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THE EFFECTS OF SOLUTION TREATMENT ON THE MECHANICAL PROPERTIES OF AGE-HARDENED A-286 BAR STOCK AT ELEVATED AND CRYOGENIC TEMPERATURE

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February 16, 1972

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16. ABSTRACT

This report presents the mechanical properties of solution treated and age hardened A-286 corrosion resistant steel bar stock. Material solution treated at 1650°F (899°C) or 1800°F (982°C), each followed by an age hardening treatment at 1325°F (718°C), was evaluated. Test specimens manufactured from 1.50 inch (3.81 cm) diameter bar stock were tested at temperatures from +1200°F (+649°C) to -423°F (-253°C). The test data indicated excellent tensile, yield, elongation and reduction-in-area properties at all testing temperatures for both solution treated and aged materials. Cryogenic temperature notched tensile, impact, and shear tests indicated excellent notch strength, ductility, and shear values. There was very little difference in the mechanical properties of the two solution treated and aged materials. The only exception was that the 1800°F (962°C) solution treated and aged material had superior stress rupture properties at 1200°F (649°C).

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THE EFFECTS OF SOLUTION TREATMENT ON THE MECHANICAL PROPERTIES OF AGE HARDENED A-286 BAR STOCK AT ELEVATED AND CRYOGENIC TEMPERATURE

SUMMARY

The mechanical properties of solution treated and precipitation hardened A-286 corrosion resistant steel bar stock were determined for the temperature range of +1200°F (+649°C) to -423°F (-253°C). The effects of solution treatments of 1650°F (899°C) and 1800°F (982°C), followed by a 1325°F (718°C) precipitation hardening treatment, on 1.5-inch (3.81 cm) diameter bar stock were determined.

The elevated temperature tensile properties such as ultimate tensile and yield strengths decreased slightly with increasing temperatures. Decrease in elongation and reduction in area were more noticable at 1200°F (649°C); however, these properties still indicated A-286 to be a ductile material.

The low temperature mechanical properties increased with decreasing temperatures except for reduction in area which decreased slightly at -423°F (-253°C). Notched tensile strength increased with decreasing temperature. The notched-to-unnotched tensile ratio decreased slightly at cryogenic temperatures, but never dropped below 1.0. Impact strength remained virtually unchanged at low temperature while shear strength increased with decreasing temperature.

There were no significant effects of solution treatment on the mechanical properties, except that the stress-rupture properties of the 1800°F (982°C) solution treated and aged material were superior.

INTRODUCTION

A-286 was developed primarily as a high strength material for elevated temperature service. The alloy is a heat treatable stainless steel containing approximately 26% nickel, 16% chromium, and 2% titanium, with smaller amounts of manganese, silicon, molybdenum vanadium, aluminum, and boron. A-286, in the annealed condition, is as machinable as the regular chromium-nickel stainless steels (Ref. 1).

An increase in strength can be obtained by cold working the material. Previous work done by this division (Ref. 2) has shown that A-286 has excellent low temperature mechanical properties which make it suitable for application at temperatures as low as -423°F (-253°C). The cold worked alloy has proved to have excellent resistance to stress corrosion when tested by alternate immersion in a 3.5 percent NaCl solution for 180 days. In a continuing program to develop and evaluate high strength materials for fastener applications, this division also investigated A-286 bolts manufactured by several different companies (Ref. 3 and 4). Work done by this division on A-286 parent alloy and weldments indicated that the mechanical properties were good over the temperature range of ambient to liquid hydrogen temperature (Ref. 5).

This report is concerned primarily with the effects of solution treatment on the aged hardened tensile, shear, impact, and stress rupture properties of A-286 corrosion resistant steel alloy.

EQUIPMENT AND TEST SPECIMENS

The equipment used in this evaluation is partially described in a report by P. C. Miller.* Cryogenic Testing is presently performed in the new cryogenic facility. We now utilize a special cryogenic extensometer which attaches directly to the specimen gage length and is usable to liquid hydrogen temperature. However, at the time the data were generated for this report a 1/2 inch (1.27 cm) differential transformer extensometer was used down to -200°F (-129°C) and a deflectometer was used for liquid nitrogen and liquid hydrogen temperature tests to record the load-strain curves. The deflectometer was also used for the elevated temperature tensile tests. The smooth tensile test specimen configuration used in this evaluation appears in Figure 1.

The V-notch tensile specimen configuration was dimensioned so that the d/D ratio of the notch diameter to the major diameter (d/D) was approximately 7.0 The V-notch diameter was approximately 0.308 inches (0.782 cm) and the major diameter was approximately 0.440 inches (1.118 cm). The shear specimens were 0.4375 inch (1.1112 cm) diameter by 2.0 inch (5.08 cm) length. Charpy V-notched impact specimens were fabricated per Federal Standard 151 Method 221.1.

The chemical composition of the material used in this investigation is shown in Table I. Prior to machining into test specimens, the 1.50 inch (3.81 cm) diameter bar material was processed as follows:

Solution Treatment: 1650°F (899°C) - Two hours - Oil quenched, or
Solution Treatment: 1800°F (982°C) - Two hours - Oil quenched.
Each was followed by an
Aging Treatment: 1325°F (718°C) - 16 hours - Air cooled.

*Low Temperature Mechanical Properties of Several Aluminum Alloys and Their Weldments, MTP-S&E-M-61-16, October 2, 1961.

Microhardness readings as shown in Figure 2a and 2b indicated little difference in the hardness of the two heat treatments. However, these readings do indicate that the greatest hardness is found at the center of the bars.

RESULTS AND DISCUSSION

The tensile test results of the elevated temperature through cryogenic temperature mechanical properties evaluation are tabulated in Tables II, III, and IV, and these properties are plotted in Figures 3 - 6.

Table II contains test data on 0.125-inch (0.318 cm) diameter specimens machined from bar stock which was solution treated at 1650°F (899°C) and aged at 1325°F (718°C). The 0.2 percent offset yield load was acquired by use of a deflectometer for all elevated temperature tensile tests and also for the liquid nitrogen and liquid hydrogen tensile tests. For all other test temperatures, 75°F (23.9°C), 0°F (-17.8°C), -100°F (-73°C), and -200°F (-129°C) the tensile yield loads were acquired by use of a 1/2-inch (1.27 cm) extensometer. Table III contains the tensile test data on 0.125-inch (0.318 cm) diameter specimens machined from bar stock which was heat treated at 1800°F (982°C) and aged at 1325°F (718°C).

Table IV contains the low temperature notched tensile strength and notched to unnotched tensile ratios for the 1650°F (899°C) and the 1800°F (982°C) solution treated and aged bar stock. These data are plotted in Figures 4 and 5.

Table V contains charpy V-notched impact test data. These low temperature tests utilized a special cover for the impact tester specimen holder, which enabled the specimen to be cooled to the test temperature of -320°F (-196°C), with liquid nitrogen (LN_2) vapor. The test set-up also utilized a recorder-controller actuated by a thermocouple attached to the V-notch in the test specimen. A second thermocouple was also attached to the V-notch and potentiometer readings were made for temperature accuracy checks. For LN_2 temperatures the specimens were pre-soaked in LN_2, prior to testing, and the test specimen holder was precooled with LN_2. For the lowest test temperature, between liquid helium and LN_2 temperatures, the impact specimens and the test fixture specimen holder were precooled with LN_2 and liquid helium was sprayed directly on the test specimen, cooling it to approximately liquid hydrogen temperature. These data are plotted in Figure 5.

Table VI contains the double shear test data for the solution treated and aged A-286 bar stock, tested at ambient temperature and at liquid nitrogen temperature. The shear ultimate and shear yield (approximated by deflectometer measurement) increased at liquid nitrogen temperature.

Table VII presents the 1200°F (649°C) stress-rupture test data taken from smooth tensile specimens (as illustrated in Figure 1) stressed to 65,000 psi (0.488 GN/m^2). These data indicate the superior stress-rupture properties of the 1800°F (982°C) solution treated and aged material. This table also indicated which specimens were used to illustrate the microstructure and fractography of the test material after exposure to the stress-rupture test.

The microstructure of the center of the test bar as revealed by a nitric, hydrochloric and acetic acid etchant is illustrated in Figure 7, representing the microstructures of the 1650°F (899°C) solution treated and aged material and the 1800°F (982°C) solution treated and aged material prior to testing. As indicated in the photomicrographs there is very little difference in the overall microstructure of the two solution treated and aged materials.

Figures 8 and 9 represent the microstructures of the 1650°F (899°C) solution treated and aged material and the 1800°F (982°C) solution treated and aged material, respectively, after stress rupture testing at 1200°F (649°C). As previously mentioned there is no apparent difference between the microstructures of the two solution treated and aged materials.

Figures 10 and 11 represent fractographs taken by Transmission Electron Microscopy (TEM) and reflected Scanning Electron Microscopy (SEM). They indicate ductility at the outer edge of the fracture, and brittleness at the center of the fracture, for the 1650°F (899°C) solution treated and aged material and the 1800°F (982°C) solution treated and aged material, respectively, after stress-rupture testing at 1200°F (649°C).

CONCLUSIONS

Based upon the results of this evaluation, solution treated and aged A-286 corrosion resistant steel bar, mechanical properties such as ultimate tensile and yield strength, notched tensile strength, shear ultimate and shear yield strength are shown to increase with decreasing temperature for both solution treated materials [1650°F (899°C) and 1800°F (982°C)]. Elongation and reduction-in-area values also increase with decreasing temperature through liquid nitrogen temperature. Impact strength remained fairly constant over the testing temperature range of ambient to liquid hydrogen (approximated) temperature.

Elevated temperature tensile test data indicate almost identical properties for the two different solution treated and aged materials. For both solution treated and aged materials, at 1200°F (649°C) there is an approximate loss (when compared to ambient temperature mechanical properties) in ultimate tensile strength of 25 percent, less than 10 percent loss in the 0.2% offset yield strength, and approximately 40 percent loss in elongation. However, the material retains a ductility greater than 15 percent elongation in four diameters (4D). The 1800°F (982°C) solution treated and aged material indicated slightly superior ultimate tensile, yield and elongation values, while the 1650°F (899°C) solution treated and aged material data indicated a slightly greater reduction in area. The greatest difference in properties of the two different solution treated and aged materials is seen in the 1200°F (649°C) stress rupture data. These data indicate the superior stress-rupture life of the 1800°F (982°C) solution treated and aged material which sustained the constant stress of 65,000 psi (0.488 GN/m^2) for approximately 2 1/3 times longer than the 1650°F (899°C) solution treated and aged material.

This evaluation indicates that for elevated temperature long time usage, the 1800°F (982°C) solution treated and aged material is superior. For low temperature usage either solution treatment is acceptable. This evaluation also indicates that A-286 precipitation hardenable, corrosion resistant steel in the solution treated and aged condition has excellent mechanical properties over the entire temperature range of +1200°F (649°C) to -423°F (-253°C). Based on this and previous testing and experience, A-286 is recommended for applications where high strength and resistance to stress corrosion cracking is an important consideration.

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3. Montano, J. W.: "Mechanical Properties of High Strength A-286 Bolts at Cryogenic Temperatures" IN-P&VE-M-64-1, February 25, 1964, available from the author.

4. Montano, J.W.: "Low Temperature Mechanical Properties of High Strength A-286 Bolts, NASA TM X-53407, March, 1966

5. Morgan, W. R.: "Low Temperature Mechanical Properties of A-286 Alloy and its Weldments," IN-P&VE-M-62-4, May 28, 1962, available from the author.

TABLE I

CHEMICAL COMPOSITION OF A-286 ALLOY BAR STOCK

Fe	Si	Cr	Ti	Mo	V	C	B	Mn	Si	Al
Bal.	25.35	14.93	2.13	1.32	0.29	0.05	0.005	1.40	0.48	0.14

MSFC Analysis

TABLE II

MECHANICAL PROPERTIES OF A-286 TENSILE SPECIMENS
[.125-INCH (.3175 cm) DIAMETER] SOLUTION TREATED 1650°F (899°C) AND AGED AT 1325°F (718°C)

Test Temp. °F (°C)	U.T.S. ksi	U.T.S. (GN/m²)	.2% Offset Y.S. ksi	.2% Offset Y.S. (GN/m²)	Elongation 1/2-Inch (1.27 cm) (4D)	Reduction In Area (%)	No. of Tests
+1200 (+649.0)	118.3	(0.816)	*100.2	(0.691)	17.6	43.0	5
+1000 (+538.0)	133.3	(0.919)	*100.0	(0.689)	19.0	43.8	2
+ 800 (+427.0)	139.3	(0.960)	* 98.2	(0.677)	21.5	43.0	2
+ 75 (+ 23.9)	159.4	(1.099)	110.6	(0.762)	30.0	47.6	4
0 (- 17.8)	166.2	(1.146)	116.9	(0.806)	33.0	48.9	4
- 100 (- 73.0)	177.8	(1.226)	116.4	(0.802)	34.0	48.8	4
- 200 (-129.0)	182.9	(1.261)	122.5	(0.845)	33.5	48.8	4
- 320 (-196.0)	207.6	(1.431)	*139.6	(0.962)	45.0	50.4	4
- 423 (-253.0)	236.0	(1.627)	*151.1	(1.042)	44.0	44.7	4

*Yield Load Obtained by use of a Deflectometer

TABLE III

MECHANICAL PROPERTIES OF A-286 TENSILE SPECIMENS
[.1250-INCH (.3175 cm) DIAMETER] SOLUTION TREATED 1800°F (982°C) AND AGED AT 1325°F (718°C)

Test Temp. °F (°C)	U.T.S. ksi	U.T.S. (GN/m^2)	.2% Offset Y.S. ksi	.2% Offset Y.S. (GN/m^2)	Elongation 1/2-Inch (1.27 cm) (4D%)	Reduction In Area (%)	No. of Tests
+1200 (+649.0)	123.1	(0.849)	*105.3	(0.726)	19.7	34.3	4
+1000 (+538.0)	134.9	(0.930)	*103.7	(0.715)	19.7	44.8	2
+ 800 (+427.0)	142.2	(0.980)	*103.5	(0.714)	22.2	47.2	3
+ 75 (+ 23.9)	162.1	(1.118)	111.1	(0.766)	32.0	49.4	4
0 (- 17.8)	166.2	(1.146)	115.5	(0.796)	32.5	50.8	4
- 100 (- 73.0)	173.7	(1.198)	118.2	(0.815)	34.5	50.0	4
- 200 (-129.0)	179.9	(1.240)	116.4	(0.802)	36.0	51.5	4
- 320 (-196.0)	211.8	(1.460)	*131.0	(0.903)	44.5	50.6	4
- 423 (-253.0)	233.2	(1.608)	*149.0	(1.027)	44.0	47.4	4

* Yield Load Obtained by use of a Deflectometer

TABLE IV

LOW TEMPERATURE NOTCHED TENSILE STRENGTH AND NOTCHED/UNNOTCHED TENSILE RATIOS OF A-286 BAR, SOLUTION TREATED AT 1650°F (899°C) OR 1800°F (982°C) AND AGED AT 1325°F (718°C)

Test Temperature °F (°C)	Notched Tensile Strength 1650°F ksi	(899°C) (GN/m^2)	1800°F ksi	(982°C) (GN/m^2)	Notched/Unnotched Tensile Ratio 1650°F (899°C)	1800°F (982°C)
+75 (+24)	202.9	(1.399)	200.4	(1.382)		
	202.5	(1.396)	200.1	(1.380)		
	194.7	(1.342)	190.8	(1.316)		
Average	200.0	(1.379)	197.1	(1.359)	1.25	1.22
0 (-18)	207.1	(1.428)	200.8	(1.384)		
	207.4	(1.430)	197.7	(1.363)		
Average	207.3	(1.429)	199.2	(1.373)	1.25	1.20
-100 (-73)	214.2	(1.477)	206.7	(1.425)		
	214.2	(1.477)	201.4	(1.389)		
Average	214.2	(1.477)	204.0	(1.406)	1.20	1.17
-200 (-129)	221.4	(1.526)	206.0	(1.420)		
	220.5	(1.520)	220.7	(1.522)		
Average	221.0	(1.524)	213.4	(1.471)	1.21	1.19
-320 (-196)	237.0	(1.634)	236.7	(1.632)		
	235.6	(1.624)	236.3	(1.629)		
	237.4	(1.637)	235.3	(1.622)		
Average	236.7	(1.632)	236.1	(1.628)	1.14	1.115
-423 (-253)	253.8	(1.750)	250.3	(1.726)		
	245.9	(1.695)	249.7	(1.722)		
	252.4	(1.740)	245.0	(1.689)		
Average	250.7	(1.728)	248.3	(1.712)	1.06	1.06

TABLE V

CHARPY V-NOTCHED IMPACT TEST DATA FOR SOLUTION TREATED AND AGED A-286 BAR

Test Temp. °F	Test Temp. °C	Average Impact Energy 1650°F Ft - Lb	(899°C) (Joules)	1800°F Ft - Lb	(982°C) (Joules)	Number of Tests 1650°F (899°C)	Number of Tests 1800°F (982°C)
75	(+ 23.9)	45.2	(61.283)	44.9	(60.876)	4	4
-320	(-196.0)	46.3	(62.774)	43.2	(58.571)	4	4
-423	(-252.8)	45.8	(62.096)	43.9	(59.520)	4	4

TABLE VI

DOUBLE SHEAR TEST DATA FOR SOLUTION TREATED AND AGED A-286 BAR

Test Temp. °F	Test Temp. °C	Ultimate Shear Strength 1650°F ksi	(899°F) (GN/m^2)	1800°F ksi	(982°C) (GN/m^2)	*0.2% Offset Shear Yield 1650°F ksi	(899°C) (GN/m^2)	1800°F ksi	(982°C) (GN/m^2)
75	(+ 23.9)	99.3	(0.685)	102.8	(0.709)	58.3	(0.402)	61.0	(0.420)
-320	(-196.0)	127.4	(0.878)	128.7	(0.887)	76.8	(0.529)	74.4	(0.513)

* Shear Yield Obtained by use of a Deflectometer
Average of 4 Tests for each Temperature and each Solution Treatment.

TABLE VII

STRESS RUPTURE PROPERTIES OF A-286 SMOOTH TENSILE SPECIMENS [.1250-INCH (.3175 cm) DIAMETER]
SOLUTION TREATED AT 1650°F (899°C) AND 1800°F (982°C) AND AGED AT 1325°F (718°C)

Stress		Time to Failure Hours		Elongation in 4D%		Reduction in Area	
ksi	(GN/m^2)	1650°F (899°C)	1800°F (982°C)	1650°F (899°C)	1800°F (982°C)	1650°F (899°C)	1800°F (982°C)
65.0	(0.448)	39.6	64.0	6.5	10.0	17.4	19.0
"	"	24.6	* 68.2	8.0	7.0	17.4	20.7
"	"	* 30.1	67.6	4.5	5.5	13.2	17.4
"	"	21.0	68.9	5.5	9.0	17.4	19.4
Average		28.8	67.2	6.1	7.9	16.3	19.0

For Specimen Dimensions See Figure 1

* Specimens Used for Photomicrographs and for Fractographic Analysis
See Figures 8 - 11.

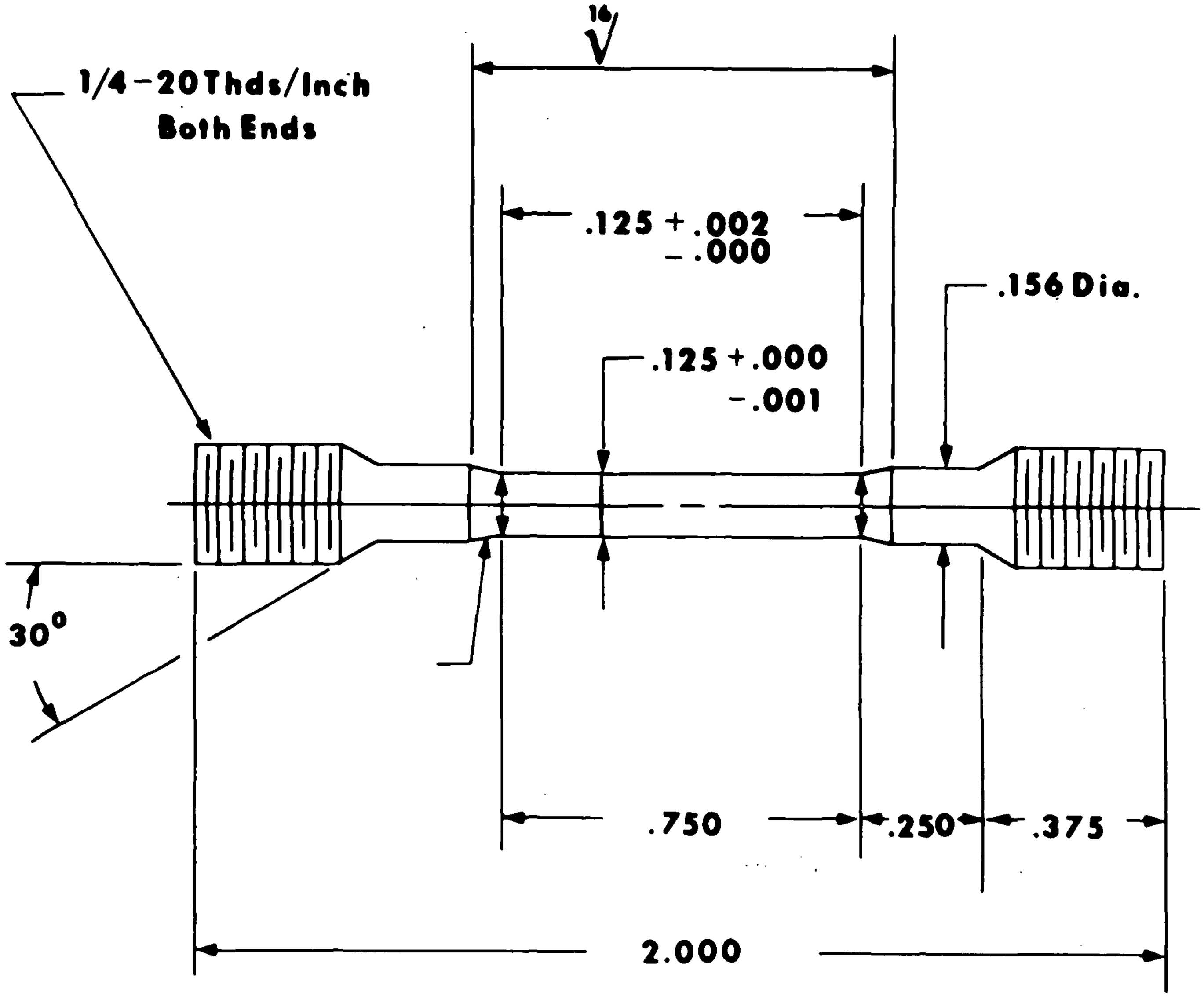
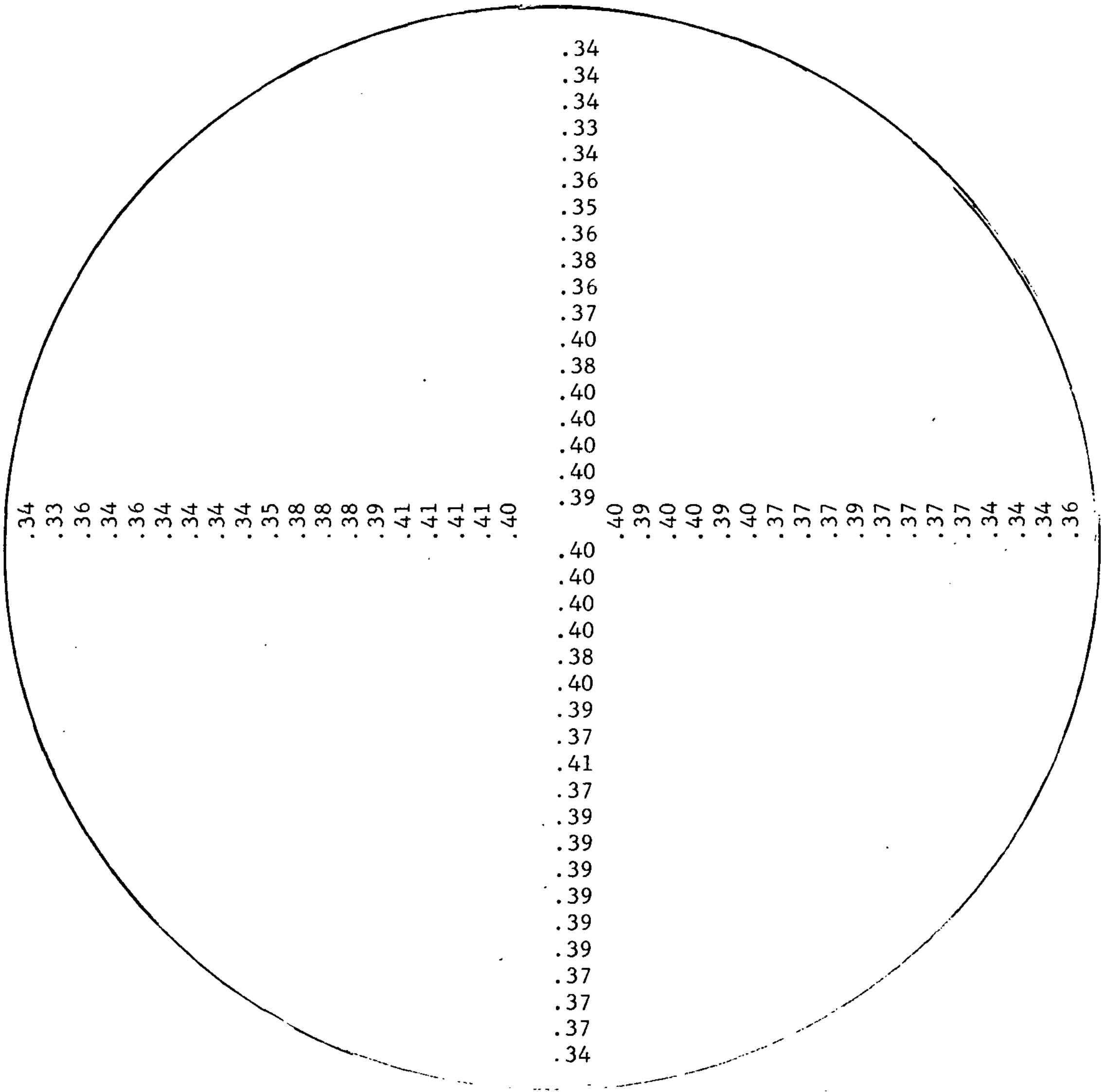


FIGURE 1. TENSILE SPECIMEN CONFIGURATION

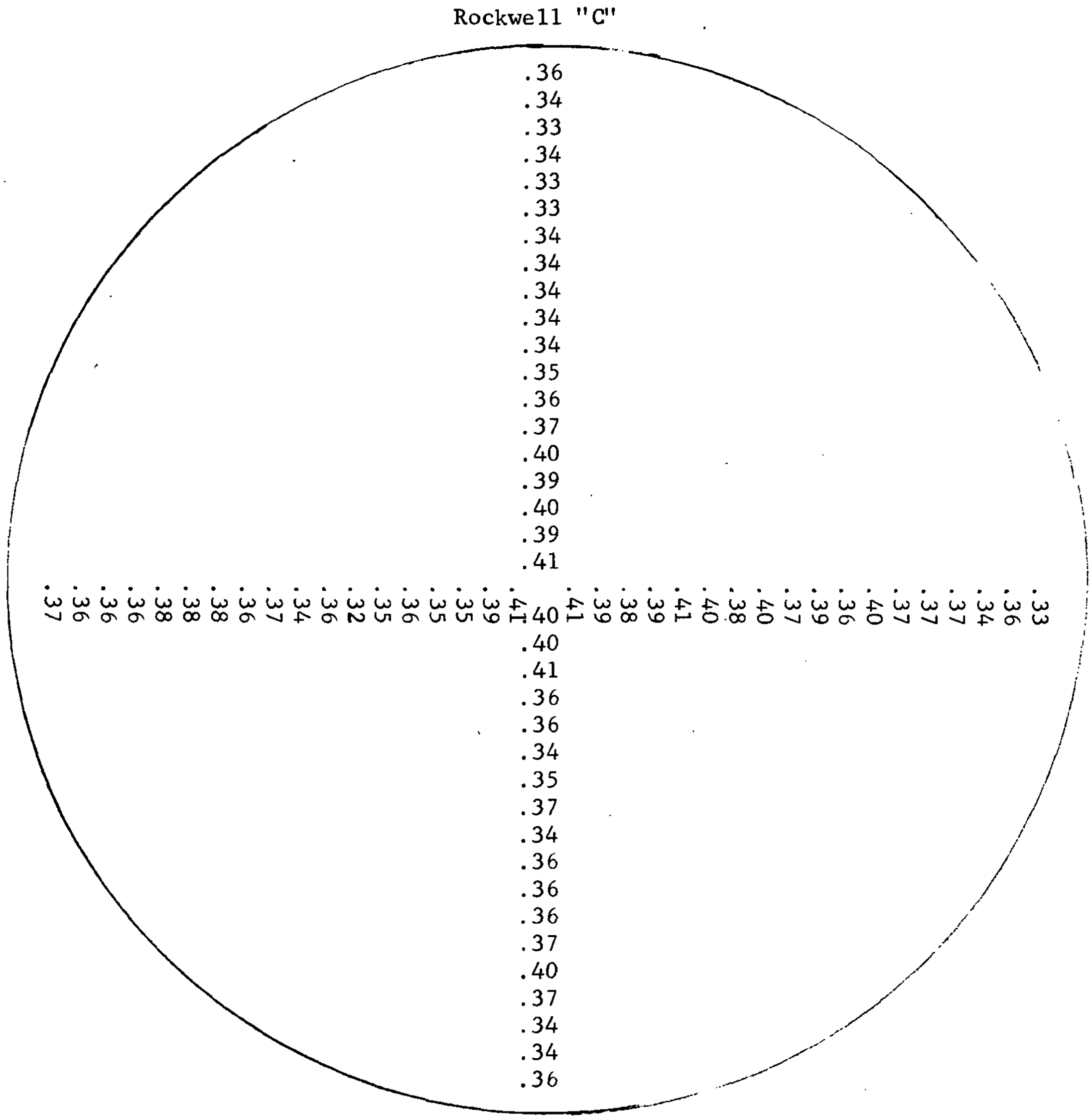
Rockwell "C"



A-286

Rockwell "C" Hardness
(Converted from D.P.H.)
Range: Rc 33-41
Average: Rc 37.4

FIGURE 2A - EFFECT OF 1650°F (899°C) SOLUTION TREATMENT ON THE AGE HARDENED MICROHARDNESS OF A-286 S.S. - 1.5-INCH (3.8 CM) DIAMETER BAR



A-286

Rockwell "C" Hardness
(Converted from D.P.H.)
Range: Rc 32-41
Average: Rc 36.7

FIGURE 2B - EFFECT OF 1800°F (982°C) SOLUTION TREATMENT ON THE AGE HARDENED MICROHARDNESS OF A-286 S.S. 1.5-INCH (3.7 CM) DIAMETER BAR

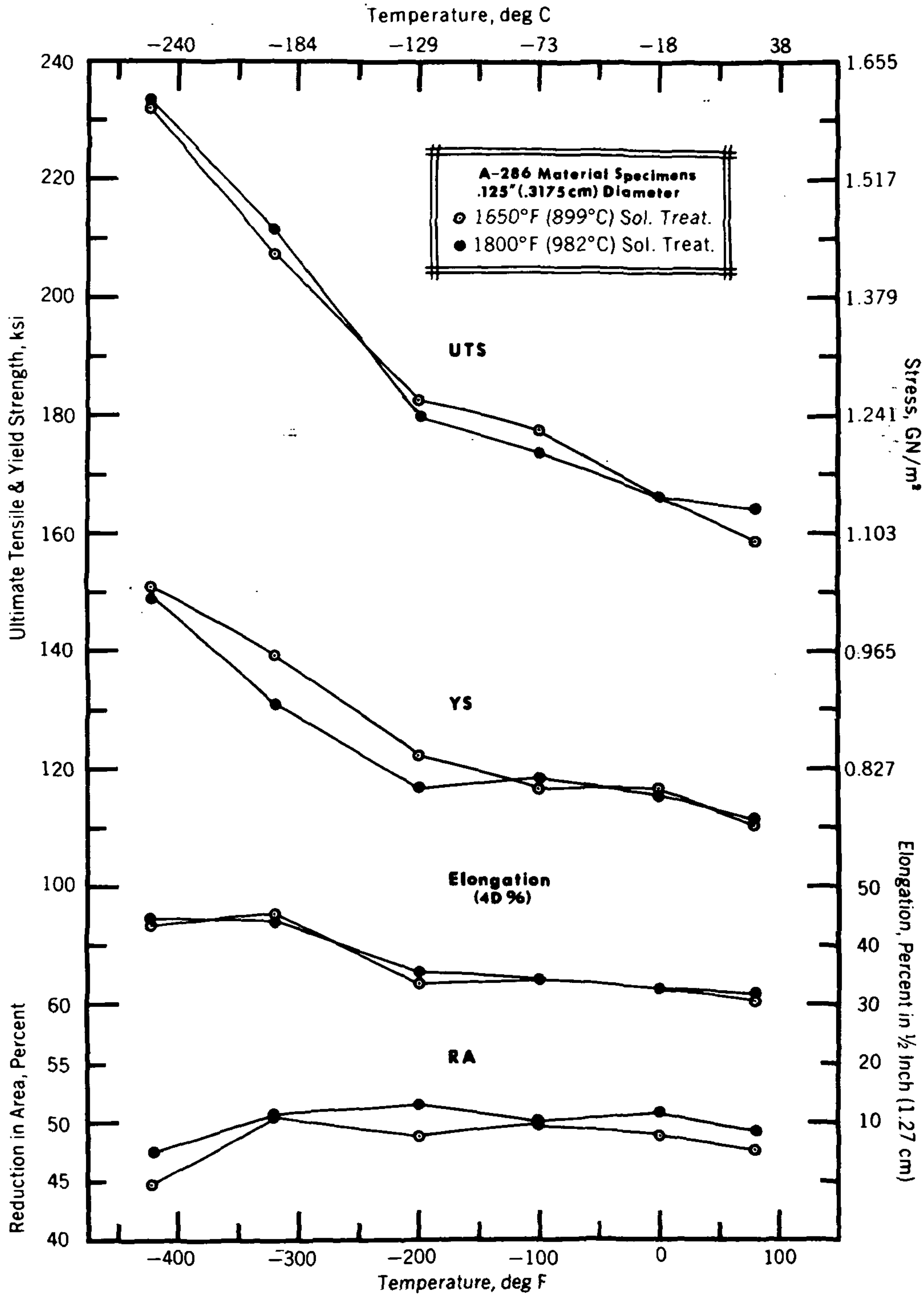


FIGURE 3 - LOW TEMPERATURE MECHANICAL PROPERTIES OF A-286 STAINLESS STEEL SOLUTION TREATED AT 1650°F AND 1800°F AND AGED AT 1325°F

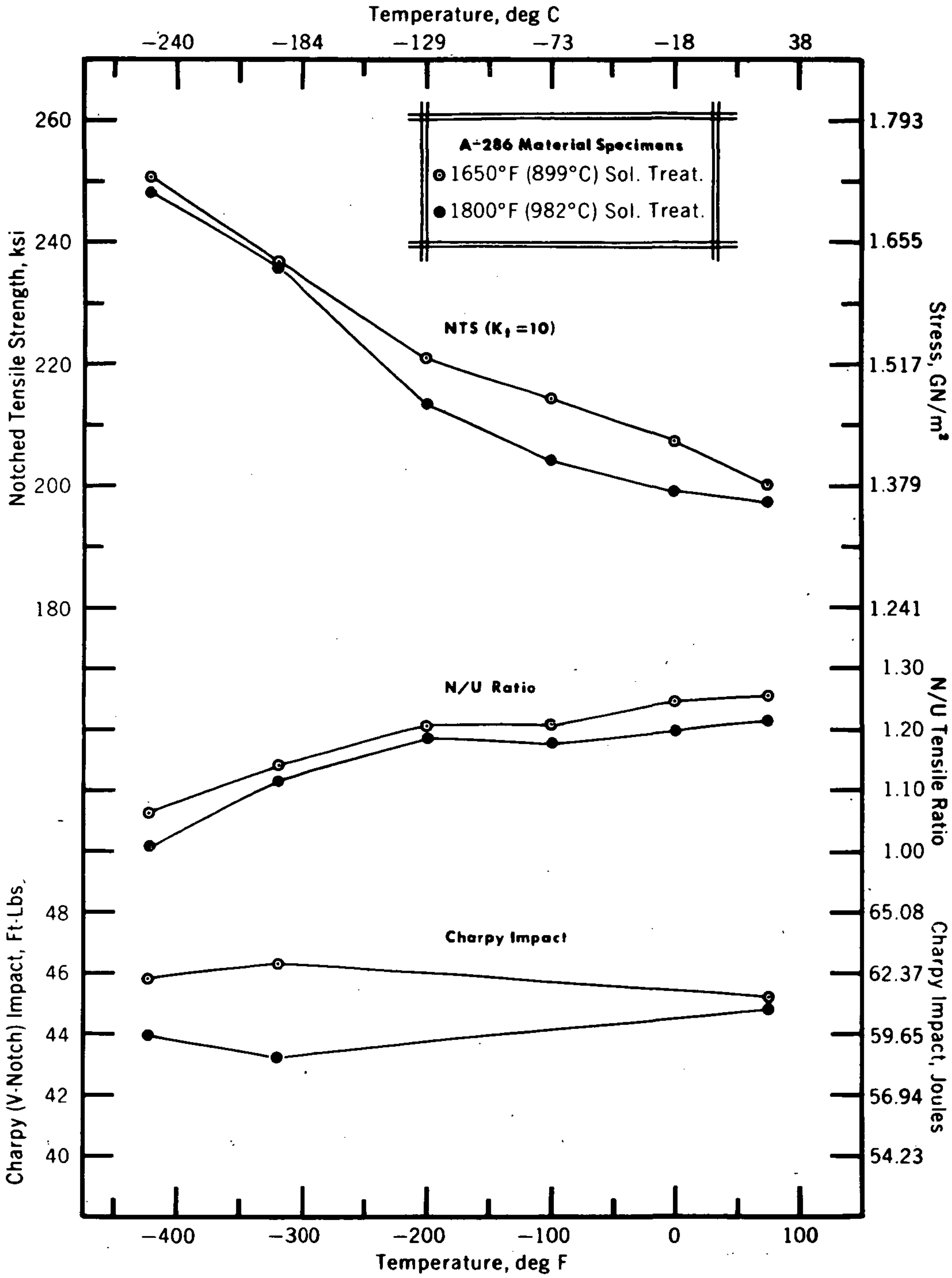


FIGURE 4 - LOW TEMPERATURE NOTCHED TENSILE AND CHARPY IMPACT PROPERTIES OF A–286 BAR SOLUTION TREATED AT 1650°F AND 1800°F AND AGED AT 1325°F

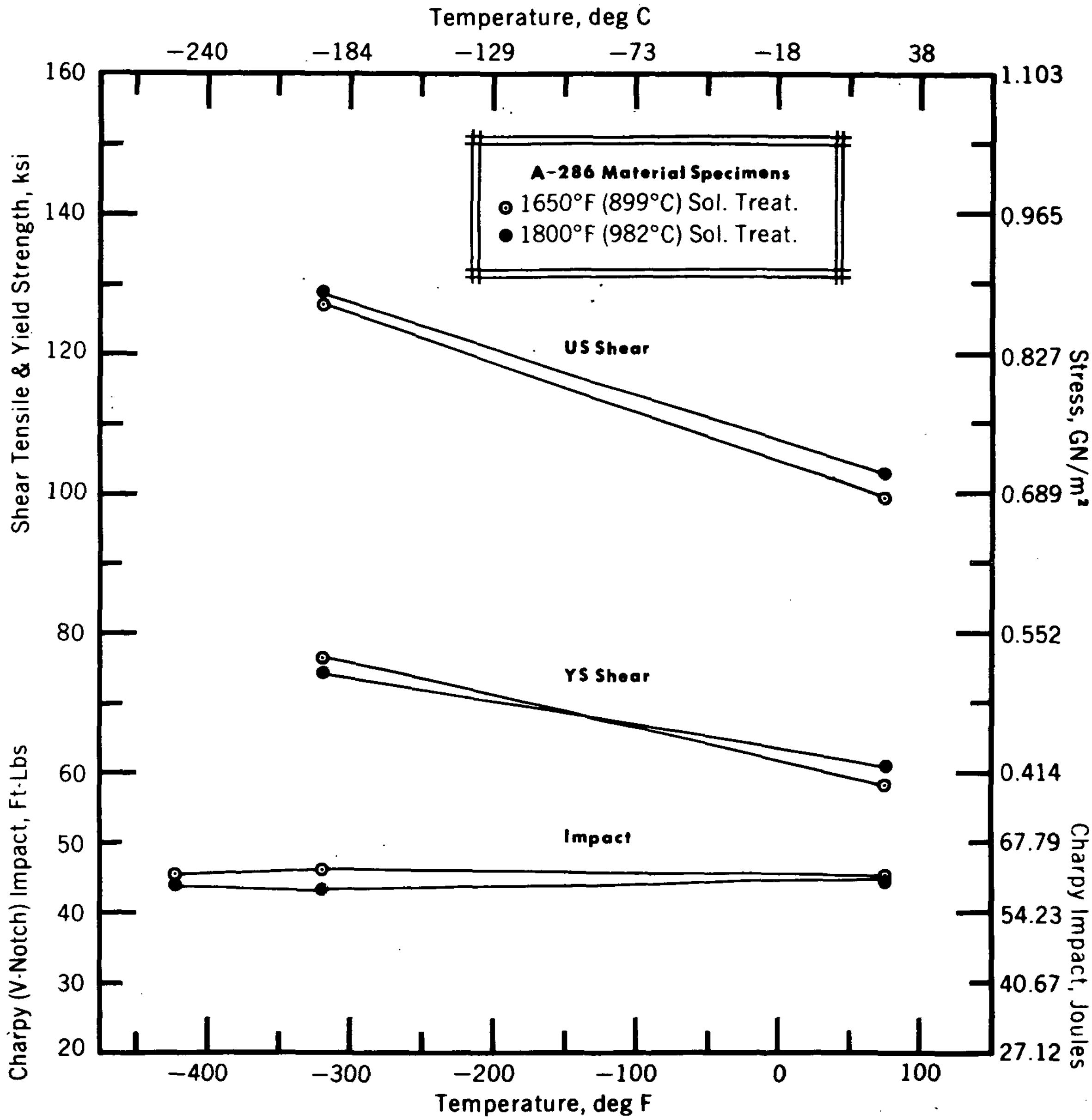


FIGURE 5 - LOW TEMPERATURE IMPACT AND SHEAR PROPERTIES OF A-286 BAR SOLUTION TREATED AT 1650°F AND 1800°F AND AGED AT 1325°F

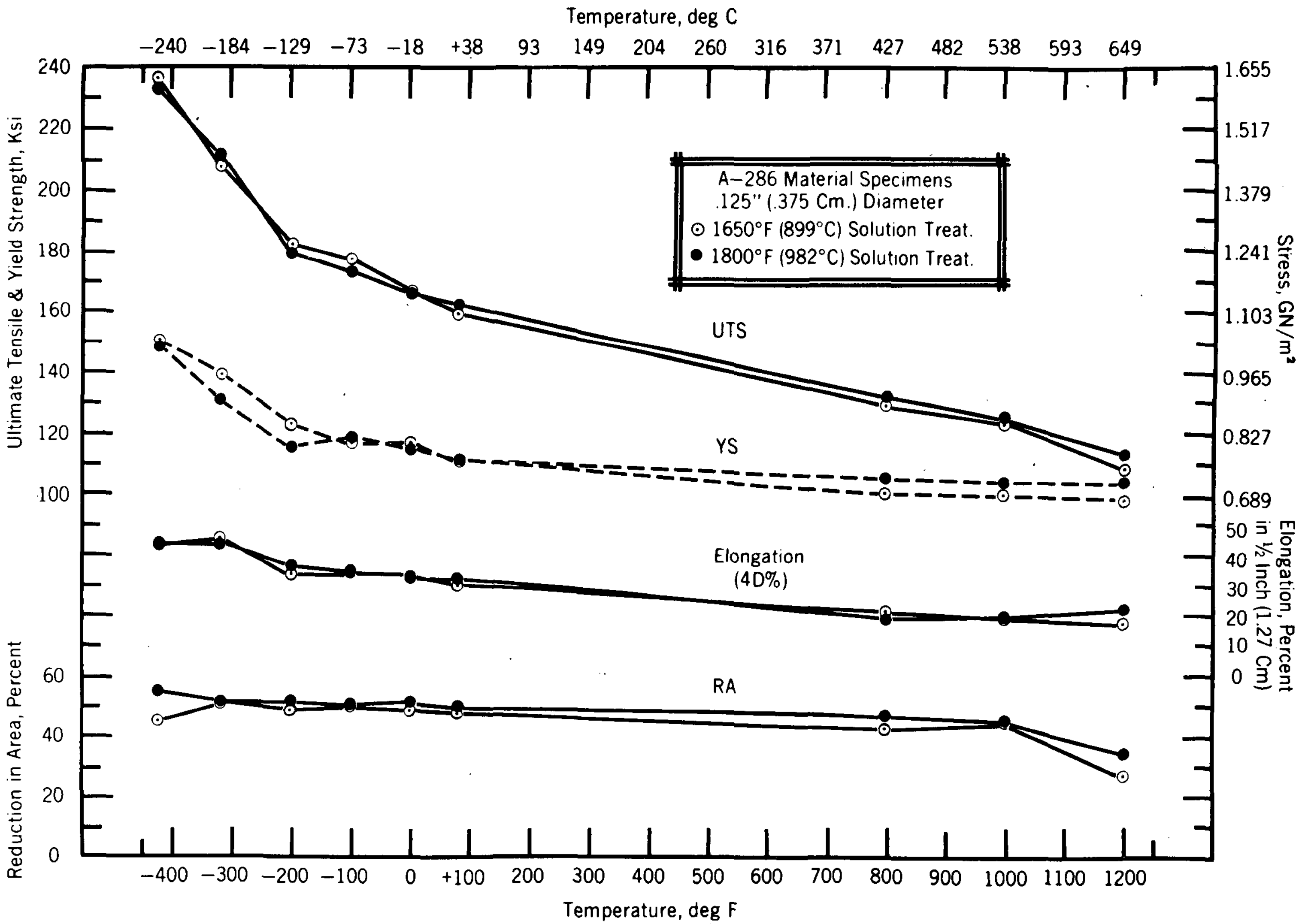
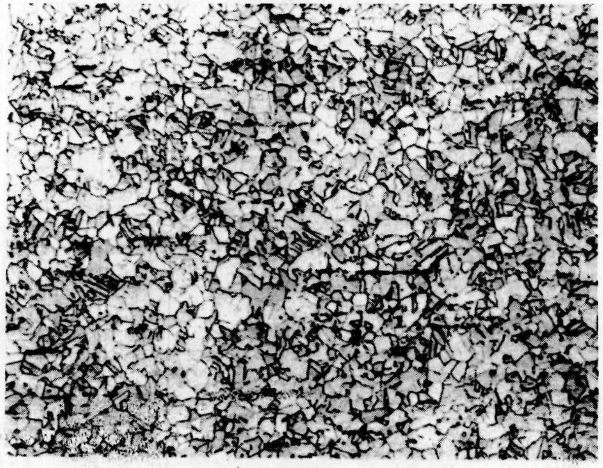
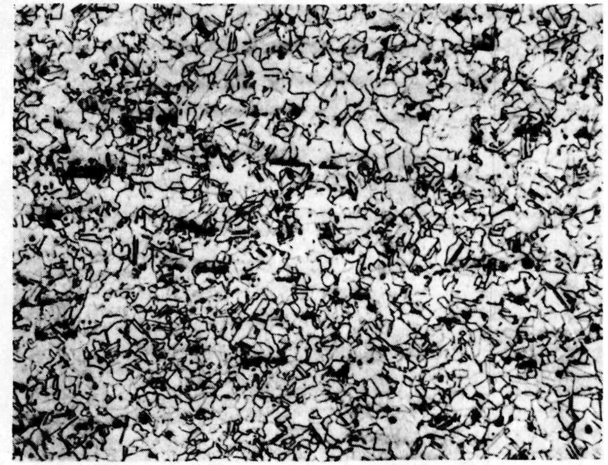
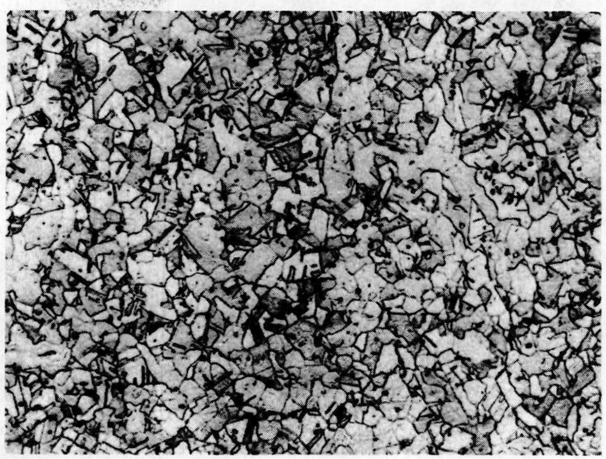


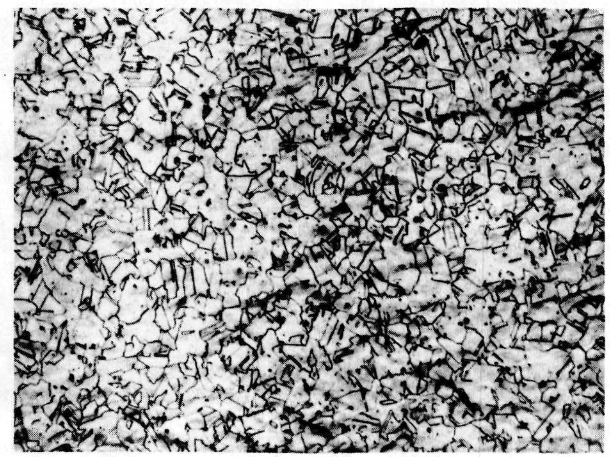
FIGURE 6 · MECHANICAL PROPERTIES OF A–286 TENSILE SPECIMENS SOLUTION TREATED AT 1650°F AND 1800°F AND AGED AT 1325°F





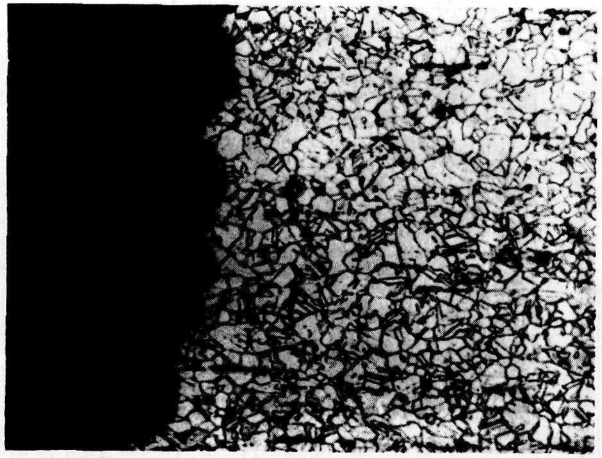
1650°F (899°C) Solution Treatment Longitudinal 1800°F (982°C) Solution Treatment

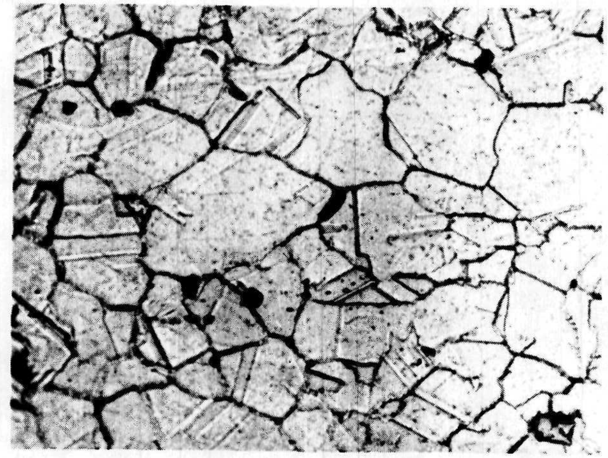




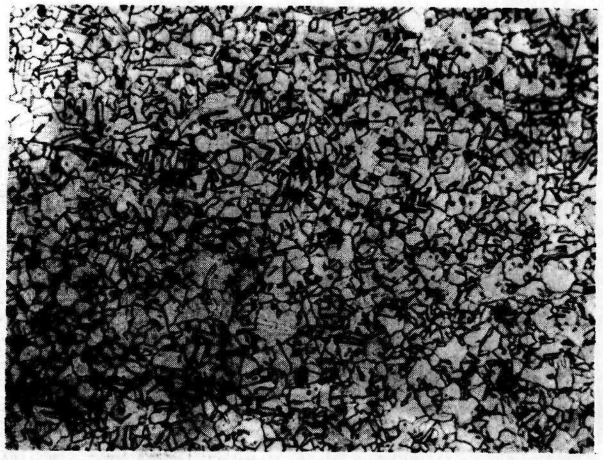
1650°F (899°C) Solution Treatment Transverse 1800°F (982°C) Solution Treatment

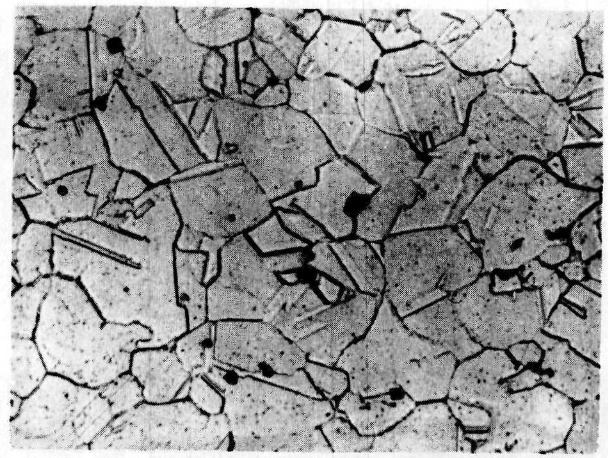
FIGURE 7 - MICROSTRUCTURE OF A-286 BAR [1.5 INCH (3.8 CM) DIAMETER] SOLUTION TREATED, AS INDICATED, AND AGE HARDENED
Etchant: 10% HNO_3, 15% HCL, 10% Acetic Acid Mixture Mag. 100X





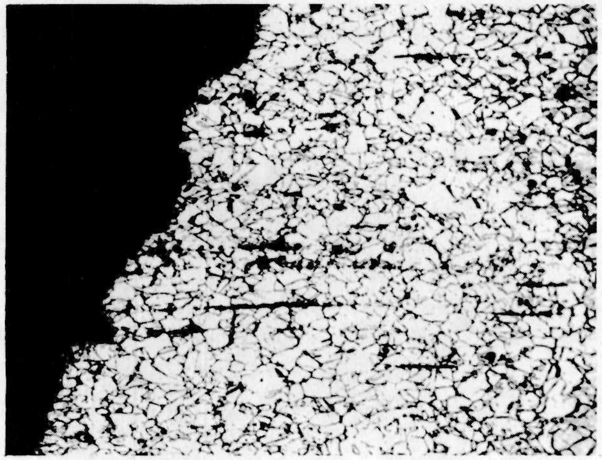
MAG 100X Longitudinal MAG 500X

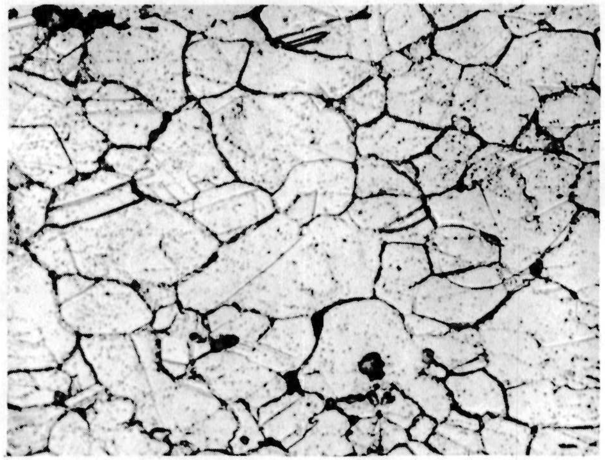




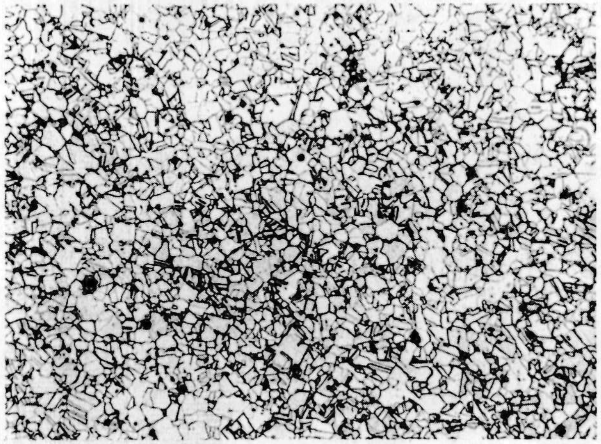
MAG 100X Transverse MAG 500X

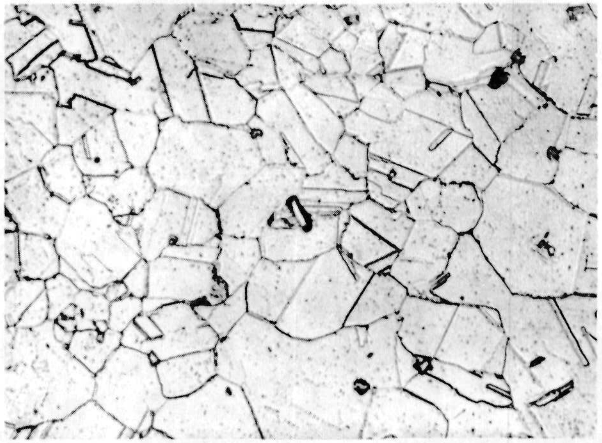
FIGURE 8 - A-286 BAR SPECIMEN, SOLUTION TREATED AT 1650°F (899°C) AND AGED AT 1325°F (718°C) MICROSTRUCTURE, AFTER 1200°F (649°C) STRESS RUPTURE TEST. Etchant: 10% HNO_3, 15% HCL, 10% Acetic Acid





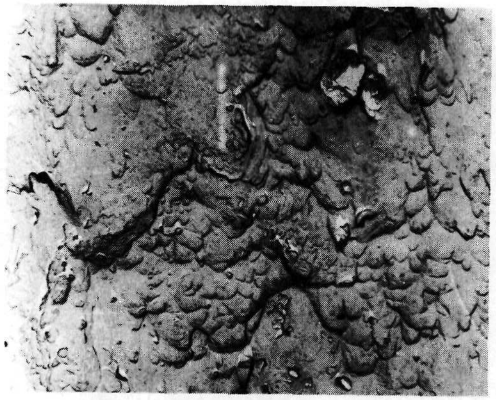
MAG 100X Longitudinal MAG 500X



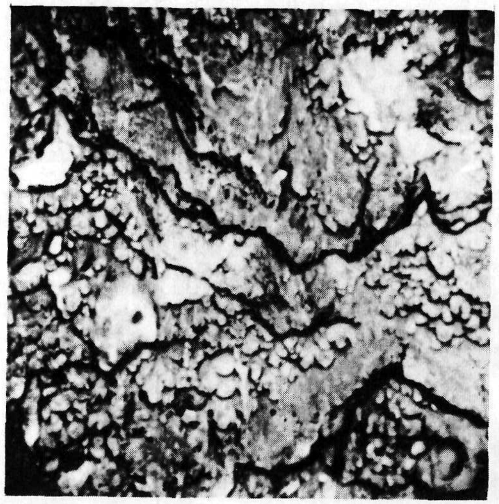


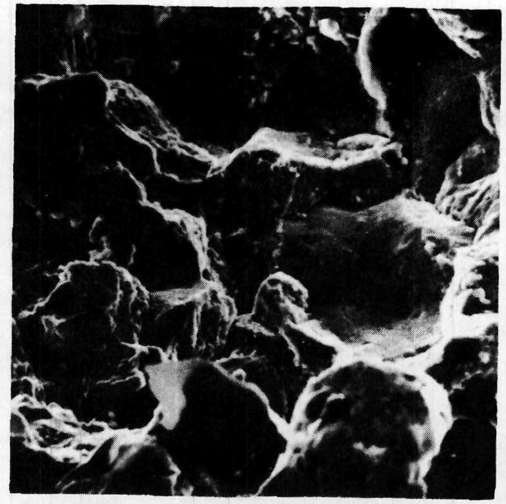
MAG 100X Transverse MAG 500X

FIGURE 9 - A-286 BAR SPECIMEN, SOLUTION TREATED AT 1800°F (982°C) AND AGED AT 1325°F (718°C) MICROSTRUCTURE, AFTER 1200°F (649°C) STRESS RUPTURE TEST. Etchant: 10% HNO_3, 15% HCL, 10% Acetic Acid



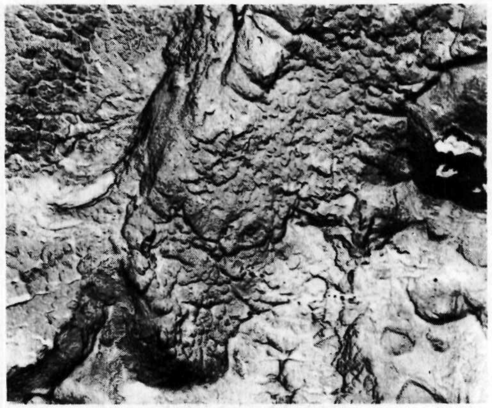
MAG 2400X Edge **TEM Fractographs** Center MAG 2400X





MAG 1000X Edge **SEM Fractographs** Center MAG 1000X

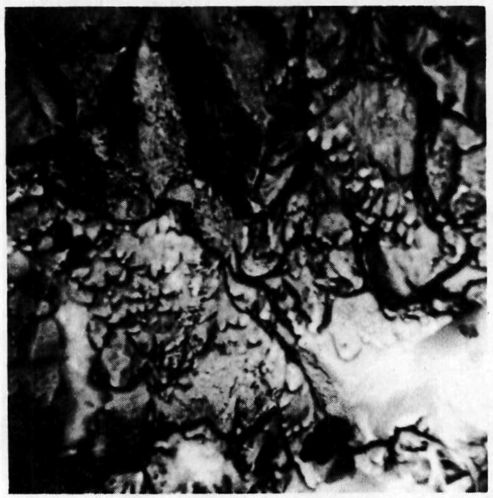
FIGURE 10 - A-286 BAR SPECIMEN, SOLUTION TREATED AT 1650°F (899°C) AND AGED AT 1325°F (718°C) FRACTOGRAPHS, AFTER 1200°F (649°C) STRESS RUPTURE TEST.



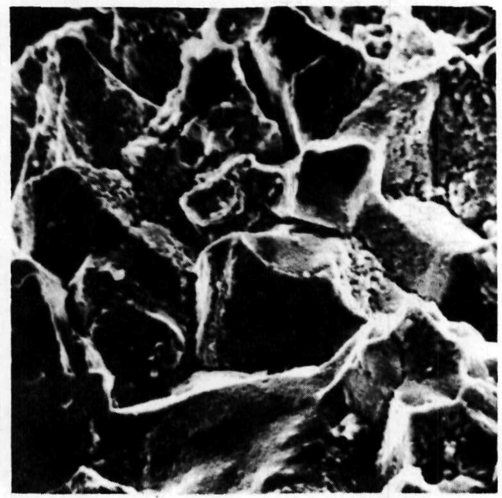
MAG 3150X Edge

TEM Fractographs

Center MAG 3150X



MAG 1000X Edge



SEM Fractographs

Center MAG 1000X

FIGURE 11 - A-286 BAR SPECIMEN, SOLUTION TREATED AT 1800°F (982°C) AND AGED AT 1325°F (718°C) FRACTOGRAPHS, AFTER 1200°F (649°C) STRESS RUPTURE TEST.

APPROVAL

THE EFFECTS OF SOLUTION TREATMENT ON THE MECHANICAL PROPERTIES OF AGE HARDENED A-286 BAR STOCK AT ELEVATED AND CRYOGENIC TEMPERATURE

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.

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