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PREDICTING STRESS CORROSION CRACKING IN
WELDED STEEL BASED ON RESIDUAL STRESS
MEASUREMENTS

By D. H. Brewer

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**Kansas City
Division**

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ERRATA
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- Page 6, para. 2: "...276 MPa." becomes "...284 MPa."
- Page 6, para. 4: "Assuming a circular surface..."
becomes
"Assuming an $a/2c = 36$ surface..."
"17" becomes "19"
"...was one-fourth..."
becomes
"...was about one-fourth..."
- Page 10, para. 1: "...curve and the values of..."
becomes
"...curve (Figure 6) and the values of..."
"...rosette 27, 32 mm..."
becomes
"rosette 27 in the base metal, 32 mm..."
- Pages 12, 13, 25, 26, 27, and 28 have connecting lines
deleted from figures.
- Page 14, para. 4: "...and 283 MPa."
becomes
"...and 284 MPa."
- para. 5: "...flow..." becomes "...flaw..."
- Page 24, para. 1: "...2,290..." becomes "...2,515..."
- para. 3: "A semicircular ($a = c$) surface flaw
geometry will be assumed, because it
requires the least stress to propagate."
becomes
"A surface flaw of $a/2c = 0.36$ has been
established as the equilibrium growth
condition."
"...283 MPa..." becomes "...284 MPa..."
"...2.29 mm..." becomes "...2.515 mm..."
- Page 29, lines 1 and 5: "q" becomes "Q" (2 places)
line 8 is changed to become
" $a/2c = 0.36, \phi_0 = 1.47$ and $\phi_0^2 = 2.16$, and"
line 9; the fraction becomes $0.0025/2.16$
line 10: "...17.1..." becomes "...19.20..."
- para. 1: "...is in excess of..."
becomes
"...is about..."

line 15: the fraction becomes 0.0025/2.16
line 16: the fraction becomes 0.0025/2.16
line 17: "1157 MPa" becomes "1041.67 MPa"
para. 2: "...is in excess of..."
becomes
"...is about..."

Page 34, para. 1: "...276 MPa..." becomes "...284 MPa..."
para. 2: "This shows that..."
becomes
"Under these conditions..."

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SUMMARY

Residual stress in a material is as effective as externally applied stress in causing stress corrosion cracking. In order to measure residual stresses, X-ray diffraction and strain gauge rosette capabilities were developed. The X-ray diffraction measurements were made by another company. Strain gauge measurements were made at Bendix Kansas City.

The X-ray diffraction measurements showed all compressive stresses. This would lead to the conclusion that residual stresses alone would not produce stress corrosion cracking. The strain gauge rosette measurements showed the heat affected zone (HAZ) to have a maximum residual tensile stress of 276 MPa.

The ultrasonic flaw detection system cited¹ measured crack depth mean and variance on a welded test coupon. A statistical correction was applied to the measured crack depth statistics taking into account the fact that a larger crack has a higher probability of being found, and the actual crack depth varies in a known manner from the measured crack depth. From this statistically corrected distribution a crack depth was chosen so that 99 percent of crack depths were smaller.

Assuming a circular surface crack geometry, using the 99 percent confidence interval crack depth and the maximum measured residual stress, a stress intensity factor was calculated to be $17 \text{ MPa}\sqrt{\text{m}}$. This value of stress intensity was one-fourth the values of 70 and $71 \text{ MPa}\sqrt{\text{m}}$ listed as K_{Isc} for sump tank water and synthetic sea water environments respectively. From these calculations the conclusion is that residual stresses alone are not sufficient to cause stress corrosion cracking. Residual stresses are significant and, when superimposed on externally applied stresses, may cause a critical situation.

Hardness measurements show the weld metal hardness to be $R_C 40$, the base metal to be $R_C 41$, and the HAZ to range from $R_C 44$ to 48. The microstructure of the HAZ shows the presence of a second phase which may account for the higher hardness, higher residual stress, and lower resistance to stress corrosion cracking.

A computer program was written to reduce strain gauge rosette resistance measurements to principal stresses and their orientation. Two other programs were adapted for plotting the stress field information for ease of visualization.

DISCUSSION

SCOPE AND PURPOSE

Development of a residual stress measurement capability was required to evaluate the potential of residual stress for causing stress corrosion cracking. A welded test coupon made from HP-9-4-20 steel was the specimen on which the residual stress measurements were made. Residual stress measurement by X-ray diffraction was selected as one method because it is nondestructive. Residual stress measurement by strain gauge rosettes was also chosen because of the Material Engineering Laboratory's familiarity with strain gauge technology.

Ultrasonic inspection of base and weld material was expected to pass defects of a certain size. A combination of residual stress and defect geometry was used to calculate a stress intensity factor. This stress intensity factor was compared with several values of K_{Isc} to determine the potential for stress corrosion cracking in several environments.

Computer programs were written and adapted to reduce strain gauge rosette data to principal stresses and orientation, to calculate the stresses parallel and perpendicular to the weld, and to plot various stress field relationships.

PRIOR WORK

Stress corrosion cracking is a type of failure that occurs when certain metals are subjected to stresses in a corrosive environment. Residual stresses are as effective as externally applied stresses in producing stress corrosion cracking.² From the principles of fracture mechanics it is known that a crack of critical size subjected to a specified stress will propagate to failure. These principles have been applied to stress corrosion cracking to define the combination of stress and critical crack size which will propagate in a corrosive medium. The critical stress intensity factor for stress corrosion cracking, K_{Isc} , is calculated by using the stress intensity factor equation for a specified crack geometry. Experimental determination of the K_{Isc} value was done either by dead weight loading fatigue pre-cracked cantilever specimens in the corrosive medium and finding the load required to cause failure at 1000 hours^{3,4} or by use of a bolt loaded, wedge open loaded (WOL) specimen precracked and placed in the corrosive medium.^{3,4,5}

ACTIVITY

Residual Stress Measurements

Residual stress measurements were made using X-ray diffraction and strain gauge rosette methods on test coupons of welded HP-9-4-20 steel (Figures 1 and 2).

X-ray diffraction residual stress measurements were made using the "ordinary Glocker" method of producing data. A general discussion of the X-ray diffraction method of residual stress measurement is provided in Appendix A. X-ray diffraction residual stress measurements were made on the coupon as shown in Figure 1. Measurements were made parallel and perpendicular to the weld from the centerline of the weld out to 44 mm on one side only. Measurements were made at 3 mm intervals on lines 25 and 152 mm from the beginning of the weld. The weld bead had been removed by a fly cut machining operation out to 22 mm from the centerline of the weld. This cut removed the bead and some of the skin to a depth of about 0.4 mm below the hot rolled and pickled surface. Neither chemical milling nor electropolishing was performed in preparation for making the stress measurements. The data obtained are listed in Table 1. The data in Table 1 are in this format for use in the computer programmed data plotting routine discussed later. The columns entitled "PAR" and "PERP" are stress measurements in MPa taken parallel and perpendicular to the weld. "END" is the distance from the beginning edge of the weld at which the measurements were taken. "C/L" is the distance from the centerline of the weld at which the measurements were taken. Plots of the relationships between measured stresses and distance from the centerline of the weld are shown in Figure 3. The location of the heat affected zone (HAZ) is based on analysis of Figure 2 and lies in the region 10 to 16 mm from the centerline. Its location is an expected location and is subject to variation as a result of normal variation in weld cross sections. All values of residual stress observed using this technique were compressive except for one value showing zero stress. The significance of this is that there is no danger of stress corrosion cracking in the absence of some externally applied stress.

Strain gauge rosette measurements were made using a Micro-Measurements gauge Type EA-06-062RE-120 (Vishay Intertechnology, Inc). A general discussion of strain gauge rosette measurements is given in Appendix B. To obtain a surface suitable for mounting the rosettes, two fly cuts 38 mm wide were cut 0.8 mm deep perpendicular to the weld as illustrated in Figure 1. These cuts were made subsequent to taking the X-ray data, since it was not discovered until then that the hot rolled and pickled surface was not suitable for strain gauge mounting. Rosettes were attached to the test coupon as shown in Figure 1 and aligned as shown in

○ LOCATION OF STRAIN GAUGE ROSETTE MEASUREMENTS

□ LOCATION OF X-RAY DIFFRACTION MEASUREMENTS

Figure 1. Steel Test Coupon

Figure 4. Hole boring was accomplished using a 1.2-mm-diameter, carbide-tipped end mill in the boring jig driven by a drill press. Drilling was interrupted after each 0.25 mm increment up to 1.75 mm to take strain readings. The principal stresses (σ_1 and σ_2) are determined from reduction of the strain gauge measurements, and β is the angle between σ_1 and Element 1 of the rosette. The stress calculated perpendicular to the weld is σ_x , and σ_y is the stress

X-RAY DATA TAKEN AT 3.175 mm INCREMENTS
TO RIGHT OF CENTERLINE

ROSETTE DATA TAKEN AT POINTS INDICATED BY
TIC MARKS

Figure 2. Tracing of Weld Cross Section
Photomacrograph

calculated parallel to the weld. These data are listed in Table 2 for each rosette at each of seven drilling depths. Figure 5 shows the stress distribution on both sides of the weld. As mentioned previously, the location of HAZ in Figure 3 is an expected location subject to variation as a result of normal variation in weld cross section. With this possible variation in mind, analysis of Figure 2 indicates that rosettes 1, 2, 3, 4, 17, 18, 19, and 20 are located over weld metal; rosettes 5 and 21 are located over the heat affected zone; and the remaining rosettes are located over base metal. The weld metal is in compression as denoted by the negative slope of the curve and the values of stress obtained. The heat affected zone and the base metal are in tension as indicated by the positive slope of the curves and the values of stress obtained. The significance of these observations in terms of potential for stress corrosion cracking is that the weld metal will be immune since it is in compression. The HAZ and base metal on the other hand may be susceptible depending on the value of the stresses and the size of possible defects. The highest individual value of tensile residual stress (principal value) measured at rosette 5 is approximately 255 MPa and at rosette 21 is approximately 283 MPa. This compares to a maximum individual tensile residual stress of approximately 276 MPa at rosette 27, 32 mm from the centerline of the weld. Stress corrosion cracking would be expected to occur first in the HAZ because K_{Isc} is lowest in that area.

Comparison of X-ray data (Figure 3) with strain gauge data (Figure 5) shows no similarity in the trend of the stress fields. This was not considered too surprising since the two methods did not measure the same stress field. The X-ray diffraction method

Table 1. X-Ray Diffraction Data

PERP* (MPa)	PAR** (MPa)	END (mm)	C/L*** (mm)
-231	-175	25	0
-288	-175	25	3
-231	-344	25	6
-110	-344	25	10
-0-	-110	25	13
-59	-344	25	16
-231	-570	25	19
-288	-1114	25	23
-457	-570	25	25
-401	-514	25	29
-457	-457	25	32
-457	-570	25	35
-601	-627	25	38
-681	-570	25	41
-681	-570	25	44
-627	-59	152	0
-681	-288	152	3
-344	-514	152	6
-344	-681	152	10
-175	-791	152	13
-175	-627	152	16
-59	-1224	152	19
-175	-1224	152	22
-288	-570	152	25
-344	-344	152	29
-288	-401	152	32
-288	-570	152	35
-401	-737	152	38
-570	-627	152	41
-627	-570	152	44

*Perpendicular

**Parallel

***Centerline

measures stress to a depth of 5 to 10 μm . The strain gauge rosette method averages the stress which is relieved by drilling, in this case to a depth of 1.78 mm in 0.25 mm increments.

X-ray diffraction measurements are affected by surface stress introduced by surface processing procedures such as machining, shot peening, and case hardening. Such surface treatments may be important because they affect the potential for stress corrosion

Figure 3. Comparison of Stresses Versus Distances From the Centerline of the Weld for X-Ray Data

Figure 3 Continued. Comparison of Stresses Versus Distances From the Centerline of the Weld for X-Ray Data

Figure 4. Strain Gauge Orientation

cracking. In bulk material, however, the use of electropolishing to eliminate the effects of surface disturbances is desirable, and the use of an electropolished and strain gauged calibration specimen would be necessary to obtain the best correlation between X-ray diffraction and strain gauge data.

The strain gauge rosette method is a macro-measurement compared to the X-ray diffraction method. Unless a surface treatment creates a disturbance to a depth great enough to be measured effectively by the strain gauge method, it will be averaged into insignificance.

Several noteworthy conditions existed during the data acquisition processes of both methods. The transition from fly cut to hot rolled and pickled surface during the X-ray diffraction measurements did not seem to produce an obvious difference in results. Boring for strain gauge measurements was difficult because of the toughness of the material. Carbide mills dulled rapidly causing the holes to be slightly out-of-round and not have thoroughly flat bottoms. One end mill was required for each hole.

The X-ray diffraction method showed the surface to contain all residual compressive stresses with the exception of one value of zero. The strain gauge rosette method showed maximum residual tensile stresses in the HAZ of 255 and 283 MPa.

Preexisting Surface Cracks

The ultrasonic flow detection system described in Reference 1 measured crack depth mean and variance on a welded test coupon.

Table 2. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{p1} (MPa)	σ_{p2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 1, 0.000 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.79	-4.34	16.06	16.06	-4.34
0.51	-0.40	-43.92	37.78	-32.13	25.99
0.76	-0.67	-116.80	-153.13	-117.28	-152.65
1.02	-0.62	-158.30	-76.46	-156.17	-78.60
1.27	-0.64	-176.02	-258.21	-177.88	-256.35
1.52	-0.65	-174.51	-283.24	-176.51	-281.24
1.78	-0.64	-183.95	-308.89	-186.64	-306.20
Rosette 2, 3 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.79	51.02	-19.31	-19.31	5.10
0.51	0.66	-35.85	-120.52	-119.28	-37.09
0.76	0.70	-19.93	-207.53	-206.08	-21.37
1.02	0.74	15.44	-342.46	-341.64	14.62
1.27	0.75	40.89	-438.99	-438.37	40.27
1.52	0.77	36.61	-505.80	-505.73	36.54
1.78	0.78	46.82	-544.41	-544.34	46.75
Rosette 3, 6 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.99	-36.61	-75.7	-75.70	-36.61
0.51	0.79	-60.74	-197.60	-197.60	-60.74
0.76	0.77	-65.98	-304.75	-304.68	-66.05
1.02	0.75	-74.53	-419.75	-419.20	-75.08
1.27	0.71	-91.56	-470.08	-468.15	-93.49
1.52	0.71	-106.04	-489.32	-486.84	-108.52
1.78	0.70	-109.28	-497.32	-494.22	-112.38
Rosette 4, 10 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.69	-53.50	-152.72	-151.75	-54.47
0.51	-0.62	-197.12	-137.96	-195.60	-139.48
0.76	-0.53	-293.03	-196.71	-286.89	-202.84
1.02	-0.42	-407.76	-275.24	-390.59	-292.41

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{p1} (MPa)	σ_{p2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 4, Continued 10 mm From Centerline and 25 mm From End of Test Coupon					
1.27	-0.41	-446.78	-287.79	-425.61	-308.95
1.52	-0.43	-456.92	-277.72	-435.13	-299.51
1.78	-0.41	-447.13	-261.72	-422.23	-286.62
Rosette 5, 13 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.58	-69.71	45.64	40.95	-65.02
0.51	0.56	-188.99	116.80	102.11	-174.30
0.76	0.53	-243.66	147.41	121.83	-218.08
1.02	0.51	-271.58	187.40	154.10	-238.28
1.27	0.53	-301.92	253.80	218.84	-266.96
1.52	0.52	-319.16	246.97	206.64	-278.82
1.78	0.51	-325.23	253.04	210.70	-282.89
Rosette 6, 16 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.39	22.96	0.55	3.86	19.65
0.51	0.43	41.02	41.02	41.02	41.02
0.76	0.45	67.15	55.92	57.16	65.91
1.02	0.46	84.81	73.57	74.67	83.70
1.27	0.46	90.67	79.43	80.60	89.49
1.52	0.47	102.42	91.29	92.32	101.42
1.78	0.48	114.38	103.15	104.11	113.42
Rosette 7, 19 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.49	-90.94	61.36	48.19	-77.77
0.51	0.45	-149.55	70.53	46.88	-125.90
0.76	0.46	-190.92	92.18	63.91	-162.65
1.02	0.46	-224.70	116.04	81.43	-190.09
1.27	0.46	-239.80	111.42	75.15	-203.53
1.52	0.45	-262.48	104.46	65.78	-223.80
1.78	0.45	-239.80	111.35	72.67	-201.12

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{p1} (MPa)	σ_{p2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 8, 22 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.79	12.62	12.62	12.62	12.62
0.51	0.00	17.37	56.12	37.78	37.78
0.76	0.03	9.58	78.53	46.33	41.78
1.02	0.02	-4.14	92.32	46.40	41.78
1.27	0.04	-4.83	105.63	54.95	45.85
1.52	0.04	-9.45	110.18	54.95	45.78
1.78	0.04	-14.00	114.73	54.95	45.78
Rosette 9, 25 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.52	-26.68	6.14	3.79	-24.34
0.51	0.39	-14.00	24.27	18.68	-8.41
0.76	0.46	11.58	60.47	55.57	16.48
1.02	0.44	18.89	84.05	76.67	26.27
1.27	0.55	-12.27	125.48	118.25	-5.03
1.52	0.54	0.55	143.55	135.41	8.69
1.78	0.54	0.55	143.55	135.41	8.69
Rosette 10, 29 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.49	-25.23	14.48	11.17	-21.93
0.51	0.39	-25.79	36.54	27.44	-16.69
0.76	0.33	-26.75	59.02	42.20	-9.93
1.02	0.26	-34.13	77.22	49.57	-6.48
1.27	0.28	-28.89	93.49	64.40	0.21
1.52	0.27	-40.47	94.25	60.95	-7.17
1.78	0.29	-34.40	99.01	68.40	-3.79
Rosette 11, 11 mm From Centerline and 32 mm From End of Test Coupon					
0.25	0.74	37.02	135.14	134.93	37.23
0.51	0.70	61.71	164.30	163.61	62.40
0.76	0.75	50.61	186.16	186.02	50.75
1.02	0.76	42.61	215.67	215.53	42.75

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{p1} (MPa)	σ_{p2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 11, continued 11 mm From Centerline and 32 mm From End of Test Coupon					
1.27	0.73	39.02	197.74	197.26	39.51
1.52	0.76	46.61	200.91	200.78	46.75
1.78	0.68	59.92	209.12	207.33	61.71
Rosette 12, 35 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.39	9.38	29.23	26.34	12.27
0.51	0.39	-3.86	42.47	35.71	2.90
0.76	0.20	-9.86	61.43	39.85	11.72
1.02	0.24	-12.76	77.22	53.30	11.17
1.27	0.22	-16.96	81.43	53.30	11.17
1.52	0.19	-11.72	89.08	57.36	19.99
Rosette 13, 38 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.73	-26.54	63.43	63.16	-26.27
0.51	0.60	-11.93	73.43	70.40	-8.89
0.76	0.62	7.52	140.17	136.79	10.89
1.02	0.57	18.20	141.83	136.03	23.99
1.27	0.61	9.86	174.78	169.68	14.96
1.52	0.64	26.89	206.98	203.19	30.68
1.78	0.61	8.89	200.36	194.57	14.69
Rosette 14, 41 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.62	-14.20	38.82	37.44	-12.82
0.51	0.45	-19.51	44.13	37.44	-12.82
0.76	0.39	-13.51	62.74	51.51	-2.34
1.02	0.36	-23.17	72.39	56.05	-6.83
1.27	0.33	-23.65	85.22	64.53	-2.96
1.52	0.37	-23.58	97.42	77.36	-3.52
1.78	0.37	-29.92	103.77	81.91	-8.07

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{P1} (MPa)	σ_{P2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 15, 44 mm From Centerline and 25 mm From End of Test Coupon					
0.25	-0.69	5.10	18.34	5.24	18.20
0.51	-0.49	50.75	19.65	48.13	22.27
0.76	-0.66	88.18	111.28	88.53	110.94
1.02	-0.69	104.18	130.59	104.46	130.31
1.27	-0.79	108.04	126.66	108.04	125.66
1.52	-0.75	108.73	137.76	108.80	137.69
1.78	-0.75	108.73	137.76	108.80	137.69
Rosette 16, 48 mm From Centerline and 25 mm From End of Test Coupon					
0.25	0.39	-17.10	-5.39	-7.10	-15.38
0.51	0.23	3.86	41.02	30.75	14.13
0.76	0.27	-1.79	46.58	43.51	8.95
1.02	0.11	0.34	55.78	34.27	21.86
1.27	0.11	0.34	55.78	34.27	21.86
1.52	0.06	0.21	67.22	37.85	29.58
1.78	0.16	-16.96	61.91	34.96	10.00
Rosette 17, 0 mm From Centerline and 152 mm From End of Test Coupon					
0.25	-0.69	-49.85	-59.36	-49.92	-59.29
0.51	-0.79	-96.46	-121.35	-96.46	-121.35
0.76	-0.79	-125.69	-174.58	-125.69	-174.58
1.02	0.77	41.02	-432.23	-432.09	40.89
1.27	0.76	55.09	-473.67	-473.19	54.61
1.52	0.75	46.82	-501.73	-501.04	46.13
1.78	0.75	72.74	-527.66	-526.76	71.84
Rosette 18, 3 mm From Centerline and 152 mm From End of Test Coupon					
0.25	-0.51	-123.90	-95.91	-121.30	-97.91
0.51	-0.61	-194.64	-114.66	-192.09	-117.21
0.76	-0.67	-230.91	-323.30	-232.22	-321.99
1.02	-0.71	-266.83	-377.56	-267.38	-377.01
1.27	-0.71	-276.89	-406.17	-277.58	-405.48

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{p1} (MPa)	σ_{p2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 18, continued 3 mm From Centerline and 152 mm From End of Test Coupon					
1.52	No data obtained				
1.78					
Rosette 19, 6 mm From Centerline and 152 mm From End of Test Coupon					
0.25	0.79	-35.16	35.09	35.09	-35.16
0.51	-0.67	-69.77	-106.11	-70.26	-105.63
0.76	-0.73	-123.07	-181.88	-123.28	-181.68
1.02	-0.68	-160.72	-249.87	-161.68	-248.90
1.27	-0.64	-182.02	-287.30	-184.16	-285.17
1.52	-0.65	-191.26	-313.23	-193.40	-311.09
1.78	-0.65	-191.26	-313.23	-193.40	-311.09
Rosette 20, 10 mm From Centerline and 152 mm From End of Test Coupon					
0.25	-0.39	-67.43	-67.43	-67.43	-67.43
0.51	0.16	-134.52	-147.69	-143.20	-139.00
0.76	0.29	-153.55	-183.47	-176.78	-160.23
1.02	0.55	-129.41	-218.84	-214.15	-134.10
1.27	0.66	-111.76	-247.73	-245.73	-113.76
1.52	0.66	-89.29	-225.25	-223.25	-91.29
1.78	0.71	-66.74	-236.56	-235.52	-67.78
Rosette 21, 13 mm From Centerline and 152 mm From End of Test Coupon					
0.25	-0.75	-63.02	-35.44	-62.95	-35.51
0.51	-0.75	-59.98	-1.59	-59.92	-43.02
0.76	-0.77	-25.92	38.20	-25.92	38.20
1.02	-0.76	-3.93	77.77	-3.86	77.70
1.27	0.79	-185.06	283.58	283.58	-185.06
1.52	-0.77	42.47	129.83	42.47	129.83
1.78	-0.77	34.68	125.35	34.68	125.35

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{P1} (MPa)	σ_{P2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 22, 16 mm From Centerline and 152 mm From End of Test Coupon					
0.25	-0.62	8.89	0.97	8.69	1.17
0.51	-0.29	26.06	52.95	32.06	46.95
0.76	-0.16	56.40	91.77	68.46	79.70
1.02	-0.28	69.50	118.18	80.81	106.87
1.27	-0.20	50.61	107.42	67.84	90.18
1.52	-0.16	54.47	113.49	74.67	93.29
1.78	-0.06	45.23	112.80	75.29	82.74
Rosette 23, 19 mm From Centerline and 152 mm From End of Test Coupon					
0.25	-0.58	-1.17	-34.06	-2.48	-32.75
0.51	-0.55	59.98	-36.54	54.88	-31.44
0.76	-0.61	87.36	-87.36	81.91	-81.91
1.02	-0.57	125.62	-102.18	115.14	-91.70
1.27	-0.56	141.96	-130.24	128.79	-117.07
1.52	-0.55	141.76	-153.48	125.69	-137.41
1.78	-0.55	155.27	-166.99	138.45	-150.17
Rosette 24, 22 mm From Centerline and 152 mm From End of Test Coupon					
0.25	0.55	-10.07	22.34	20.62	-8.34
0.51	0.16	48.26	62.54	57.64	53.16
0.76	-0.07	76.39	108.25	90.05	94.60
1.02	-0.25	81.50	127.76	93.42	115.83
1.27	-0.21	89.77	144.10	105.70	128.17
1.52	-0.25	96.04	162.44	113.56	144.93
1.78	-0.23	105.70	166.30	122.45	149.55
Rosette 25, 25 mm From Centerline and 152 mm From End of Test Coupon					
0.25	0.52	-6.69	30.13	27.51	-4.07
0.51	0.39	61.02	91.56	65.50	87.08
0.76	0.55	88.39	181.54	176.64	93.29
1.02	0.55	90.53	214.63	208.08	97.08

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{p1} (MPa)	σ_{p2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 25, continued 25 mm From Centerline and 152 mm From End of Test Coupon					
1.27	0.54	105.21	235.18	227.60	112.80
1.52	0.60	94.39	257.73	251.87	100.25
1.78	0.58	110.11	253.73	247.52	116.31
Rosette 26, 29 mm From Centerline and 152 mm From End of Test Coupon					
0.25	-0.51	5.03	30.20	6.83	28.41
0.51	-0.49	43.16	74.26	45.78	71.64
0.76	-0.53	54.05	98.53	56.88	95.70
1.02	-0.45	66.26	121.55	72.33	115.49
1.27	-0.54	67.91	131.62	127.76	71.77
1.52	-0.44	71.91	139.34	79.70	131.55
1.78	-0.47	80.25	154.51	87.22	147.55
Rosette 27, 32 mm From Centerline and 152 mm From End of Test Coupon					
0.25	0.56	41.30	75.43	73.64	43.09
0.51	0.55	82.19	149.82	146.24	85.77
0.76	0.60	129.48	218.49	215.32	132.66
1.02	0.57	145.69	240.30	236.63	149.96
1.27	0.62	163.75	274.48	271.65	166.58
1.52	0.62	137.00	275.45	271.86	140.58
1.78	0.58	144.79	267.59	262.62	149.75
Rosette 28, 35 mm From Centerline and 152 mm From End of Test Coupon					
0.25	-0.39	18.27	30.96	20.13	29.10
0.51	-0.39	58.19	77.22	60.95	74.46
0.76	-0.75	-117.35	-313.50	-117.62	-313.23
1.02	-0.75	-92.73	-288.89	-93.01	-288.61
1.27	-0.73	-76.32	-280.62	-76.88	-280.07
1.52	-0.74	-89.77	-304.13	-90.25	-303.65
1.78	-0.73	-106.18	-324.61	-106.80	-323.98

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{p1} (MPa)	σ_{p2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 29, 38 mm From Centerline and 152 mm From End of Test Coupon					
0.25	0.00	9.51	33.72	21.65	21.65
0.51	0.34	103.97	155.55	145.89	113.63
0.76	0.35	130.72	193.67	182.37	142.03
1.02	0.43	144.10	223.53	214.15	153.48
1.27	0.39	157.89	220.56	211.39	167.06
1.52	0.30	157.41	221.05	207.33	171.13
1.78	0.43	146.10	230.63	220.43	156.30
Rosette 30, 41 mm From Centerline and 152 mm From End of Test Coupon					
0.25	0.00	15.72	33.78	24.75	24.75
0.51	-0.31	48.61	87.43	56.74	79.29
0.76	-0.50	75.70	134.59	80.32	129.97
1.02	-0.39	73.36	124.52	80.88	117.00
1.27	-0.44	73.02	137.21	80.32	129.90
1.52	-0.51	77.98	156.99	83.63	151.34
1.78	-0.47	72.46	150.17	79.70	142.93
Rosette 31, 44 mm From Centerline and 152 mm From End of Test Coupon					
0.25	0.58	1.52	63.16	60.67	4.00
0.51	0.65	18.48	123.90	122.04	20.34
0.76	0.65	56.40	189.61	187.05	58.95
1.02	0.62	86.80	198.02	195.19	89.63
1.27	0.65	82.32	215.46	212.91	84.87
1.52	0.65	94.80	227.39	224.84	97.35
1.78	0.62	85.84	224.91	221.32	89.43
Rosette 32, 48 mm From Centerline and 152 mm From End of Test Coupon					
0.25	0.55	-9.31	20.55	18.96	-7.72
0.51	0.29	18.75	48.88	42.20	25.44
0.76	-0.29	63.91	94.04	70.67	87.29
1.02	-0.32	114.52	156.30	122.86	147.96

Table 2 Continued. Results of Strain Gauge Rosette Measurements

Depth of Hole (mm)	Angle (Radian)	σ_{P1} (MPa)	σ_{P2} (MPa)	σ_x (MPa)	σ_y (MPa)
Rosette 32, continued					
48 mm From Centerline and 152 mm From End of Test Coupon					
1.27	-0.25	108.32	151.27	119.35	140.24
1.52	-0.33	105.97	153.55	115.21	144.31
1.78	-0.33	105.49	152.86	114.66	143.69

The mean and variance of measured crack depth are reported to be 1.27 and 0.2581 mm² respectively. It is known that the probability of detecting a crack increases with size. It is also known that the measured depth of the cracks differs in a statistically determinable way from the actual depth. Therefore, the distribution of measured crack depths does not correctly represent the complete sample space of cracks. To correct this error, probability theory is applied to determine the distribution of the actual depth of all cracks. Applying this method, the mean and variance of the crack population are calculated to be 2.289 mm and 0.871 mm² respectively. Under these circumstances a 99 percent confidence interval would include all cracks having a depth not greater than 2.290 mm. Information regarding crack depth, the assumption of a crack geometry, and the value of residual stress reported in the previous section will permit the value of stress intensity at a crack tip to be calculated.

Stress Intensity Factor Compared to $K_{I_{sc}}$

From the Damage Tolerant Design Handbook,⁵ the lowest value of $K_{I_{sc}}$ listed for HP-9-4-20 is 70 MPa/ $\sqrt{m}$. This value was obtained in the HAZ of a weld in an environment of sump tank water at 23°C. A $K_{I_{sc}}$ of 71 MPa/ $\sqrt{m}$ was obtained from a weld in synthetic sea water at 23°C.

A semicircular ($a = c$) surface flaw geometry will be assumed, because it requires the least stress to propagate. Using the maximum value of residual stress measured, 283 MPa, and the crack depth calculated to be deepest in a 99 percent confidence interval, 2.29 mm, a stress intensity value was calculated.

Figure 5. Stress Distribution on Both Sides of the Weld for Strain Gauge Rosette Data

Figure 5 Continued. Stress Distribution on Both Sides of the Weld for Strain Gauge Rosette Data

Figure 6. Rosette Stress Versus Depth

Figure 6 Continued. Rosette Stress Versus Depth

$$K_I = 1.120\sigma\sqrt{\pi\frac{a}{q}},$$

where

σ = measured residual stress,

a = crack depth,

$$q = \phi_o^2,$$

$$\text{and } \phi_o = \int_0^{\frac{\pi}{2}} \left(1 - \frac{c^2 - a^2}{c^2} \sin^2 \theta\right)^{1/2} d\theta.$$

When

$$c = a, \phi_o = \frac{\pi}{2} \text{ or } 1.57 \text{ and } \phi_o^2 = 2.467, \text{ and}$$

$$K_I = 1.12 (283.5) \sqrt{\pi \frac{0.00229}{2.467}} \text{ or}$$

$$K_I = 17.1 \text{ MPa}/\sqrt{\text{m}}.$$

This calculation shows that $K_{I_{scc}}$ is in excess of four times the K_I value calculated for the worst case. Another comparison is to calculate the stress required to induce stress corrosion cracking with the flaw geometry previously assumed.

$$K_{I_{scc}} = 1.12\sigma_c \sqrt{\pi \frac{0.00229}{2.467}}$$

$$70 = 1.12\sigma_c \sqrt{\pi \frac{0.00229}{2.467}}$$

$$\sigma_c = 1157 \text{ MPa}$$

This calculation shows that σ_c is also in excess of four times the measured residual stress.

The conclusion is that residual stress alone is not sufficient to cause stress corrosion cracking. Residual stress is significant, however, in that when externally applied stress is superimposed, the additive effect may be critical.

Microstructure, Hardness, and Residual Stress

The material examined in this study was 12.7 mm thick plate given the following heat treatment prior to welding.

1. Normalize at $900^{\circ} \pm 10^{\circ}\text{C}$ for 1 hour in an inert atmosphere. Air quench to room temperature.
2. Austenitize at $830^{\circ} \pm 15^{\circ}\text{C}$ for 1 hour in an inert atmosphere. Water quench to room temperature.
3. Within 8 hours of austenitizing, subzero cool to $-75^{\circ}\text{C} \pm 5^{\circ}\text{C}$ for 2 hours. Air warm to room temperature.
4. Temper at $550^{\circ} \pm 10^{\circ}\text{C}$ for 8 hours in an inert atmosphere. Air quench to room temperature.

This heat treatment produced the following range of properties in the base metal.

Ultimate tensile strength	1345 to 1480 MPa
0.2 percent offset yield strength	1240 to 1345 MPa
Hardness	R _C 39 to 44

Gas tungsten arc (TIG) welding was used with a specially developed filler metal⁶ to weld a butted double V-notch joint. The following weld parameters were used.

Current	200/250 Amperes
Voltage	10/12 Volts
Wire diameter	1.14 to 1.57 mm
Wire feed	8 to 13 mm/s
Travel	3 to 5 mm/s
Maximum interpass temperature	93°C
Shielding	196×10^{-6} to $275 \times 10^{-6} \text{ m}^3/\text{s}$
Interpass cleaning	Power wire brush

To minimize the need for post weld stress relief heat treatment, a larger than normal number of small deposition passes were made to provide tempering and stress relieving with subsequent passes. Figure 7 is a photomacrograph of the weld cross section.

Greater stress corrosion susceptibility in the HAZ has been suggested⁷ as being the result of either or both of two metallurgical factors: the formation of some untempered or partially tempered relatively high carbon martensite, or precipitation of carbides at grain boundaries or crystallographic planes.

Subsequent treatment for 24 hours at 538°C did not significantly change the toughness⁷ so the presence of untempered martensite can be ruled out.

Figures 8 through 10 show the microstructures of the weld, HAZ, and base metal. The section was etched with a mixture of 10 mL HCl, 5 mL HNO₃, and 100 mL methanol for 5 minutes at room temperature. The grain boundaries are visible but do not show precipitation of carbides. There is a finely divided second phase visible randomly distributed throughout the HAZ. This may be a carbide phase but would require the use of the electron microprobe or electron diffraction to be identified. Hardness measurements made across the weld region show that the weld metal was R_C 40, the base metal was R_C 41, and the HAZ ranged from R_C 44 to 48. This second phase in the HAZ is probably responsible for its higher hardness, higher residual stress, and lower stress corrosion cracking resistance.

Computer Programming for Data Manipulation

Four computer programs were used to make calculations from strain gauge rosette data and to plot the various stress field relationships. Program RSTRES was written to read resistance values from the strain gauge rosettes and calculate the principal stresses and their orientation. This program was run in connection with the hole boring operation on a minicomputer. Subsequent to obtaining the principal stresses and their orientation, σ_x and σ_y were calculated at each depth for each hole using the equations from Appendix B. These calculations were made with a programmable desk calculator. The data from these calculations comprise part of Table 2.

A portion of the data from Table 2 was organized into a computer file similar to Table 1. Organized in this manner it became Tape 7 for program PLOTTER. Program INFO prompts the user in the selection of plotting constants, variables, and axis labels which information became Tape 3 for use in PLOTTER. Using these programs, Figure 3 and Figure 5 were plotted. These figures are typical of more than 100 plots that were made for better visualization of the stress field.

Figure 7. Photomacrograph of Weld Cross Section (3.25X)

Figure 8. Photomicrograph of Weld Metal (Oil Immersion-500X)

Figure 9. Photomicrograph of HAZ (Oil Immersion-500X)

Figure 10. Photomicrograph of Base Metal (Oil Immersion-500X)

ACCOMPLISHMENTS

X-ray diffraction and strain gauge rosette capabilities were developed for measuring residual stress. The maximum residual stress in the test coupon was shown to be about 276 MPa in the HAZ.

A statistical method for correcting the mean and variance of a measured crack depth distribution was adopted. Based on the maximum residual stress measured, a maximum crack depth, and an assumed crack geometry, K_I was shown to be one-fourth of K_{Isc} . This shows that residual stresses alone cannot cause stress corrosion cracking. Residual stresses are, however, significant and when external stresses are superimposed they may produce a critical situation.

A computer program was written which greatly increased the speed at which the strain gauge rosette data were reduced to principal stresses and orientation. Two other computer programs were adapted to plot the stress field relationships thereby allowing the stress fields to be more easily visualized.

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Appendix A

X-RAY DIFFRACTION METHOD OF RESIDUAL STRESS MEASUREMENT

X-ray diffraction occurs in crystalline materials in accordance with the Bragg equation,

$$n\lambda = 2d\sin\theta. \quad (A-1)$$

There is an interatomic spacing, d_0 , that represents an unstrained condition. If tension or compression is applied to the material, the interatomic spacing is changed. X-ray diffraction residual stress measurements are made possible by measuring the change $\Delta d = d - d_0$ in the interatomic spacing.

Since Δd is related to the change that occurs in the diffraction angle θ the relationship between Δd and $\Delta\theta$ must be determined. This relationship can be obtained by solving Equation A-1 for d and differentiating,

$$d = 0.5n\lambda\csc\theta$$

$$\frac{\partial d}{\partial \theta} = -0.5n\lambda\cot\theta\csc\theta.$$

$$\text{Since } \Delta d = \frac{\partial d}{\partial \theta} \Delta\theta$$

$$\text{then } \Delta d = -0.5n\lambda\cot\theta\csc\theta \Delta\theta.$$

Strain in the crystalline material is the change in spacing divided by the original spacing.

$$\frac{\Delta d}{d_0} = -\cot\theta_0 \delta\theta. \quad (A-2)$$

The lattice strain in the direction normal to the lattice plane can be calculated approximately from Equation A-2:

$$\epsilon_{\psi x} = \left(\frac{\Delta d}{d_0} \right)_{\psi x} = -\cot\theta_0 (\theta_{\psi x} - \theta_0) \quad (A-3)$$

where ψ is the angle between the normals of the diffracting plane and the specimen surface as shown in Figure A-1.

In order to relate $\Delta\theta$ measured by X-ray diffraction to residual stresses, a series of stress-strain relationships and coordinate transformations must be used.

Figure A-1. Directions of Stresses and Strains in the 1, 2, 3 and x, y, z Coordinate Systems

Because of X-ray absorption, diffraction can be observed only in the vicinity of the surface (5 to 10 μm). Therefore, the stress component σ_3 normal to the specimen surface is considered to be zero. In Figure A-1, the principal stresses σ_1 and σ_2 are in the plane of the specimen surface. The relationship between the principal stresses and principal strains are shown:

$$\epsilon_1 E = \sigma_1 - \nu \sigma_2$$

$$\epsilon_2 E = \sigma_2 - \nu \sigma_1$$

$$\epsilon_3 E = -\nu(\sigma_1 + \sigma_2)$$

where E is Young's modulus and ν is Poisson's ratio.

From Figure A-1 it can be seen that a second coordinate system exists in which the X axis is in a plane containing $\epsilon_{\phi X}$ and the normal to the specimen surface. In this coordinate system the following stress-strain relationships exist:

$$\epsilon_X E = \sigma_X - \nu \sigma_Y$$

$$\epsilon_Y E = \sigma_Y - \nu \sigma_X$$

$$\epsilon_Z E = -\nu(\sigma_X + \sigma_Y) = -\nu(\sigma_1 + \sigma_2).$$

A
B
C } 4

Since σ_X and σ_Y are in the plane of the specimen surface, σ_Z is zero, identical to σ_3 in the principal stress coordinate system.

In order to make transformations between the principal coordinate system axes 1, 2, and 3 and the system x, y, and z, the following relationships exist where U is a displacement and X is a coordinate:

$$X_x = X_1 \cos \phi + X_2 \sin \phi$$

$$X_y = X_2 \cos \phi - X_1 \sin \phi$$

$$X_z = X_3$$

$$X_1 = X_x \cos \phi - X_y \sin \phi$$

$$X_2 = X_y \cos \phi + X_x \sin \phi$$

$$X_3 = X_z$$

$$U_x = U_1 \cos \phi + U_2 \sin \phi$$

$$U_y = U_2 \cos \phi + U_1 \sin \phi$$

$$U_z = U_3$$

$$U_1 = U_x \cos \phi - U_y \sin \phi$$

$$U_2 = U_y \cos \phi + U_x \sin \phi$$

$$U_3 = U_z$$

To express strain in the x, y, and z system in terms of strains in the 1, 2, and 3 system, the following relationships exist:

$$\epsilon_x = \frac{\partial U_x}{\partial X_x} = \left(\frac{\partial U_x}{\partial X_1} \right) \left(\frac{\partial X_1}{\partial X_x} \right) + \left(\frac{\partial U_x}{\partial X_2} \right) \left(\frac{\partial X_2}{\partial X_x} \right) + \left(\frac{\partial U_x}{\partial X_3} \right) \left(\frac{\partial X_3}{\partial X_x} \right)$$

$$\epsilon_x = \frac{(\partial U_1 \cos \phi + U_2 \sin \phi)}{\partial X_1} \cos \phi + \frac{\partial (U_1 \cos \phi + U_2 \sin \phi)}{\partial X_2} \sin \phi, \text{ or}$$

$$\epsilon_x = \frac{\partial U_1}{\partial X_1} \cos^2 \phi + \frac{\partial U_2}{\partial X_1} \sin \phi \cos \phi + \frac{\partial U_1}{\partial X_2} \cos \phi \sin \phi + \frac{\partial U_2}{\partial X_2} \sin^2 \phi$$

$$\frac{\partial U_1}{\partial X_1} = \epsilon_1 ; \quad \frac{\partial U_2}{\partial X_2} = \epsilon_2 ;$$

$$\sin \phi \cos \phi \left(\frac{\partial U_1}{\partial X_2} + \frac{\partial U_2}{\partial X_1} \right) = 2 \sin \phi \cos \phi \left[1/2 \left(\frac{\partial U_1}{\partial X_2} + \frac{\partial U_2}{\partial X_1} \right) \right]$$

$$\text{where } 1/2 \left(\frac{\partial U_2}{\partial X_1} + \frac{\partial U_1}{\partial X_2} \right) = 1/2 (\epsilon_{12} + \epsilon_{21}) = \epsilon_{12}$$

In a system of principal strains $\epsilon_{12} = 0$.

Therefore,

$$\epsilon_x = \epsilon_1 \cos^2 \phi + \epsilon_2 \sin^2 \phi.$$

By a similar approach

$$\epsilon_y = \epsilon_1 \sin^2 \phi + \epsilon_2 \cos^2 \phi \text{ and}$$

$$\epsilon_z = \epsilon_3 \text{ since } \frac{\partial U_2}{\partial X_2} = \frac{\partial U_3}{\partial X_3}.$$

To obtain the relationship between $\epsilon_{\psi x}$ and surface stresses, still another coordinate transformation is necessary. This coordinate system is obtained by rotating the x, y, z system about the y axis until the x axis coincides with $\epsilon_{\psi x}$ as shown in Figure A-2. The following relationship exists for making this transformation:

$$X_{\psi x} = X_x \cos \psi - X_z \sin \psi$$

$$X_{\psi y} = X_y$$

$$X_{\psi z} = X_z \cos \psi + X_x \sin \psi$$

$$X_x = X_{\psi x} \cos \psi - X_{\psi z} \sin \psi$$

$$X_y = X_{\psi y}$$

$$X_z = X_{\psi z} \cos \psi + X_{\psi x} \sin \psi$$

$$U_{\psi x} = U_x \cos \psi - U_z \sin \psi$$

$$U_{\psi y} = U_y$$

$$U_{\psi z} = U_z \cos \psi + U_x \sin \psi$$

$$\epsilon_{\psi x} = \frac{\partial U_{\psi x}}{\partial X_{\psi x}} = \left(\frac{\partial U_{\psi x}}{\partial X_x} \right) \left(\frac{\partial X_x}{\partial X_{\psi x}} \right) + \left(\frac{\partial U_{\psi x}}{\partial X_y} \right) \left(\frac{\partial X_y}{\partial X_{\psi x}} \right) + \left(\frac{\partial U_{\psi x}}{\partial X_z} \right) \left(\frac{\partial X_z}{\partial X_{\psi x}} \right)$$

Figure A-2. Directions of Stresses and Strains in the x, y, z and ψ_x, ψ_y, ψ_z Coordinate Systems

$$\epsilon_{\psi x} = \left[\frac{\partial (U_x \cos \psi - U_z \sin \psi)}{\partial X_x} \right] \cos \psi$$

$$+ \left[\frac{\partial (U_x \cos \psi - U_z \sin \psi)}{\partial X_z} \right] \sin \psi$$

$$\epsilon_{\psi x} = \frac{\partial U_x}{\partial X_x} \cos^2 \psi - \frac{\partial U_z}{\partial X_x} \sin \psi \cos \psi$$

$$+ \frac{\partial U_x}{\partial X_z} \cos \psi \sin \psi - \frac{\partial U_z}{\partial X_z} \sin^2 \psi$$

$$\frac{\partial U_x}{\partial X_x} = \epsilon_x$$

$$\frac{\partial U_z}{\partial X_z} = \epsilon_z.$$

Since U_x is not a function of X_z and U_z is not a function of X_x ,

$$\frac{\partial U_x}{\partial X_y} = \frac{\partial U_z}{\partial X_x} = 0.$$

Therefore,

$$\epsilon_{\psi z} = \epsilon_z \cos^2 \psi + \epsilon_x \sin^2 \psi.$$

From Equations 4A, 4B, and 4C

$$\epsilon_{\psi x} = \left[\frac{-\nu (\sigma_1 + \sigma_2)}{E} \right] (1 - \sin^2 \psi) + \left(\frac{\sigma_x - \nu \sigma_y}{E} \right) \sin^2 \psi$$

or

$$\epsilon_{\psi x} = \frac{\sigma_x (1 + \nu)}{E} \sin^2 \psi - \frac{\nu}{E} (\sigma_1 + \sigma_2). \quad (A-5)$$

Equation A-5 is a fundamental equation for X-ray stress measurement because it shows that in the plane containing the direction of the stress measurement and the normal to the specimen surface, $\epsilon_{\psi x}$ is linearly proportional to $\sin^2 \psi$.

If $2\theta_{\psi x}$ diffraction angles are measured for several ψ angles and plotted against $\sin^2 \psi$, the $2\theta_{\psi x}$ versus $\sin^2 \psi$ plot will be as shown in Figure A-3.

Figure A-3. Plot of $2\theta_{\psi x}$ Versus $\sin^2\psi$

Setting Equation A-3 and Equation A-5 equal,

$$- 1/2 \cot\theta_o (2\theta_{\psi x} - 2\theta_o) = \frac{\sigma_x(1+\nu)}{E} \sin^2\psi - \frac{\nu}{E}(\sigma_1 + \sigma_2)$$

and taking the partial differential

$$\frac{\partial(2\theta_{\psi x})}{\partial(\sin^2\psi)} = - \frac{2\sigma_x(1+\nu)}{E \cot\theta_o}, \text{ so that}$$

$$\sigma_x = - \frac{E}{2(1+\nu)} \cot\theta_o \left(\frac{\partial 2\theta_{\psi x}}{\partial \sin^2\psi} \right) \quad (A-6)$$

This equation shows that the slope of the line produced in Figure A-3, multiplied by a constant K, where

$$K = - \frac{E}{2(1 + \nu)} \cot \theta_0,$$

is σ_x , the stress on the surface of the specimen in the X direction.

In making X-ray stress measurements, the relationship to be determined is $2\theta_{\psi x}$ versus $\sin^2\psi$. There are several analytical approaches which can be followed to obtain this relationship. The two main approaches are termed the ordinary method and the side inclining method.

The ordinary method scans the detector in the plane of the stress to be determined as illustrated in Figure A-4. Within this constraint there are three methods of determining the relationship between $2\theta_{\psi x}$ and $\sin^2\psi$. The $\sin^2\psi$ method measures ψ versus 2θ at three or more (usually four) positions of ψ_0 , where ψ_0 is the angle of the incident X-ray beam with respect to the specimen normal.

The Glocker method measures ψ versus 2θ at $\psi_0 = 0$ degrees and 45 degrees.

The Schaal method uses only $\psi_0 = 45$ degrees and measures the difference in diffraction peak position equidistant on both sides of the incident beam.

The side inclining method scans the detector in a plane perpendicular to the plane in which the stress is to be determined, as illustrated in Figure A-5. Within this constraint there are two methods of determining the relationship between $2\theta_{\psi x}$ and $\sin^2\psi$. The $\sin^2\psi$ method measures ψ versus 2θ at three or more positions of θ . The Glocker method measures the change in ψ at $\theta = 90$ degrees and 45 degrees. The side inclining method is useful for measuring the stress in complicated shaped specimens.

Soller slits are placed before the X-ray tube and the detector to collimate both the incident and diffracted beams. This collimated beam has the advantage that minor deviations in the location of the specimen with respect to the center of goniometer notation have minimal effect on the accuracy of the measured diffraction angles.

Material properties of grain size, preferred orientation, and surface condition affect the accuracy and reproducibility of stress measurement. Grain sizes of about 30 μm (ASTM grain size is 7 μm) and smaller are necessary to avoid having to use an oscillating motion on the specimen to increase the average number

Figure A-4. Ordinary Method of Detector Scanning

of grains sampled. If only a few large grains are sampled, a biased result may be obtained. Highly preferred orientation in a material results in a lattice structure in which the intensity of the diffracted beam is strongly dependent on the angle ψ between the normal of the specimen and the normal to the diffracting lattice plane. In such cases the 2θ versus $\sin^2\psi$ relationship may be affected by elastic anisotropy and the mechanism of plastic deformation. In measuring the stress in materials having strong preferred orientation it is necessary to select the incident angles that give the maximum diffraction intensity and use the side inclining method. The surface of the specimen is important in obtaining an accurate measure of residual stresses. Surfaces which are machined or ground possess extraneous residual stresses which must be removed by chemical milling or electropolishing.

Figure A-6. Side Inclining Method of Detector Scanning

Appendix B

THE 0-45-90 DEGREE STRAIN GAUGE ROSETTE METHOD OF RESIDUAL STRESS MEASUREMENT

When a hole of small diameter ($2 R_0$ in Figure B-1) is drilled in a region containing residual stresses, a strain relaxation occurs. The strains relieved at point P (Figure B-1) when only stress σ_1 is present are

$$\begin{aligned}\epsilon_r &= -\sigma_1 \frac{1+\nu}{2E} \left[\frac{1}{r^2} - \frac{3}{r^4} \cos 2\alpha + \frac{4}{(1+\nu)r^2} \cos 2\alpha \right] ; r = \frac{R}{R_0} \\ \epsilon_\theta &= -\sigma_1 \frac{1+\nu}{2E} \left[-\frac{1}{r^2} + \frac{3}{r^4} \cos 2\alpha - \frac{4\nu}{(1+\nu)r^2} \cos 2\alpha \right], \text{ and} \\ \gamma_{r\theta} &= \frac{\sigma_1}{2G} \left(\frac{3}{r^4} - \frac{2}{r^2} \right) \sin 2\alpha.\end{aligned}\tag{B-1}$$

These equations show that the relief of both radial and tangential components of strain vary sinusoidally along a circle of radius R . If both stresses σ_1 and σ_2 exist simultaneously, the expression for the radial component becomes

$$\epsilon_r = (A + B \cos 2\alpha) \sigma_1 + [A + B \cos 2(\alpha + \pi/2)] \sigma_2\tag{B-2}$$

where

$$A = -\frac{1+\nu}{2E} \left(\frac{R_0}{R} \right)^2$$

and

$$B = -\frac{1+\nu}{2E} \left[\left(\frac{4}{1+\nu} \right) \left(\frac{R_0}{R} \right)^2 - 3 \left(\frac{R_0}{R} \right)^4 \right]$$

In order to measure the principal residual stresses σ_1 and σ_2 and their direction with respect to a reference direction, three strain measurements are required. These three measurements will provide three equations from which the stresses σ_1 , σ_2 , and β can be obtained. β is the angle between σ_1 and the reference direction.

Figure B-1. Relationship Between Principal Stresses and Strains Relieved by Hole Drilling*

A strain gauge rosette is cemented with its elements on a radius R and in directions a , b , and c spaced $\pi/4$ radians apart as shown in Figure B-2. Strains can be determined from Equation B-2 by making the following angular substitutions:

$$\alpha_a = \beta,$$

$$\alpha_b = \beta + \pi/4 \text{ rad, and}$$

$$\alpha_c = \beta + \pi/2 \text{ rad.}$$

*Courtesy Measurements Group of Vishay Intertechnology, Inc.

Figure B-2. Strain Gauge Axes With Respect to Principal Stresses and Weld Direction*

Solving Equation B-2 simultaneously in each of the three angles, σ_1 , σ_2 , and β can be obtained. The equations obtained by this method are

$$\sigma_1 = \frac{(A + B\cos 2\beta)\epsilon_a - (A - B\cos 2\beta)\epsilon_c}{4AB\cos 2\beta},$$

$$\sigma_2 = \frac{(A + B\cos 2\beta)\epsilon_c - (A - B\cos 2\beta)\epsilon_a}{4AB\cos 2\beta}, \text{ and}$$

$$2\beta = \arctan \frac{\epsilon_a - 2\epsilon_b + \epsilon_c}{\epsilon_a + \epsilon_c}.$$

*Courtesy Measurements Group of Vishay Intertechnology, Inc.

These equations provide the best results when gauges a and c are approximately positioned along the principal directions. If gauges a and b have the largest spread, the following equations will be more satisfactory:

$$\sigma_1 = \frac{(A + B\sin 2\beta)\epsilon_a - (A - B\cos 2\beta)\epsilon_b}{2AB(\sin 2\beta + \cos 2\beta)} \text{ and}$$

$$\sigma_2 = \frac{(A + B\cos 2\beta)\epsilon_b - (A - B\sin 2\beta)\epsilon_a}{2AB(\sin 2\beta + \cos 2\beta)}.$$

When σ_1 , σ_2 , and β have been calculated, stress transformation to an x, y coordinate system can be performed by the following equations:

$$\sigma_x = \sigma_1 \cos^2(\pi/4 + \beta) + \sigma_2 \sin^2(\pi/4 + \beta),$$

$$\sigma_y = \sigma_1 \sin^2(\pi/4 + \beta) + \sigma_2 \cos^2(\pi/4 + \beta), \text{ and}$$

$$\tau_{xy} = 1/2(\sigma_2 - \sigma_1)\sin 2(\pi/4 + \beta).$$

This approach was used to calculate the stresses parallel and perpendicular to the weld orientation illustrated in Figure B-2.

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