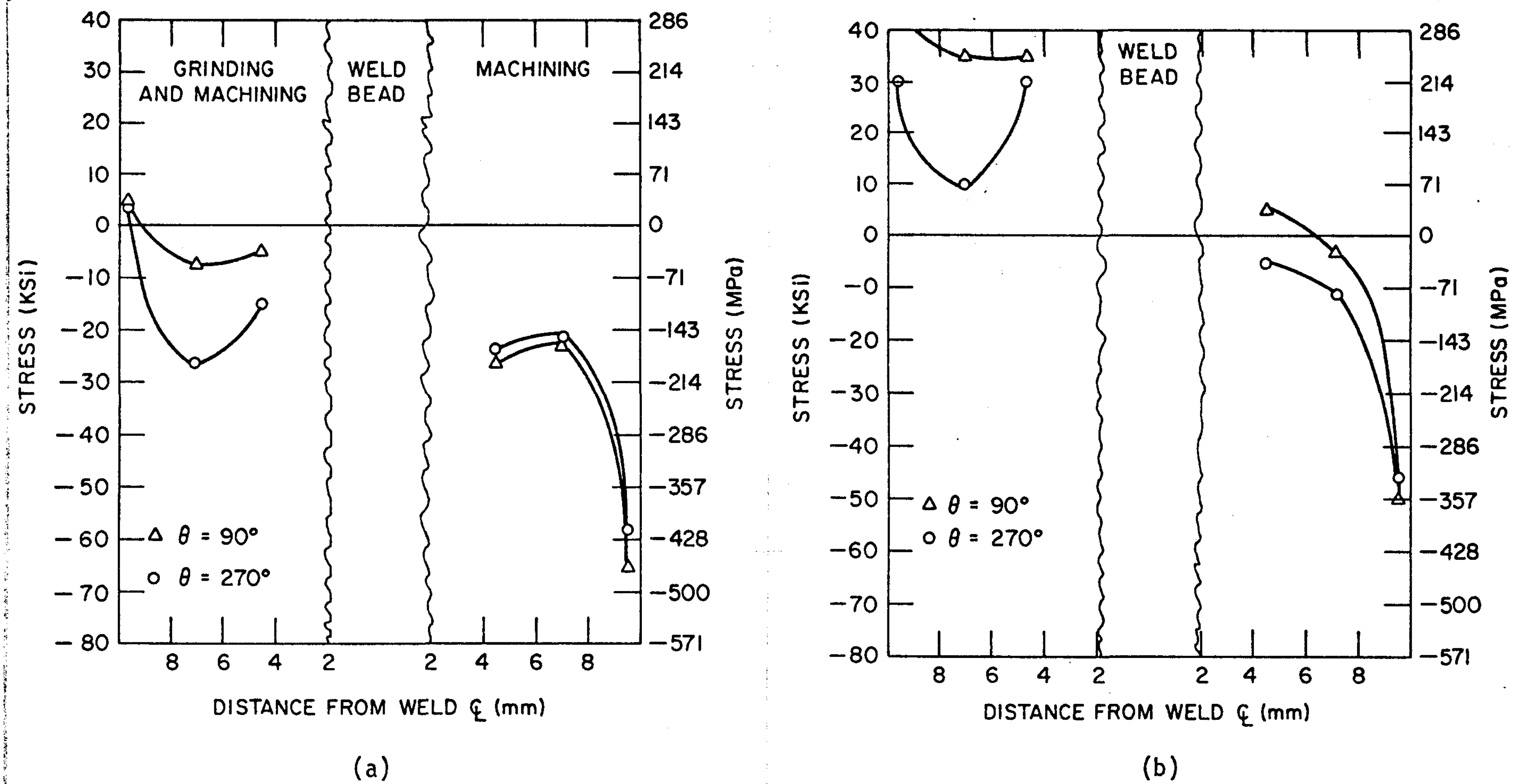


Fig. 2-9. (a) Surface Residual-stress Measurements for Mock-up Weldment W27A. (b) Total Surface Residual Stresses for Mock-up Weldment W27A. ANL Neg. Nos. 306-77-203 and 306-77-215.

inner surface of the 4-in. weldments, but also the throughwall residual stresses remain tensile through a large fraction (∿50-75%) of the wall thickness. This is not the case for the 26-in. weldment. Figure 2-10 shows the throughwall distribution of the axial residual stress ∿3 mm on either side of the weld fusion line. On the inner surface the stresses are tensile, but well below the peak levels observed in 4- and 10-in. weldments. However, the residual stresses become compressive at a depth >10% of the wall thickness.

Although only the throughwall stresses at one azimuthal position in one 26-in. weldment were actually measured, it should be noted that there is excellent agreement with the throughwall distribution predicted by the finite-element program developed at Battelle-Columbus under EPRI support (15).

If a crack does initiate on the inner surface and propagate, the residual stresses will redistribute. The nominal redistribution of stress in a 26-in. weldment caused by a growing crack has been calculated and is shown in Table 2.6. The results show that for crack lengths <10% of the wall thickness, very little re-distribution occurs. Thus, a crack that initiates on the inner surface would have its radial growth arrested by the compressive stress field after growing through only a relatively small (<10%) portion of the wall thickness. However, it may then grow circumferentially. Also, in addition to the residual stresses considered here, the stresses caused by service loads must be considered before any final conclusions about the crack-arrest behavior of throughwall cracks in large-diameter piping can be drawn.

Table 2-6

REDISTRIBUTION OF STRESS AT GAUGE POSITION 1, ∿3 MM FROM THE WELD FUSION LINE, CAUSED BY A GROWING CRACK

Crack Depth (mm)	Nominal Stress (MPa) at			
	Crack Tip	t/4	t/2	OD
0 (ID)	193	-221	-124	76
1	112	-218	-122	78
2	32	-216	-119	81
3	-47	-213	-116	83

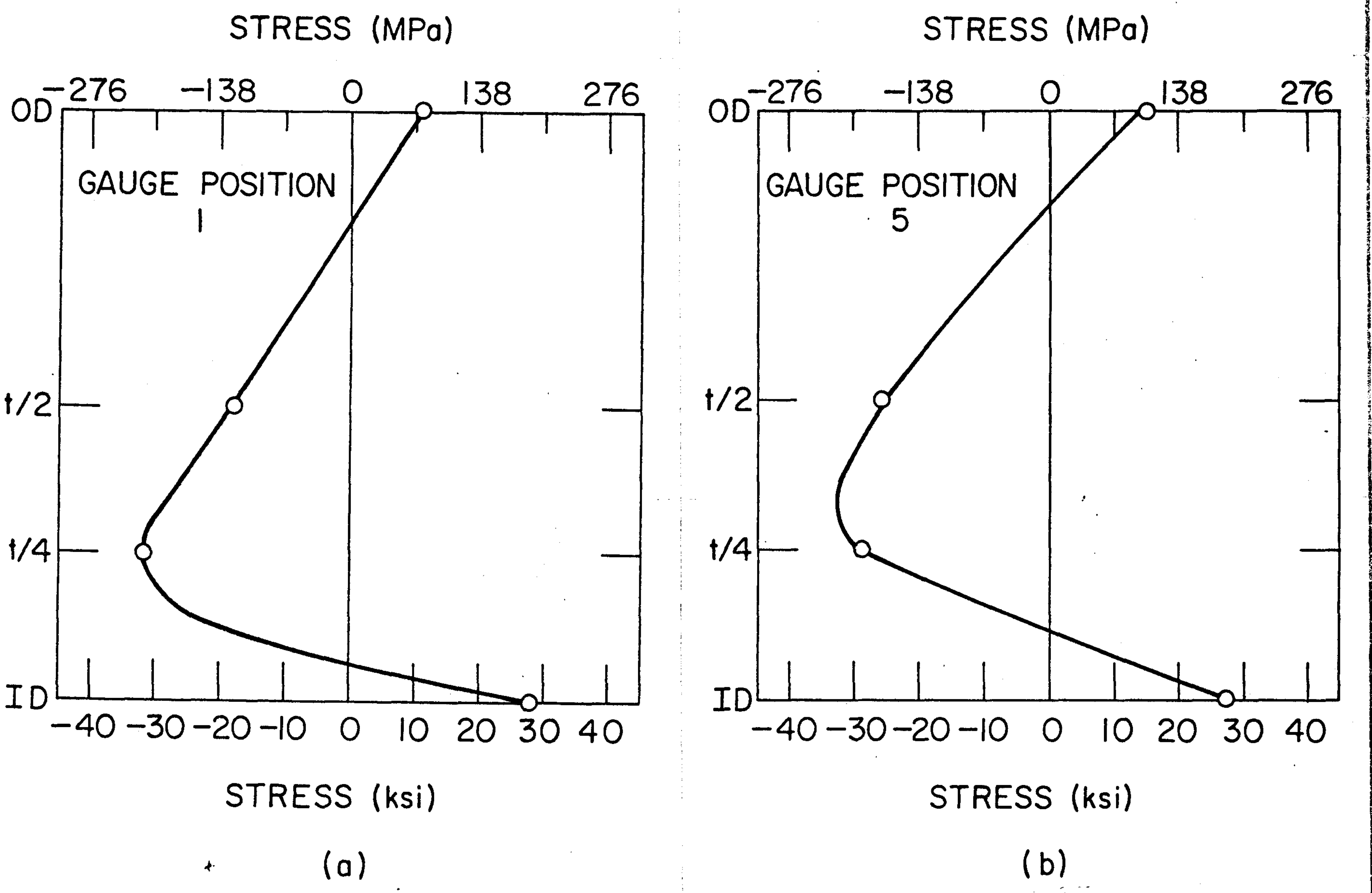


Fig. 2-10. Throughwall Distribution of Axial Residual Stress ∿6 mm on Either Side of the Weld Center Line. ANL Neg. No. 306-78-740.

Section 3

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