NASA TECHNICAL MEMORANDUM

NASA TM X-64729

A MECHANICAL PROPERTY AND STRESS CORROSION EVALUATION OF 431 STAINLESS STEEL ALLOY

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March 7, 1973

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TM X-64729	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE A MECHANICAL PROPERTY AND STRESS CORROSION EVALUATION OF 431 STAINLESS STEEL ALLOY		5. REPORT DATE March 7, 1973 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) J. W. Montano		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS NASA-George C. Marshall Space Flight Center Marshall Space Flight Center, AL 35812		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. 13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D. C.		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Work performed by Astronautics Laboratory, Science and Engineering

16. ABSTRACT

This report presents the mechanical properties of type 431 stainless steel in two conditions: annealed bar and hardened and tempered bar. Test specimens, manufactured from approximately 1.0 inch (2.54 cm) diameter bar stock, were tested at temperatures of 80°F (+26.7°C), 0°F (-17.8°C), -100°F (-73°C), and -200°F (-129°C). The test data indicated excellent tensile strength, notched/unnotched tensile ratio, ductility, shear, and impact properties at all testing temperatures.

Results of the alternate immersion stress corrosion tests on stressed and unstressed longitudinal tensile specimens 0.1250 inch (0.3175 cm) diameter and transverse "C"-ring specimens, machined from 1.0 inch (2.54 cm) diameter bar stock, indicated that the material is not susceptible to stress corrosion cracking when tested in a 3.5 percent NaCl solution for 180 days.

17. KEY WORDS Cryogenic Temperature Fractography	18. DISTRIBUTION STATEMENT Unclassified - Unlimited J. W. Montano

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	38	NTIS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

SUMMARY

This report presents the mechanical and stress corrosion properties of 431 stainless steel in two conditions: annealed bar and hardened and tempered bar. The mechanical properties were evaluated at temperatures from +80°F (+26.7°C) to -200°F (-129°C). The tensile test data for longitudinal tensile specimens indicate both increasing ultimate tensile strength and 0.2 percent offset yield strength with decreasing temperatures for both conditions of the bar. Elongation remained fairly constant and the reduction in area decreased slightly with decreasing test temperature. The notched to unnotched tensile ratio (K_t=10) decreased slightly with decreasing test temperature, yet remained above 1.0, except for the 0.93 value at -200°F (-129°C) for the hardened and tempered material. Charpy V-notched impact strength decreased noticably with decreasing test temperature; however, the -200°F (-129°C) impact energy still indicated a high degree of toughness. The double shear strength of both the annealed and the hardened and tempered material increased consistently with decreasing test temperature.

Results of the 180 day alternate immersion stress corrosion test in a 3.5 percent NaCl solution indicated that the annealed and the hardened and tempered longitudinal bar specimens and the transverse "C"-ring bar specimens were not susceptible to stress corrosion cracking, even when stressed to 100 percent of the 0.2 percent yield strength. Tensile tests made on the specimens after exposure to the stress corrosion media indicated that the alloy was not affected by exposure. The applied stress, however, produced a slight increase in yield strength with increased stress in the annealed material specimens and produced a large increase in yield strength in the 100 percent stressed hardened and tempered material specimens.

INTRODUCTION

Due to the numerous situations which dictate the use of a high strength stainless steel possessing good stress corrosion resistance, type 431 martensitic stainless steel bar stock was chosen for evaluation. This alloy is a heat treatable stainless containing approximately 16% chromium, 2% nickel, and 0.15% carbon.

431 stainless steel is used in highly stressed aircraft components, including fasteners, pump shafts, and valve stems. This alloy is known to be resistant to atmospheric corrosion and offers the best resistance to marine atmospheres of all the hardenable type stainless grades.

Recommendations, made by the "ASM Committee on Heat Treating of Stainless Steel" (Ref. 1), which were utilized in this investigation, include the following:

(1) 431 stainless steel alloy is sensitive to heat treating variables and to avoid contamination all parts and heat treating fixtures must be cleaned thoroughly prior to heat treatment.

(2) Oil quenching gives the maximum corrosion resistance and ductility

(3) A portion of the austenite retained in quenching may be transformed by sub-zero cooling to about -100°F (-73°C) immediately after quenching. To obtain maximum transformation of retained austenite, two or more complete tempering cycles are necessary after sub-zero cooling. Parts should be air cooled to room temperature between the tempering cycles.

This investigation was concerned primarily with the effects of cryogenic temperatures on the ductility (elongation, reduction in area, and notched-to-unnotched tensile ratio), toughness (impact) and shear properties of the alloy and the effects of alternate immersion testing in a 3.5 percent NaCl solution on the stress corrosion resistance of the alloy in the annealed and in the hardened and tempered conditions.

MATERIAL PROCESSING

The chemical composition of the as-received material used in this investigation is shown in Table I. This material, which had been hot rolled annealed per QQS-763c, was divided into two groups for processing. One group was machined into test specimens in the as received, annealed, condition. Prior to machining the second group the material was processed as follows:

Cleaning:	Hot alkaline cleaned
Type Furnace:	Air atmosphere
Material Processing:	Care was exercised so that the material was not contaminated with perspiration, oil, grease, pencil marking or other carbonaceous material. Clean gloves were utilized in handling the material prior to the 1875°F (1024°C) treatment.
Hardening Treatment:	1875°F (1024°C) - 1/2 Hour - Oil Quench Cooled to room temperature in water Cooled to -100°F (-73°C) for 2 hours.
Tempering Treatment:	550°F (288°C) for 2 hours - air cool Cooled to -100°F (-73°C) for 2 hours Reheated to 550°F (288°C) - hold for 2 hours - air cool.
Scale Removal:	Cleaned with 10-15% Nitric Acid + 1-2% Hydrofluric Acid at 100-120°F (38-49°C) for 5-10 minutes. Washed with water to remove residue, wiped to remove smut.

EQUIPMENT AND MECHANICAL TEST SPECIMENS

The equipment, except for the shear die, used in the mechanical properties evaluation is described in a report by the author (Ref. 2). The tensile test specimens are illustrated in Figures 1 and 2. Impact specimens were machined from bar stock to the Federal Standard No. 151 configuration. Shear specimens were 2.00 inches (5.08 cm) in length by 0.3125 inches (0.8967 cm) in diameter.

The double shear die is made of nickel plated 8740 alloy steel of Rockwell C-40 hardness and the shear die inserts are made of MP-35N multiphase alloy of Rockwell C-53 hardness. The die is designed so the the center insert thickness is 1.0 diameter and the outer insert is 1/2 diameter thickness. The particular design used for this evaluation was chosen after examination of considerable amounts of data generated by the "Fasteners Testing Development Group" (FTDG), a committee established under the Department of Defense, Project No. 5300-001, under the direction of the Navy Bureau of Weapons and the Aeronautical Materials Laboratory.

The double shear die inserts were rotated after each test so that at least three tests could be made on one set of inserts. At the lower cryogenic temperatures sometimes only one test could be accomplished per set of inserts, however, most of these inserts could be refaced and used again.

STRESS CORROSION TEST SPECIMENS AND TEST PROCEDURE

The equipment used in the stress corrosion testing is described in a report by Williamson (Ref. 3). The stress corrosion tensile test specimen is illustrated in Figure 3 and the "C"-ring specimen configuration is shown in Figure 4. Prior to manufacturing the "C"-ring specimens approximately 0.0312 inches (0.0793 cm) was removed from the bar diameter. The "C"-ring specimens were stressed in the transverse direction by the constant deflection method, explained in Appendix 1, and were placed in a 3.5 percent NaCl solution for 180 days of alternate immersion testing (10 minutes in solution, 50 minutes above solution). Longitudinal tensile specimens were also stressed and subjected to the same corrosion bath as illustrated in Figure 5.

The stress corrosion testing schedule is outlined below:

HARDNESS Rockwell C	TEST Specimen	APPLIED STRESS (% of 0.2% Y.S.)	SPECIMENS PER Stress Level
28	"C"-Ring	50, 75, 100	4
28	Tensile	0, 75, 100	4
42	"C"-Ring	50, 75, 100	4
42	Tensile	0, 75, 100	4

RESULTS AND DISCUSSION

The test results of the ambient through cryogenic temperature mechanical properties evaluation are tabulated in Table II and these properties are plotted in Figure 6.

Table II contains test data on annealed and on hardened and tempered 1.0 inch (2.54 cm) diameter bar longitudinal round tensile specimens [0.50 inch (1.27 cm) diameter], longitudinal round shear specimens [0.3125 inch (0.8967 cm) diameter], and Charpy V-notched impact specimens. The tensile test data indicate an increasing ultimate tensile and 0.2 percent yield strengths with decreasing temperature for both conditions of the material. The elongation in 4D percent and the reduction in area indicated excellent ductility, over the test temperature range, for the annealed and for the hardened and tempered material specimens. The notched-to-unnotched tensile ratio decreased slightly with decreasing test temperatures, yet remained above 1.0 except for a 0.93 value at -200°F (-129°C) for the hardened and tempered material specimens. Charpy V-notched impact strength decreased progressively with decreasing test temperature; however, the -200°F (-129°C) impact energy still indicated a high degree of ductility for both conditions of the material. The double shear ultimate and shear yield (approximated by deflectometer measurement) strengths of both the annealed and the hardened and tempered material increased consistently with decreasing temperature.

Table III contains tensile test data prior to and after 180 days of alternate immersion testing in a 3.5 percent NaCl solution. These data indicate that the annealed and the hardened and tempered longitudinal bar specimens were not susceptible to stress corrosion cracking, even when stressed to 100 percent of the 0.2 percent yield strength. The applied stress, however, produced a slight increase in yield strength with increased stress in the annealed material specimens and a large increase in yield strength in the 100 percent stressed hardened and tempered material specimens. There were no failures in the tensile specimens or in the "C"-ring specimens exposed to the alternate immersion test for 180 days. Figures 7-10 illustrate typical "C"-ring and longitudinal tensile specimens, prior to and after 180 days of alternate immersion testing in a 3.5 percent NaCl solution.

Figures 11 and 12 illustrate the longitudinal and transverse microstructure of the annealed and of the hardened and tempered conditions as revealed by a Picric-Hydrochloric acid etchant.

Figures 13-20 illustrate fractographs taken by Scanning Electron Microscopy (SEM) at 2300X magnifications. These fractographs were made on smooth and V-notched round tensile specimens and on Charpy V-notched impact specimens, and on round shear specimens fractured at temperatures for ambient to -200°F (-129°C). The well defined dimples shown in the fractographs (Figures 13-16) of the annealed material specimens indicated that 431 stainless steel has good toughness over the temperature range investigated. Figures 17-20 represent fractographs of the hardened and tempered (Rc 42 hardness) material specimens indicating excellent ductility for all of the specimens fractured at most of the test temperatures. However, at the lower test temperatures, the tendency toward brittleness increased in the V-notched tensile specimen fractures, as shown in the fractographs of Figure 18.

CONCLUSIONS

Based upon the results of this evaluation of type 431 stainless steel bar in two conditions, annealed and hardened and tempered, the following conclusions are drawn:

(1) The ultimate tensile and 0.2 percent yield strength of the longitudinal test specimens increased with decreasing temperatures.

(2) Elongation remained fairly constant over the test temperature range while the reduction in area decreased slightly with decreasing temperature.

(3) The notched to unnotched tensile ratio (K_t=10) decreased slightly with decreasing test temperature yet retained good ductility at -200°F (-129°C).

(4) Charpy V-notched impact strength decreased noticeably with decreasing temperature yet retained a high degree of toughness at -200°F (-129°C).

(5) The double shear ultimate and shear yield (approximated by deflectometer measurement) increased consistantly with decreasing test temperatures.

(6) Considering the overall mechanical properties obtained in our evaluation, it would be reasonable to consider bar material, annealed or hardened and tempered as indicated in this evaluation, for cryogenic applications to -200°F (-129°C).

(7) Type 431 stainless steel alloy in the annealed condition and in the hardened and tempered conditions as used in this evaluation is not susceptible to stress corrosion cracking, even when stressed to 100 percent of the 0.2 percent yield strength and exposed to a 3.5 percent NaCl solution for 180 days of alternate immersion testing.

REFERENCES

1. Metals Handbook, 8th Edition Vol-2, "Heat Treating, Cleaning and Finishing," 1964

2. Montano, J. W. : "A Mechanical Property and Stress Corrosion Evaluation of Custom 455 Stainless Steel Alloy," TMX-64682, August 2, 1972.

3. Williamson, J. G. : "Stress Corrosion Studies of AM-355 Stainless Steel," NASA TMX-53317, August 9, 1965.

APPENDIX 1

METHOD FOR STRESSING "C"-RING STRESS CORROSION SPECIMENS

The following is a procedure for stressing "C"-ring stress corrosion specimens:

1. Measure with a micrometer to the nearest 1/1000 of an inch the outside parallel to the stressing screw (averaging the two ends of the ring) and the wall thickness.

2. Set up a table to calculate the final diameter (OD_f) required to give the desired stress using the following equations:

$$OD_f = OD - \Delta$$

$$\Delta = \frac{f \cdot \pi \cdot D^2}{4 \cdot E \cdot t \cdot Z}$$

where
Δ = Change of OD giving desired stress, inches
f = Desired stress, psi
OD = Outside diameter, inches
t = Wall thickness, inches
D = Mean diameter (OD-t), inches
E = Modulus of elasticity
Z = Constant (function of ring D/t)

OD_f = Final outside diameter of stress "C"-ring, inches

3. To simplify calculations, certain terms in the above equation may be combined into a constant that will be applicable for a group of rings of the same alloy and size.

Let $\frac{4 \cdot E}{\pi} = K$, a constant

Then $\Delta = \frac{f \cdot D^2}{K \cdot t \cdot Z}$

TABLE I
CHEMICAL COMPOSITION OF 431 STAINLESS STEEL BAR STOCK

ANALYSIS	FE	CR	MN	NI	SI	C	S	P
MSFC	Main	15.86	0.54	2.55	0.38	0.15	0.021	0.03
Armco Steel	"	15.68	0.48	2.36	0.44	0.14	0.024	0.024

Armco Steel Co. Heat No. 36571
Hot Rolled Annealed per QQS-763C Amend 2 Cond. A.

TABLE II
Low Temperature Mechanical Properties of 431 Stainless Steel
Longitudinal Round Tensile and Shear Specimens and MIL-STD 151
Charpy V-Notched Impact Specimens
Machined From 1.0-Inch (2.54cm) Diameter Bar

Hardness Rockwell C	Test Temperature °F	(°C)	Ultimate Tensile Strength Ksi	(GN/m²)	0.2% Offset Yield Strength Ksi	(GN/m²)	Elongation 2.00-Inch (5.08cm) 4 D%	RA %	Avg. Kt	N/U* Tensile Ratio	Average Impact-Energy Ft-Lb.	Joules	No. of Impact Tests	Shear Strength** FSu Ksi	(GN/m²)	FSy Ksi	(GN/m²)
28	80	(-26.7)	128.3	(0.884)	117.8	(0.812)	20.7	59.8	11.7	1.54	56.5	(76.6)	5	82.0	(0.565)	67.0	(0.462)
	0	(-17.8)	135.1	(0.931)	124.3	(0.857)	20.9	57.5	11.0	1.53	45.0	(61.0)	1	84.3	(0.581)	66.0	(0.455)
	-100	(-73.0)	144.4	(0.996)	129.6	(0.894)	21.0	55.9	11.1	1.50	20.4	(27.6)	2	92.9	(0.640)	74.2	(0.512)
	-200	(-129.0)	155.6	(1.073)	141.7	(0.977)	21.2	53.7	12.4	1.42	17.2	(23.3)	3	106.1	(0.732)	85.8	(0.592)
42	80	(-26.7)	198.3	(1.367)	137.2	(0.946)	20.1	57.4	9.6	1.36	49.2	(66.7)	5	126.1	(0.869)	100.9	(0.696)
	0	(-17.8)	206.1	(1.421)	137.0	(0.944)	19.8	57.8	9.0	1.36	53.8	(72.9)	2	132.2	(0.911)	109.3	(0.754)
	-100	(-73.0)	218.3	(1.505)	148.6	(1.024)	19.6	54.8	8.6	1.28	46.5	(63.0)	1	141.6	(0.976)	115.8	(0.798)
	-200	(-129.0)	226.7	(1.563)	154.6	(1.066)	19.5	53.1	9.3	0.93	19.8	(26.8)	2	161.2	(1.111)	127.3	(0.878)

* Values represent an average of 5 smooth and 5 notched tensile specimens for each condition and each temperature.
** Values represent an average of 4 shear specimens for each condition and each temperature.

TABLE III

Mechanical Properties of 431 Stainless Steel Longitudinal Tensile Specimens*

0.1250 Inch (0.3175 cm) Diameter

Exposed To Alternate Immersion Testing In A 3.5 Percent NaCl Bath

Hardness Rockwell C	Exposure Time Days	Applied Stress Percent of Yield Strength	Ultimate Tensile Strength Ksi (GN/m^2)	0.2% Offset Yield Strength Ksi (GN/m^2)	Elongation 1/2-Inch (1.27cm) 4D%	R.A. (%)	Modulus X 10^{-6} Psi (GN/m^2)
28	0	0	125.4 (0.865)	116.1 (0.800)	21.5	62.8	28.4 (0.196)
	180	0	126.2 (0.870)	115.8 (0.798)	21.7	64.7	28.9 (0.199)
	180	75	126.4 (0.871)	117.2 (0.808)	23.7	63.6	30.1 (0.207)
	180	100	127.0 (0.876)	119.5 (0.824)	22.5	63.1	29.5 (0.203)
42	0	0	195.8 (1.350)	137.1 (0.945)	21.0	65.3	27.2 (0.187)
	180	0	197.0 (1.358)	142.2 (0.980)	21.7	64.7	27.8 (0.192)
	180	75	195.8 (1.350)	145.1 (1.000)	22.0	64.1	26.8 (0.185)
	180	100	197.8 (1.364)	164.6 (1.135)	22.0	63.4	26.7 (0.184)

*Values represent an average of 4 tests per stress level for each condition.

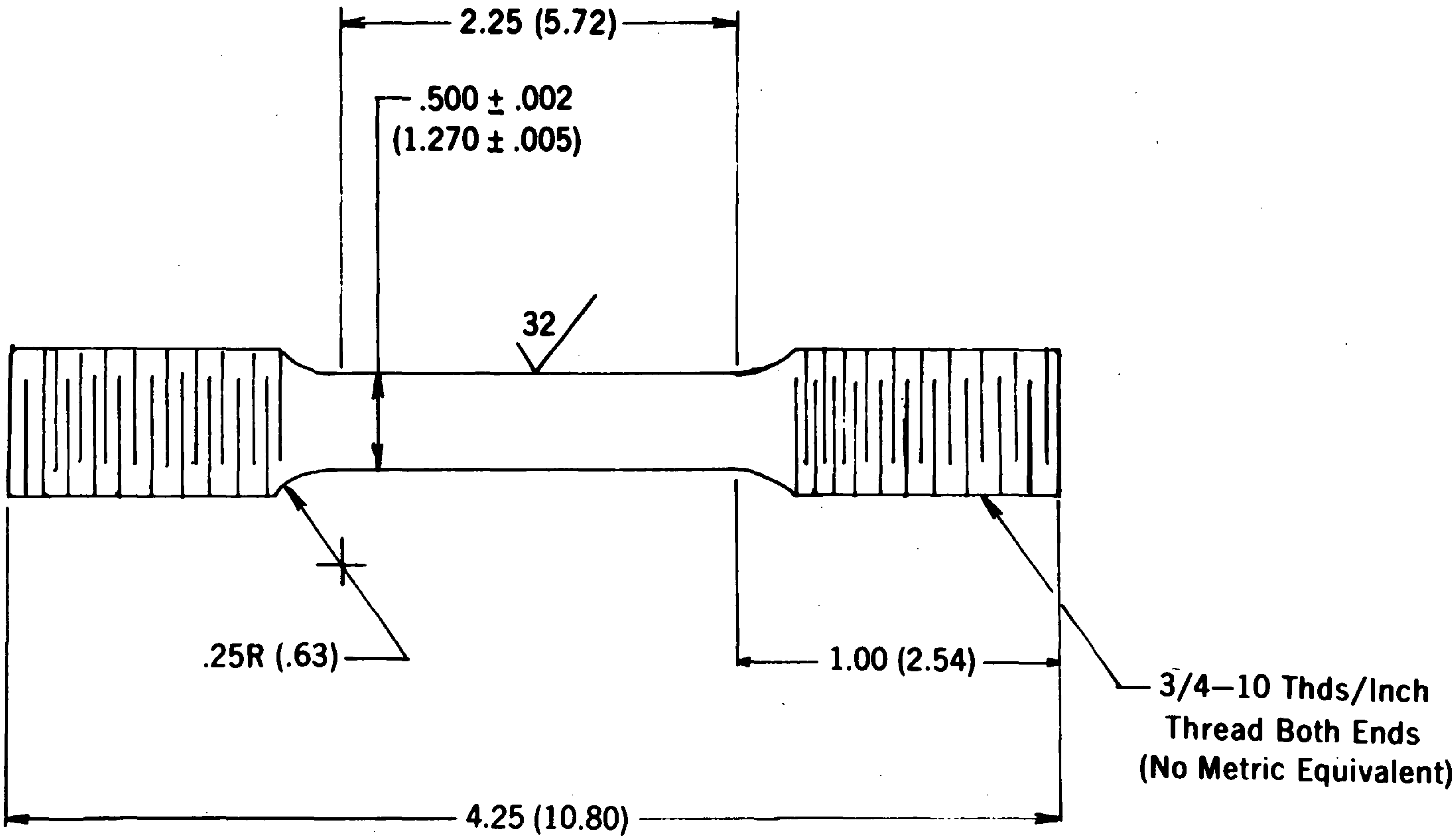


FIGURE 1 - ROUND SMOOTH TENSILE SPECIMEN CONFIGURATION

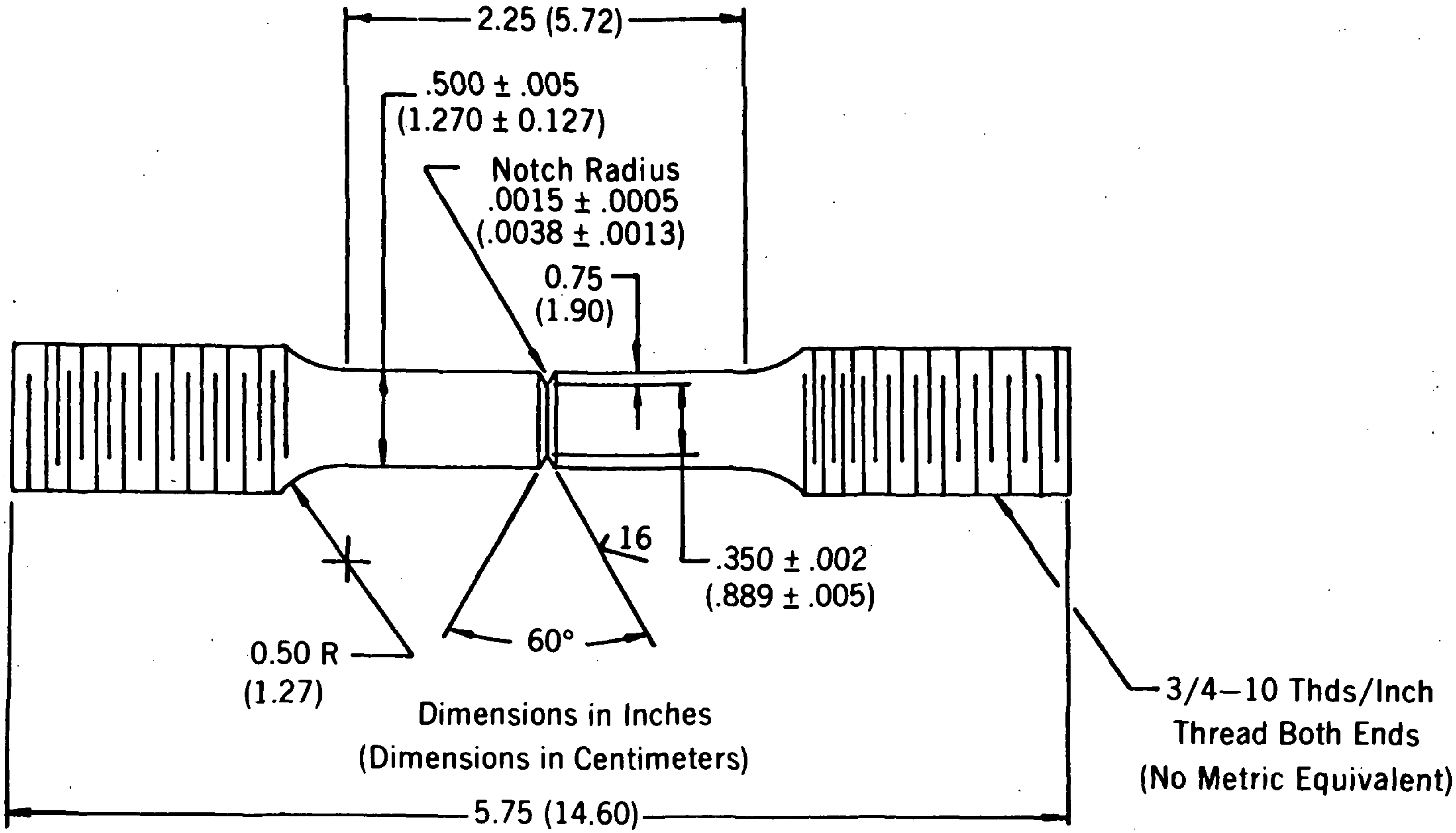


FIGURE 2 - ROUND V—NOTCH TENSILE SPECIMEN CONFIGURATION

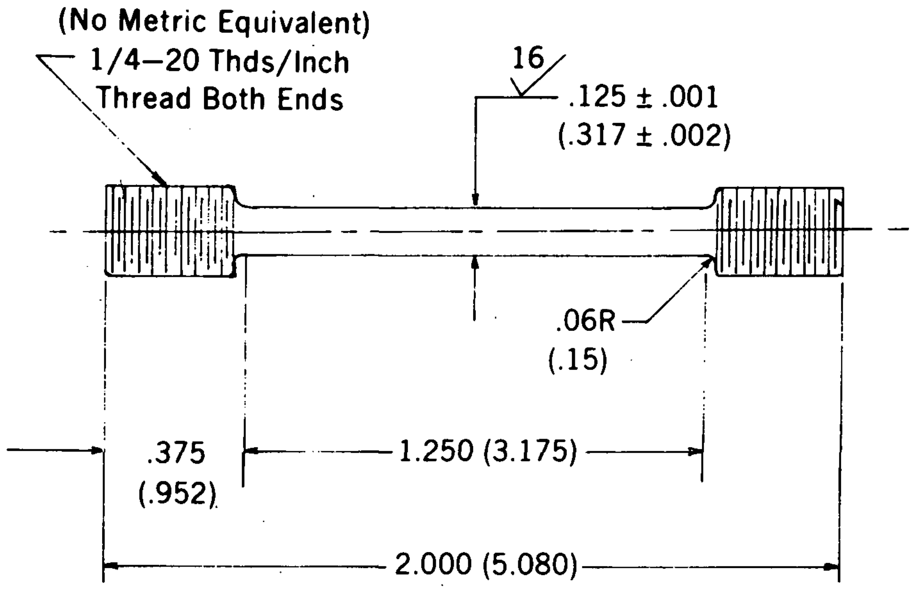


FIGURE 3 - STRESS CORROSION TENSILE SPECIMEN

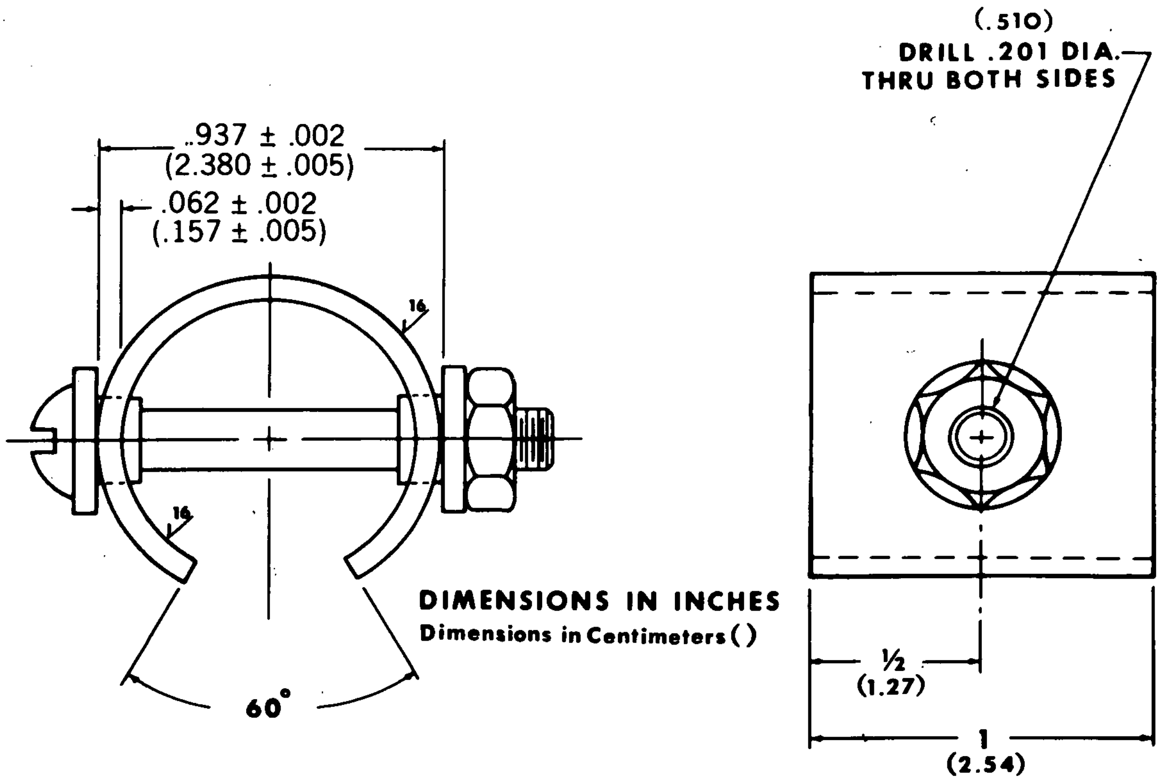


FIGURE 4 - STRESS CORROSION 'C' - RING SPECIMEN

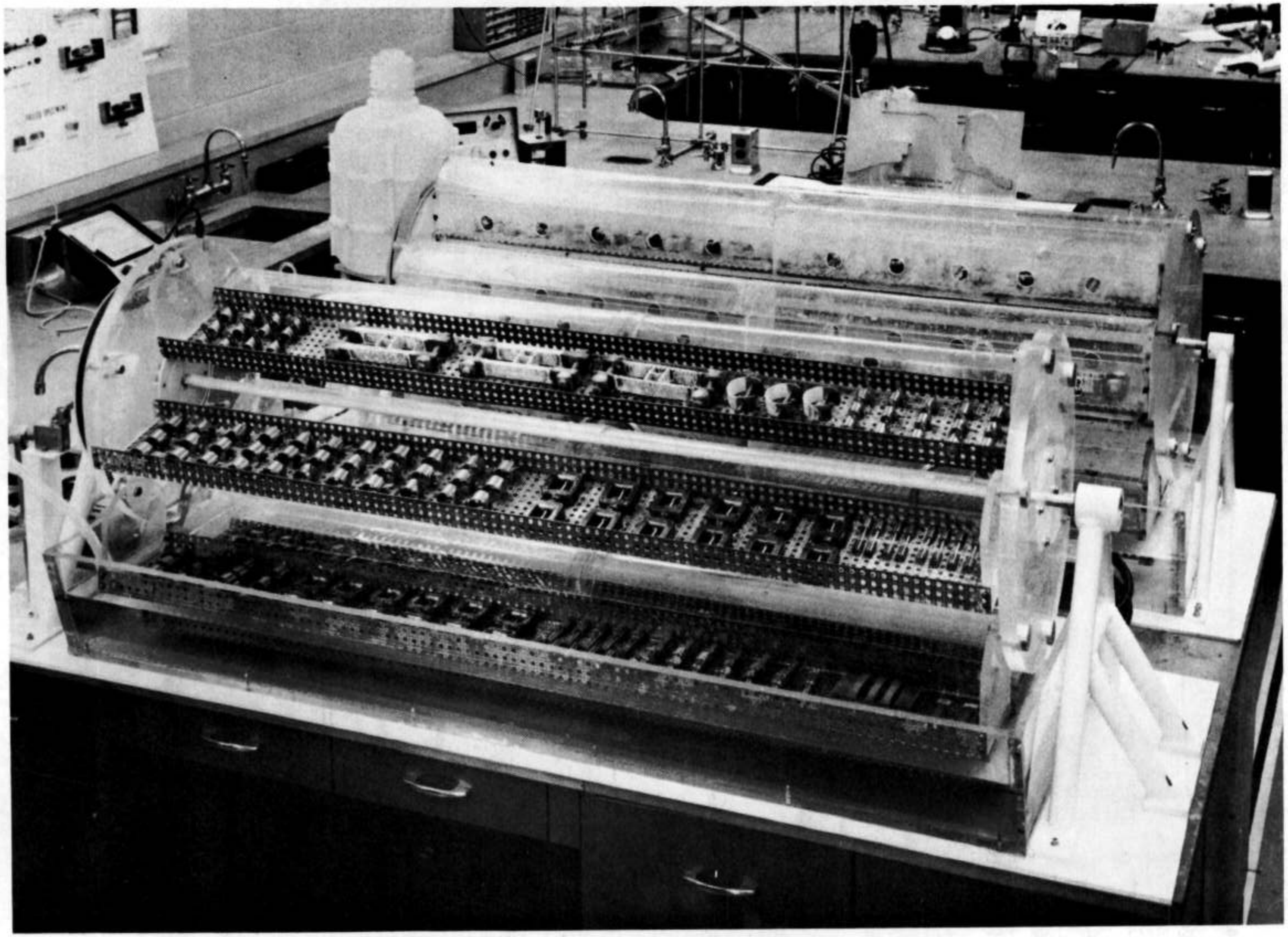


FIGURE 5 - ALTERNATE IMMERSION BATH

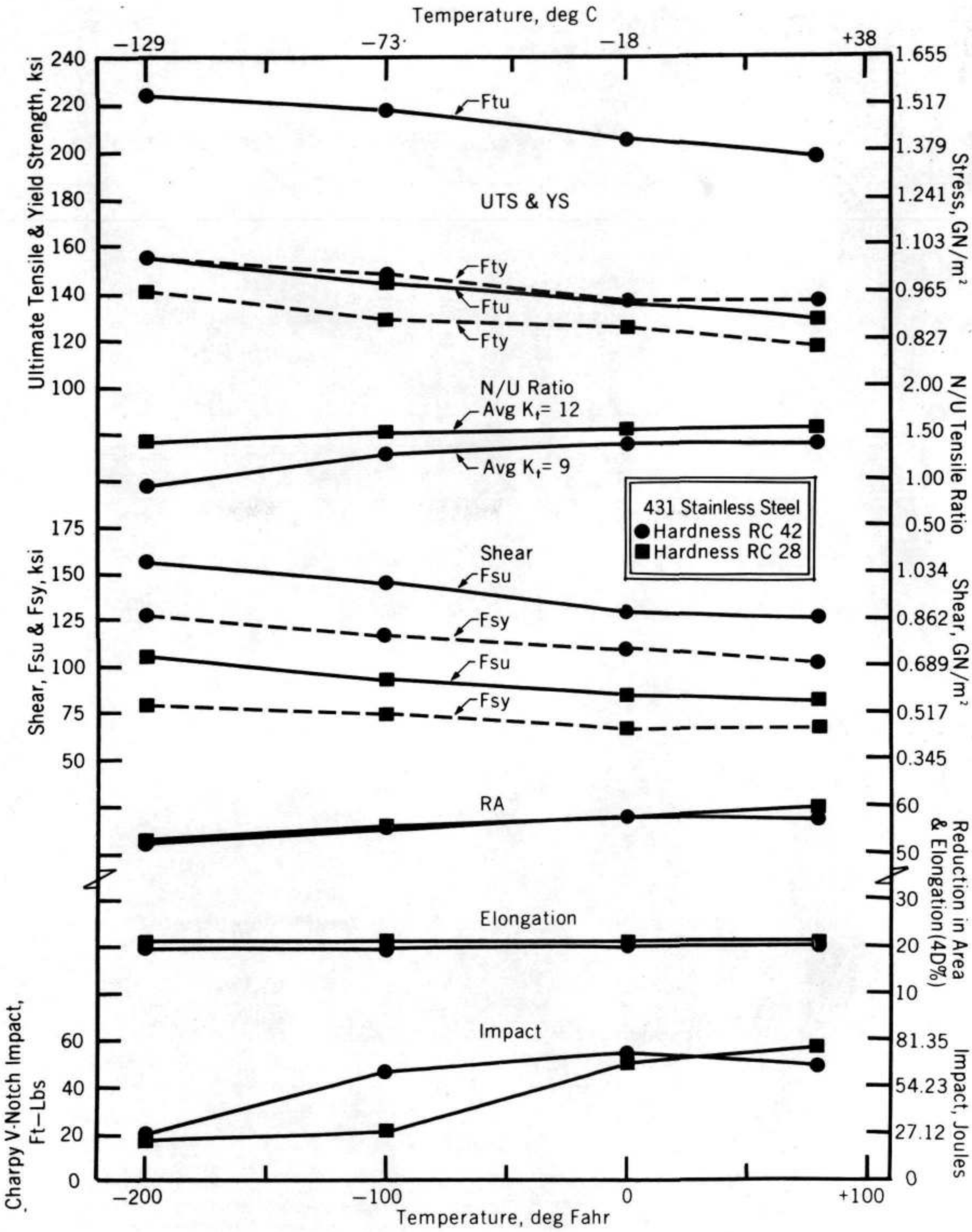
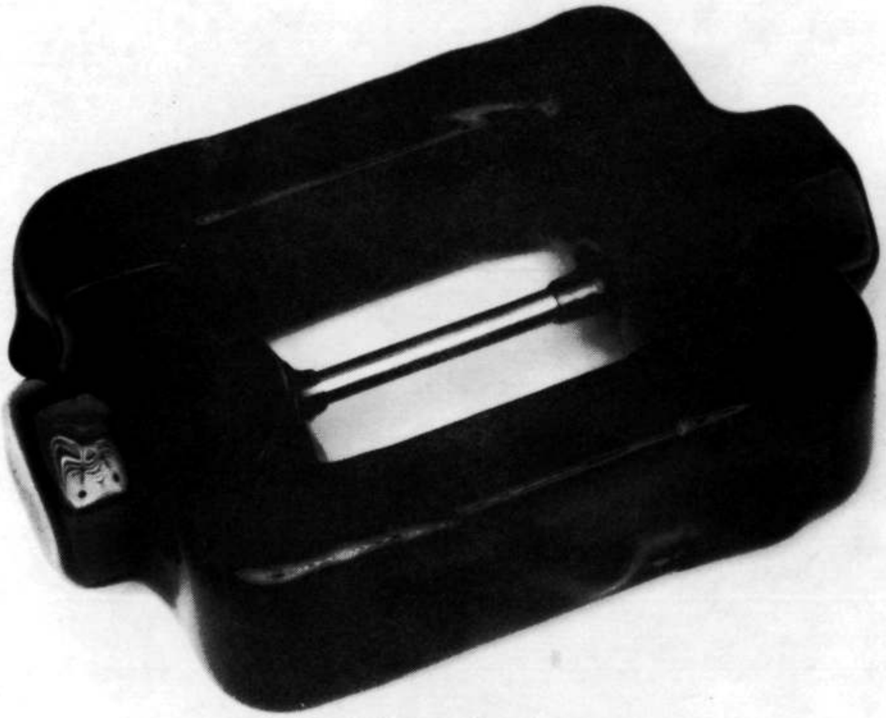


FIGURE 6 - LOW TEMPERATURE MECHANICAL PROPERTIES OF 431 STAINLESS STEEL BAR

Prior to Testing

After 180 Day Test

FIGURE 7 - TYPE 431 STAINLESS STEEL ANNEALED TRANSVERSE 'C'—RING SPECIMEN STRESSED TO 100% OF THE YIELD STRENGTH



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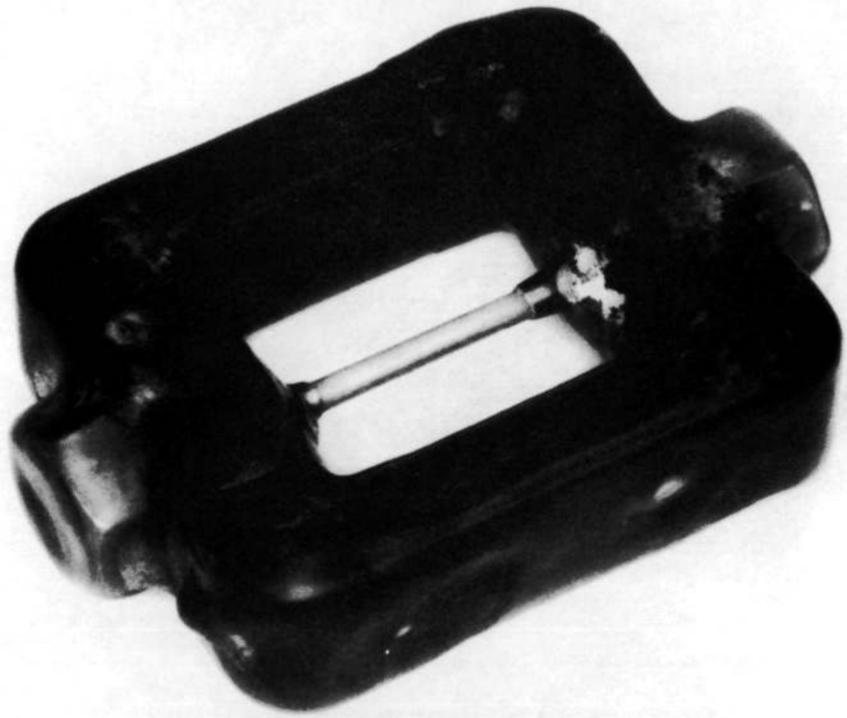


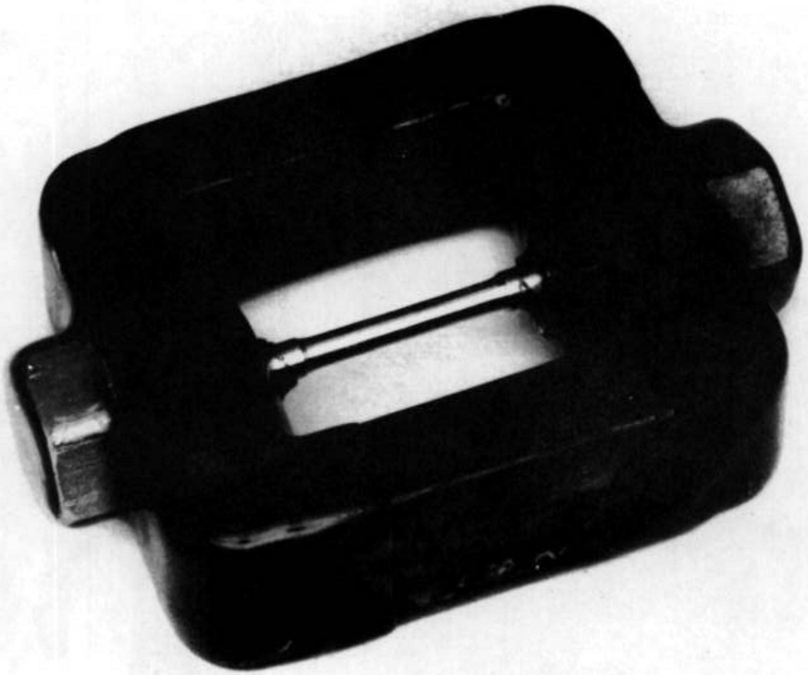
After 180 Day Test

FIGURE 8 - TYPE 431 STAINLESS STEEL ANNEALED LONGITUDINAL ROUND TENSILE SPECIMEN STRESSED TO 100% OF THE YIELD STRENGTH

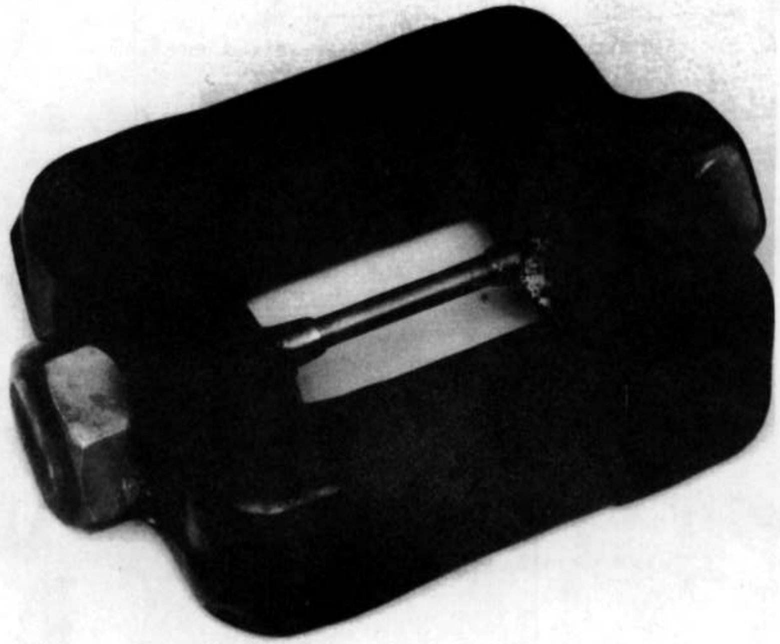
Prior to Testing

After 180 Day Test

FIGURE 9 - TYPE 431 STAINLESS STEEL, HARDENED AND TEMPERED, TRANSVERSE 'C'—RING SPECIMEN STRESSED TO 100% OF THE YIELD STRENGTH

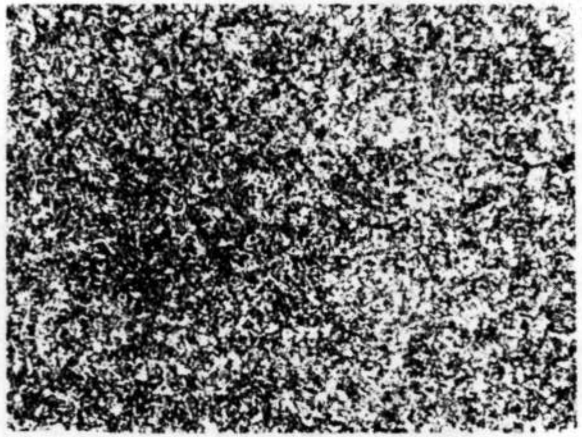


Prior to Testing

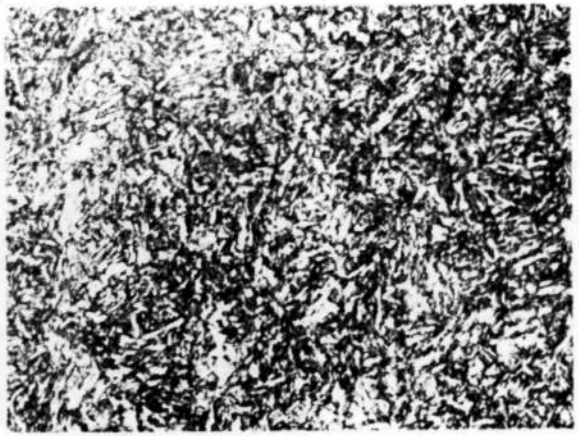


After 180 Day Test

FIGURE 10 - TYPE 431 STAINLESS STEEL, HARDENED AND TEMPERED, LONGITUDINAL ROUND TENSILE SPECIMEN STRESSED TO 100% OF THE YIELD STRENGTH

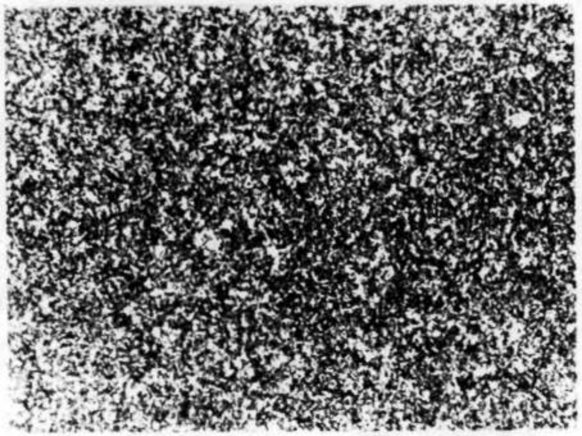


Mag 100X

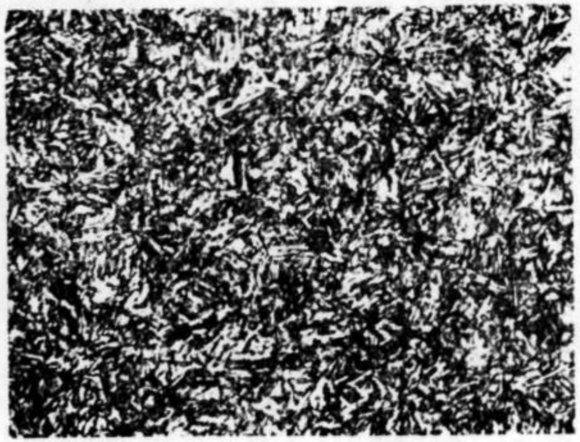


Mag 500X

Longitudinal



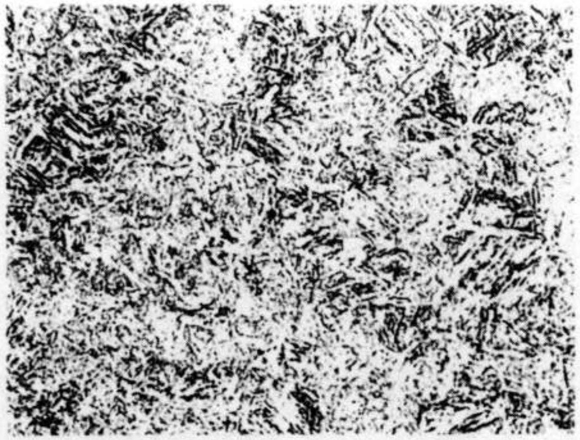
Mag 100X

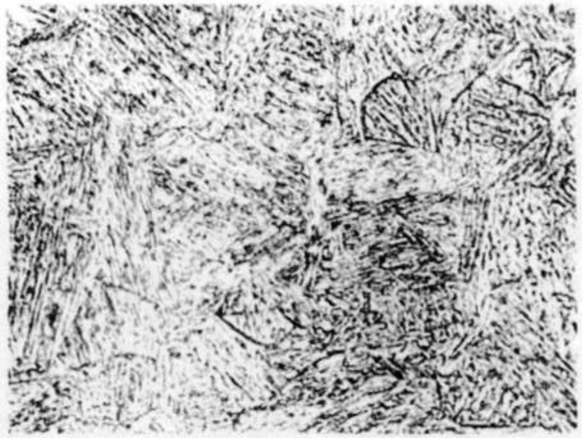


Mag 500X

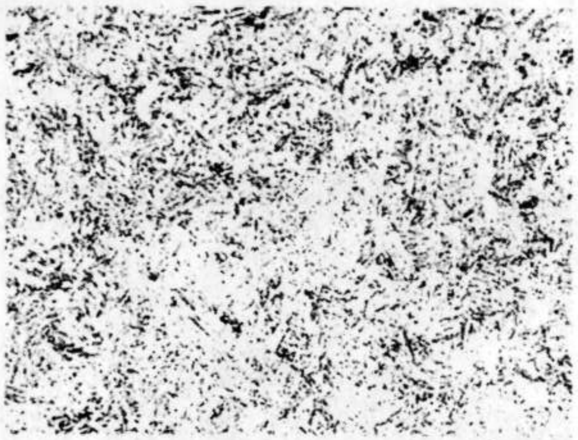
Transverse

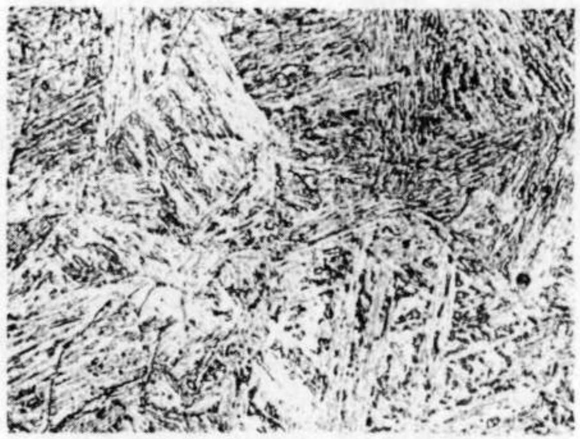
FIGURE 11 - MICROSTRUCTURE OF 431 STAINLESS STEEL, ANNEALED, BAR
Etchant : Picric - Hydrochloric





Mag 100X Longitudinal Mag 500X





Mag 100X Transverse Mag 500X

FIGURE 12 - MICROSTRUCTURE OF 431 STAINLESS STEEL, HARDENED AND TEMPERED, BAR
Etchant : Picric - Hydrochloric

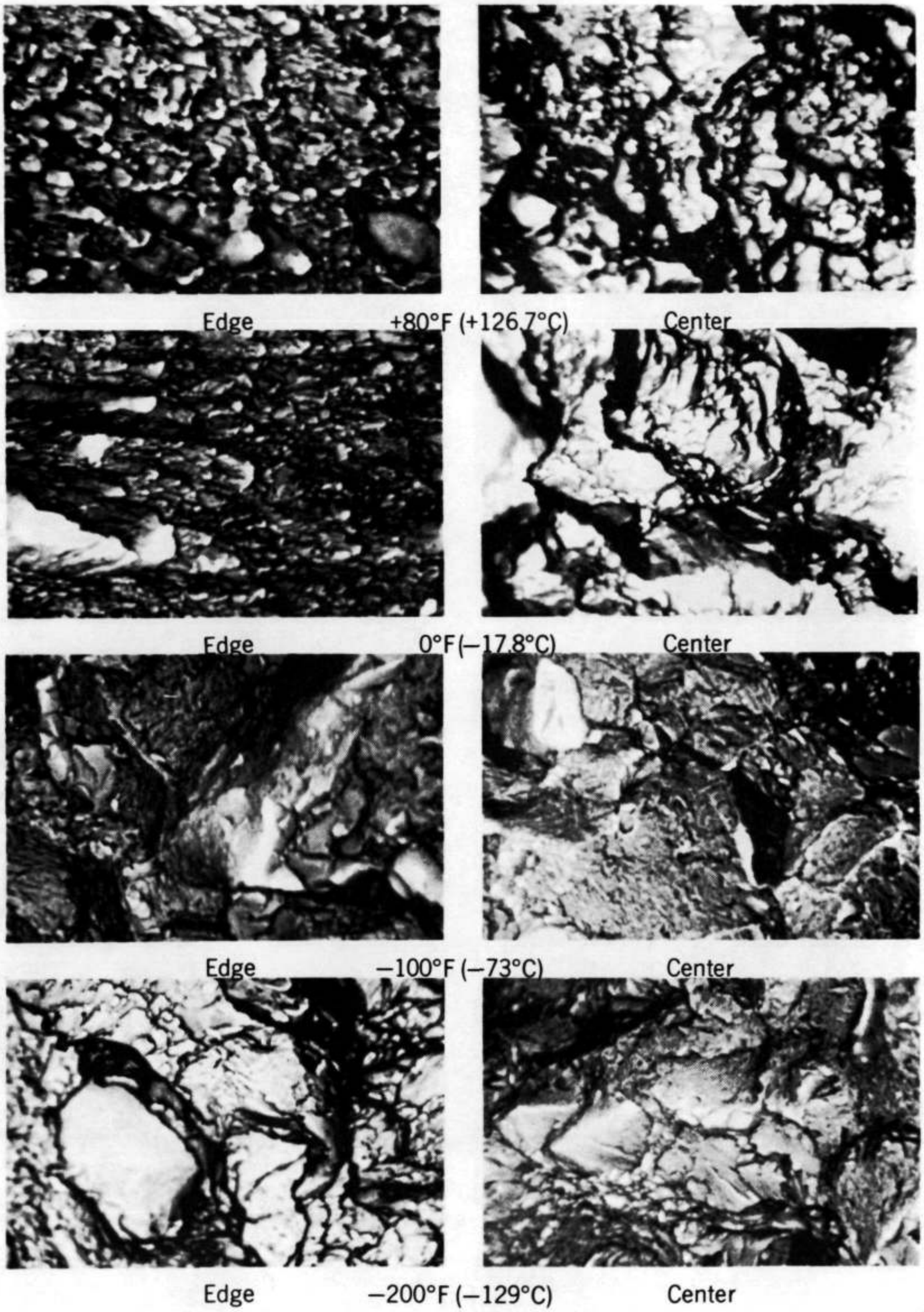


FIGURE 13 - SEM FRACTOGRAPHS OF 431 STAINLESS STEEL ANNEALED SMOOTH BAR TENSILE FRACTURES 2300X MAG

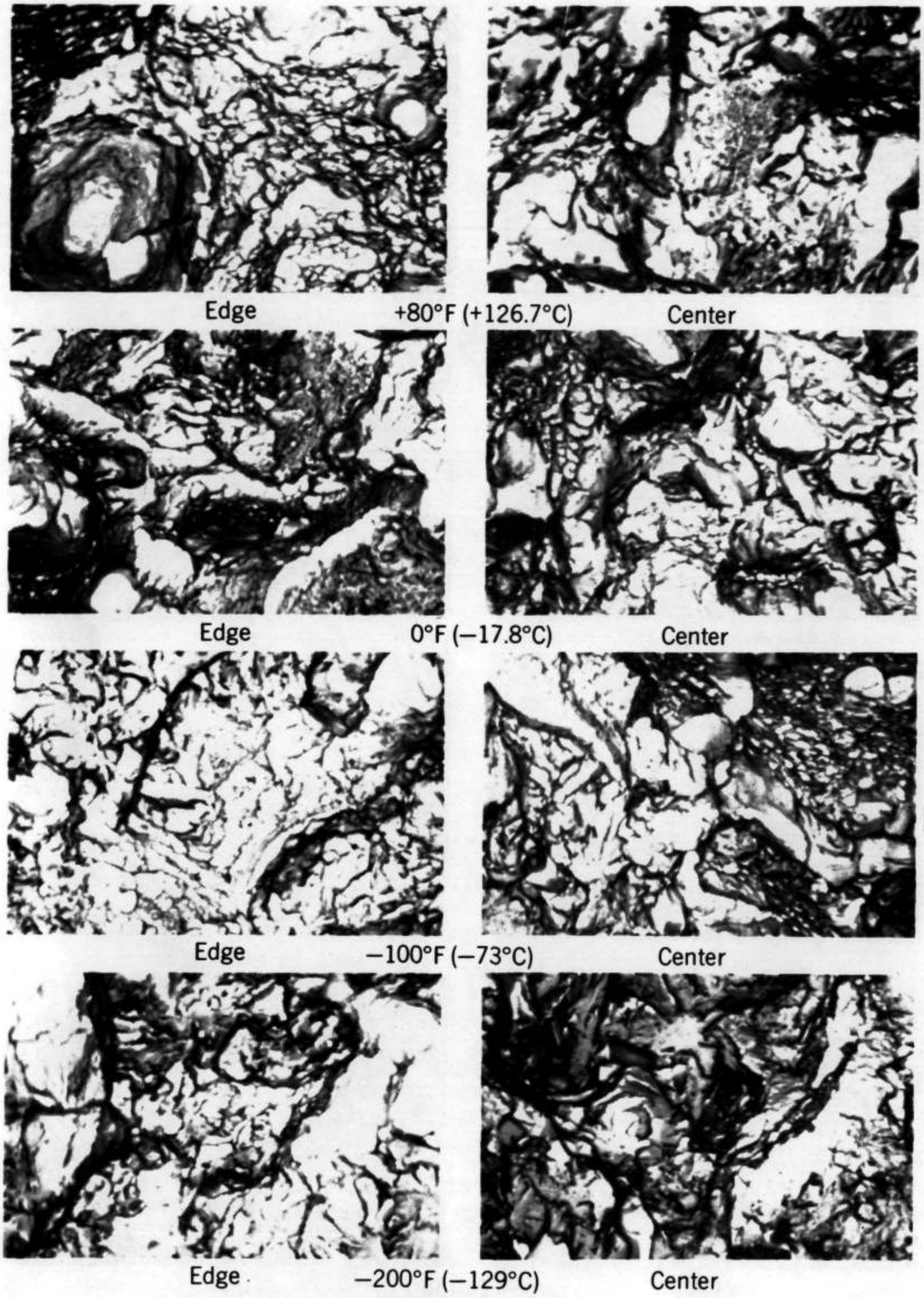


FIGURE 14 · SEM FRACTOGRAPHS OF 431 STAINLESS STEEL ANNEALED V–NOTCH BAR TENSILE FRACTURES 2300X MAG

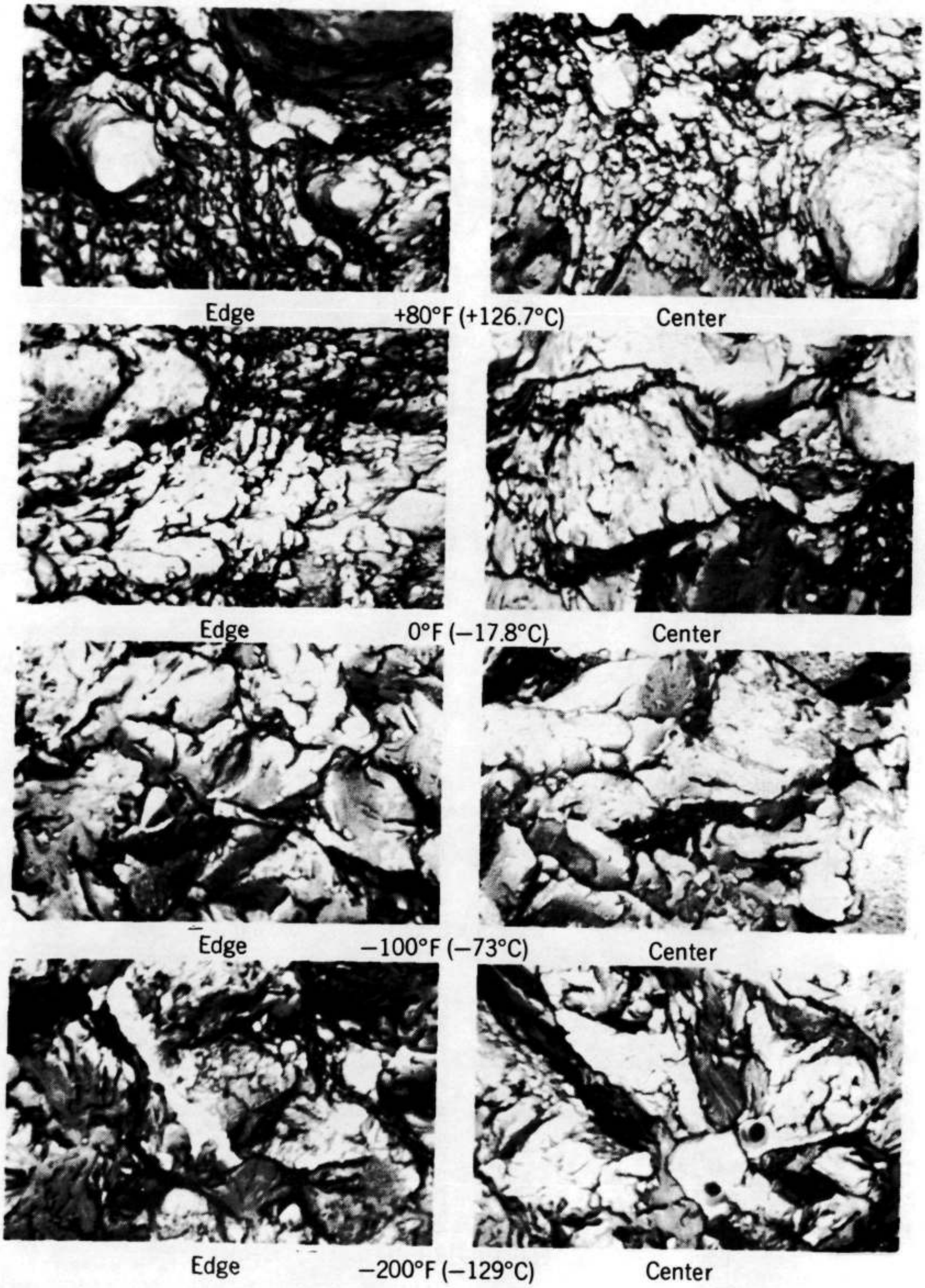


FIGURE 15 - SEM FRACTOGRAPHS OF 431 STAINLESS STEEL ANNEALED CHARPY V–NOTCHED IMPACT BAR SPECIMEN FRACTURES

2300X MAG

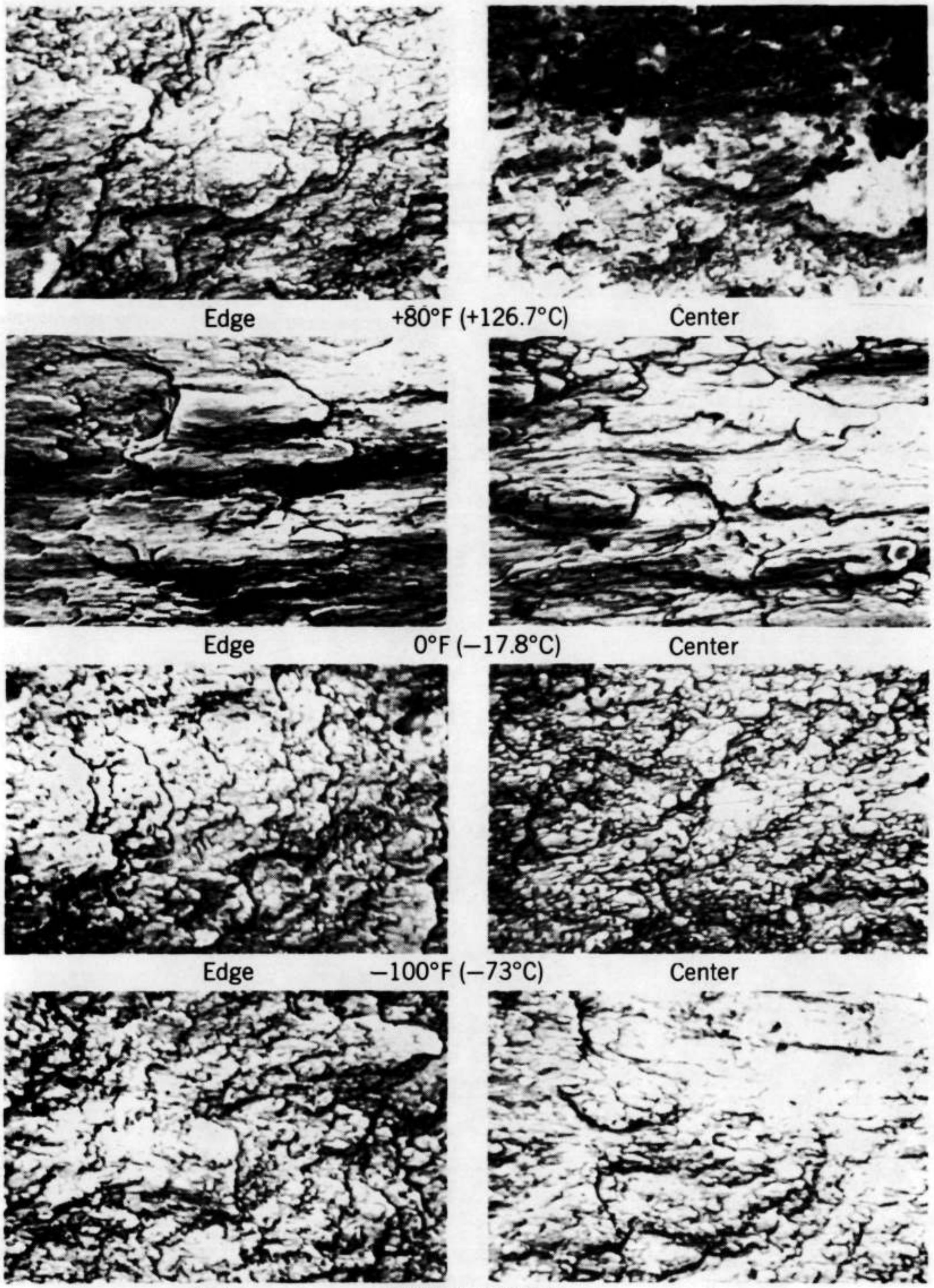


FIGURE 16 - SEM FRACTOGRAPHS OF 431 STAINLESS STEEL ANNEALED DOUBLE SHEAR SPECIMEN FRACTURES 2300X MAG

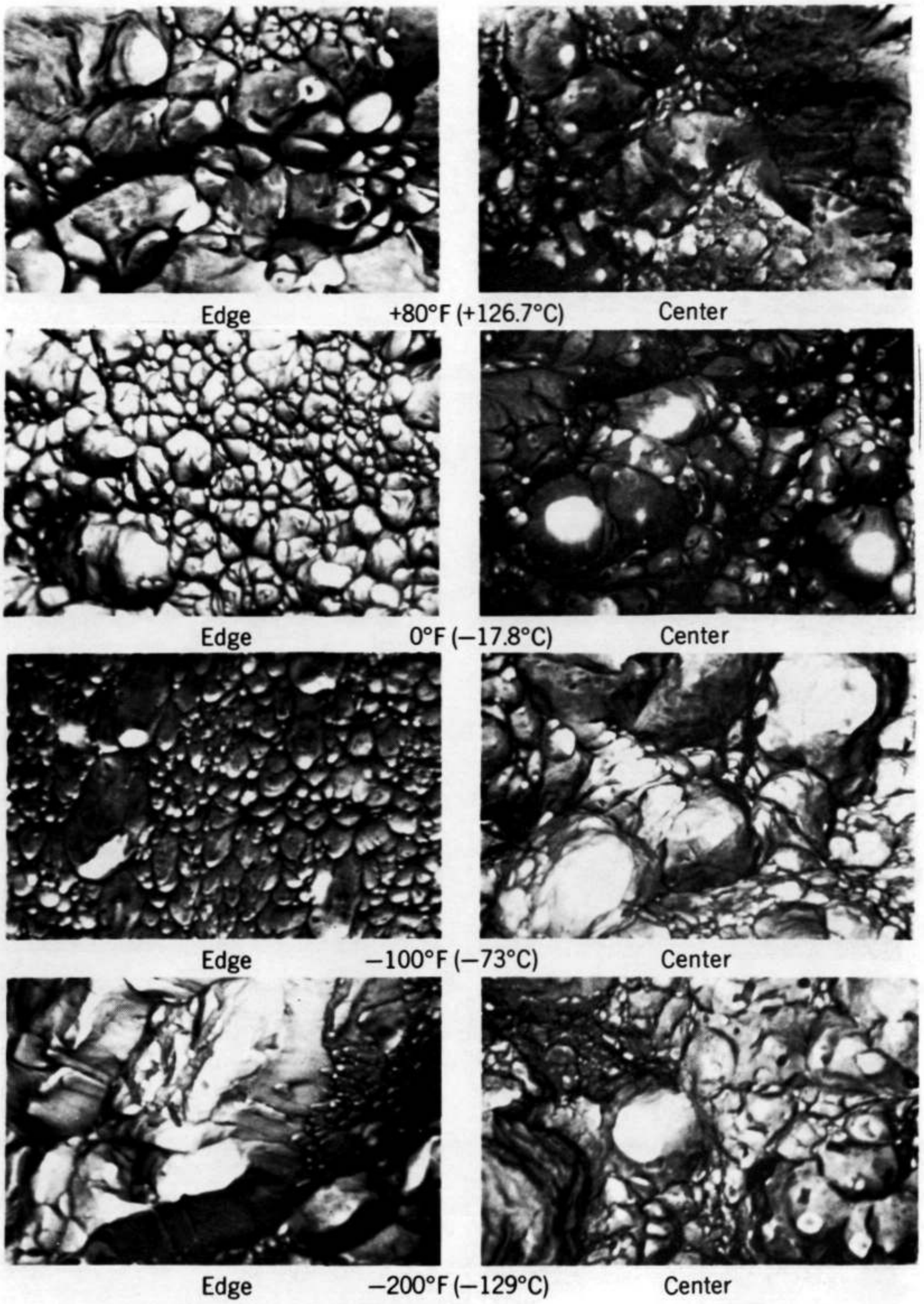


FIGURE 17 - SEM FRACTOGRAPHS OF 431 STAINLESS STEEL HARDENED AND TEMPERED SMOOTH BAR TENSILE FRACTURES 2300X MAG

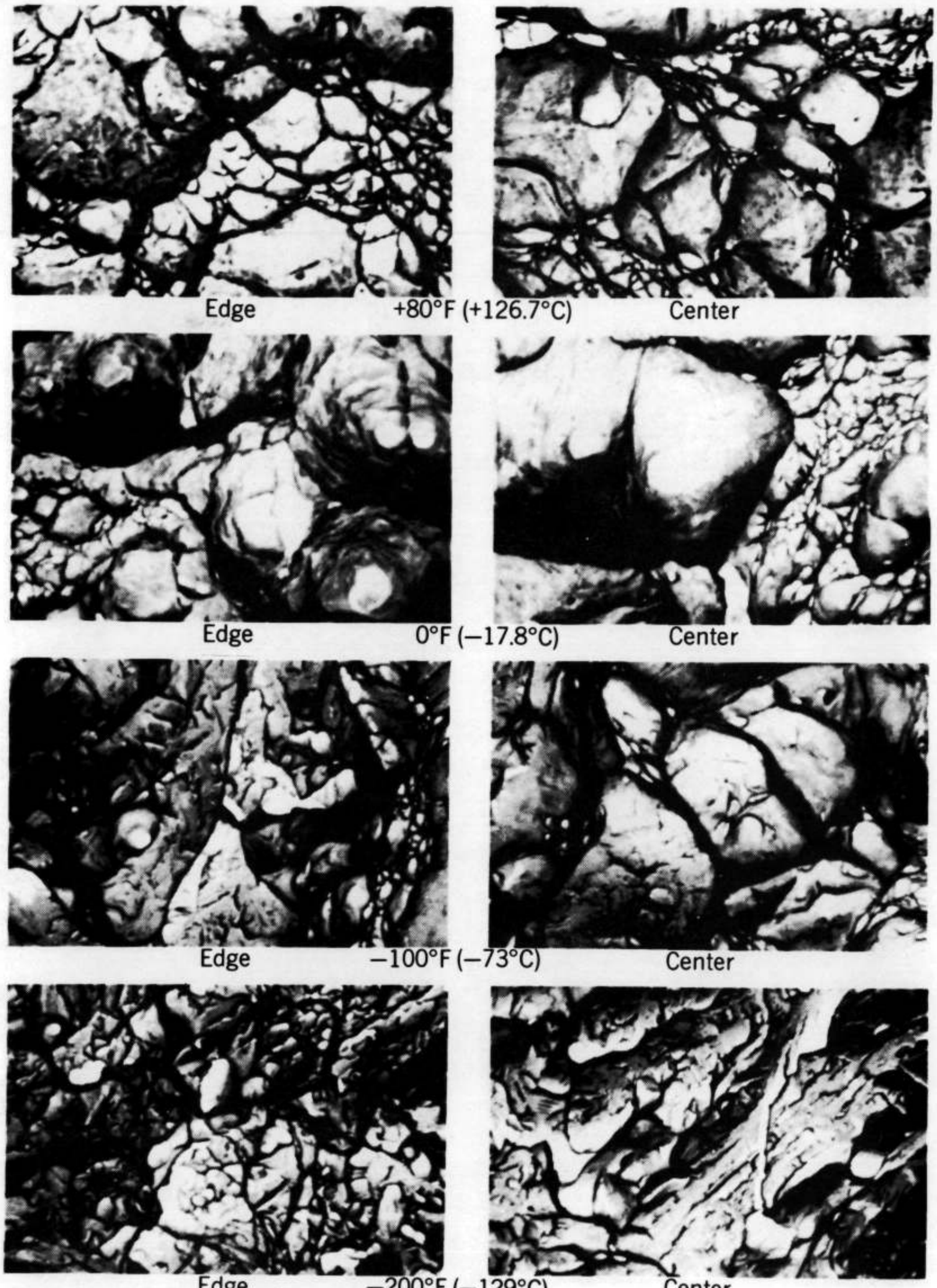


FIGURE 18 - SEM FRACTOGRAPHS OF 431 STAINLESS STEEL HARDENED AND TEMPERED V—NOTCH BAR TENSILE FRACTURES 2300X MAG

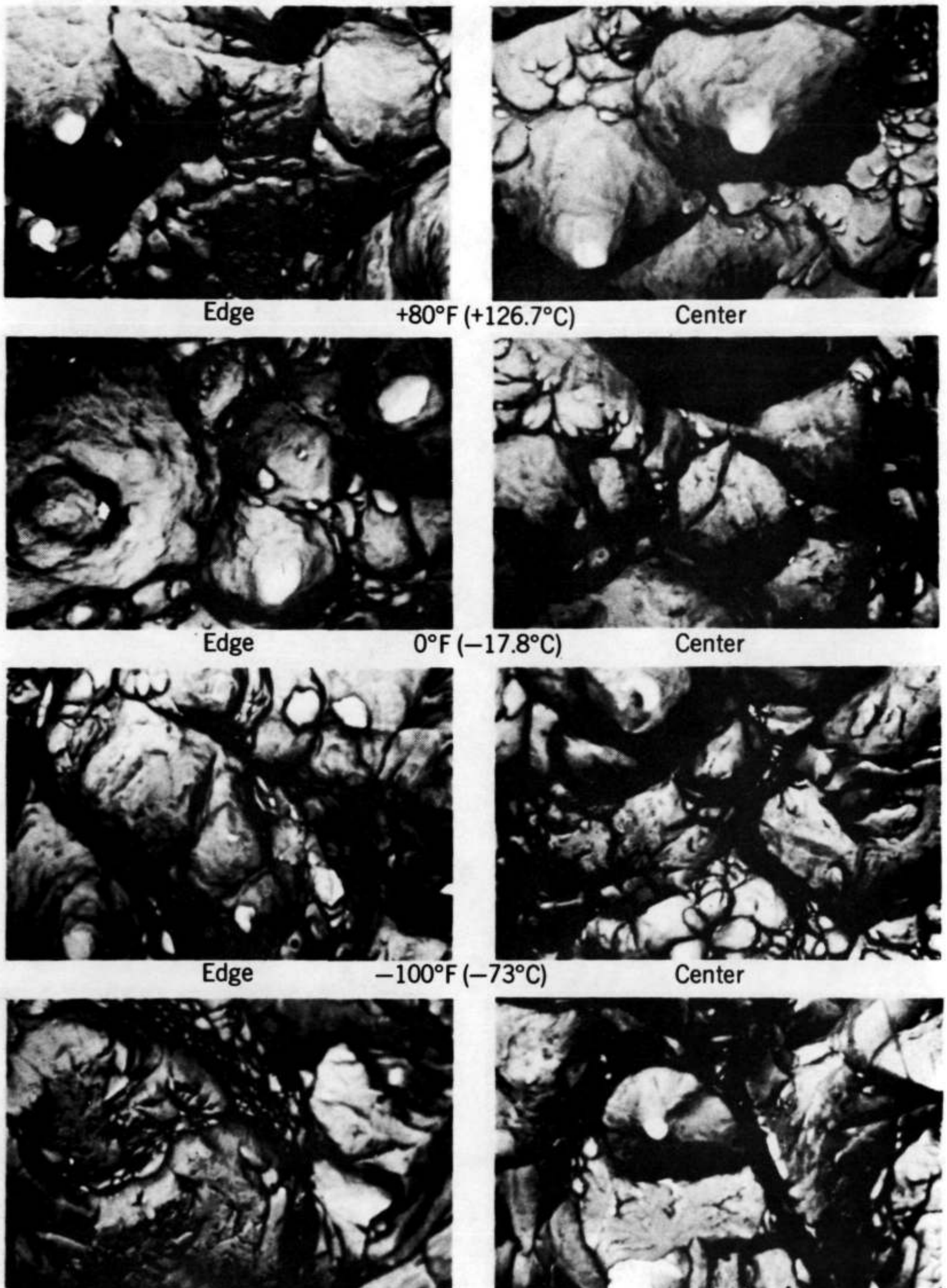


FIGURE 19 - SEM FRACTOGRAPHS OF 431 STAINLESS STEEL HARDENED AND TEMPERED CHARPY V—NOTCHED IMPACT BAR SPECIMEN FRACTURES 2300X MAG

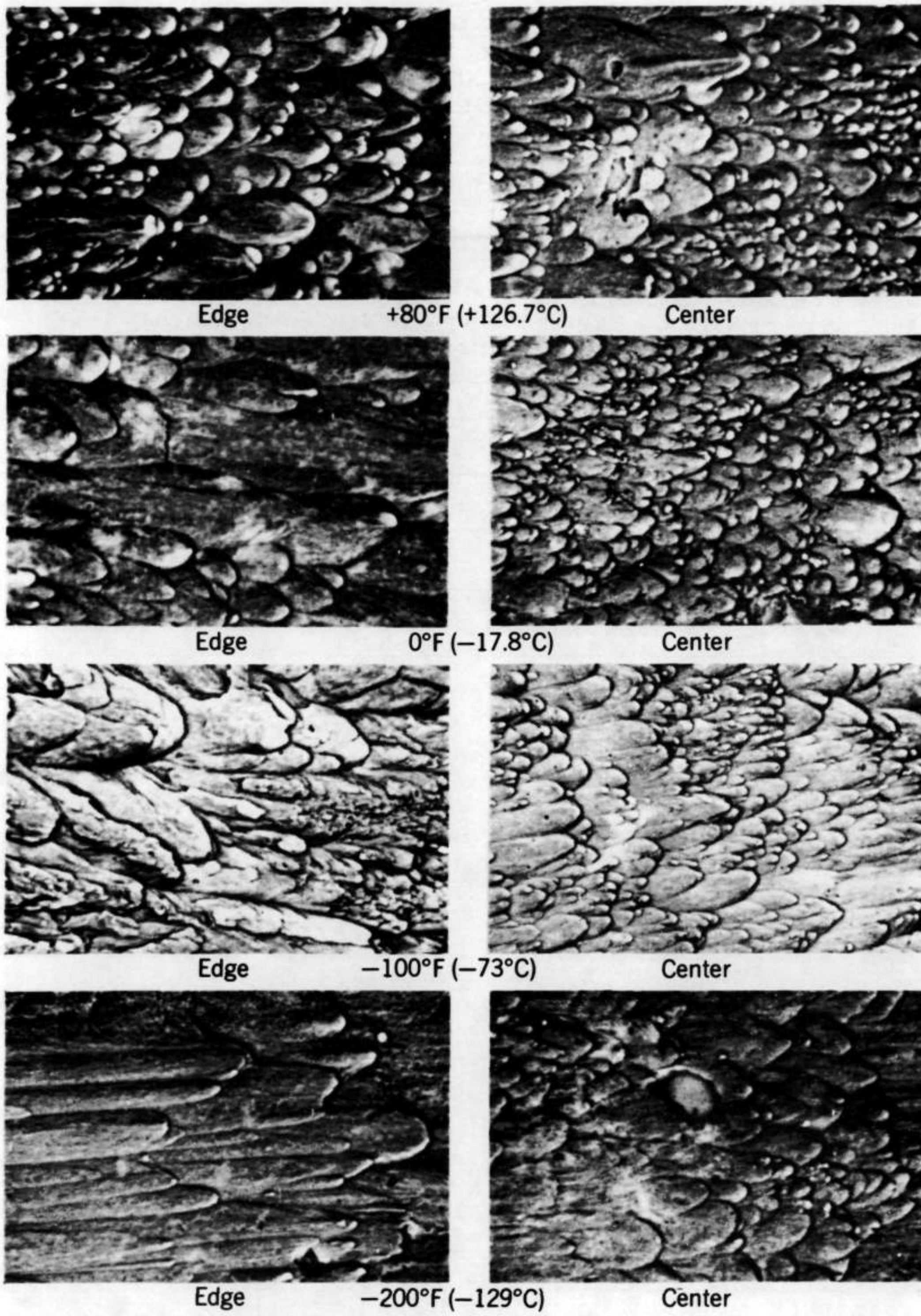


FIGURE 20 - SEM FRACTOGRAPHS OF 431 STAINLESS STEEL HARDENED AND TEMPERED DOUBLE SHEAR SPECIMEN FRACTURES 2300X MAG

APPROVAL

A MECHANICAL PROPERTY AND STRESS CORROSION EVALUATION OF 431 STAINLESS STEEL ALLOY

By

J. W. Montano

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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