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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
AMS	Aerospace Material Specification
MIL	Military Specification
MSFC	Marshall Space Flight Center
ASRM	Advanced Solid Rocket Motor
LTV	Ling-Tempco-Vought
HD	High Density (Conoco Grease)
GTAW	Gas Tungsten-Arc Welding
SCC	Stress Corrosion Cracking
SEM	Scanning Electron Microscopy
UTS	Ultimate Tensile Strength
YS	Yield Strength
E	Modulus of Elasticity (Young's Modulus)
EL	Elongation
RA	Reduction in Area
D.P.H.	Diamond Pyramid Hardness
Rc	Rockwell C
°C	Degrees Celsius or Centigrade
°F	Degrees Fahrenheit
amp	Ampere
cm	Centimeter
mm	Millimeter
in	Inch

MPa	Mega Pascal [Mega Newtons per Square Meter (1 ksi = 6.8948 MPa)]
ksi	Kilopounds per Square Inch

TECHNICAL PAPER

STRESS CORROSION EVALUATION OF HP 9Ni–4Co–0.30C STEEL PLATE WELDS

INTRODUCTION

Weldments of HP 9Ni–4Co–0.30C steel are planned for use in the Advanced Solid Rocket Motor (ASRM) program. However, no data were available on the effect of the welding procedure on the stress corrosion cracking (SCC) resistance of this material. This program was initiated to investigate such effect, as well as the effect of the stress relief after welding.

This study was performed by employing a standard test method for SCC evaluations. Round tensile specimens stressed to several stress levels were exposed to the following corrosive environments: high humidity [near 100-percent relative humidity at 38 °C (100 °F)], alternate immersion in 3.5-percent sodium chloride (NaCl) per American Society for Testing and Materials (ASTM) G44-88,[1] or 5-percent salt spray at 35 °C (95 °F) per ASTM B117–90.[2] The test duration was 3 months or until specimens failed. The data obtained indicate that the tested welds are susceptible to SCC (intergranular failure) in salt environments. This mode of failure was confirmed by Scanning Electron Microscopy (SEM) analysis. Susceptibility to SCC can be reduced to some extent by stress relief of the material. These findings must be considered when designing aerospace structures involving welds of HP 9Ni–4Co–0.30C steel.

Throughout this program, English units were used. These units were converted to the metric system.

EXPERIMENTAL PROCEDURE

HP 9Ni–4Co–0.30C steel plate material [46 cm (18 in) by 15 cm (6 in) by 1.27 cm (0.5 in)] per Aerospace Material Specification (AMS)–6526,[3] with the chemical analysis shown in Table 1A, was used for this evaluation. This material was fabricated by Ling-Tempco-Vought (LTV) Steel and heat treated at Cal-Doran to the 538 °C (1,000 °F) double tempered condition per Military Specification MIL–H–6875[4] (table 2). Afterwards, the material was welded at Marshall Space Flight Center (MSFC) by using the straight polarity plasma arc welding process. A weld diagram is presented in Figure 1. HP 9Ni–4Co–0.20C steel filler wire in the form of a spool was used. This wire was provided by United States Welding Corp. (Lot No. 403229). Its chemical composition is presented in Table 1B. The details of the welding procedure are presented in the appendix.

The welding material was divided into two sections, one of which was not stress relieved. From this section, 33 round tensile specimens [5.08 cm (2 in) total length, 0.3175 cm (1/8 in) gauge length diameter] were fabricated by B&B Precision Machine, Inc., along the plate and across the weld (weld near the center of the sample). The specimen configuration is shown in Figures 2A (metric units) and 2B (English units).

The other section of the welded material was stress relieved by MSFC at 510 °C (950 °F) for 3 hours. Eight specimens were machined, also along the plate and across the weld. The mechanical properties obtained from stress-relieved and *nonstress-relieved* materials are presented in Table 3A. The mechanical properties of the welding wire are presented in Table 3B.

All the specimens were stressed per ASTM G49–85[5] and were cleaned with acetone and alcohol prior to exposure. The stressing frames (PH 13–8 Mo, H1000 condition) were made per Figures 3 through 6B. Conoco HD calcium grease No. 2 was used on the threads and at the ends of the specimens to minimize galvanic interaction between the specimens and the frames in those areas.

The *nonstress-relieved* specimens were stressed to 50, 75, and 90 percent of the 0.2-percent offset yield strength (YS). The stressing device used is shown in Figure 7. These specimens were exposed in triplicate to 3.5-percent NaCl alternate immersion, 5-percent salt spray, and high humidity (Figs. 8 through 10). One *nonstress-relieved* specimen was also exposed unstressed to each media.

The postweld single stress-relieved [510 °C (950 °F)] specimens were stressed to 50, 75, and 90 percent of the yield strength and exposed in duplicate to 3.5-percent NaCl alternate immersion (additional stress-relieved specimens were not available to test in other media or to expose unstressed).

The test duration was 3 months, and the specimens were inspected each workday. Many failures occurred within the 3-month period. The failed specimens were cleaned with a warm 50-percent lactic/50-percent phosphoric acid solution, washed with water, followed by cleaning with acetone and with alcohol. Then, SEM was performed. Several specimens were examined metallographically to determine whether the failures occurred in the weld metal or in the heat-affected zones. Microhardness readings (D.P.H. readings converted to Rockwell C) were also obtained.

The specimens that did not fail during the 3-month exposure were tensile tested. The original gauge length diameter of 0.3175 cm (0.125 in) was used for these calculations.

RESULTS AND DISCUSSION

Table 4 presents the complete test results for the stress-relieved and the *nonstress-relieved* specimens which were stressed and exposed to the test environments. These SCC results were previously reported in Reference 6. All the *nonstress-relieved* welds tested in salt spray and alternate immersion failed. Time to failure ranged from 1 to 18 days in salt spray and from 7 to 36 days in alternate immersion. One *nonstress-relieved* specimen, which was stressed to 75 percent of YS, failed in high humidity after a 3-month exposure. The failed *nonstress-relieved* specimens are shown in Figure 11A. Some of these specimens fractured in more than one place, as seen in Figure 12. The *nonstress-relieved* specimens stressed to 50, 75, and 90 percent of YS, that did not fail after a 3-month exposure, are presented in Figure 13. The unstressed *nonstress-relieved* specimens that were exposed to various corrosive media are shown in Figure 14.

The stress-relieved specimens, stressed to 75 and 90 percent of YS and exposed to alternate immersion, failed in 8 to 18 days (Fig. 11B). Stress relief of the welds proved to be beneficial to some extent, as no failures occurred at 50 percent of YS in 3 months. The stress-relieved specimens that did not fail are presented in Figure 15.

Photomicrographs of several stress-relieved and *nonstress-relieved* specimens are presented in Figures 16 through 23. Three stress-relieved specimens, which failed after relatively short time exposures to the 3.5-percent NaCl alternate immersion bath, were examined metallographically. One of these specimens, stressed to 90 percent of YS, failed in the heat-affected zone (Fig. 16), and two specimens, stressed to 75 percent of YS, failed in the weld metal (Figs. 17 and 18). Microhardness readings (D.P.H. readings converted to Rockwell C) and cracking are shown in Figure 16.

Five *nonstress-relieved* specimen failures were examined metallographically: three that failed in alternate immersion (Figs. 19, 20, and 21) and two that failed in salt spray (Figs. 22 and 23). Three of these failures occurred in the heat-affected zone (Figs. 20, 22, and 23), and two occurred in the weld metal (Figs. 19 and 21). Microhardness readings (D.P.H. readings converted to Rockwell C) are presented in Figure 19.

Figures 24 to 33 show the fracture surface of several failed specimens (stress relieved and *nonstress-relieved*). All of these photomicrographs were obtained by use of SEM except for those shown in Figure 29B. As seen in these figures, there was a tendency to brittle intergranular type failures with little or no ductility present.

The stress relief had a positive effect on the mechanical properties as shown in Table 3A. The yield strength was significantly higher on stress-relieved material, even though the ultimate tensile strength (UTS) was slightly lower. The elongation (EL) and reduction in area (RA) were higher for the stress-relieved welds, which indicates less brittleness. However, changes in the welding process and/or heat treatment before and after welding should be considered to minimize SCC susceptibility.

Table 5 shows the mechanical properties of the specimens that did not fail in the SCC test. The UTS, YS, RA, and modulus (E) values for the stress-relieved specimens, after being exposed for 3 months to alternate immersion, were significantly lower than the initial values.

No reduction in mechanical properties occurred in the *nonstress-relieved* specimens exposed to high humidity as shown in Table 5. The yield strengths obtained from these specimens are even higher than the average yield strength obtained initially from nonexposed specimens. This tendency is more noticeable on the stressed specimens. The two unstressed *nonstress-relieved* specimens tested in salt environments suffered reduction in the load carrying ability, especially after exposure to salt spray.

The susceptibility of this alloy to general corrosion in salt environments is evidenced by Figures 14 and 15. Although the specimens showed more tolerance to a high-humidity environment (Figs. 13 and 14), corrosion protection is mandatory for components made from this alloy and its weldments.

CONCLUSIONS

The results of this investigation indicate that the tested HP 9Ni–4Co–0.30C steel plate material welded by straight polarity plasma arc is highly susceptible to SCC in 3.5-percent NaCl alternate immersion and 5-percent salt spray in the *nonstress-relieved* condition.

The susceptibility to SCC in alternate immersion was reduced (to some extent) with stress relief. The stress-relief procedure also resulted in a higher yield strength, even though the ultimate tensile strength was slightly reduced. The values for EL and RA were also higher for stress-relieved material.

Because of the significant improvements derived from the stress relief, this procedure is recommended for reducing SCC susceptibility of HP 9Ni–4Co–0.30C steel plate welds. However, changes in the welding process and/or heat treatment schedules before and after welding should be considered to further reduce SCC susceptibility. Current tests are being conducted on HP 9Ni–4Co–0.30C steel shear formed ring forging welds, and the results will be presented in a separate report.

APPENDIX

Welding Procedure for HP 9Ni–4Co–0.30C Steel (MSFC)

The plate material was ground to remove mill scale and warpage, and the edges were milled straight and square for the weld joint. The material was welded without grooving (square butt). Cleaning was performed by solvent degrease. The material was tack welded prior to final welding by using the Gas Tungsten-Arc Welding (GTAW) process and HP 9Ni–4Co–0.20C steel filler wire.

The material was placed on an aluminum weld fixture in the flat position, and the back side of the weld was purged with high-purity helium gas, maintaining a pressure of 25.4 to 50.8 mm (1 to 2 in) of water column. A trailing shield followed the torch to purge the top side of the weld with high-purity argon gas at a rate of 1.42 to 1.70 m^3 per hour (50 to 60 ft^3 per hour).

The first weld pass (root pass) was made in a full-penetration, key-hole mode with a flying start (no hole drilled). No filler wire was added during the first pass. Welding was done in the direct-current, straight-polarity mode using the plasma arc welding process. Current was held in the 305 to 325 amp range. The voltage was held at 27 volts. Torch travel was between 11.4 and 12.7 cm per minute (4.5 and 5.0 in per minute).

The second pass was welded using nearly the same parameters as the root pass, except 0.114-cm (0.045-in) diameter HP 4Ni–4Co–0.20C steel filler wire was added at a rate of 178 to 203 cm per minute (70 to 80 in per minute).

In both passes, the torch was set at a 3° lead angle and fitted with 0.45-cm (0.177-in) diameter tungsten electrode (2-percent thoria) and 0.396-cm (0.156-in) diameter orifice. Interpass temperature was ambient.

REFERENCES

1. ASTM G44–88, "Standard Practice for Evaluating Stress Corrosion Cracking Resistance of Metals and Alloys by Alternate Immersion in 3.5-Percent Sodium Chloride Solution," 1988.

2. ASTM B117–90, "Standard Test Method of Salt Spray (Fog) Testing." 1990.

3. AMS–6526C, "Steel Bars, Forgings, Tubing and Rings, Consumable Electrode Vacuum Melted, Annealed," issued May 1, 1968, Revised January 1, 1989.

4. MIL–H–6875G, "Heat Treatment of Steels, Process for," September 16, 1983.

5. ASTM G49–85, "Standard Practice for Preparation and Use of Direct Tension Stress–Corrosion Test Specimens," issued in 1985, reapproved in 1990.

6. Memo EH24 (90–85), From EH24/ Mr. Montano to EH21/Mr. Munafo, Subject: Stress Corrosion Evaluation of HP 9Ni–4Co–0.30C Plate Welds (Straight Polarity Plasma Arc), December 28, 1990.

Table 1A.
Chemical Analysis of HP 9Ni–4Co–0.30C Steel

	Friend Metals Analysis (Heat No. 3843459)	AMS–6526C	
		Min	Max
Carbon	0.34	0.29	0.34
Manganese	0.26	0.10	0.35
Silicon	0.02	—	0.20
Phosphorus	0.006	—	0.010
Sulfur	0.002	—	0.010
Chromium	1.02	0.90	1.10
Nickel	7.29	7.00	8.00
Cobalt	4.33	4.25	4.75
Molybdenum	0.92	0.90	1.10
Vanadium	0.090	0.06	0.12
Copper	0.19	—	0.35
Iron	Balance	Balance	

Table 1B.
Chemical Analysis of HP 9Ni–4Co–0.20C Steel Welding Wire*

Element	United States Welding Corporation Analysis	AMS 6468A		Target Maxima
		Minimum	Maximum	
Carbon	0.16	0.14	0.17	—
Manganese	0.42	0.40	0.55	—
Silicon	0.17	0.15	0.25	—
Phosphorus	0.004	—	0.008	0.006
Sulfur	0.004	—	0.008	0.005
Chromium	1.03	0.90	1.05	—
Nickel	9.88	9.75	10.25	—
Cobalt	3.88	3.50	4.00	—
Molybdenum	0.46	0.40	0.50	—
Vanadium	0.06	0.06	0.10	—
Copper	0.03	—	0.10	—
Oxygen	0.0012	—	0.0050 (50 ppm)	25 ppm
Nitrogen	0.0012	—	0.0080 (80 ppm)	50 ppm
Hydrogen	0.00012	—	0.0010 (10 ppm)	5 ppm
Iron	Balance		Balance	

*Heat Reference No. 21330, Lot No. 403229

Table 2.
Heat Treatment Procedure Followed on HP 9Ni–4Co–0.30C Steel Plate Before Welding
(Heat Treated at Cal-Doran per MIL–H–6875G A/2)

Operation	Medium	Temperature °C	Temperature °F	Time
Austenitize	Endothermic Gas	843 ± 14	1,550 ± 25	60 to 75 minutes
Quench	Salt	157–163	315–325	
Sub Zero	CO_2	–73 ± 6	–100 ± 10	2 to 2¼ Hours
Warm	Air	16 °C minimum	60 °F minimum	
Temper	Air	538–543	1,000–1,010	2 to 2¼ Hours
Cool	Air	Below 38	Below 100	
Temper	Air	538–543	1,000–1,010	2 to 2¼ Hours
Cool	Air			

NOTE: The final hardness obtained after this heat treatment was Rockwell C 47 (BHN 461).

Table 3A.
Mechanical Properties of HP 9Ni–4Co–0.30C Steel Plate Welds

	UTS		YS		EL	RA	Young's Modulus (E)	
	MPa	ksi	MPa	ksi	(%)	(%)	MPa×10^{-3}	lb/in^2×10^{-6}
*Nonstress-Relieved**	1,662	241.1	1,205	174.8	3.0	31.5	183	26.6
Stress Relieved at † 510 °C (950 °F) for 3 Hours	1,627	235.9	1,453	210.8	6.1	52.0	191	27.7

NOTE: Tensile test data obtained from round tensile specimens with a 0.3175-cm (0.125-in) gauge length diameter.
* Average of 3 specimens.
† Average of 2 specimens.

Table 3B.
Mechanical Properties of HP 9Ni–4Co–0.20C Steel Welding Wire
(Metals Technology, Inc.)

UTS		YS		RA	EL
MPa	ksi	MPa	ksi	(%)	(%)
1,465	212.5	1,094	158.6	53.4	17.0

NOTE: Tensile test data obtained from round tensile specimens with a 0.635-cm (0.25-in) gauge length diameter.

Table 4.
Stress Corrosion Results of HP 9Ni–4Co–0.30C Steel Plate Welds

Group I

Double Tempered at 538 °C (1,000 °F), Welded, *Nonstress-Relieved*

100 Percent Relative Humidity at 38 °C (100 °F) (93 Days)					Alternate Immersion in 3.5-Percent NaCl (92 Days)		5-Percent Salt Spray (92 Days)	
Percent YS	Stress Level MPa	Stress Level ksi	Failure Ratio	Days To Failure	Failure Ratio	Days To Failure	Failure Ratio	Days To Failure
50	607	88	0/3	—	3/3	20,34,36	3/3	5,11,18
75	903	131	1/3	93	3/3	7,12,13	3/3	5,5,5
90	1,089	158	0/3	—	3/3	7,8,11	3/3	1,5,5

Group II

Double Tempered at 538 °C (1,000 °F), Welded, Stress Relieved at 510 °C (950 °F)

Alternate Immersion in 3.5-Percent NaCl (92 Days)				
Percent YS	Stress Level MPa	Stress Level ksi	Failure Ratio	Days To Failure
50	724	105	0/2	–
75	1,089	158	2/2	15,18
90	1,303	189	2/2	8,8

Table 5.
Mechanical Properties of HP 9Ni–4Co–0.30C Steel Welded Plate Round Tensile Specimens After SCC Test*

Environment	Applied Stress	UTS		YS		RA	EL†	Modulus of Elasticity (E)	
	Percent YS	MPa	ksi	MPa	ksi	(Percent)	(Percent)	MPa×10^{-3}	(lb/in^2×10^{-6})
Double Tempered at 538 °C (1,000 °F), Welded, *Nonstress-Relieved*									
High Humidity (93 Days)	0	1,586	230	1,262	183	44	—	174	25.2
	50	1,669	242	1,427	207	54	—	181	26.2
	50	1,675	243	1,386	201	45	—	190	27.6
	50	1,682	244	1,379	200	40	—	185	26.9
	75	1,627	236	1,393	202	45	—	181	26.3
	75	1,751	254	1,517	220	41	—	184	26.7
	90	1,655	240	1,524	221	30	—	193	28.0
	90	1,689	245	1,544	224	24	—	188	27.3
	90	1,634	237	1,469	213	48	—	184	26.7
3.5-Percent NaCl Alternate Immersion (92 Days)	0	1,613	234	1,193	173	50	—	187	27.1
5-Percent Salt Spray (92 Days)	0	1,476	214	993	144	17	8	170	24.5
Double Tempered at 538 °C (1,000 °F), Welded, Stress Relieved at 510 °C (950 °F)									
3.5-Percent NaCl Alternate Immersion (92 Days)	50	1,489	216	1,296	188	43	8	166	24.1
	50	1,489	216	1,289	187	24	6	167	24.2

*Based on a 0.3575-cm (0.125-in) gauge length diameter (original diameter).
†Hyphen indicates failure out of the gauge marks.

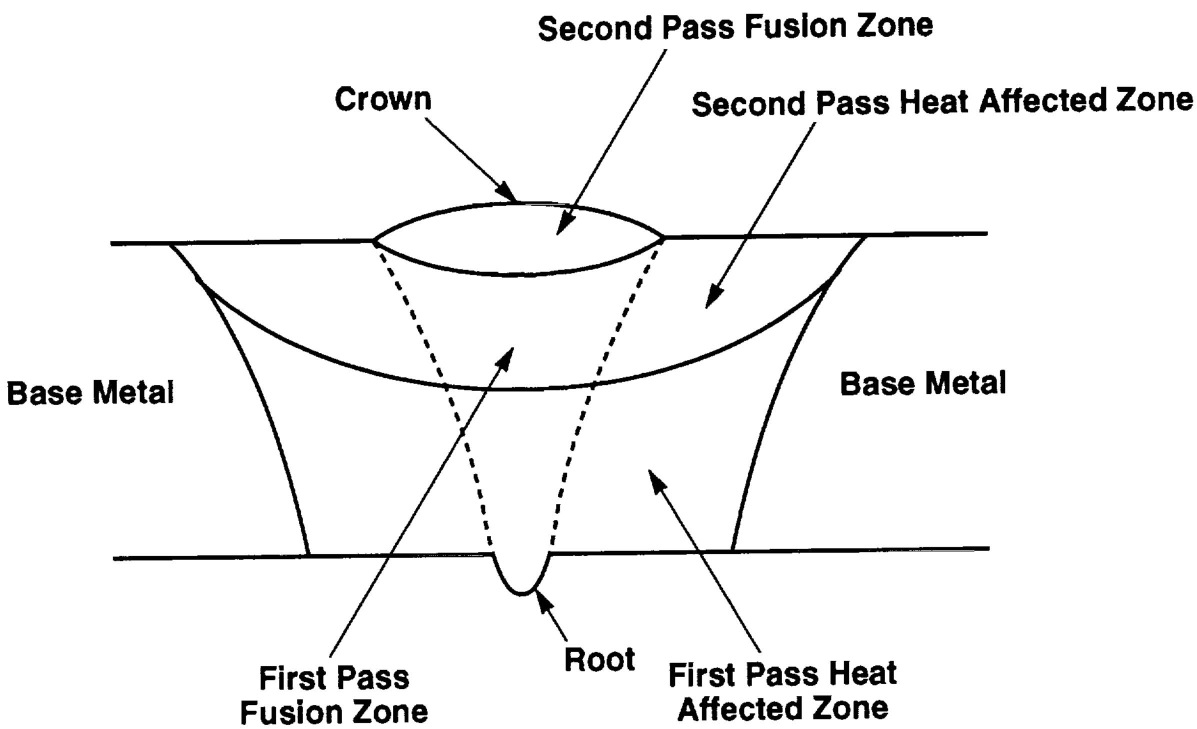
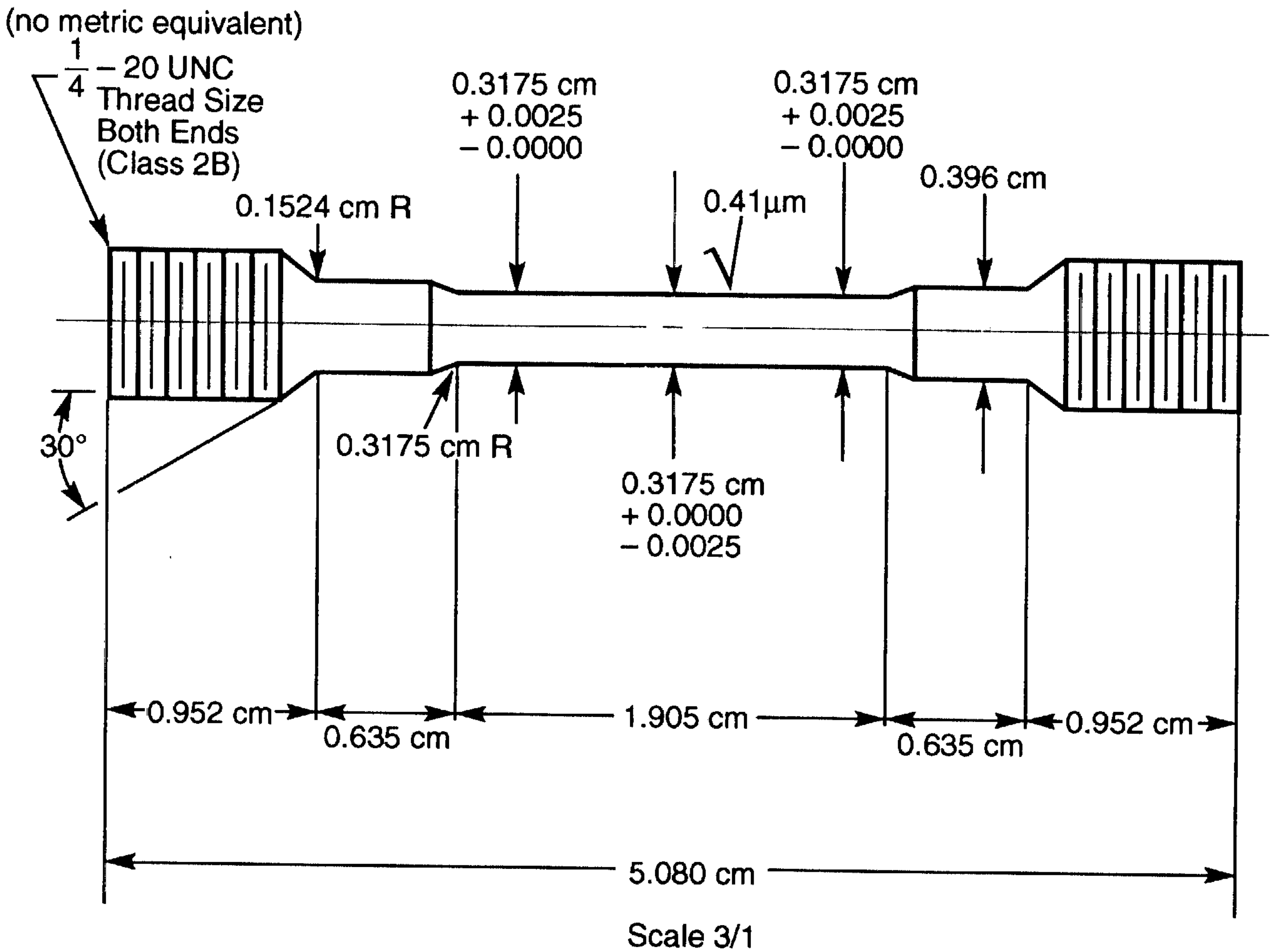
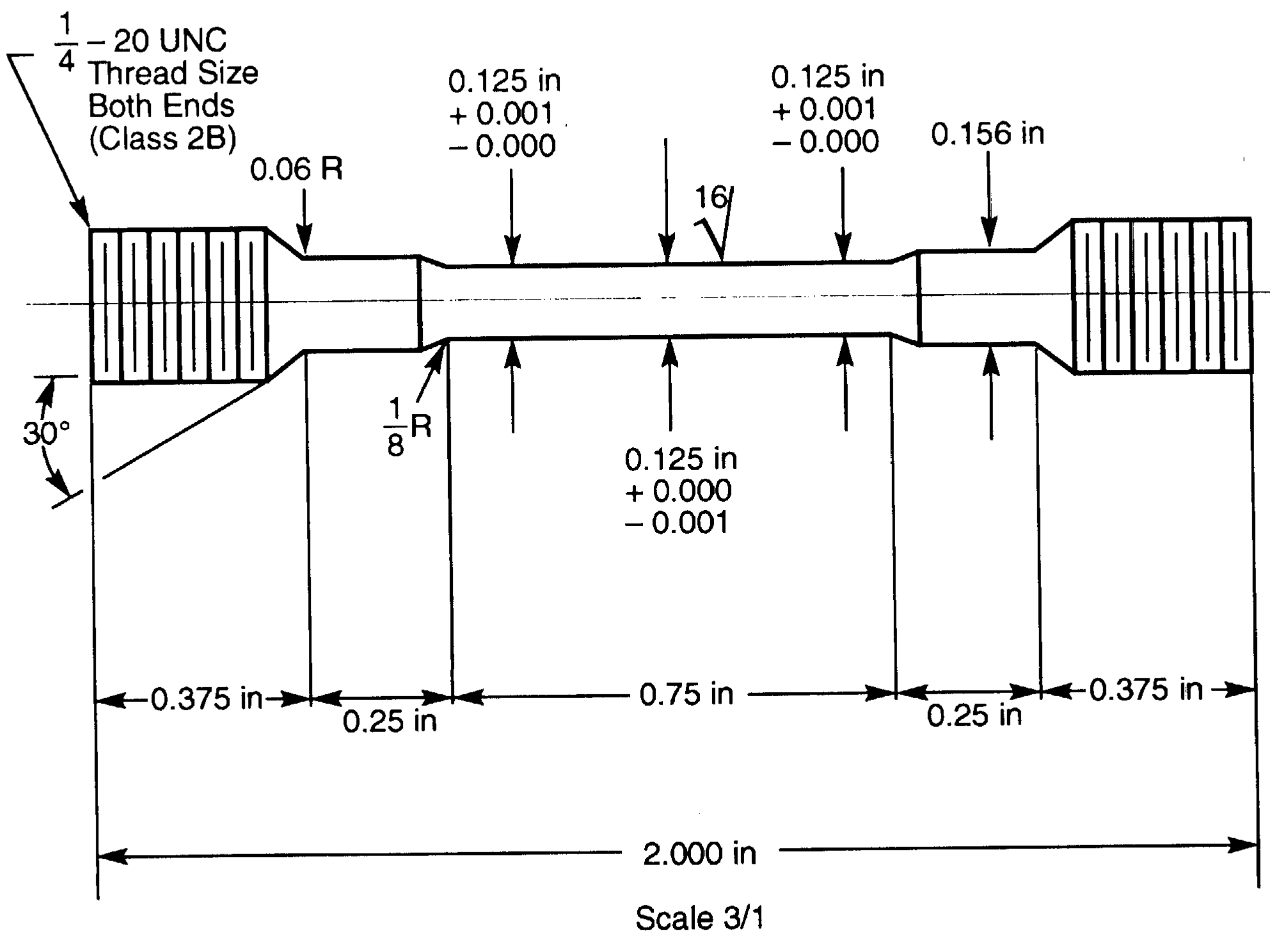


Figure 1. Weld Diagram.



Notes:
(1) Thread dimensions must be as specified (measurement by fabricator is mandatory).
(2) No undercutting of radii permitted.
(3) Taper gauge length to center of specimen.
(4) Gauge section to be concentric with axis within 0.005 cm TIR and parallel.
(5) No file marks or nicks permitted within gauge section.

Figure 2A. Round Tensile Specimen With a 0.3175-cm Gauge Length Diameter (Metric Units).



Notes: (1) Thread dimensions must be as specified (measurement by fabricator is mandatory).
(2) No undercutting of radii permitted.
(3) Taper gauge length to center of specimen.
(4) Gauge section to be concentric with axis within 0.002 in TIR and parallel.
(5) No file marks or nicks permitted within gauge section.

Figure 2B. Round Tensile Specimen With a 0.125-in Gauge Length Diameter (English Units).

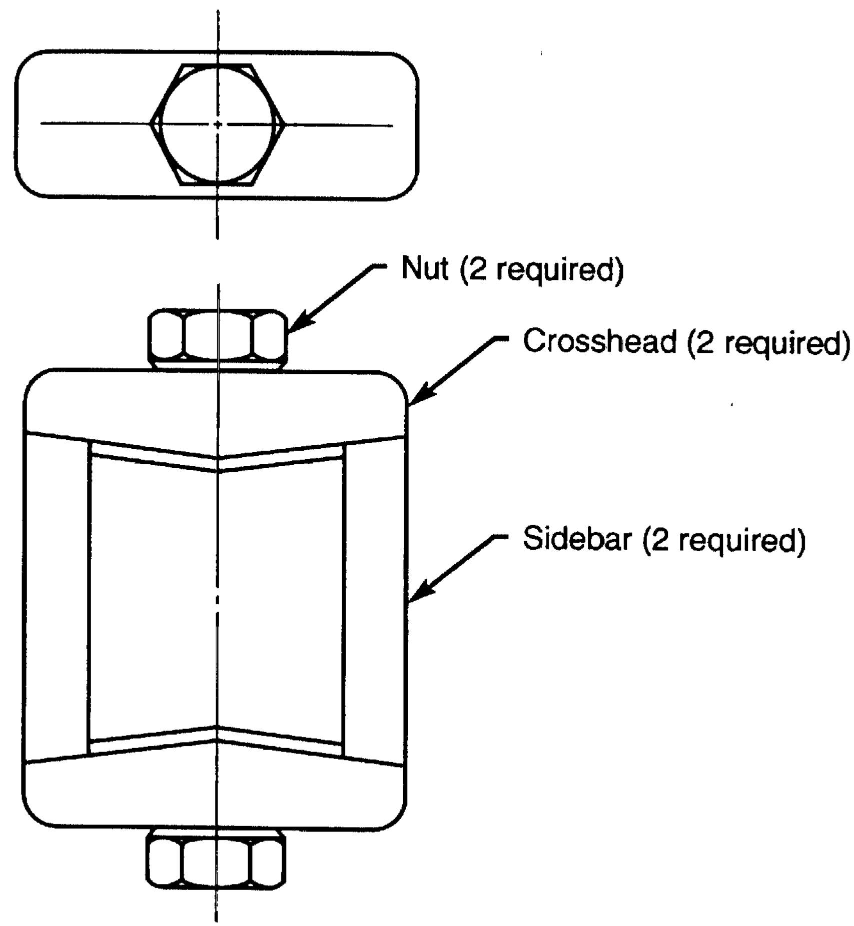


Figure 3. Frame Assembly for Round Tensile Specimens.

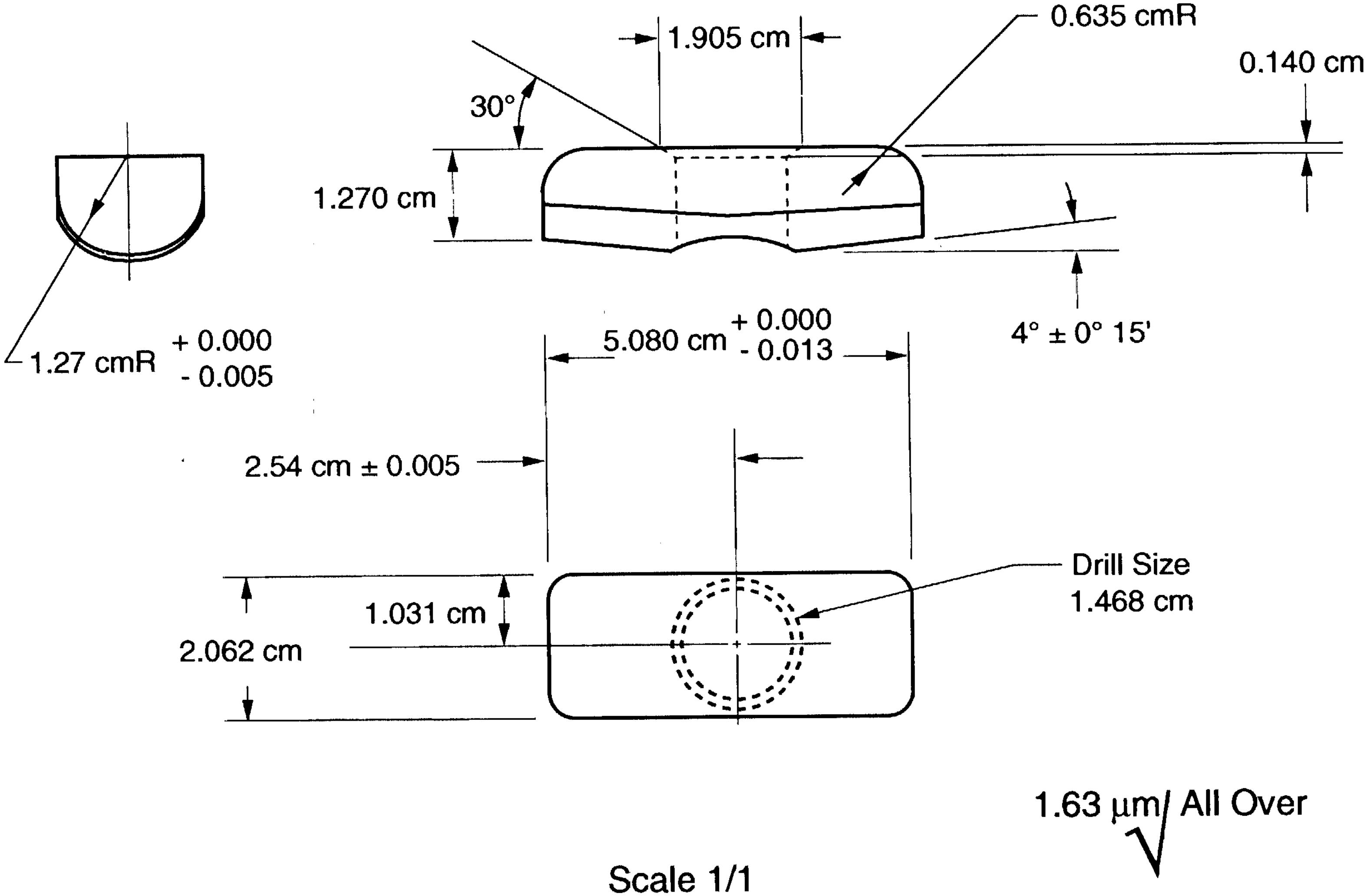


Figure 4A. Stress Corrosion Frame Crosshead (Metric Units).

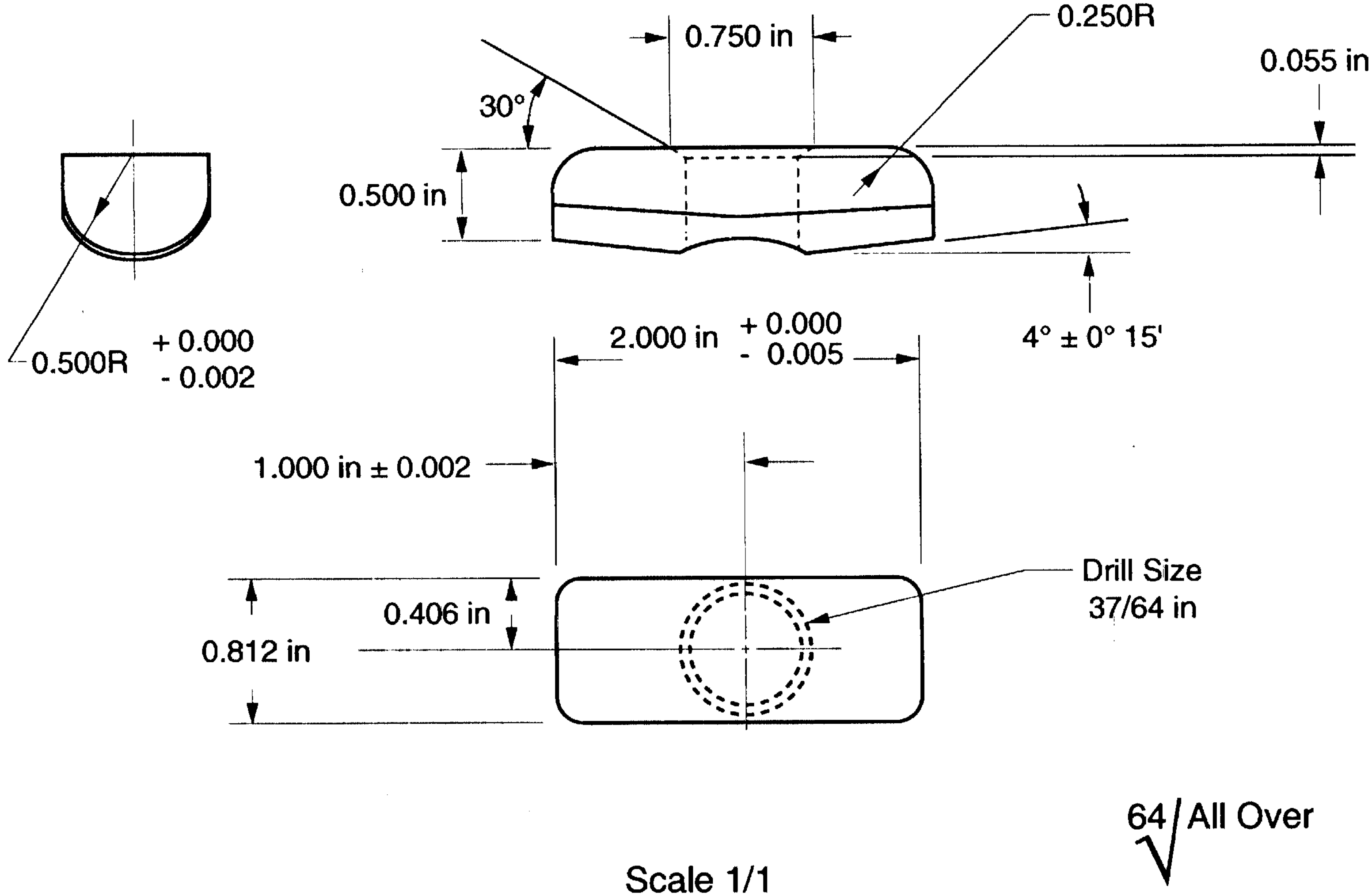


Figure 4B. Stress Corrosion Frame Crosshead (English Units).

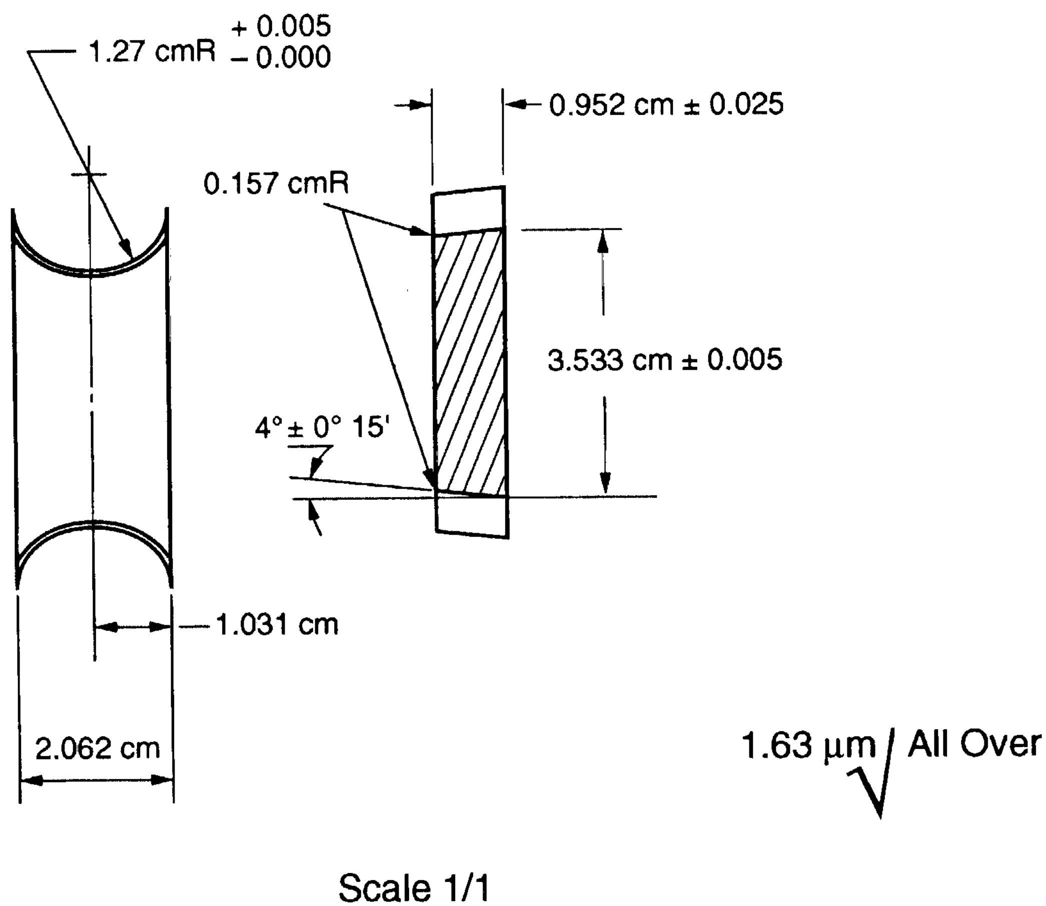


Figure 5A. Stress Corrosion Frame Side Bar (Metric Units).

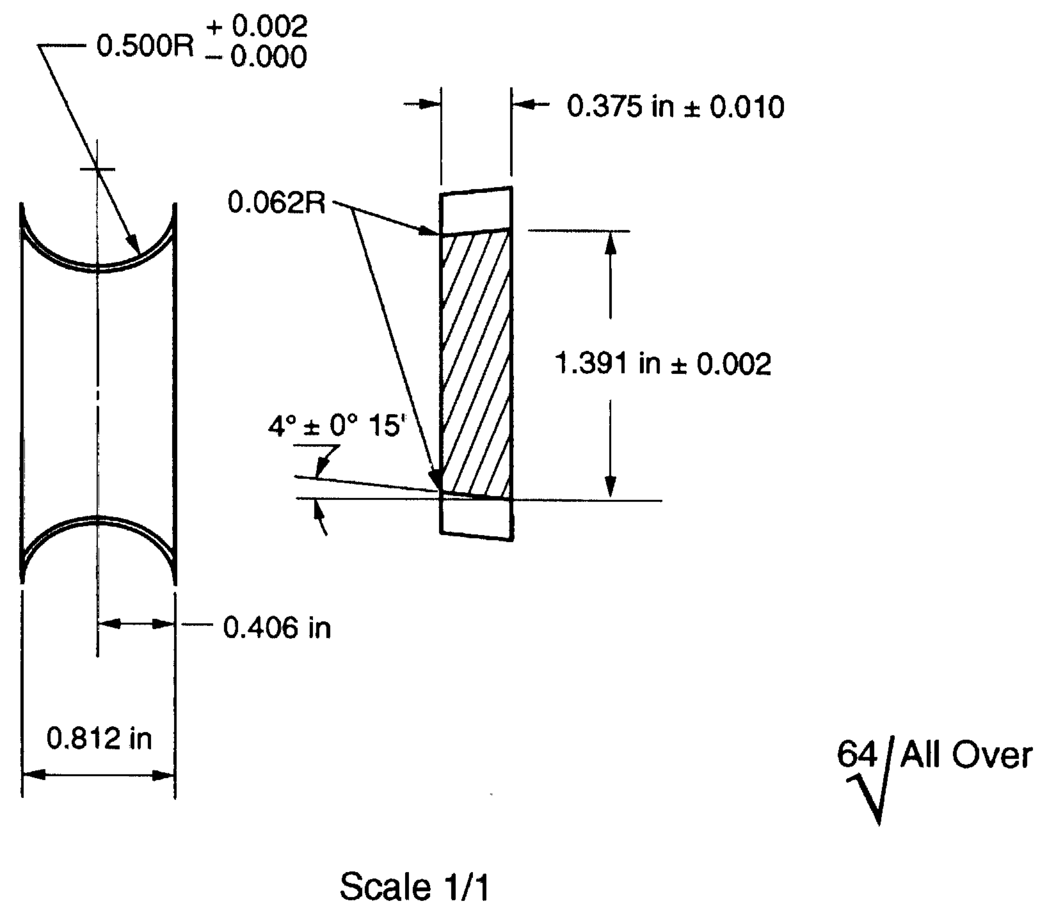
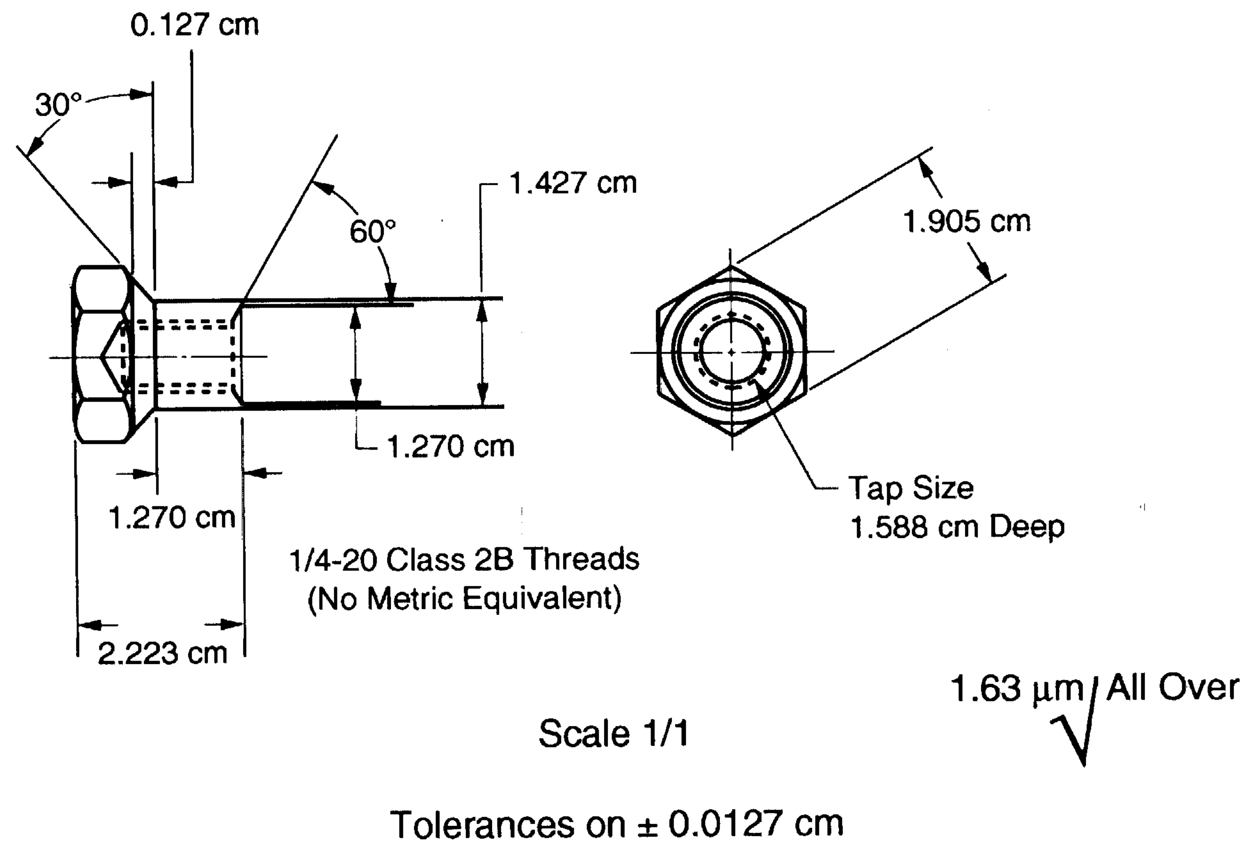
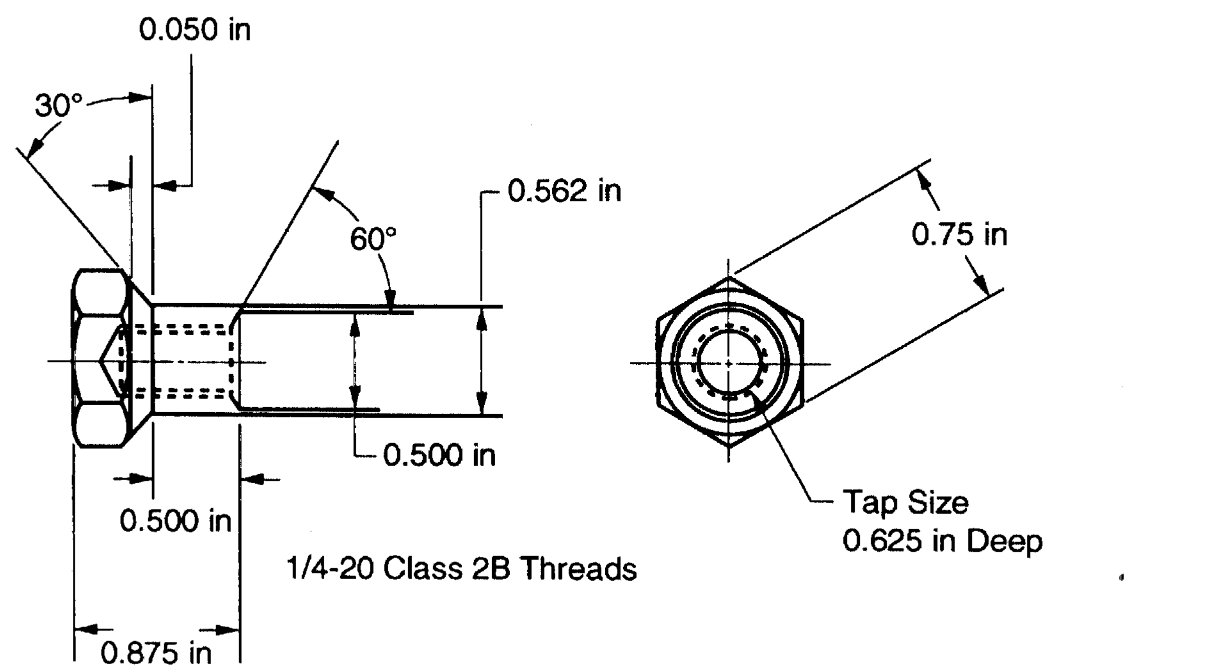


Figure 5B. Stress Corrosion Frame Side Bar (English Units).



Note: Thread dimensions must be as specified (measurement by fabricator is mandatory).

Figure 6A. Stress Corrosion Frame Nut (Metric Units).



Scale 1/1

64 / All Over

Tolerances on ± 0.005

Note: Thread dimensions must be as specified (measurement by fabricator is mandatory).

Figure 6B. Stress Corrosion Frame Nut (English Units).

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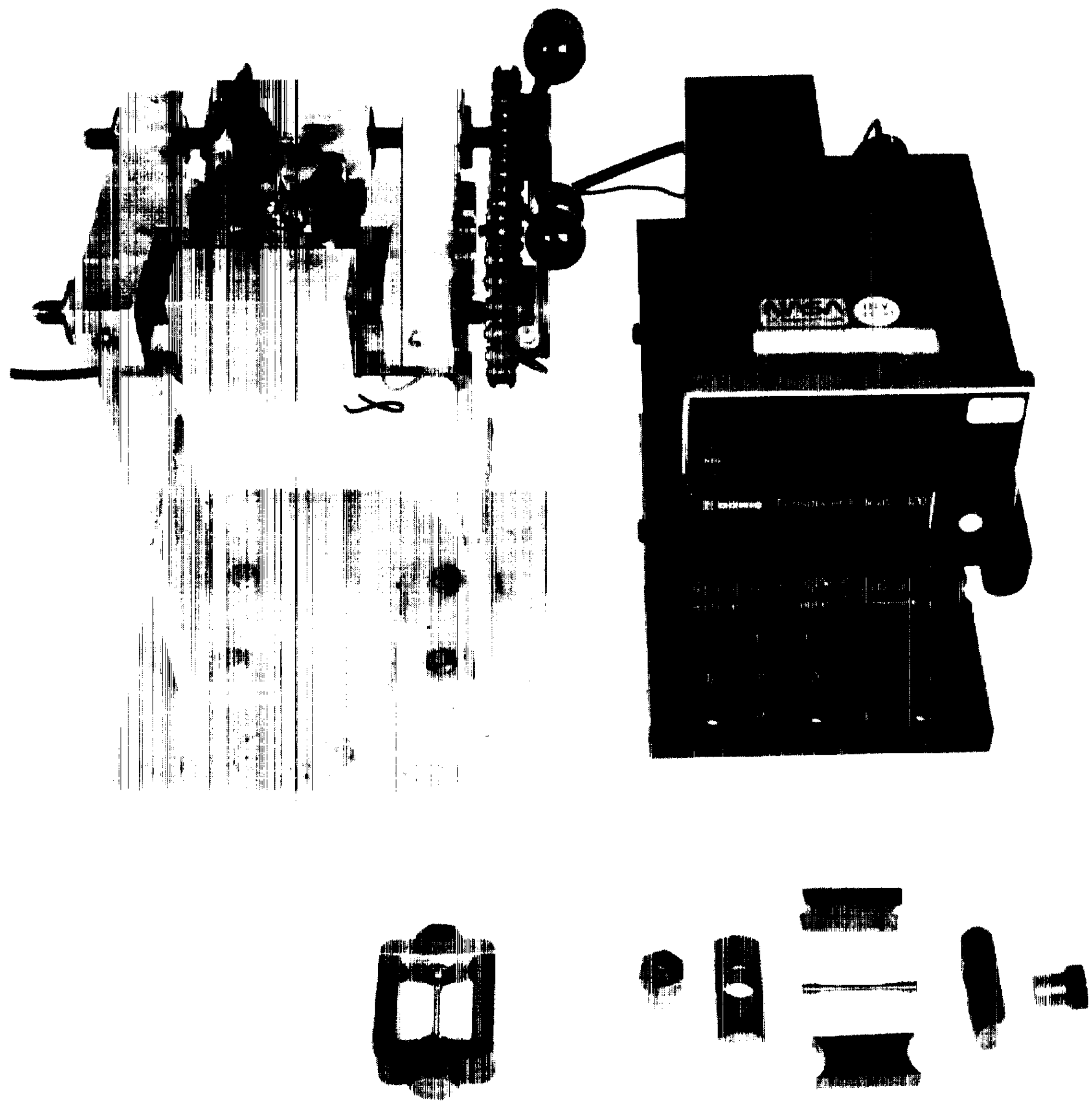

Figure 7. Device and Frames Used to Stress Round Tensile Specimens.

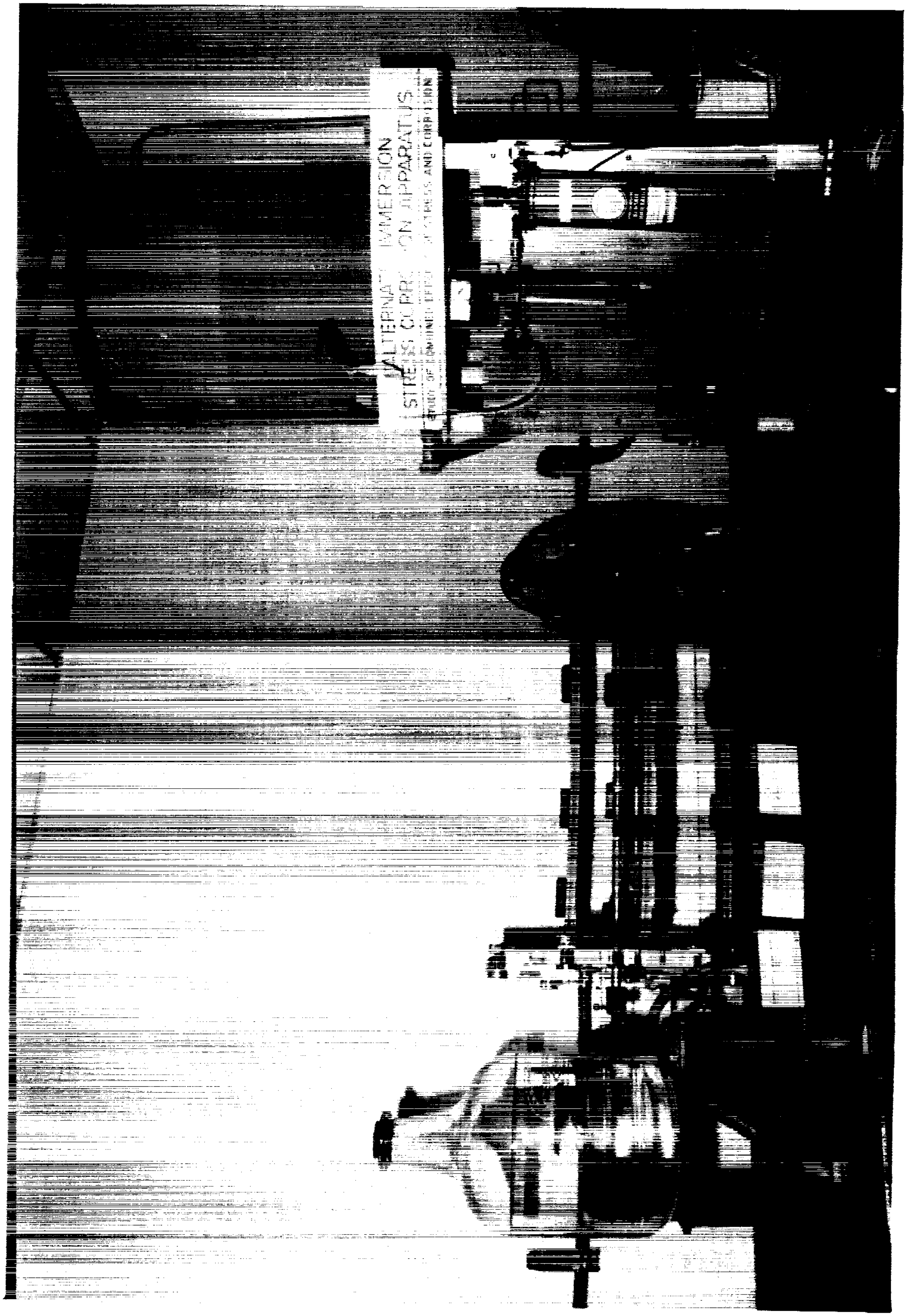

Figure 8. Alternate Immersion Tester.

Figure 9. Salt Spray Apparatus.

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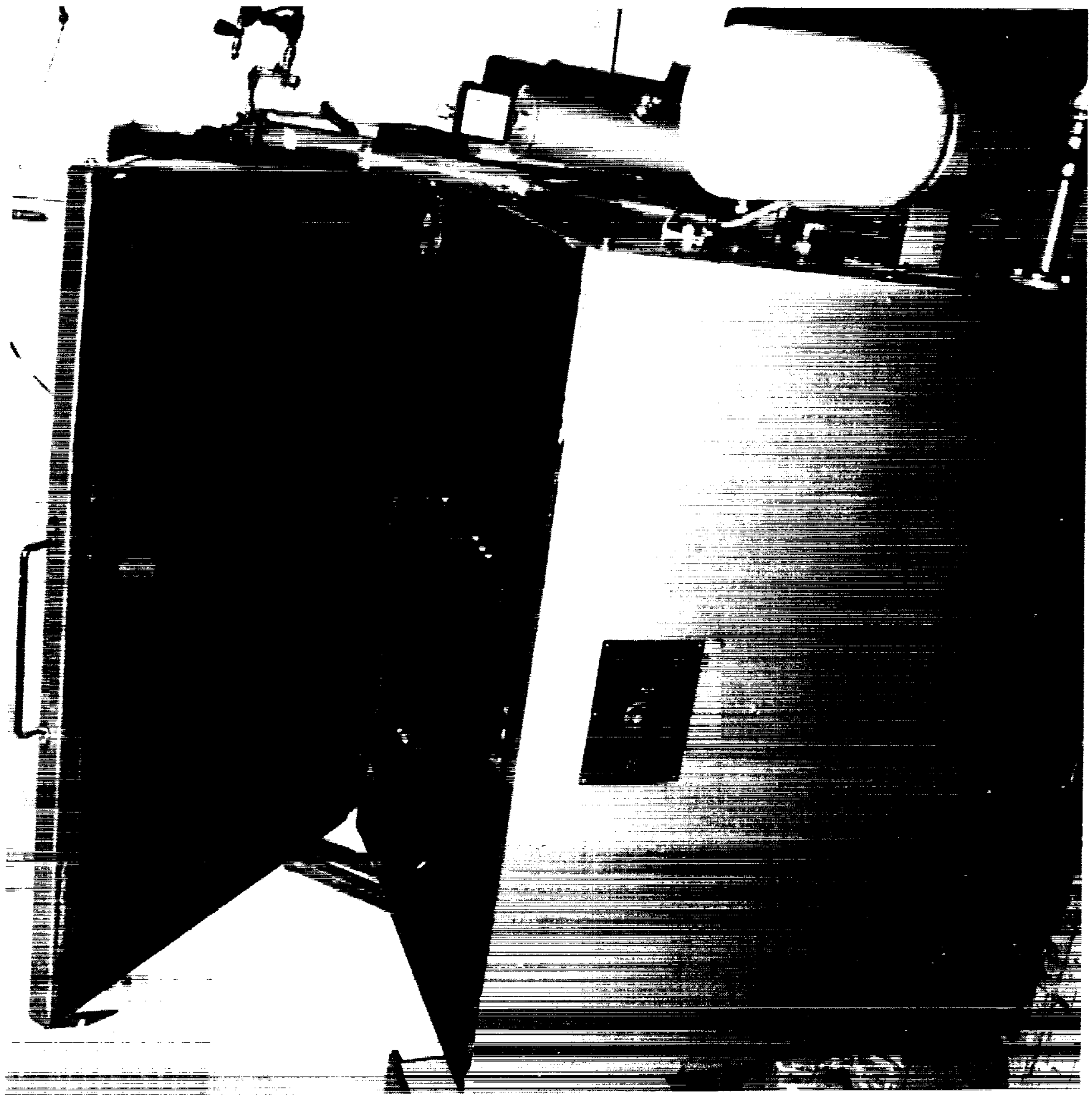
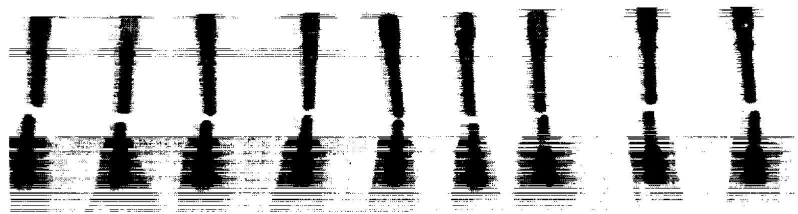


Figure 10. High Humidity Cabinet.

% YS	50	50	50	75	75	75	90	90	90
Days to Failure	34	20	36	12	7	13	8	7	11

3.5% NaCl Alternate Immersion

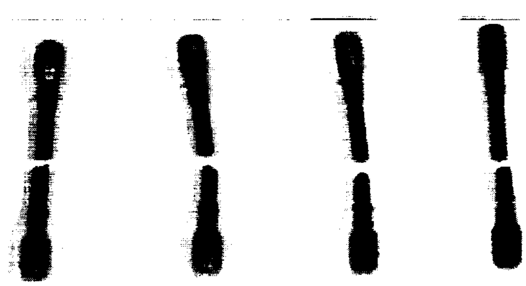


% YS	50	50	50	75	75	75	90	90	90
Days to Failure	11	5	18	5	5	5	1	5	5

5% Salt Spray

75% YS
Failed in 93 Days
High Humidity

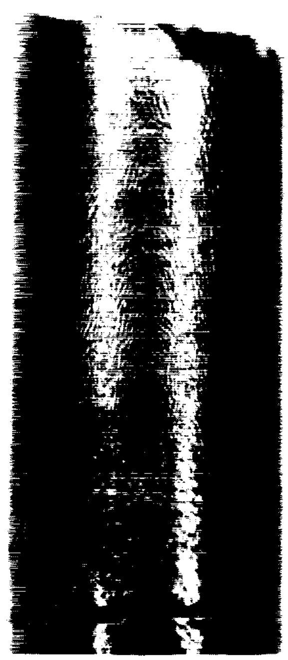
Figure 11A. Tensile Specimens Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to Various Percentages of the Yield Strength, and Failed After Exposure to Various Corrosive Environments.



% YS	75	75	90	90
Days to Failure	18	15	8	8

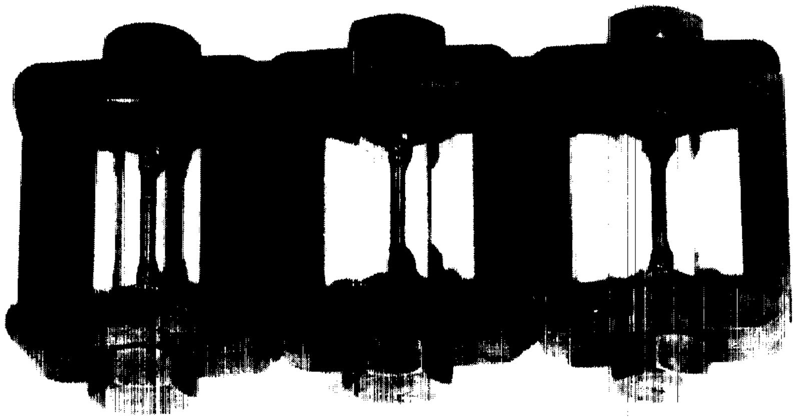
Figure 11B. Tensile Specimens Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 and 90 Percent of the Yield Strength, and Failed in 3.5-Percent NaCl Alternate Immersion.

15.2X Mag.
50% of YS, 20 Days to Fail

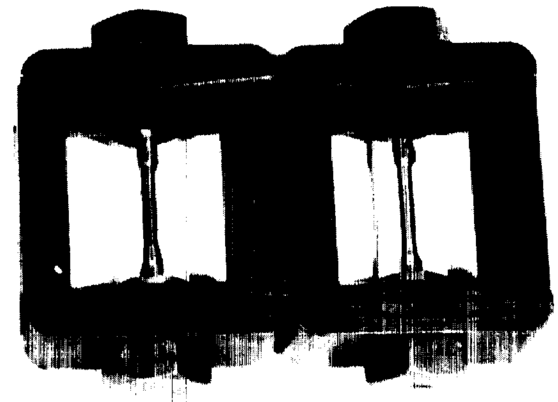


11.5X Mag.
90% of YS, 8 Days to Fail

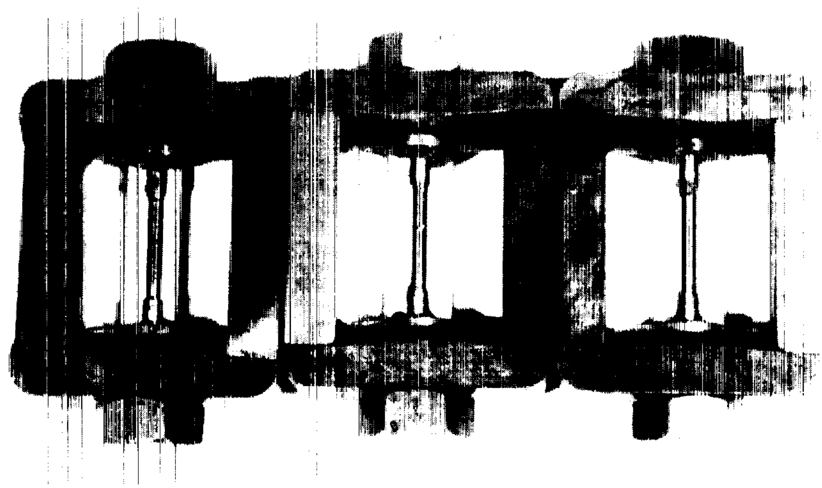
Figure 12. Tensile Specimens Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to Various Percentages of the Yield Strength, and Failed in 3.5-Percent NaCl Alternate Immersion.



50% of YS



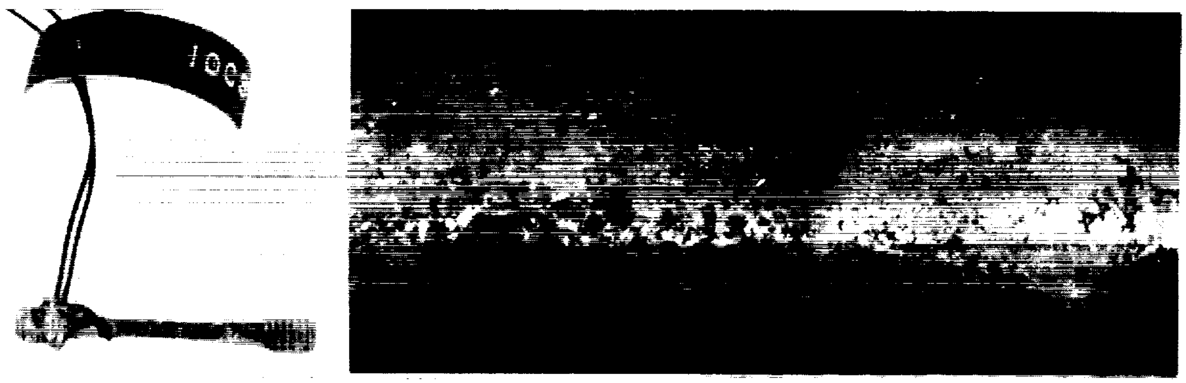
75% of YS



90% of YS

Figure 13. Tensile Specimens Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to Various Percentages of the Yield Strength, and Exposed to 93 Days of High Humidity.

93 Days in High Humidity 12X Mag.



92 Days in 3.5% NaCl Alternate Immersion 12X Mag.

92 Days in 5% Salt Spray 12X Mag.

Figure 14. Tensile Specimens Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Exposed Unstressed to Various Corrosive Environments.

Figure 15. Tensile Specimens Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 50 Percent of the Yield Strength, and Exposed to 92 Days of 3.5-Percent NaCl Alternate Immersion.

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BLACK AND WHITE PHOTOGRAPH

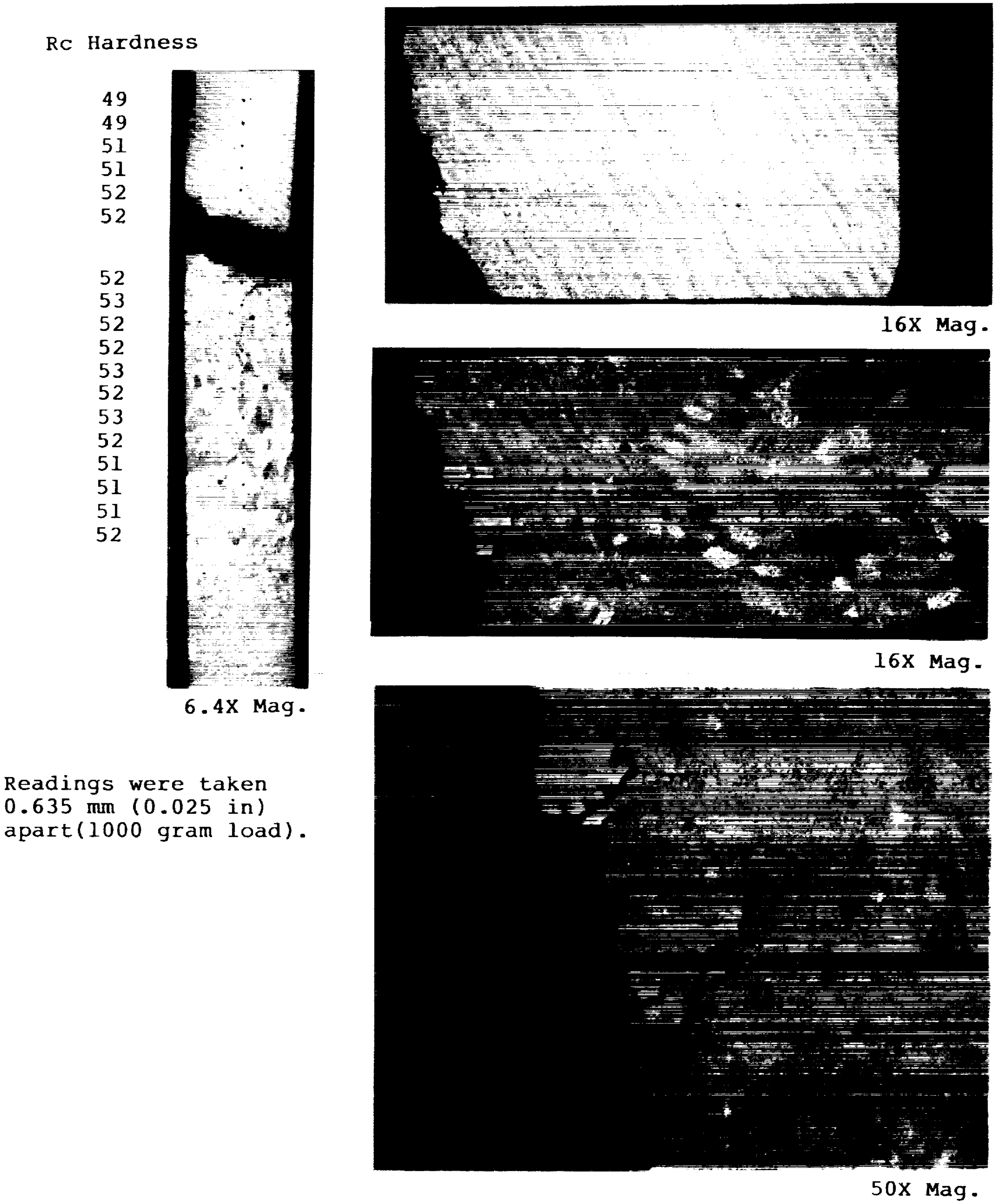
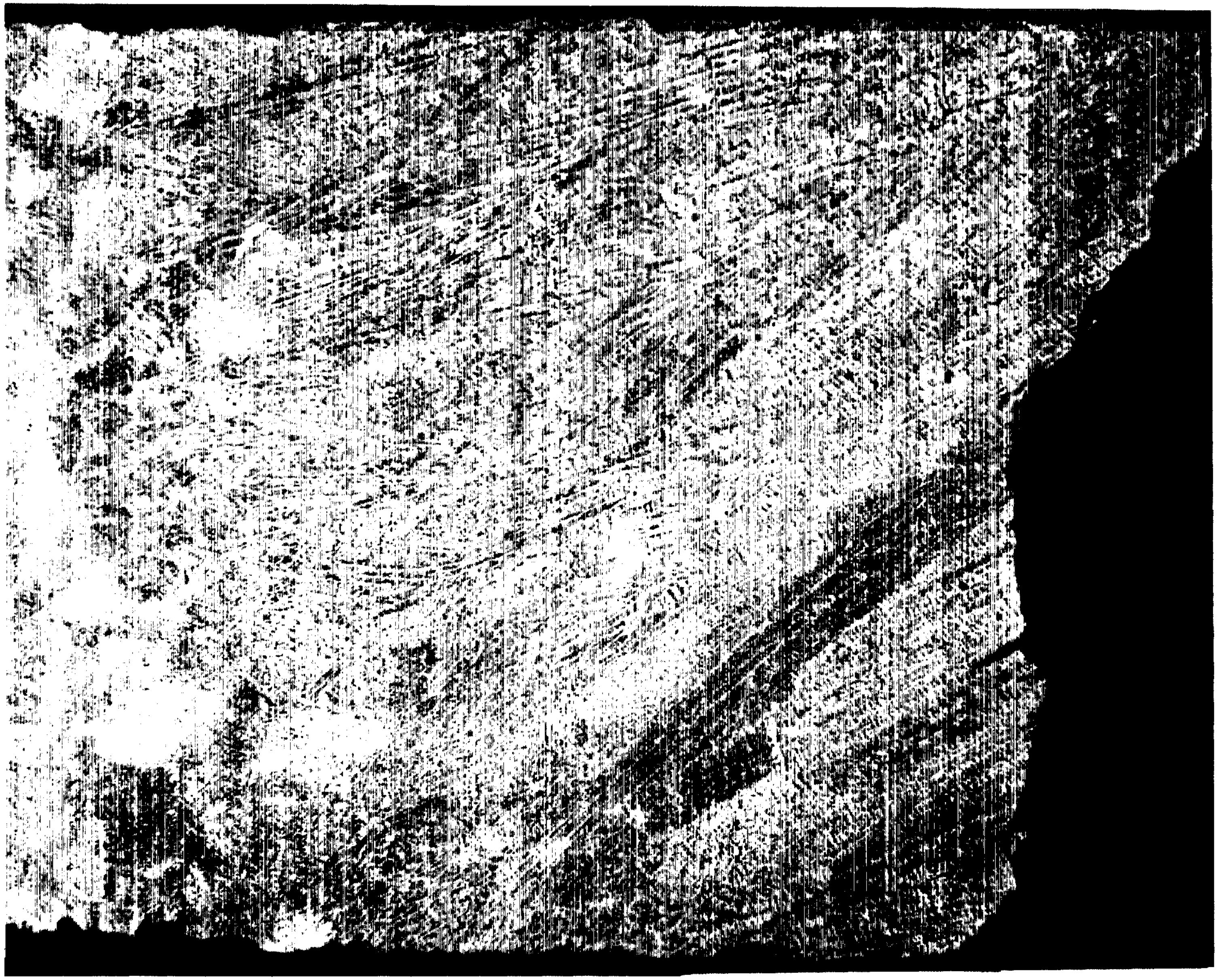


Figure 16. Photomicrographs Showing Microhardness Readings and Cracking of a Tensile Specimen Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 90 Percent of the Yield Strength, and Failed in the Heat-Affected Zone After 8 Days of Exposure to 3.5-Percent NaCl Alternate Immersion. Etchant: Kallings.

25X Original Mag.

Figure 17. Photomicrograph of a Tensile Specimen Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Failed in the Weld Metal After 15 Days of Exposure to 3.5-Percent NaCl Alternate Immersion. Etchant: Kallings.



25X Original Mag.

Figure 18. Photomicrograph of a Tensile Specimen Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Failed in the Weld Metal After 18 Days of Exposure to 3.5-Percent NaCl Alternate Immersion. Etchant: Kallings.

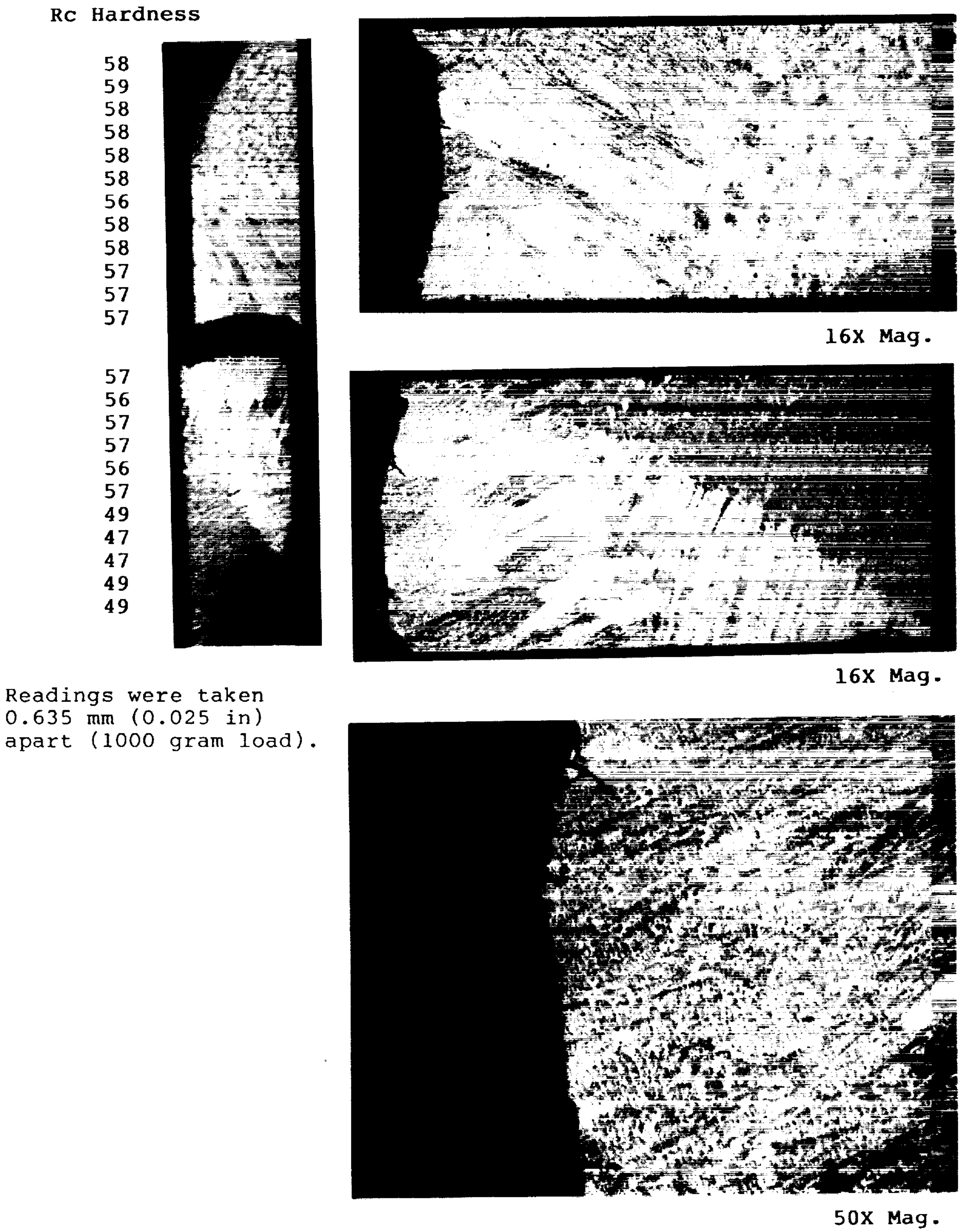
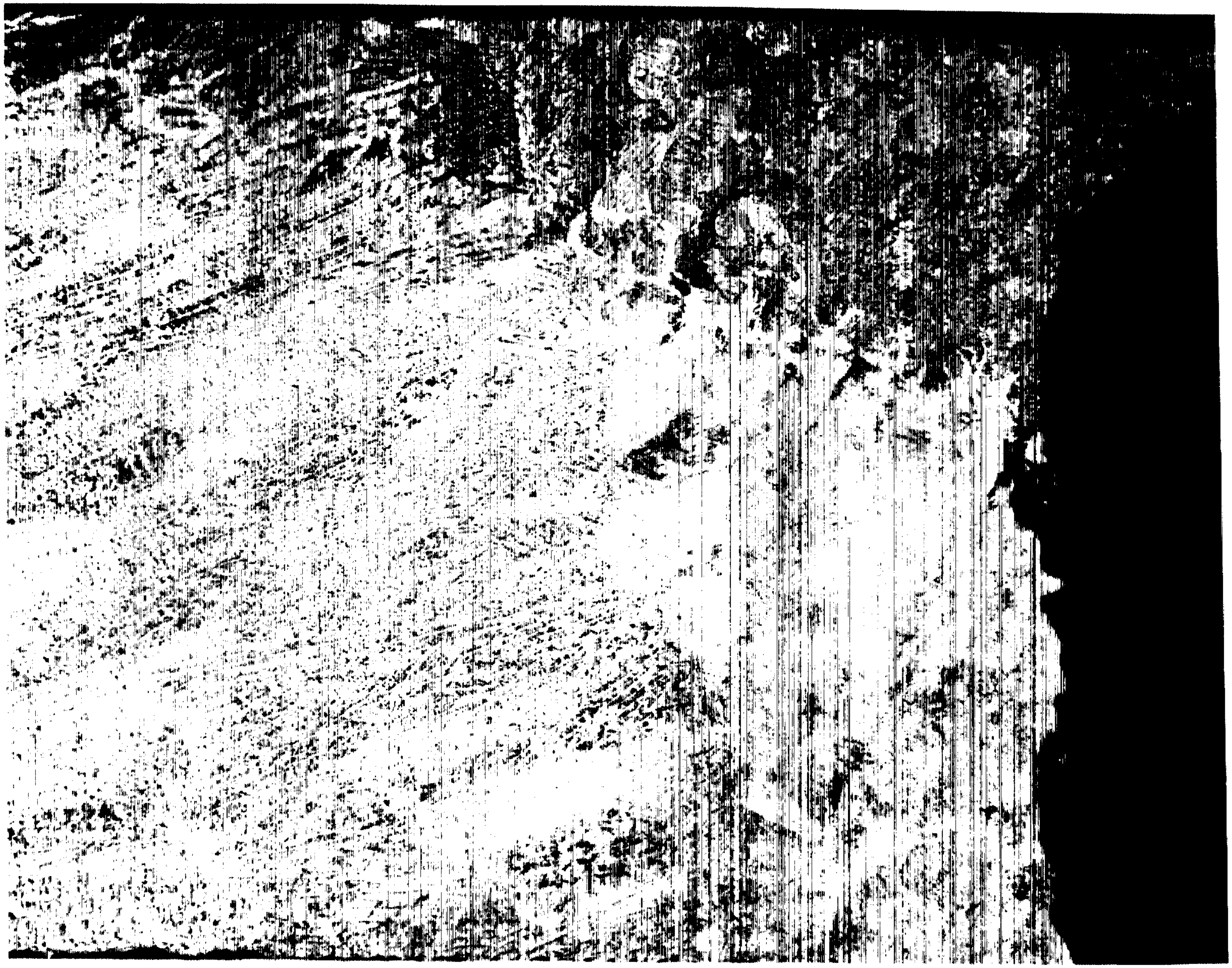


Figure 19. Photomicrographs Showing the Microstructure and Microhardness Readings of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 90 Percent of the Yield Strength, and Failed in the Weld Metal After 7 Days of Exposure to 3.5-Percent NaCl Alternate Immersion. Etchant: Kallings.

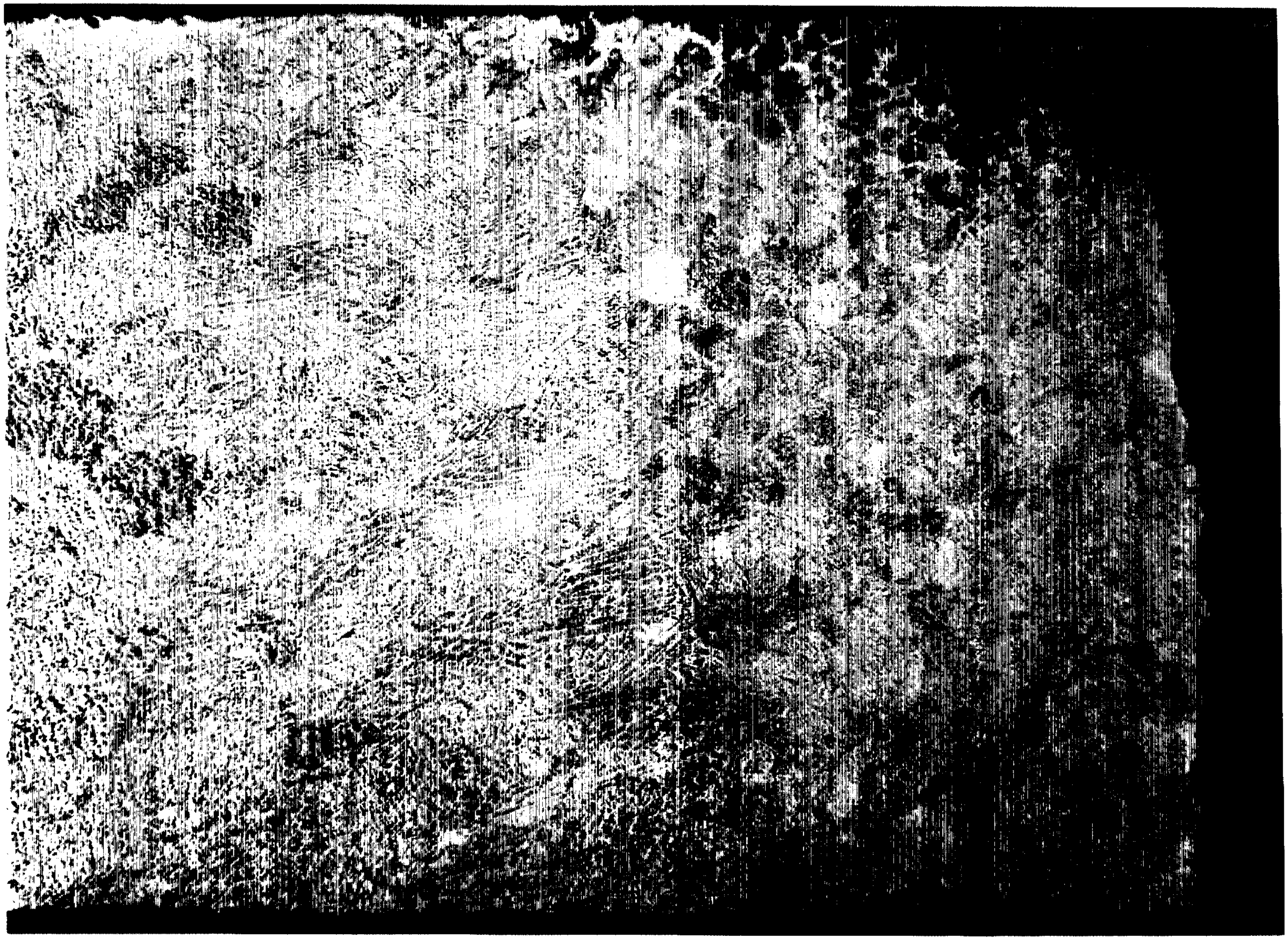


25X Original Mag.

Figure 20. Photomicrograph of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Failed in the Heat-Affected Zone After 7 Days of Exposure to 3.5-Percent NaCl Alternate Immersion. Etchant: Kallings.

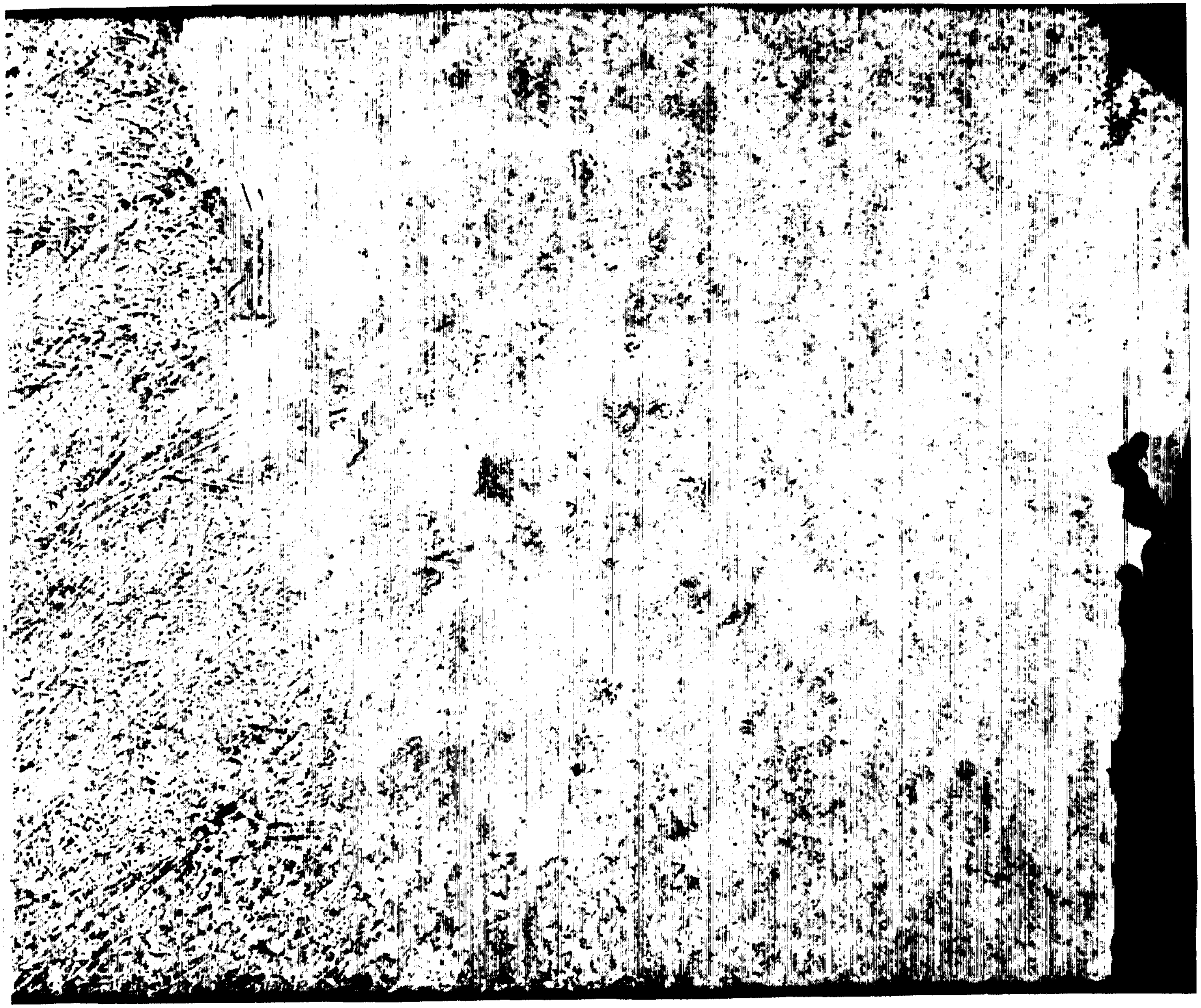
25X Original Mag.

Figure 21. Photomicrograph of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Failed in the Weld Metal After 13 Days of Exposure to 3.5-Percent NaCl Alternate Immersion. Etchant: Kallings.



25X Original Mag.

Figure 22. Photomicrograph of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 50 Percent of the Yield Strength, and Failed in the Heat-Affected Zone After 5 Days of Exposure to 5-Percent Salt Spray. Etchant: Kallings.



25X Original Mag.

Figure 23. Photomicrograph of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Failed in the Heat-Affected Zone After 5 Days of Exposure to 5-Percent Salt Spray. Etchant: Kallings.

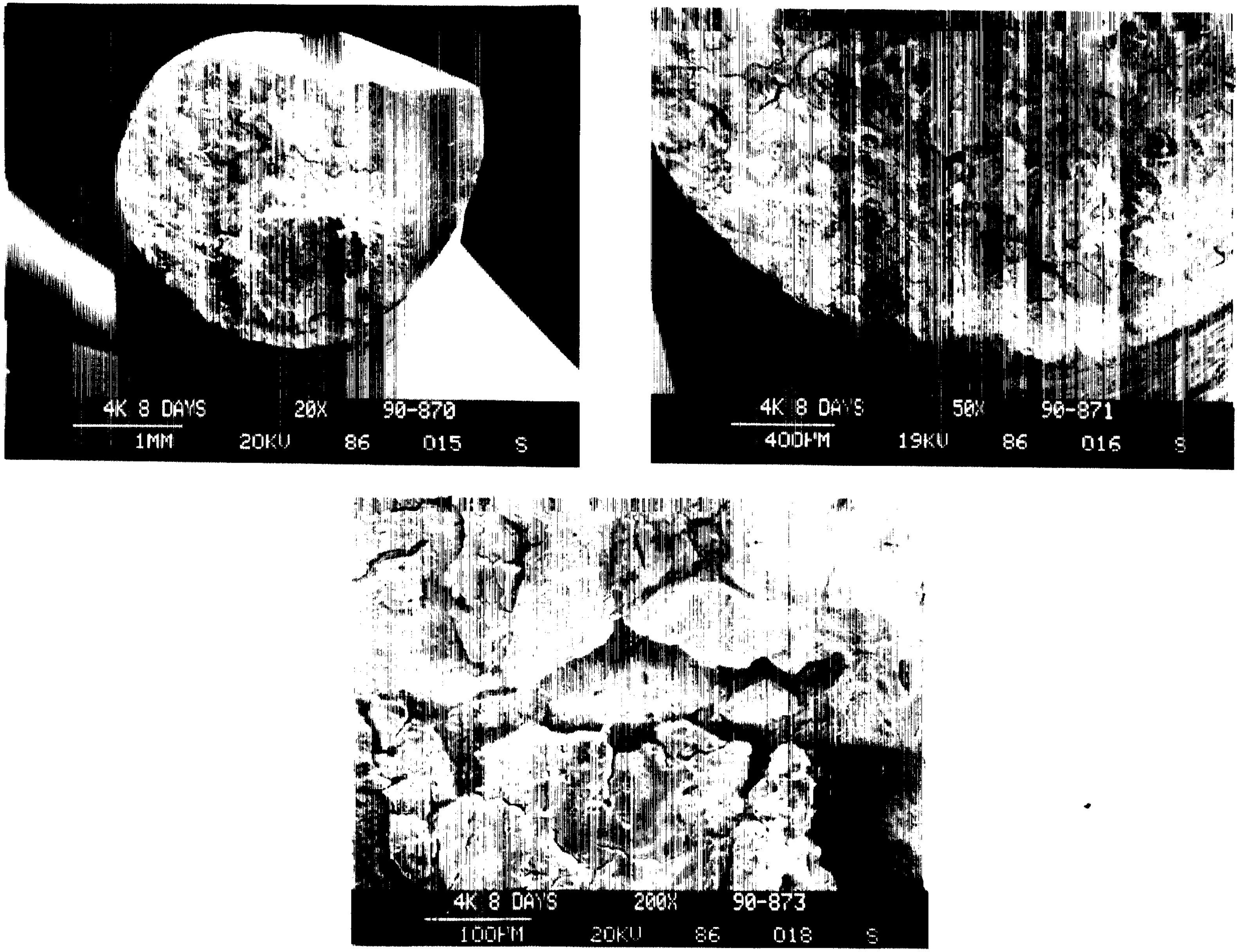


Figure 24. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 90 Percent of the Yield Strength, and Exposed to 8 Days of 3.5-Percent NaCl Alternate Immersion.

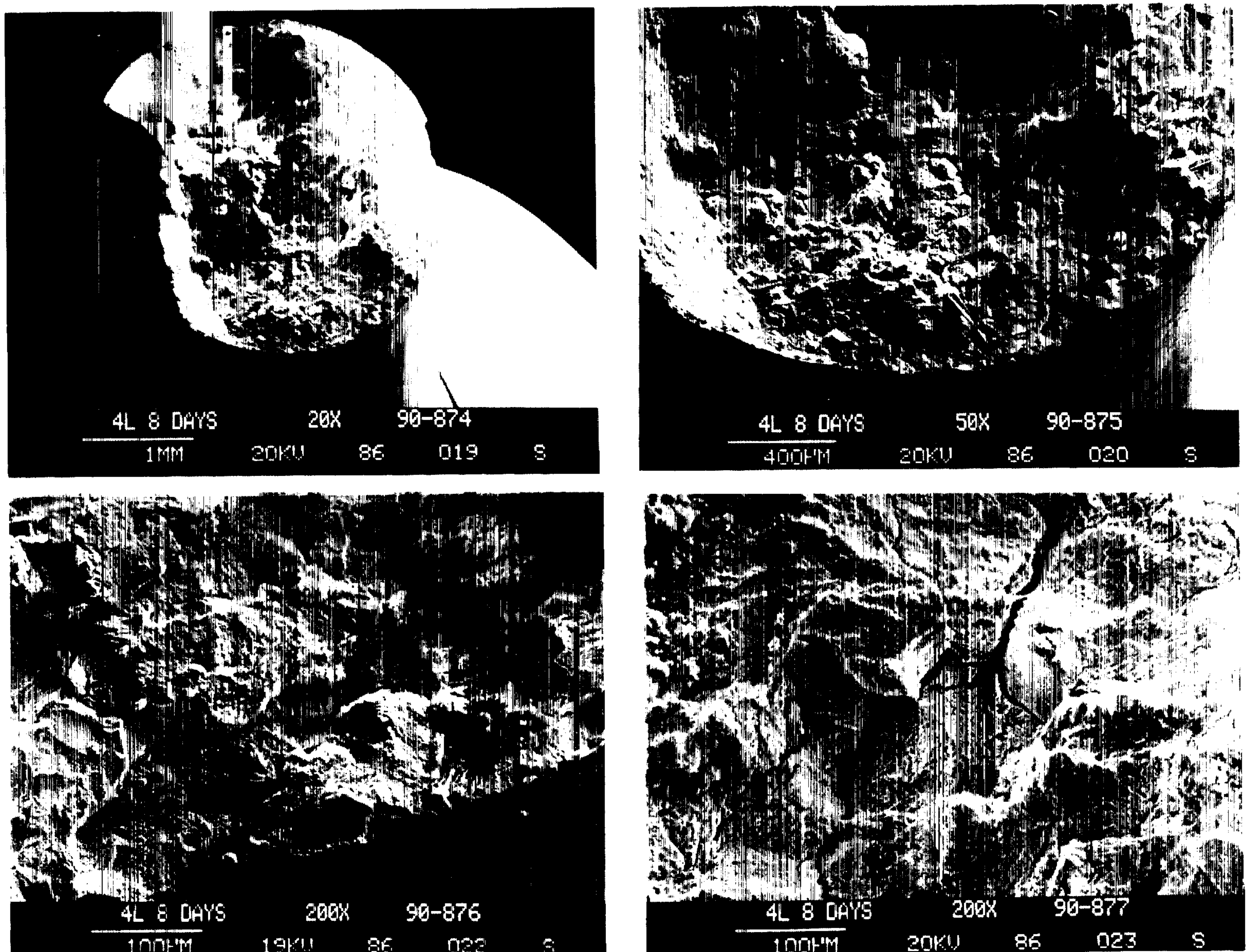


Figure 25. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 90 Percent of the Yield Strength, and Exposed to 8 Days of 3.5-Percent NaCl Alternate Immersion.

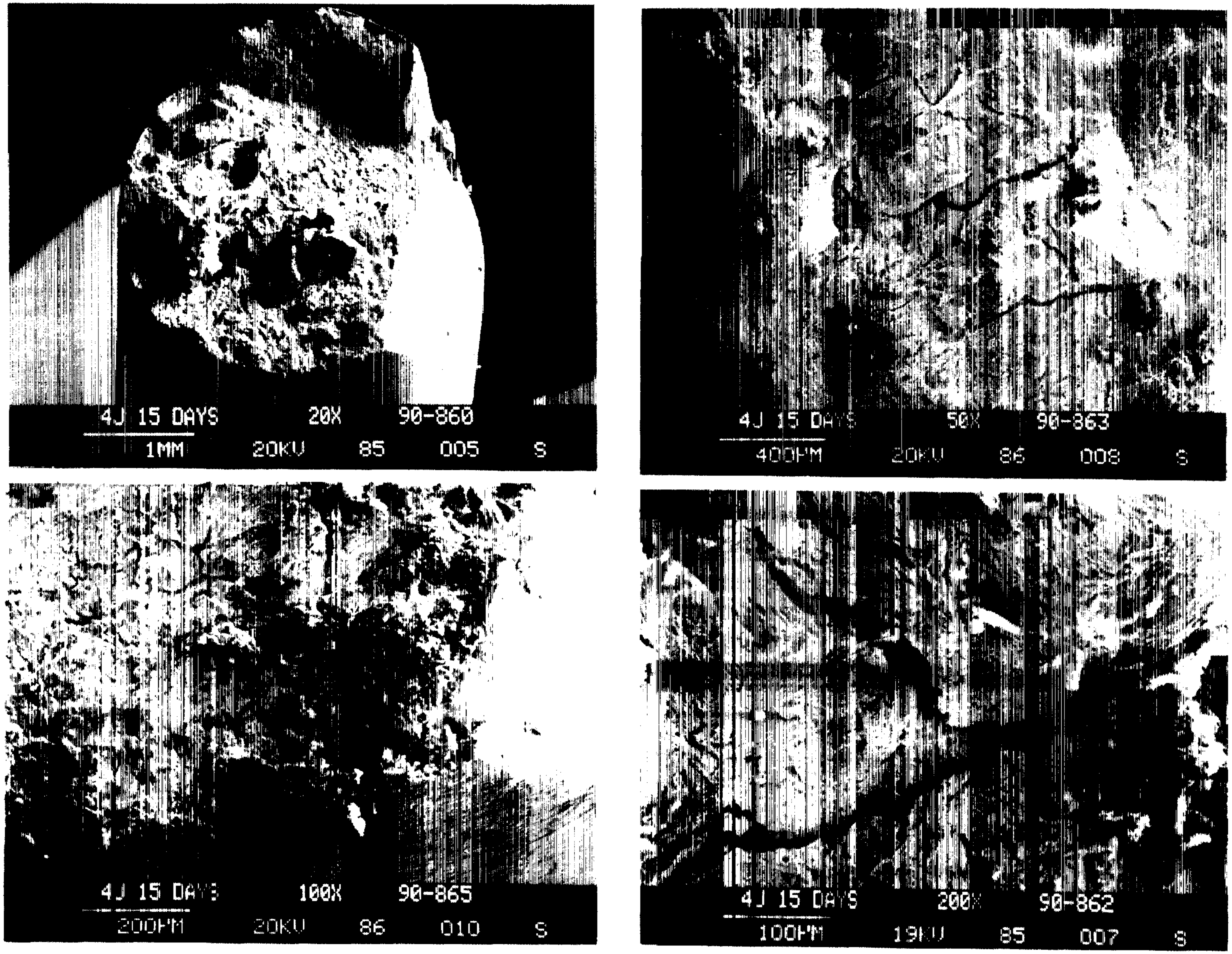


Figure 26. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Exposed to 15 Days of 3.5-Percent NaCl Alternate Immersion.

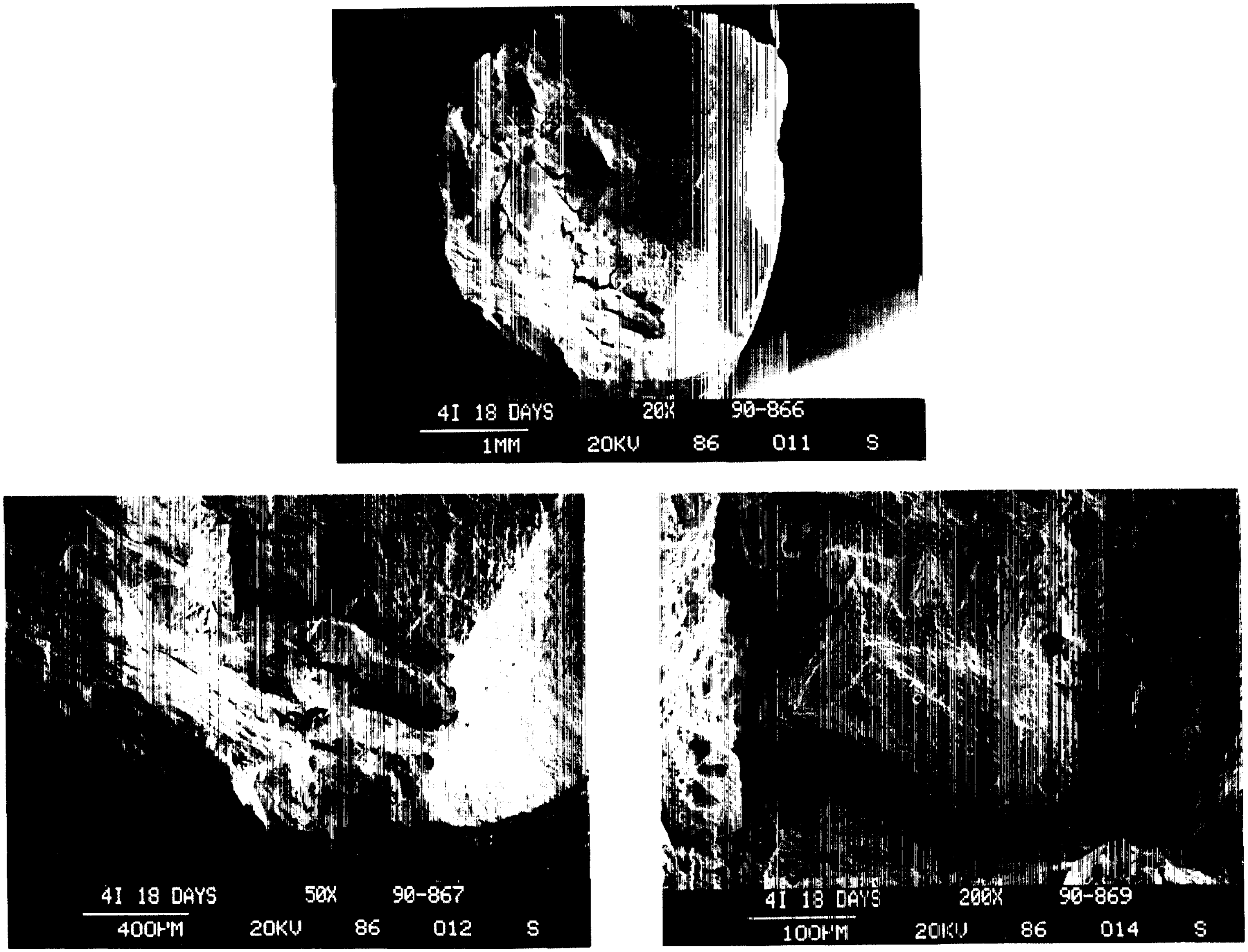


Figure 27. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Stress Relieved at 510 °C (950 °F) HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Exposed to 18 Days of 3.5-Percent NaCl Alternate Immersion.

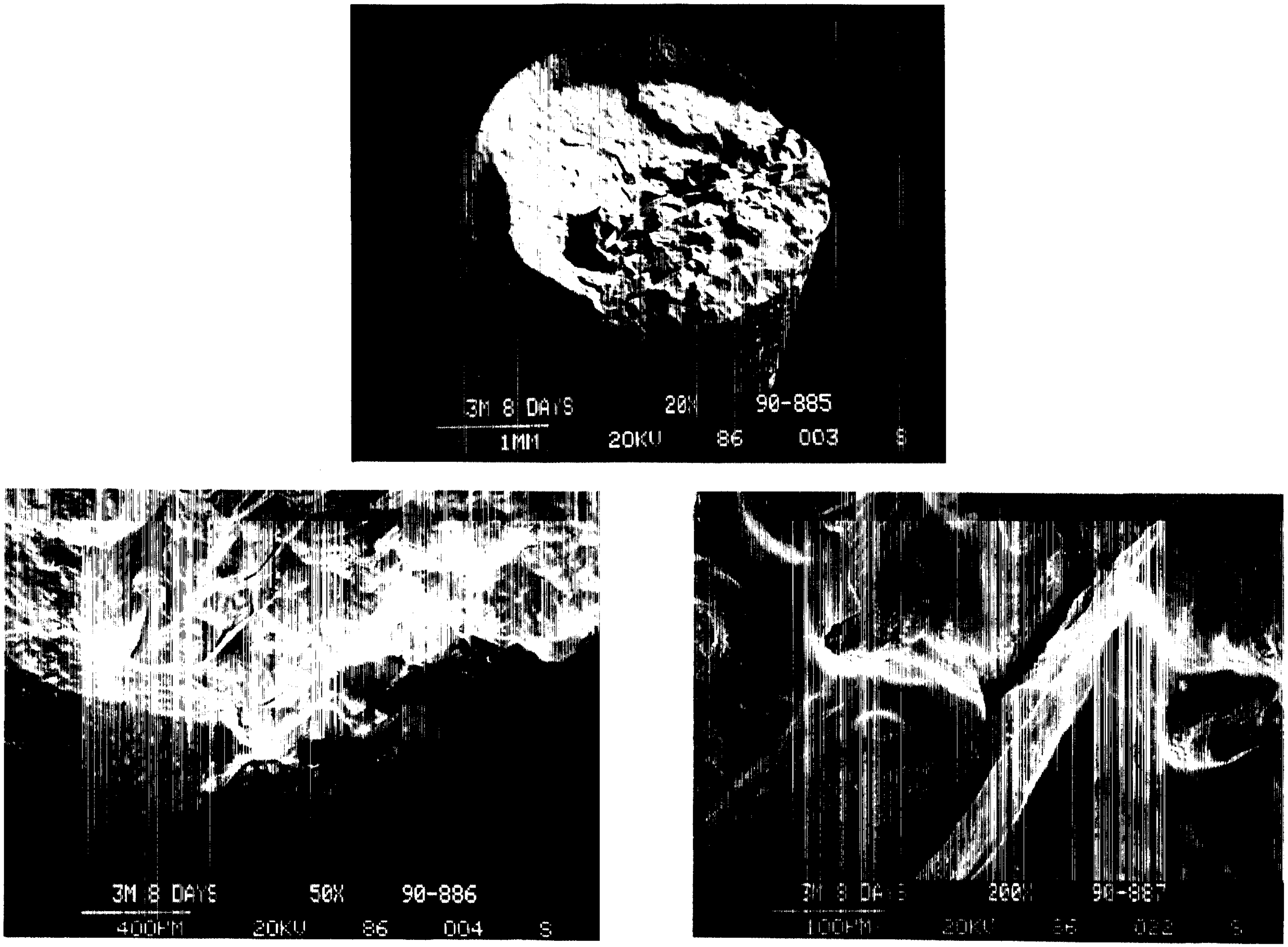


Figure 28. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 90 Percent of the Yield Strength, and Exposed to 8 Days of 3.5-Percent NaCl Alternate Immersion.

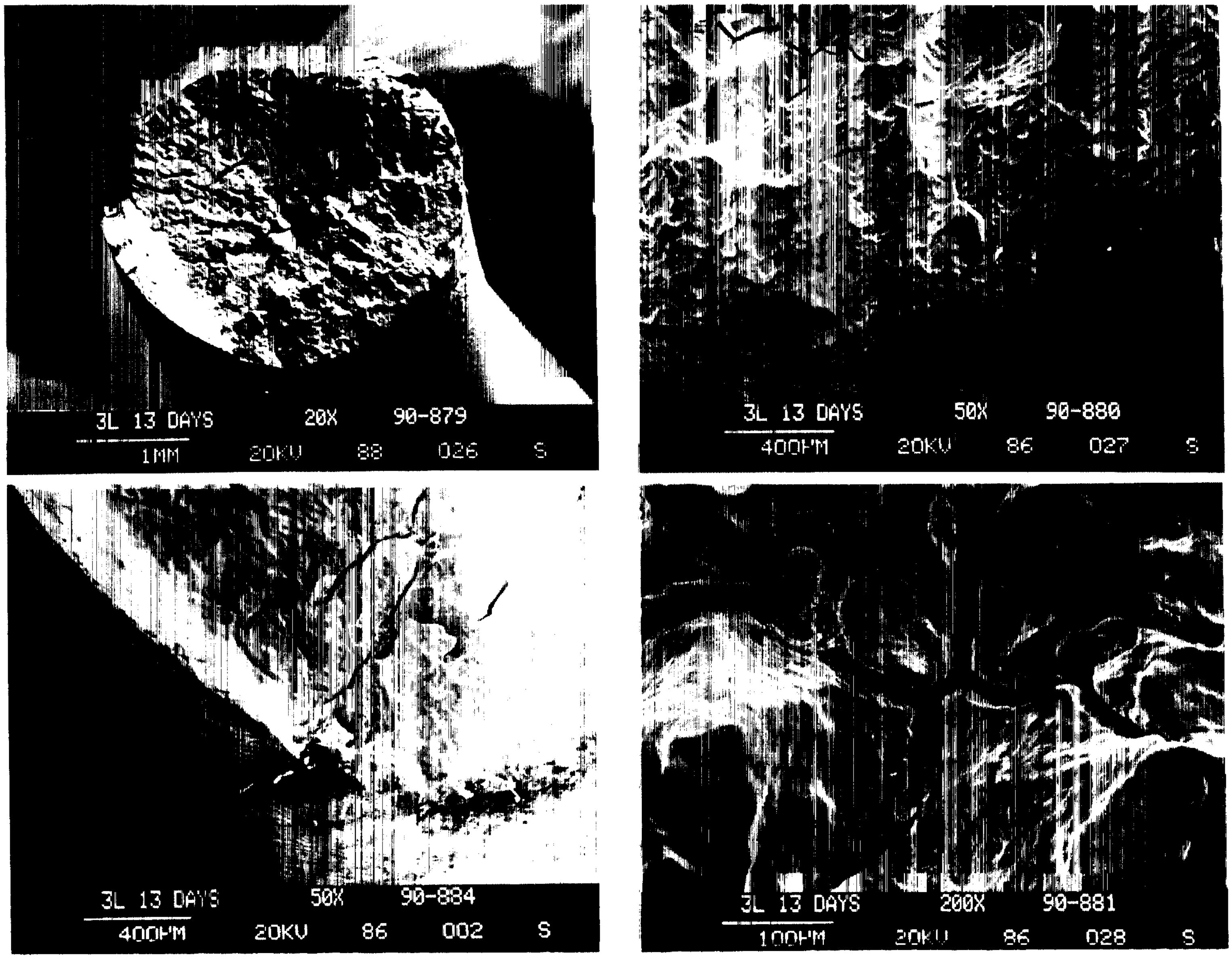
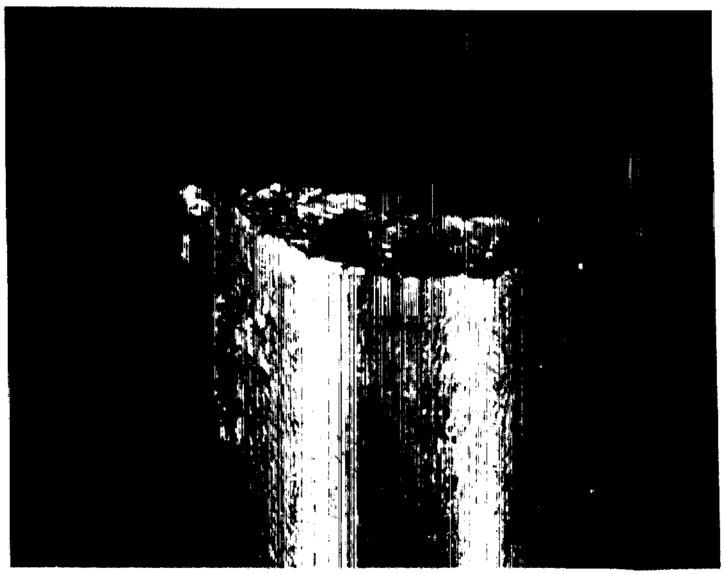
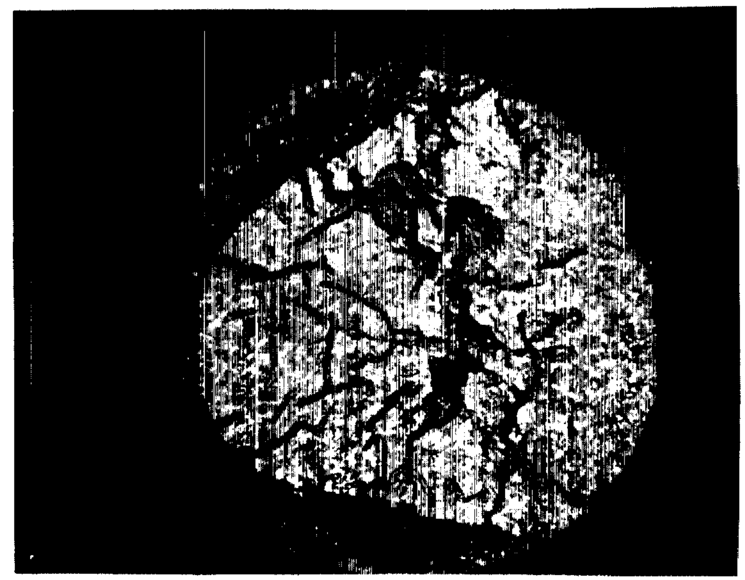


Figure 29A. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Exposed to 13 Days of 3.5-Percent NaCl Alternate Immersion.



25X Mag.



25X Mag.

Figure 29B. Fractured Surface of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Exposed to 13 Days of 3.5-Percent NaCl Alternate Immersion.

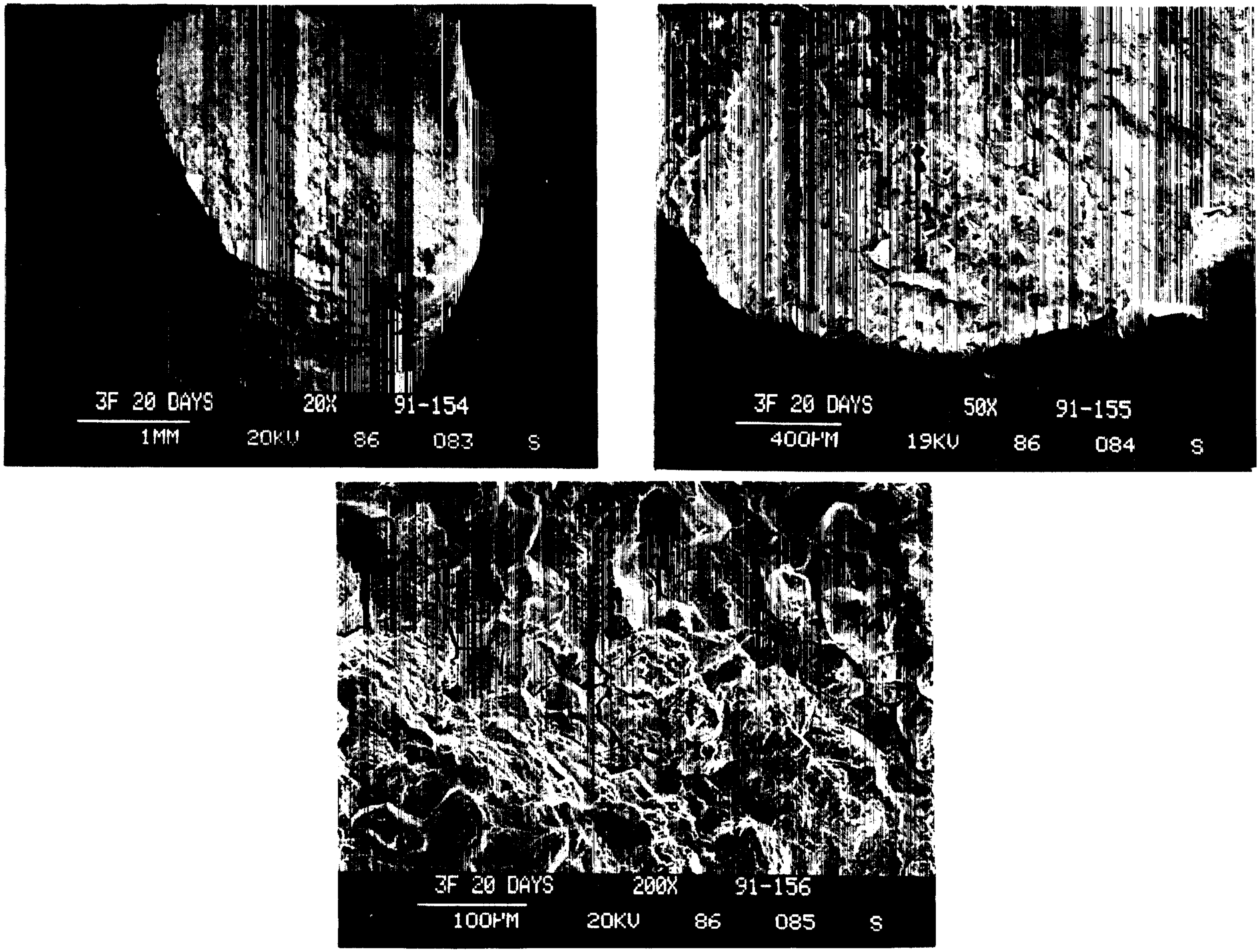


Figure 30. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 50 Percent of the Yield Strength, and Exposed to 20 Days of 3.5-Percent NaCl Alternate Immersion.

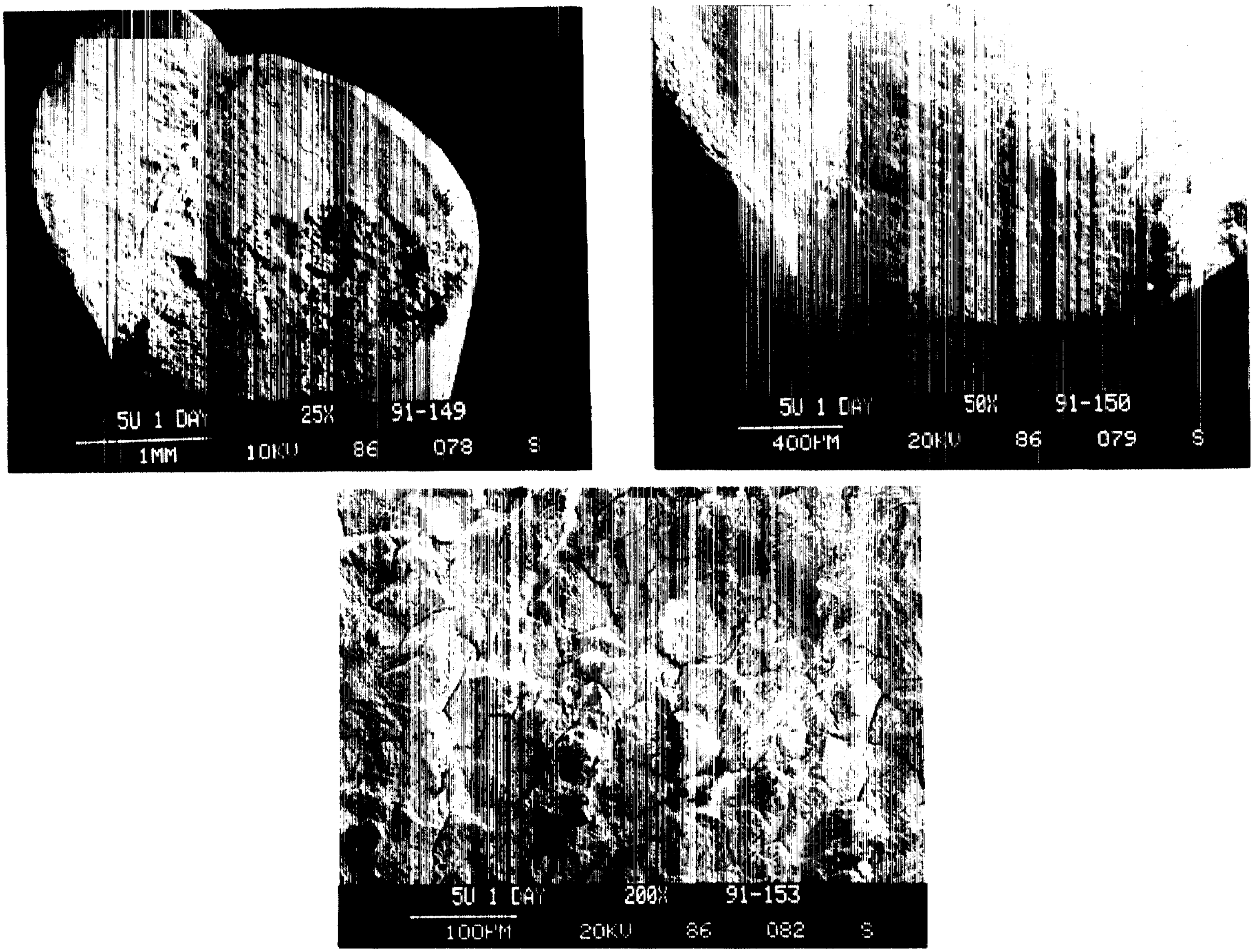


Figure 31. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 90 Percent of the Yield Strength, and Exposed to 1 Day of 5-Percent Salt Spray.

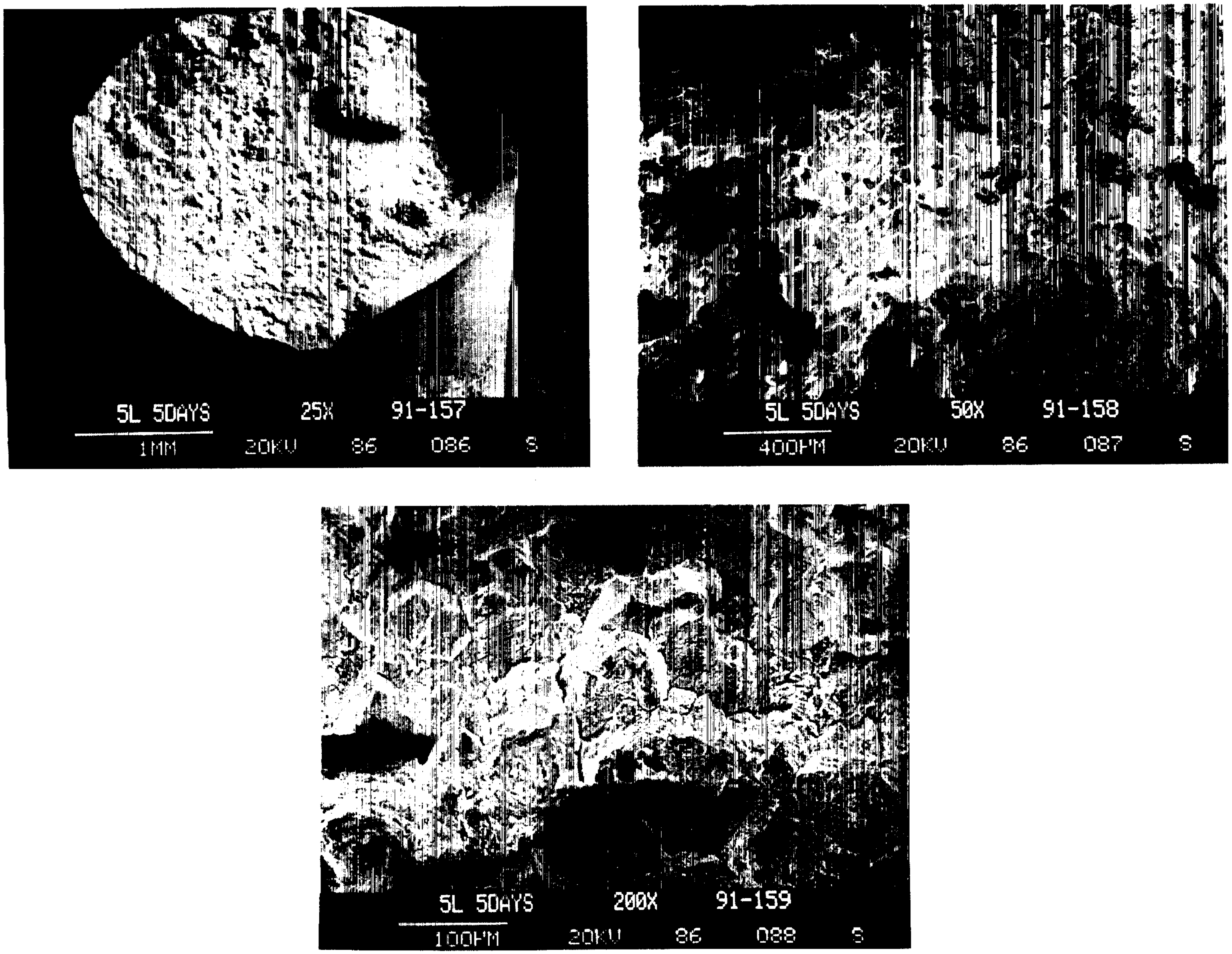


Figure 32. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 50 Percent of the Yield Strength, and Exposed to 5 days of 5-Percent Salt Spray.

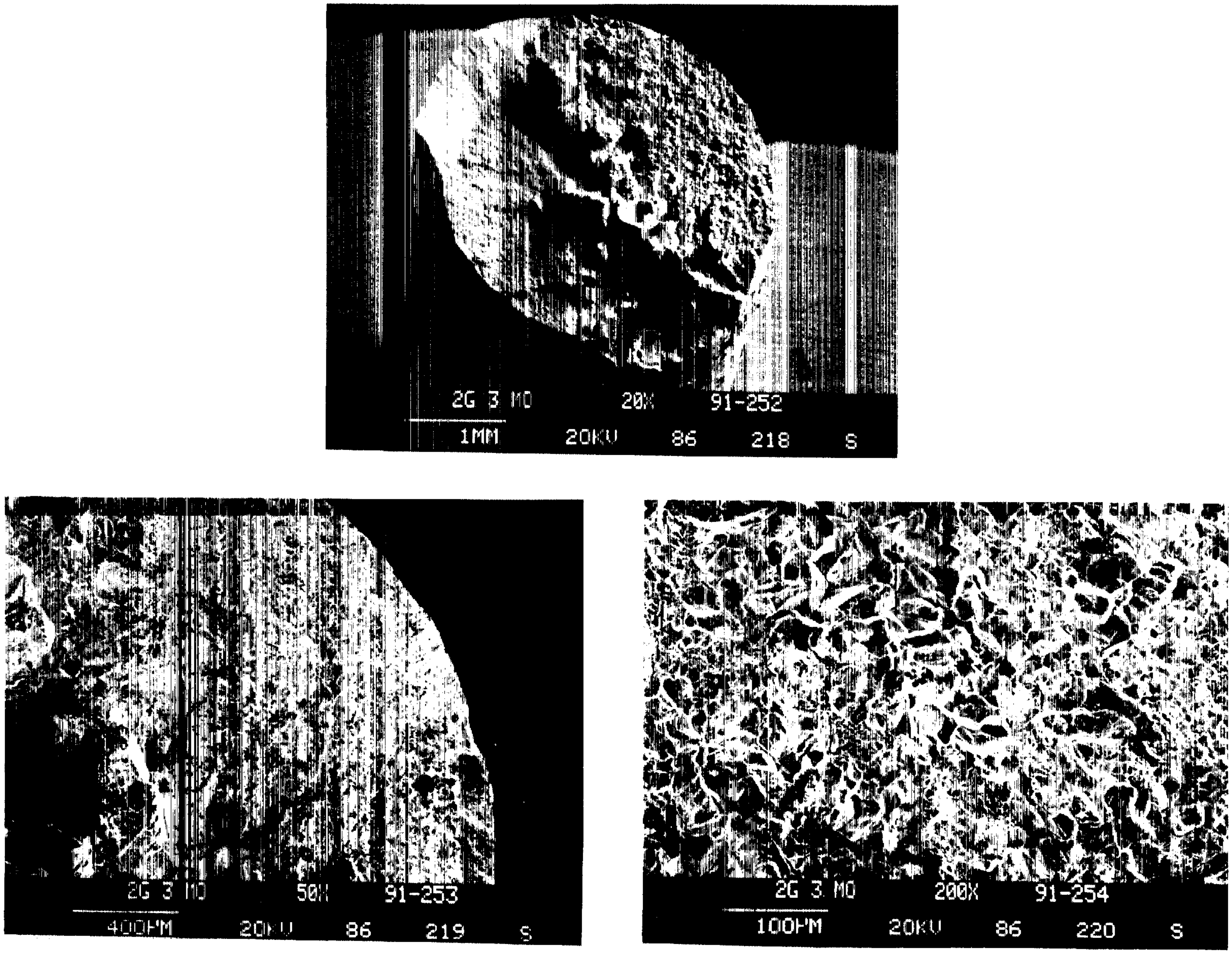


Figure 33. SEM Views of the Fractured Surface of a Tensile Specimen Obtained From a Welded and Nonstress-Relieved HP 9Ni–4Co–0.30C Steel Plate, Stressed to 75 Percent of the Yield Strength, and Exposed to 3 Months of High Humidity.

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13. ABSTRACT *(Maximum 200 words)*

A stress corrosion cracking (SCC) investigation was conducted on HP 9Ni-4Co-0.30C steel plate welds (welded by using straight polarity plasma arc and HP 9Ni-4Co-0.20C weld wire) since this material is being considered for use in the Advanced Solid Rocket Motor (ASRM) program. Prior to the welding, the material was double tempered at 538 °C (1,000 °F). After welding, only part of the material was stress relieved at 510 °C (950 °F) for 3 h. Round tensile specimens obtained from *nonstress-relieved* material were tested in 100-percent relative humidity at 38 °C (100 °F), in 3.5-percent NaCl alternate immersion, and in 5-percent salt spray at 35 °C (95 °F). Specimens obtained from stress-relieved material were tested in alternate immersion. The stress levels were 50, 75, and 90 percent of the corresponding 0.2-percent yield strength (YS).

All the *nonstress-relieved* specimens exposed to salt spray and alternate immersion failed.

Stress-relieved specimens (exposed to alternate immersion) failed at 75 and 90 percent of YS. No failures occurred at 50 percent of YS in the stress-relieved specimens which indicates a beneficial effect of the stress relief on the SCC resistance of these welds. The stress relief also had a positive effect on the mechanical properties of the welds (the most important being an increase of 21 percent on the YS).

Under the conditions of these tests, the straight polarity plasma arc welded HP 9Ni-4Co-0.30C steel plate was found highly susceptible to SCC in the *nonstress-relieved* condition. This susceptibility to SCC was reduced by stress relieving.

14. SUBJECT TERMS
Advanced Solid Rocket Motor (ASRM), HP 9Ni-4Co-0,30C Steel Plate Welds, Straight Polarity Plasma Arc, Stress Corrosion Cracking (SCC)

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