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Properties of Cryogenically Worked Materials

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Project Manager: James R. Faddoul
Materials and Structures Division
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16. Abstract

A program was conducted to determine whether the mechanical properties of cryogenically worked 17-7PH stainless steel are suitable for service from ambient to cryogenic temperatures. It was determined that the stress corrosion resistance of the cryo-worked material is quite adequate for structural service. The tensile properties and fracture toughness at room temperature were comparable to titanium alloy 6Al-4V. However, at cryogenic temperatures, the properties were not sufficient to recommend consideration for structural service.

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PROPERTIES OF CRYOGENICALLY WORKED MATERIALS

Approved

Fred R. Schwartzberg

Fred R. Schwartzberg
Program Manager

MARTIN MARIETTA CORPORATION
P.O. Box 179
Denver, Colorado 80201

FOREWORD

This report describes the results of a program to study the properties of cryogenically-worked materials. The program was conducted by Martin Marietta Corporation, Denver Division under NASA Contract NAS3-17776.

This work was performed under the management of NASA Project Manager Mr. James R. Faddoul.

Martin Marietta Program Manager for the activity was Fred R. Schwartzberg. Mr. Ted F. Kiefer served as Principal Investigator.

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I. INTRODUCTION

In selecting materials for aerospace applications, the materials engineer and designer are constantly searching for higher strength to density ratio materials that can thus provide higher structural efficiency. Although some materials with higher strength are available, certain sacrifices such as decreased toughness, reduced weldability, and/or increased susceptibility to stress corrosion must be made. However, many existing materials will provide higher strength while demanding only minimal or perhaps no behavior sacrifices.

The prospects for achieving strengthening through cryogenic working were evaluated by Martin Marietta Aerospace under NASA Contract NAS3-12028. The results of this work showed that several stainless steel alloys could be strengthened without degrading other properties. The most promising materials were identified as PH 14-8Mo and 17-7PH stainless steel. However, further characterization was required to confirm the preliminary findings with respect to fracture toughness behavior and to optimize the thermo-mechanical processing procedures. This program was aimed at gaining such additional characterization.

This program was divided into three major activities:

1) Optimization of thermomechanical processing and characterization of room temperature properties;

2) Determination of cryogenic mechanical properties;

3) Determination of fracture toughness properties at -293 to 20K (70 to -423°F).

II. PROGRAM PLAN

This program consisted of five tasks, as follows:

- Task I - Material Certification
- Task II - Cryogenic Properties Determination
- Task III - Fracture Toughness Determination
- Task IV - Analysis
- Task V - Reporting

The following paragraphs summarize the activities associated with the first four tasks.

A. TASK I - MATERIALS CERTIFICATION

The prior work, performed under NASA Contract NAS3-12028, showed that PH 14-8Mo stainless steel exhibited significantly higher strengths when deformed at cryogenic temperatures than when treated at room temperature. Preliminary indications suggested that fracture toughness and stress corrosion resistance were not drastically reduced. It was therefore intended to continue this work using alloy PH 14-8Mo stainless steel. However, it was discovered that the alloy is not available in thicknesses greater than 0.25 cm (0.100-inch), due to thermal processing limitations. Because it was intended to assess behavior for thin and thick gage material, the previous results were re-analyzed to determine whether other alloys could be considered as candidates for testing. It was found that 17-7PH stainless steel showed response to cryogenic straining almost as well as PH 14-8Mo stainless steel. However, no stress corrosion data for cryo-worked material were available. Because the 17-7PH is available in thicker gages, it was decided to compare its stress corrosion resistance with that of PH 14-8Mo. If the stress corrosion resistance of the two alloys was found to be comparable then testing would proceed with the 17-7 PH.

Following the successful demonstration of adequate stress corrosion resistance, sufficient 17-7PH material was procurred in two different thicknesses for performance of the program. Routine mechanical property characterization of the as-received stock of both thicknesses was performed.

Based on the results of the as-received material testing and prior program results, four cryo-worked conditions* were to be selected

*Condition is a combination of strain level and thermal treatment.

for room temperature tensile property evaluation of each gage thickness.

B. TASK II - CRYOGENIC PROPERTIES DETERMINATION

The objective of this task was to characterize the liquid nitrogen and liquid hydrogen temperature tensile properties of a number of conditions for each gage. Specifically, nine conditions were to be evaluated for the thinner stock and four conditions for the thicker material.

C. TASK III - FRACTURE TOUGHNESS DETERMINATION

Based on the results of the prior data, and Task I and II information, conditions for fracture testing of both gages of materials at the three test temperatures were to be selected. For the thin stock, 11 conditions were to be evaluated, and for the thick stock, eight conditions.

D. TASK IV - ANALYSIS

The principal objective of this task is to evaluate the cryo-working process as a technique for producing high strength-to-density ratio materials with adequate fabrication and operational characteristics.

III. EXPERIMENTAL PROCEDURE

This chapter describes the materials processing treatments, specimens, and experimental techniques used in the cryogenic working evaluation.

A. MATERIALS

For the initial material selection study, government furnished material (1 sq meter (9 sq ft) of each alloy - PH 14-8Mo and 17-7PH stainless steel) was received. The material was residual from the prior program.

Following the stress-corrosion evaluation, alloy 17-7PH stainless steel was procured in sufficient quantity to permit all testing of a single gage to be performed using stock from a single heat or lot.

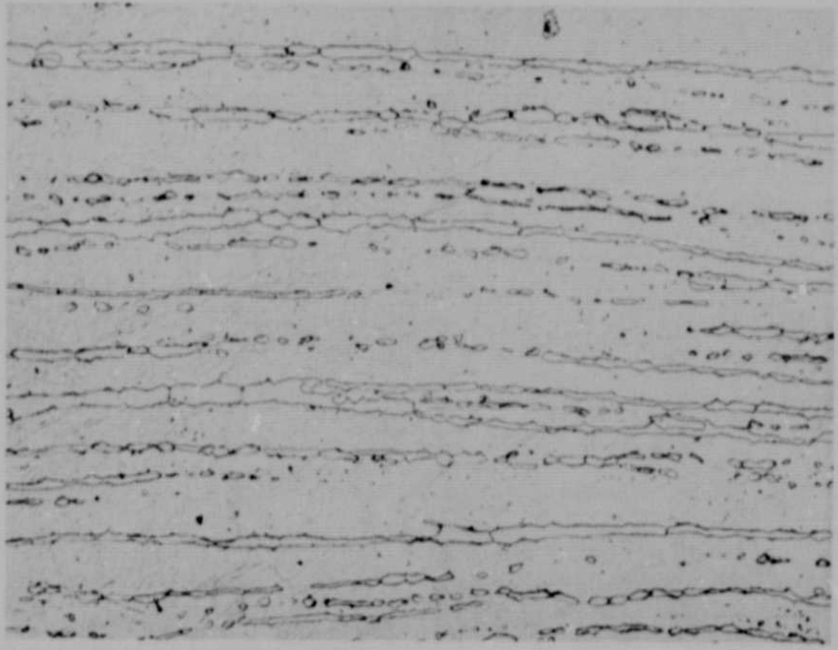
For thin gage testing, one sheet 91.4 cm (36") x 243.8 cm (96") of 1.27 mm (0.050 in.) material was purchased. Similarly, for thick gage testing, one plate of material 238.8 cm (94") x 238.8 cm (94") with a nominal gage of approximately 9.04 mm (0.34 in.) was procured. Both items were procured in the annealed condition (Condition A). Heat identification, and vendor and Martin Marietta chemical analyses are given in Table III-1.

Table III-1 Material Certification Data for 17-7PH Stainless Steel

Thickness mm (in.)	Producer	Heat No.	Chemical Analysis, weight percentage								Analysis Source
			C	Mn	P	S	Si	Cr	Ni	Al	
1.27 (0.050)	Republic	8051242	0.076	0.78	0.026	0.004	0.43	16.87	7.24	--	Vendor
			0.082	0.80	--	--	0.44	17.3	7.00	0.96	MMC
9.04 (0.340)	G. O. Carlson	36050-1A	0.078	0.62	0.023	0.008	0.25	16.93	7.38	1.36	Vendor
			0.075	0.64	--	--	0.28	17.07	7.38	1.45	MMC

Metallographic examination of both gages showed conventional microstructures for annealed 17-7PH stainless steel alloy. Both gages exhibited ferrite banding. The thick gage stock showed broad, rather continuous ferrite; the thin stock exhibited a finer, discontinuous ferrite network. Figure III-1 shows photomicrographs of the alloy structure.

(a) Sheet Stainless Steel Enlarged 400X



(b) Plate Stainless Steel Enlarged 400X

Figure III-1
Photomicrographs of As-Received 17-7PH Stainless Steel
(Etchant: 29% HNO_3; 29% Acetic Acid; 42% HCL)

B. SPECIMEN DESIGN

Specimens were designed for pin loading to permit cryogenic straining or testing. Different specimen configurations were used for each material gage. For the thin gages, a specimen incorporating three pin holes at each end was used. Figure III-2 gives the specifications for this design. Due to premature failures during tensile testing after cryo-straining, the gage width was reduced after straining from a nominal value of 2.54 mm (1-in.) to 1.27 mm (0.50 in.)

The configuration of the thick gage specimen is given in Figure III-3. Due to the extremely poor surface quality of this material, it was necessary to machine the surface in the gage section to obtain a finish suitable for testing. Resulting thickness was a nominal 5 mm (0.20 in.).

C. MEASUREMENT AND INSTRUMENTATION

Photogridding was used for determination of gross plastic strains. Using a 2.54 mm (0.100-in.) grid, excellent accuracy was achieved in measuring the uniform elongation on as-received tensile specimens and the final strain level in all cryo-strain specimens.

Resistance strain gages were used for yield strength and elastic modulus determination. A single gage was used for each specimen. Although this technique is satisfactory for yield strength determination, it normally is not sufficient to provide accurate modulus data (dual gages located on each surface of the specimen to cancel bending effects are often used to provide more precise modulus data). Hence, the modulus data given in this report can not be considered as exact.

D. CRYO-WORKING PROCEDURE

The procedure used for cryo-working is in accordance with the procedure previously used in NASA Contract NAS3-12028 (NASA CR-72798). Basically, specimens were immersed in an open-ended, foam-insulated container capable of holding liquid nitrogen. Specimens were strained using a dial-indicator to measure stroke. After several straining sequences, the stroke that characterized a specific strain level was established. After removal from the tensile apparatus, the final strain was measured using the photogrid system. As shown by the experimental results (Section IV), actual strain levels were in generally good agreement with desired levels.

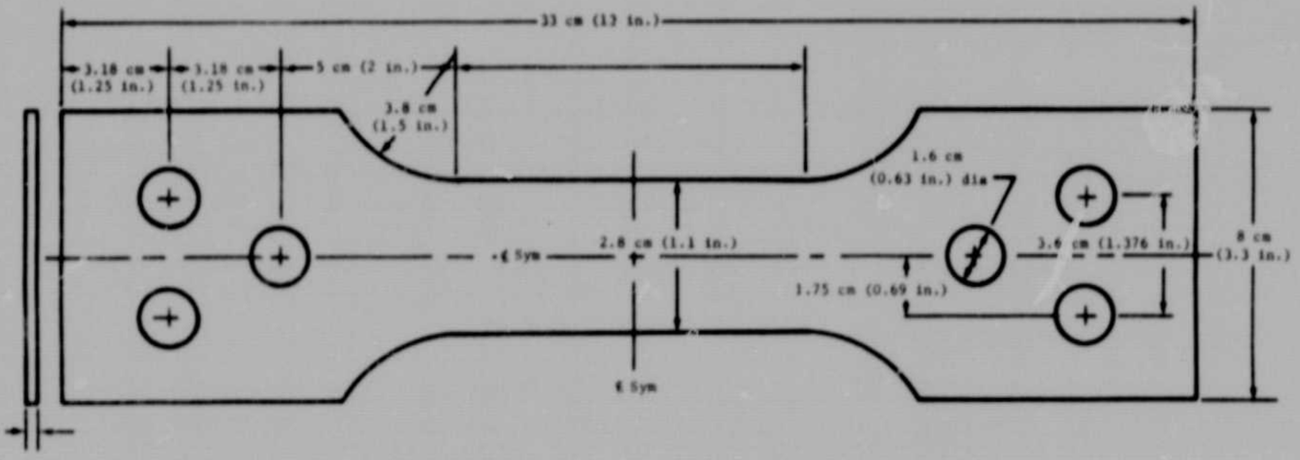


Figure III-2 Specifications for Thin Gage Specimen

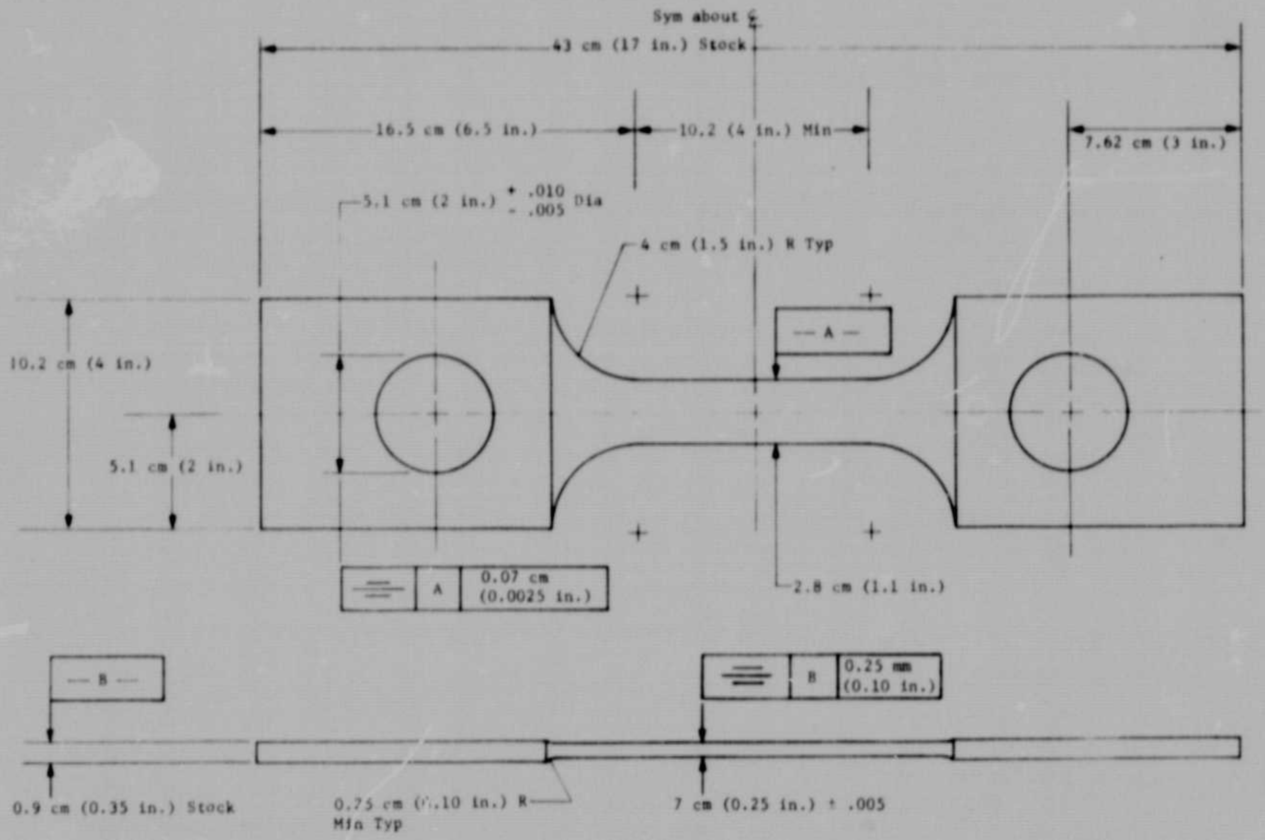


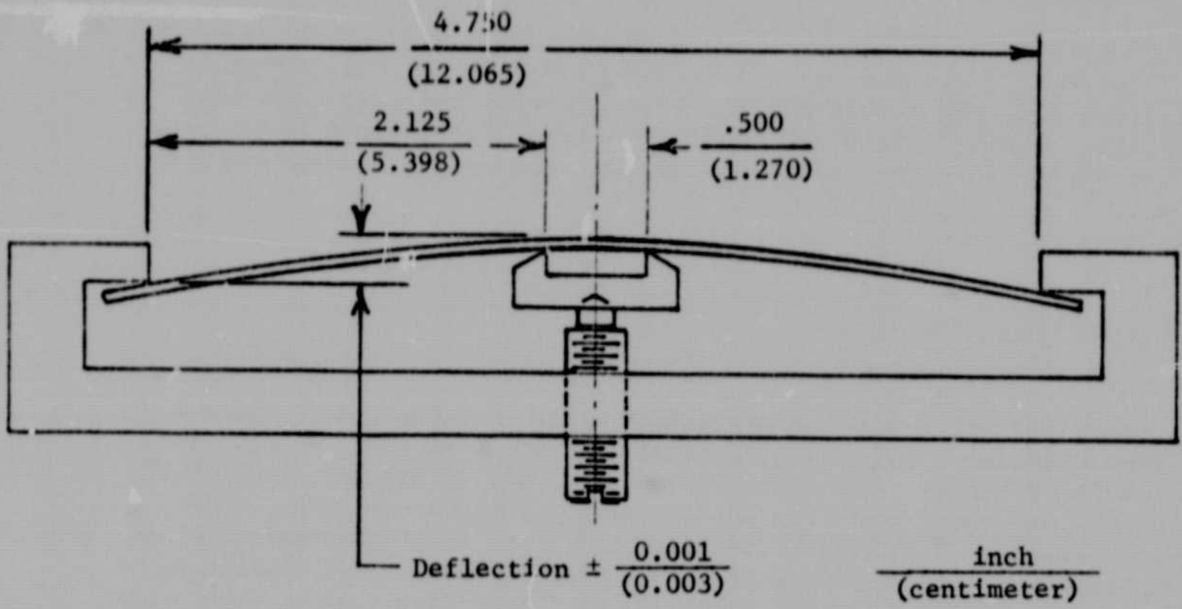
Figure III-3 Specifications for Thick Gage Specimen

E. FLAW PREPARATION

Flaws for fracture toughness specimens were electrodischarge machined into the specimen after cryostraining and aging and then fatigue cycled to sharpen the crack tips. All fatigue sharpening was performed using axial loading, at stresses not exceeding 150 ksi.

F. STRESS CORROSION TEST

Stress corrosion testing was achieved using a four point loaded beam specimen. Figure III-4 gives a diagram of the specimen and loading fixture. A dial indicator was used to measure deflection of the specimen. An alternate immersion tester was used to provide specimen exposure. The standard cycle of 10 minutes immersion followed by two 50 minute periods of air exposure. The solution was made of reagent grade NaCl salt and deionized water, with a specific gravity adjusted to 1.023.



$$*\text{Deflection (max)} = \frac{\sigma}{3Et}\left(3/4\ \ell^2 - a^2\right)$$

Where:

σ = Outer fiber stress.

a = Distance from load point to support = 2.125 inches (5.398 cm).

t = Thickness.

E = Modulus of Elasticity

ℓ = Length between supports = 4.750 inches (12.065 cm).

* Reference: *New Departure Handbook, Vol II.* Seventh Edition.

Stress Corrosion Specimen Assembled in Fixture.

Figure III-4
The Method and Fixture Design Used to Apply Load to Stress Corrosion Specimens

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. TASK I--MATERIALS CERTIFICATION

1. Materials Selection

Room temperature tensile testing of the as-received, government-furnished PH 14-8Mo and 17-7PH stainless steel confirmed the material to be in an annealed condition. Properties were in good agreement with those previously determined. Data are summarized below:

Alloy	Ultimate Strength MN/m^2	(ksi)	Yield Strength MN/m^2	(ksi)	Elongation, %
PH 14-8Mo Stainless Steel 1.78 mm (0.070 in.) Thick	972	(141)	321	(46.5)	25
	966	(140)	358	(51.9)	26
Average	969	(140)	340	(49.2)	26
17-7PH Stainless Steel 1.27 mm (0.050 in.) Thick	862	(125)	270	(39.1)	51
	835	(121)	259	(37.5)	50
Average	848	(123)	264	(38.3)	50

To prepare material for stress corrosion testing, blanks were cryo-strained at 77K (-320°F) to various strain levels and aged at 756K (900°F) for one hour. A single blank of each condition* was tensile tested to provide room temperature strength data as a basis for selection of corrosion stress levels. Data are summarized below:

Alloy	Prestrain Level, %	Ultimate Strength MN/m^2	(ksi)	Yield Strength MN/m^2	(ksi)
PH 14-8Mo Stainless Steel	10	2042	(296)	1835	(266)
	15	2194	(318)	2146	(311)
17-7PH Stainless Steel	12	1773	(257)	1545	(224)
	18	2111	(306)	2070	(300)

Stress corrosion testing was performed for a 30 day period at 75 and 90% of the yield strength for each of the above conditions. One specimen failed after two weeks of alternate immersion exposure. The failed specimen was 17-7PH stainless steel, 1545 MN/M^2 (224 ksi) yield strength, exposed at the 90% level. All other 17-7PH specimens survived the 30 day period without failure. No failures occurred in the PH 14-8Mo specimens. Visual examination of specimens of both alloys showed no evidence of crack

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*Condition is a combination of strain level and thermal treatment.

networks, pitting, or rust deposits. Metallographic examination of sections removed from each specimen revealed no evidence of intergranular attack. Even the failed specimen was free from intergranular attack. No reason for the premature failure was apparent. As a result of examination of the metallographic sections with the NASA-LeRC Project Monitor during a plant visit, it was decided to proceed with the scheduled program using the 17-7PH stainless steel alloy.

2. Characterization of As-Received Mechanical Properties

Tensile and yield strength properties for both gages of as-received 17-7PH material are summarized in Figure IV-1. Agreement of properties for the two gages is surprisingly close. As anticipated for this type of material, both yield and ultimate strength increase significantly with reduction in temperature. Because of failures in the pin hole and filet regions, an accurate characterization of the tensile strength at 20K (-423°F) was not possible. Although such behavior suggests brittle behavior, examination of the tabular data (Tables IV-1 and IV-2) show good ductility to 20K (-423°F). Uniform elongation at this temperature exceeded 13 percent. At 77K (-320°F), ductility was greater than 20 percent. The uniform elongation, at 77, (-320°F) was 23 percent for the thin sheet and 20 percent for thick stock. This property governs the maximum cryo-straining level.

3. Room Temperature Properties of Cryo-Worked Material

Based on the uniform elongation data and the strength level data from NASA CR73798, cryo-worked strain levels were selected. A maximum level of 22 percent was selected for the thin sheet. Based on the prior data, it was decided that a minimum strain of 12 percent was required to achieve a sufficient margin over conventionally processed material to make cryo-working feasible. The thick stock (9.04 mm) was evaluated later in the program, and as a result of preliminary data generated for thin stock (1.27 mm), it was concluded that the loss of ductility above 15 percent strain made the high strain levels impractical. Evaluation of prior data suggested that thermal processing (aging) could be best performed at a single temperature with variations in aging time. Hence the same temperature used for the previous work 756K (900°F) was selected. Aging times varied from 1 to 10 hours. Conditions selected for the various room temperature tests are given below:

Material Gage	Strain Level, %	Aging Time, hr
Thin (1.27 mm)	12	1
	15	1
	18	1
	22	1
Thick (9.04 mm)	12	1
	12	4
	15	4
	15	10

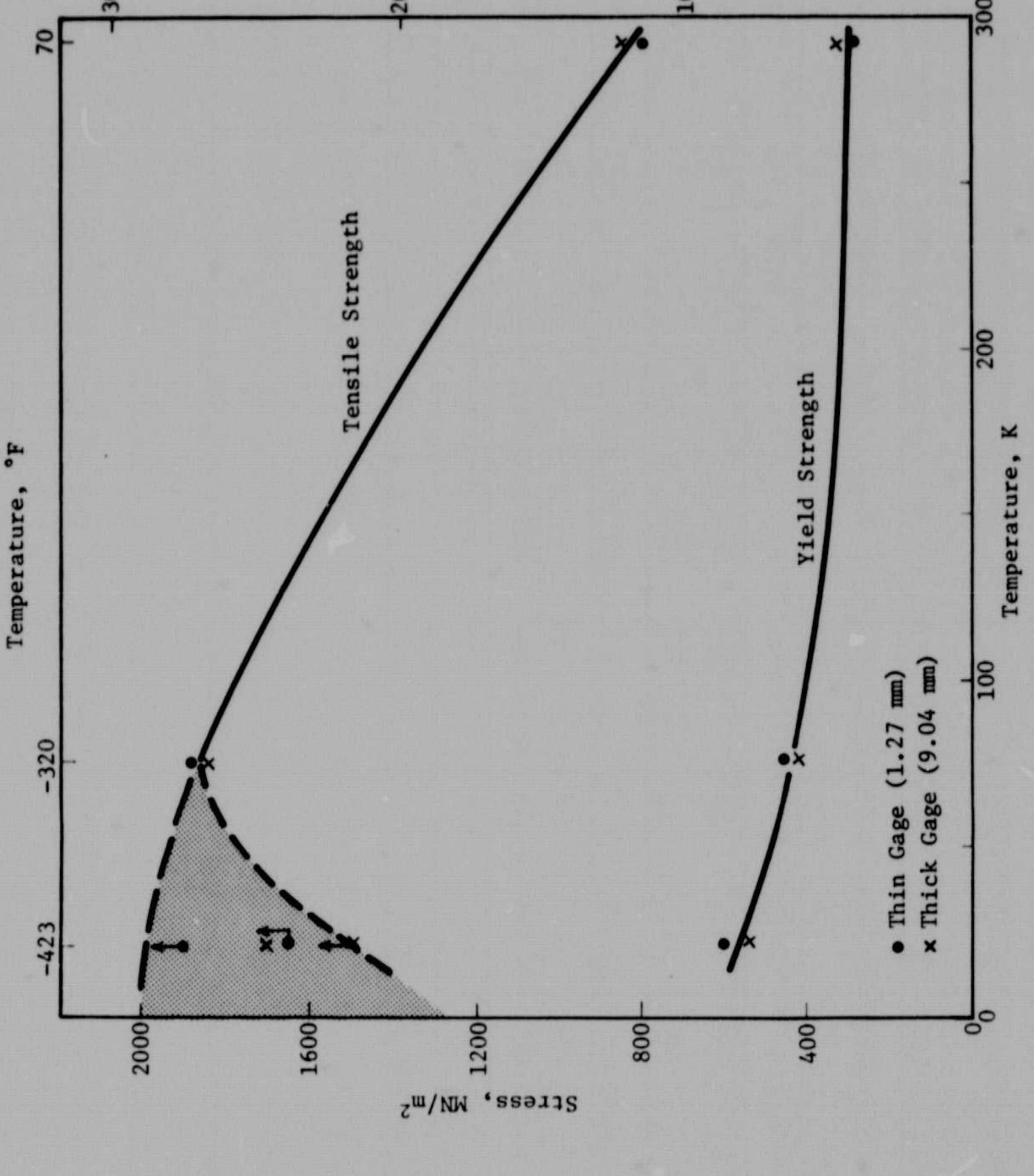

Figure IV-1
Tensile Strength of As-Received 17-7PH Stainless Steel as a Function of Temperature

Figure IV-1

Table IV-1 Tensile Properties of Thin, (1.27 mm) As-Received 17-7PH Stainless Steel

Temperature K	(°F)	Tensile Strength MN/m^2	(ksi)	Yield Strength MN/m^2	(ksi)	Elongation, % Uniform	Total	Modulus of Elasticity 10^3 MN/m^2	(10^3 ksi)
293	(70)	798	(115.7)	260	(37.7)	35.0	41.0	189	(27.4)
293	(70)	789	(114.5)	297	(43.2)	40.0	49.0	179	(26.0)
Average		794	(115.1)	278	(40.4)	37.5	45.0	184	(26.7)
77	(-320)	1848	(268.0)	405	(58.8)	23	26	201	(29.1)
77	(-320)	1884	(273.2)	474	(68.8)	23	26	214	(31.1)
Average		1866	(270.6)	440	(63.8)	23	26	206	(30.1)
20	(-423)	>1655	(>240.0)*	600	(87.0)	>13	--*	221	(32.0)
20	(-423)	>1888	(>273.8)*	604	(87.6)	>15	--*	227	(33.0)
Average		--	--	602	(87.3)	--	--	224	(32.5)

*Pin hole failure.

Table IV-2 Tensile Properties of Thick, (9.04 mm) As-Received 17-7PH Stainless Steel

Temperature K	(°F)	Tensile Strength MN/m^2	(ksi)	Yield Strength MN/m^2	(ksi)	Elongation, % Uniform	Total	Modulus of Elasticity 10^3 MN/m^2	(10^3 ksi)
293	(70)	845	(122.6)	310	(44.9)	20	32	197	(28.6)
293	(70)	859	(124.6)	322	(46.7)	20	31	191	(27.7)
Average		852	(123.6)	316	(45.8)	20	31.5	194	(28.2)
77	(-320)	1847	(267.9)	432	(62.6)	20	20	201	(29.1)
77	(-320)	1582*	(229.5)	437	(63.4)	>12	--*	208	(30.1)
Average		1847	(267.9)	434	(63.0)	20	20	204	(29.6)
20	(-423)	1495*	(216.8)	538	(78.0)	>13	--*	180	(26.1)
20	(-423)	1680	(243.6)	555	(80.5)	13	18	214	(31.0)
Average		1680	(243.6)	545	(79.2)	13	18	197	(28.6)

*Failed in filet region.

The longer aging times for the thick material were based on preliminary results from thin gage testing.

Test results for the thin and thick material are given in Tables IV-3 and IV-4, respectively.

Data for the thin gage, also presented graphically in Figure IV-2, show a continuous increase in strengthening with increase in straining level. Note that the largest strength increase occurs between 12 and 15 percent. The relation between yield and ultimate should be noted. At 12 percent, a significant difference exists; at 15-22 percent, yield and ultimate exhibit little difference. This effect is more apparent by examination of the ductility behavior; elongation drops sharply from almost 10 percent at the 12 percent strain level to approximately 2 percent for the higher strain levels. The thick gage data (Table IV-4) show little significant effect of aging on strength reduction. Comparison with the thin gage data for the 12 and 15 percent strain levels show reasonably good strength property agreement. For all cases, the thick gage material exhibited low ductility.

Table IV-3

Room Temperature Tensile Properties of Thin, (1.27 mm) Cryogenically-Worked 17-7PH Stainless Steel

Cryogenic Strain, %		Aging* Time, hr	Tensile Strength, MN/m^2 (ksi)	Yield Strength, MN/m^2 (ksi)	Elongation, %	Modulus of Elasticity, 10^3 MN/m^2 (10^3 ksi)
Nominal	Actual					
12	11.5	1	1894 (274.9)	1766 (256.2)	8.2	201 (29.2)
12	11.5	1	1888 (273.8)	1749 (253.6)	10.5	194 (28.2)
Average			1891 (274.3)	1757 (254.9)	9.4	198 (28.7)
15	15.2	1	2137 (310.0)	2102 (304.8)	2.5	196 (28.4)
15	15.2	1	2128 (308.6)	2099 (304.5)	2.7	194 (28.2)
Average			2133 (309.3)	2100 (304.6)	2.6	195 (28.3)
18	17.6	1	2250 (326.4)	2214 (321.2)	2.2	186 (27.0)
18	18.9	1	2286 (331.5)	2241 (325.1)	2.3	194 (28.1)
Average			2268 (328.8)	2228 (323.1)	2.3	190 (27.6)
22	22.0	1	2344 (339.9)	2313 (335.5)	2.0	205 (29.8)
22	21.9	1	2313 (335.4)	2297 (333.2)	2.0	204 (29.6)
Average			2326 (337.7)	2305 (334.4)	2.0	205 (29.7)

*Aged at 756K (900°F).

Table IV-3

Table IV-4

Room Temperature Tensile Properties of Thick, (9.04 mm) Cryogenically-Worked 17-7PH Stainless Steel

Cryogenic Strain, %		Aging* Time, hr	Tensile Strength, MN/m^2 (ksi)	Yield Strength, MN/m^2 (ksi)	Elongation, %	Modulus of Elasticity, 10^3 MN/m^2 (10^3 ksi)
Nominal	Actual					
12	9.5	1	1884 (273.2)	1858 (269.4)	2.5	148 (21.6)
12	12.4	1	1990 (288.7)	--§ --	2.5	150 (22.2)
Average			1937 (281.0)	1858 (269.4)	2.5	149 (21.9)
12	13.1	4	1982 (287.5)	1925 (279.2)	2.1	188 (27.2)
12	12.1	4	1879 (272.5)	1822 (264.3)	--†	179 (25.9)
Average			1930 (280.0)	1874 (271.8)	2.1	184 (26.6)
15	16.0	4	2056 (298.1)	2020 (292.9)	1.9	184 (26.7)
15	14.5	4	2047 (296.9)	1982 (287.4)	2.7	181 (26.2)
Average			2052 (297.5)	2001 (290.2)	2.3	182 (26.4)
15	14.8	10	1972 (286.1)	1818 (263.7)	1.2	190 (27.6)
15	14.8	10	1986 (288.1)	1920 (278.4)	1.5	184 (26.7)
Average			1979 (287.1)	1869 (271.0)	1.4	187 (27.2)

*Aged at 756K (900°F).
†Failed outside gage length.
§Gage failure.

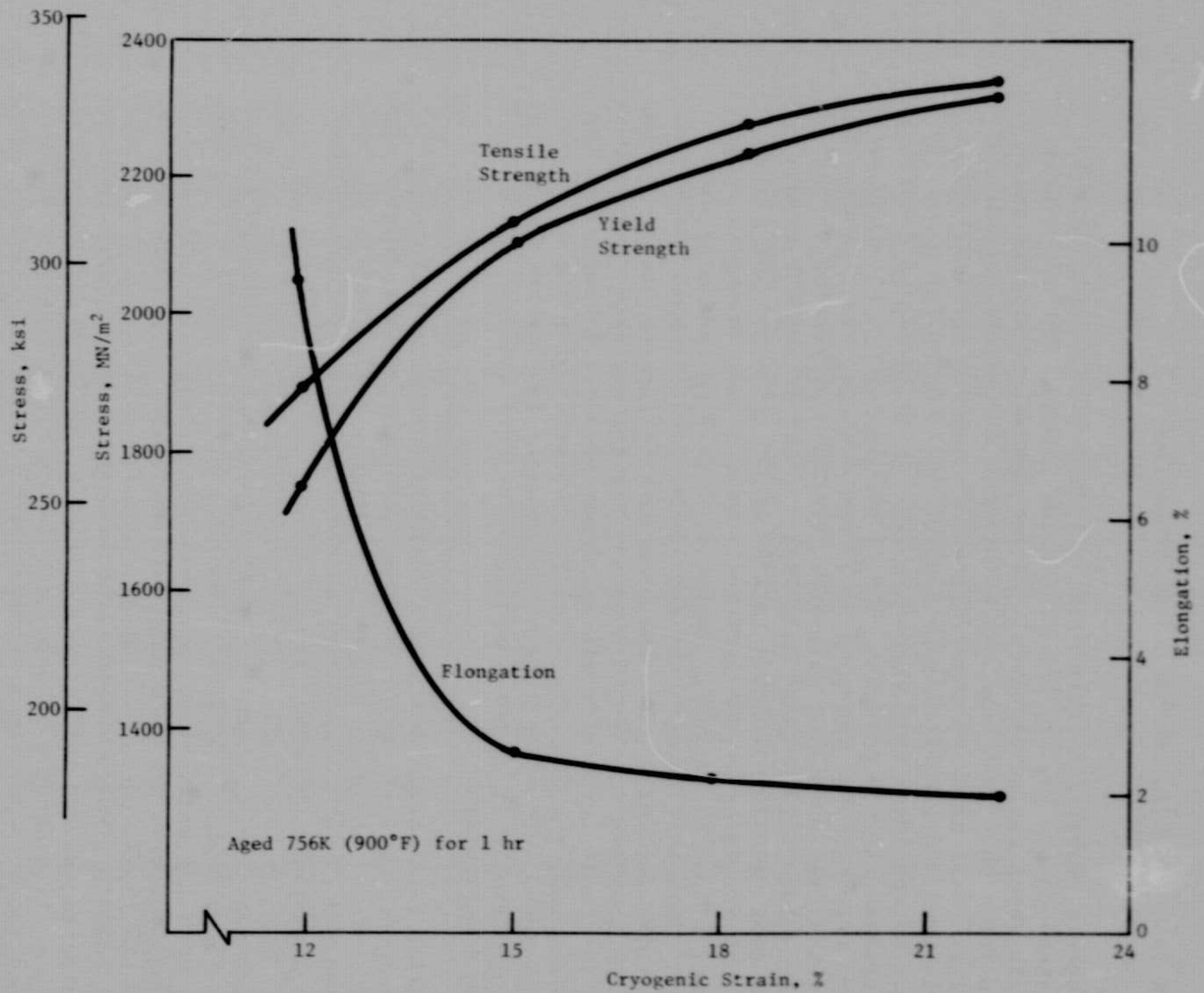

Figure IV-3
Room Temperature Tensile Properties of Thin, (1.27 mm) Cryogenically Worked 17-7PH Stainless Steel as a Function of Cryogenic Strain Level

B. TASK II--CRYOGENIC PROPERTIES DETERMINATION

Cryogenic properties tests were performed for the thin material strained to the 12, 15, and 18 percent levels. The 22 percent strain level was not included. Three thermal treatments were used for each strain level in an attempt to improve tensile ductility. Test data for the 77K (-320°F) tests are summarized in Table IV-5 and graphically in Figure IV-3. Aging for 6 and 12 hours of specimens cold worked to 12% strain increased ductility to approximately 6 percent. The 15 and 18 percent strained specimens were aged for times up to 10 and 8 hours, respectively, but showed little ductility recovery. Strength properties varied from a low value of 2330 MN/m^2 (338 ksi) for the 12 percent strain specimens aged for 12 hours to 2844 MN/m^2 (412 ksi) for the 18 percent strain specimens aged for 1 hour. Considering the high strength levels, ductility values of 1 to 3 percent are quite good. Agreement between the duplicate tests for each condition was quite good except for the premature failure of one 12 percent strain specimen aged for 1 hour and the low strength found for one of the 18 percent strain specimens aged for 8 hours. In the latter case, the ducility level is consistent with the strength level found, but the strength is extremely low for the 18 percent strain level. It is not understood why this specimen exhibited such low strength.

Tensile tests performed at 20K (-423°F) demonstrated further strengthening with most conditions showing strengths greater than 2750 MN/m^2 ($\sim$400 ksi). However, specimens failed before reaching yield and exhibited ductility values less than 1 percent. Data are summarized in Table IV-6.

Thick gage 17-7PH stainless steel alloy was strained only to 12 and 15 percent for cryogenic tensile property testing. Test data for both 77K (-320°F) and 20K (-423°F) are given in Table IV-7. Comparison with the thin gage data shows some interesting trends. For the 12 percent strain level, aged for 1 hour, and tested at 77K (-320°F), the strength level is significantly higher than indicated for the thin stock; similarly the thick gage material is much less ductile. Apparently 1 hour did not provide sufficient aging to develop a strength level attendant with ductility. However, the 4 hour aging treatment improved ductility, but not to the level of the thin stock. The 15 percent strain specimens of the thick stock tested at 77K (-320°F) exhibited equivalent strength to the thin gage material, but much lower ductility.

Table IV-5
Tensile Properties of Thin, (1.27 mm) Cryogenically-Worked 17-7PH Stainless Steel at 77K (-320°F)

Cryogenic Strain, % Nominal	Cryogenic Strain, % Actual	Aging* Time, hr	Tensile Strength, MN/m^2 (ksi)	Yield Strength, MN/m^2 (ksi)	Elongation, %	Modulus of Elasticity, 10^3 MN/m^2 (10^3 ksi)
12	12.2	1	2180† (316.2)	2180 (316.2)	0.3	205 (29.7)
12	12.2	1	2471 (358.4)	2252 (326.6)	3.3	207 (30.0)
Average			2471 (358.4)	2216 (321.4)	3.3	206 (29.8)
12	12.4	6	2396 (347.5)	2116 (306.9)	5.0	202 (29.3)
12	12.1	6	2444 (354.5)	2166 (314.1)	7.0	186 (27.0)
Average			2420 (351.0)	2140 (310.5)	6.0	194 (28.1)
12	12.1	12	2428 (352.2)	2093 (303.6)	8.6	214 (31.1)
12	12.2	12	2227 (323.0)	2131 (309.1)	4.2	201 (29.2)
Average			2330 (337.9)	2112 (306.3)	6.4	208 (30.1)
15	15.2	1	2699 (391.4)	2628 (381.2)	2.2	211 (30.6)
15	15.4	1	2694 (390.8)	2603 (377.5)	1.7	203 (29.5)
Average			2696 (391.1)	2616 (379.3)	2.0	207 (30.0)
15	15.1	4	2630 (381.4)	2510 (364.0)	2.8	210 (30.5)
15	15.0	4	2637 (382.4)	2573 (373.2)	3.4	219 (31.7)
Average			2633 (381.9)	2542 (368.6)	3.1	214 (31.1)
15	15.2	10	2529 (366.8)	2402 (348.4)	2.0	216 (31.3)
15	15.2	10	2515 (364.8)	2430 (352.5)	2.2	207 (30.0)
Average			2522 (365.8)	2416 (350.4)	2.1	212 (30.7)
18	18.0	1	2854 (414.0)	2766 (401.3)	1.2	201 (29.2)
18	18.1	1	2834 (411.0)	2758 (400.0)	1.2	203 (29.5)
Average			2844 (412.5)	2763 (400.7)	1.2	202 (29.3)
18	18.4	4	2755 (399.6)	2668 (387.0)	1.5	207 (30.0)
18	18.6	4	2703 (392.1)	2603 (377.6)	1.5	214 (31.1)
Average			2729 (395.3)	2636 (382.3)	1.5	210 (30.5)
18	18.7	8	2285§ (331.5)	2185 (316.9)	3.4	179 (26.0)
18	18.1	8	2679 (388.5)	2606 (377.9)	2.0	207 (30.0)
Average			2679 (388.5)	2606 (377.9)	2.7	193 (28.0)

*Aged at 756K (900°F).

†Premature failure.

§Not averaged; no apparent reason for low strength.

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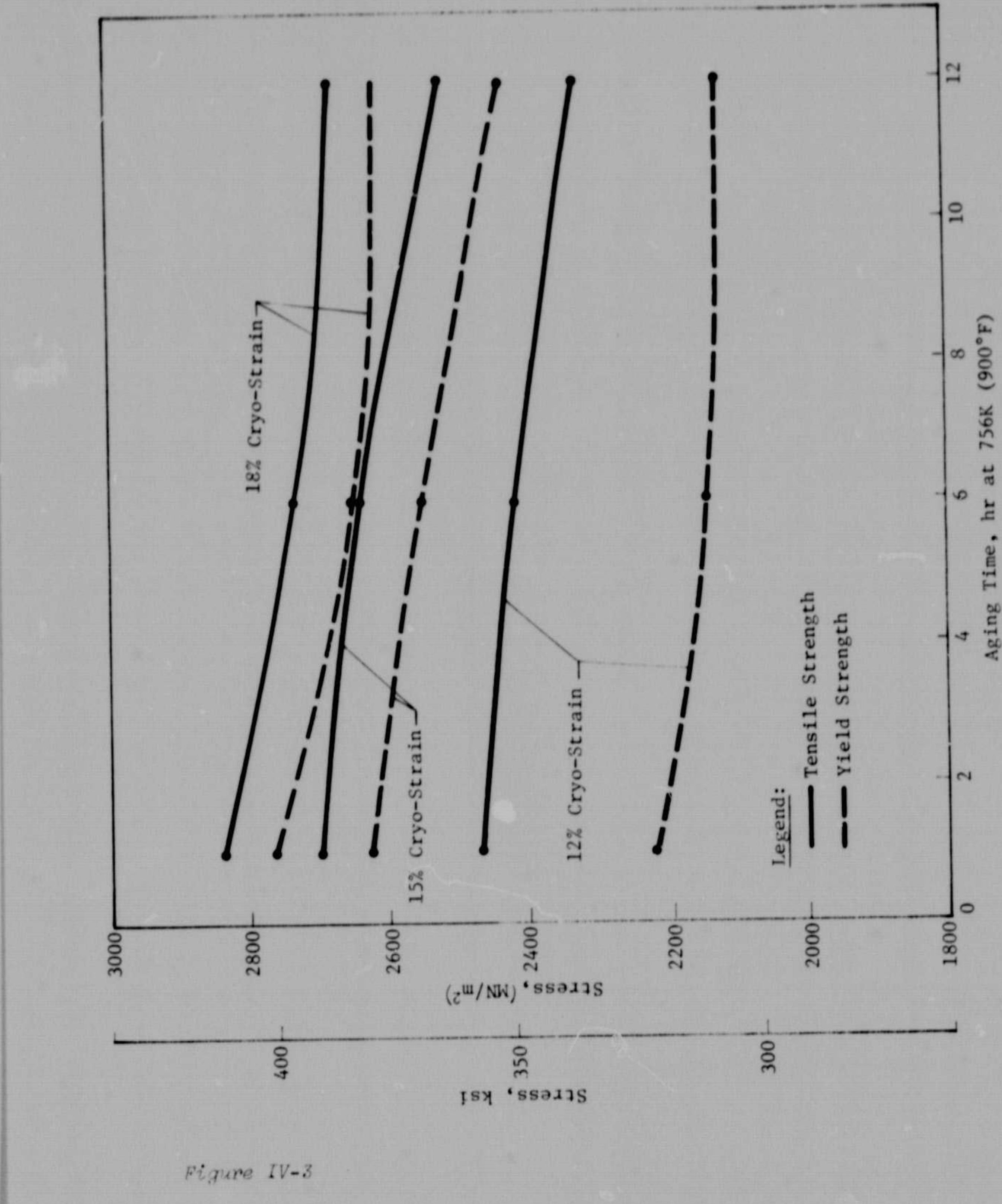

Figure IV-3
Strength Properties of Thin, (1.27 mm) Cryogenically Worked 17-7PH at 77K (-320°F) as a Function of Aging Time

Figure IV-3

Table IV-6

Tensile Properties of Thin, (1.27 mm) Cryogenically-Worked 17-7PH Stainless Steel at 20K (-423°F)

Cryogenic Strain, %		Aging* Time, hr	Tensile Strength, MN/m^2 (ksi)		Yield Strength, MN/m^2 (ksi)		Elongation, %	Modulus of Elasticity, 10^3 MN/m^2 (10^3 ksi)	
Nominal	Actual								
12	12.2	6	Pin Hole Failure					177	(25.7)
12	12.0	6	2517	(365.1)	2500	(362.6)	1.4	188	(27.3)
Average			2517	(365.1)	2500	(362.6)	1.4	182	(26.5)
15	15.1	1	2959	(429.1)		--	0.7	197	(28.5)
15	15.0	1	Pin Hole Failure				--	--	--
Average			2959	(429.1)			0.7	197	(28.5)
15	15.0	4	2782	(403.5)	--	--	0.6	201	(29.1)
15	15.1	4	2897	(420.2)	--	--	0.5	197	(28.5)
Average			2839	(411.8)			0.6	199	(28.8)
15	15.1	10	2798	(405.8)	--	--	0.5	197	(28.5)
15	15.1	10	2772	(402.0)	--	--	0.8	193	(28.0)
Average			2785	(403.9)	--	--	0.6	195	(28.2)
18	17.9	4	2965	(430.1)	--	--	0.6	--	--
18	18.0	4	3005	(435.9)	--	--	0.5	--	--
Average			2985	(432.9)			0.6		

*Aged at 756K (900°F).

Table IV-7
Tensile Properties of Thick, (2.04 mm) Cryogenically-Worked 17-7PH Stainless Steel at 20K (-320 and -423°F)

Temperature K	(°F)	Cryogenic Strain, % Nominal	Actual	Aging Time, hr	Tensile Strength MN/m^2	(ksi)	Yield Strength MN/m^2	(ksi)	Elongation, %	Modulus of Elasticity 10^3 MN/m^2	(10^3 ksi)
77	(-320)	12	12.2	1	2738	(397.0)	2608	(378.1)	0.4	201	(29.1)
		12	12.4	1	2007*	(290.9)	--	--	0.2	200	(29.0)
		Average			2738	(397.0)	2608	(378.1)	0.3	200	(29.0)
		12	11.6	4	2340	(339.2)	2226	(322.7)	1.2	170	(24.6)
		12	12.4	4	2173	(315.0)	2136	(309.7)	1.2	172	(25.0)
		Average			2256	(327.1)	2181	(316.2)	1.2	171	(24.8)
		15	15.0	4	2582	(374.4)	2539	(368.2)	0.8	198	(28.7)
		15	15.0	4	2349	(340.6)	2288†	(339.3)†	1.0	183	(26.6)
		Average					2539	(368.2)	0.9	190	(27.6)
		15	14.8	10	1911	(277.0)	--	--	0.5	190	(27.6)
		15	15.0	10	2162	(313.4)	--	--	0.5	195	(28.3)
		Average			2043	(296.2)				192	(28.0)
20	(-423)	12	11.5	1	1735	(251.6)	--	--	0	199	(28.8)
		12	12.5	1	2180	(316.1)	--	--	0	182	(26.4)
		Average			--	--			0	190	(27.6)
		12	12.4	4	1960	(284.1)	--	--	0	183	(26.5)
		12	12.1	4	1586	(230.0)	--	--	0	179	(26.0)
		Average			--	--			0	181	(26.2)
		15	15.2	4	1934	(280.4)	--	--	0	178	(25.8)
		15	14.2	4	1993	(289.0)	--	--	0	177	(25.6)
		Average			--	--			0	178	(25.7)
		15	14.5	10	1710	(247.9)	--	--	0	184	(26.7)
		15	14.5	10	1732	(251.1)	--	--	0	184	(26.7)
		Average			--	--	--	--	0	184	(26.7)

*Premature failure.

†0.1% offset.

All thick specimens tested at 20K (-423°F) were brittle, failing without any measurable ductility. The stress vs strain records showed no evidence of plastic deformation.

C. TASK III--FRACTURE TOUGHNESS DETERMINATION

Surface flaw specimens were used to evaluate the fracture behavior of the thin 17-7PH stainless steel at room temperature, 77K (-320°F), and 20K (-423°F). Critical stress intensity values were calculated using the Shah and Kobayashi magnification solution including plasticity effects. The data, shown graphically in Figure IV-4 and tabulated in Table IV-8, show a factor of two decrease in toughness with decrease in temperature. At room temperature, toughness decreases with increasing strain level. However at 77K (-320°F), the differences in toughness resulting from aging treatment are small. Decreasing the temperature to 20K (-423°F) causes a continued decrease in toughness.

Surface-flawed specimens used to evaluate the thick material showed some unusual results. Examination of the fractured faces showed that the electrodischarge machined precrack did not propagate in-plane. Fatigue extension followed a curved path, as shown in Figure IV-5. It is likely that this behavior is due to a tendency to delaminate resulting from the ferrite banding (see fig III-1,B). Remaining specimens were modified to produce a through-center notch (CN) and then tested to failure. Test results are given in Table IV-9. At room temperature, two CN tests were performed. The toughness of the 12 percent strained specimen was about 10 percent higher than the comparable thin surface flaw tests. The 15 percent strained sample, aged for 4 hours, exhibited extremely high toughness, however, in this specimen the flaw length was too great for the width and the data ($2a/w = .50$) obtained is not valid. The cryogenic tests exhibited lower toughness than the room temperature tests but significantly greater than the comparable thin gage tests. Examination of the fracture faces of the cryogenically tested CN specimens also indicated the tendency toward delamination which was proposed as the cause for the slant fatigue growth in surface flaw specimens.

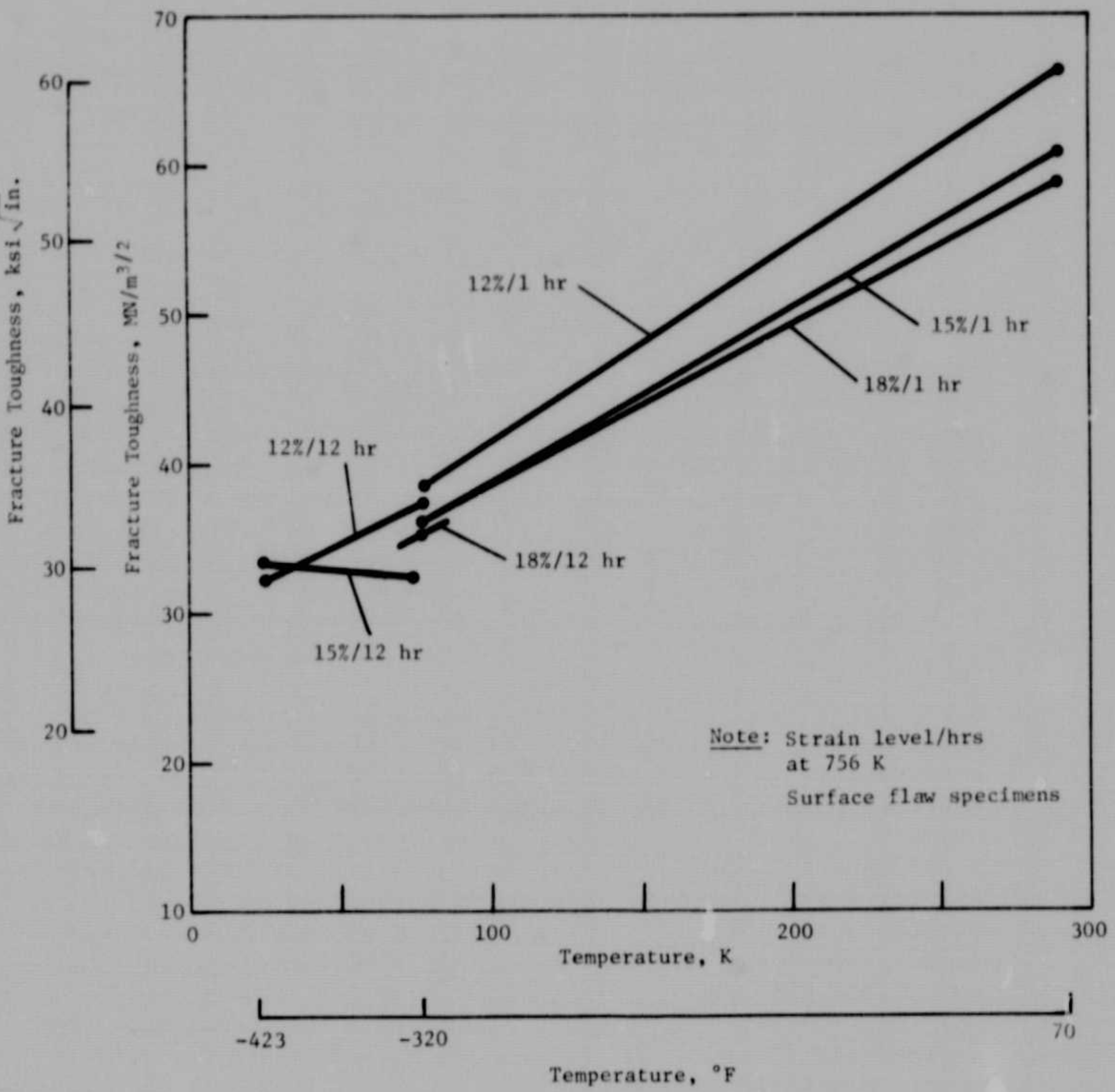

Figure IV-4
Effect of Temperature on the Fracture Toughness of Thin, (1.27 mm) Cryogenically Worked 17-7PH

Table IV-8 Fracture Toughness of Thin, (1.27 mm) Cryogenically-Worked 17.7PH Stainless Steel

Temperature K	(°F)	Cryogenic Strain, % Nominal	Actual	Aging Time, hr	Crack Size Depth, mm	(in.)	Width, mm	(in.)	Fracture Stress MN/m^2	(ksi)	Fracture Toughness $MN/m^{3/2}$	(ksi $\sqrt{in.}$)
293	(70)	12	12.0	1	0.889	(0.035)	2.92	(0.115)	1393	(202)	70.3	(63.9)
		12	11.9	1	0.635	(0.025)	2.31	(0.091)	1524	(221)	63.5	(57.7)
		Average									66.9	(60.3)
		15	15.2	1	0.864	(0.034)	3.15	(0.124)	648	(94)	60.9	(55.4)
		15	15.0	1	0.864	(0.034)	3.15	(0.124)	662	(96)	60.2	(54.7)
		Average									60.6	(55.0)
		18	18.0	1	0.711	(0.028)	2.59	(0.102)	896	(130)	59.1	(53.7)
		18	18.0	1	0.711	(0.028)	2.49	(0.098)	931	(134)	59.5	(54.1)
		Average									59.3	(53.9)
77	(-320)	12	11.8	1	0.940	(0.037)	3.10	(0.122)	717	(104)	38.5	(35.0)
		12	12.2	1	0.965	(0.038)	3.15	(0.124)	717	(104)	39.1	(35.5)
		Average									38.8	(35.2)
		12	12.0	12	0.686	(0.027)	2.36	(0.093)	1454	(211)	37.0	(33.6)
		12	12.1	12	0.711	(0.028)	2.52	(0.099)	1393	(202)	37.7	(34.3)
		Average									37.4	(34.0)
		15	15.1	1	0.762	(0.030)	2.49	(0.098)	896	(127)	37.5	(34.1)
		15	15.2	1	0.711	(0.028)	2.72	(0.107)	820	(119)	35.6	(32.4)
		Average									36.6	(33.2)
		15	15.0	12	0.965	(0.038)	3.18	(0.125)	634	(92)	32.6	(29.6)
		15	15.0	12	0.965	(0.038)	3.22	(0.127)	634	(92)	32.6	(29.6)
		Average									32.6	(29.6)
		18	17.9	1	0.787	(0.031)	2.72	(0.107)	724	(105)	35.4	(32.2)
		18	17.9	1	1.14	(0.045)	4.06	(0.160)	676	(98)	37.7	(34.3)
		Average									36.6	(33.2)
		18	18.0	12	0.889	(0.035)	3.08	(0.118)	731	(106)	36.0	(32.7)
		18	18.5	12	0.737	(0.029)	2.77	(0.109)	1310	(190)	36.5	(33.2)
		Average									36.3	(33.0)
20	(-423)	12	11.9	12	0.635	(0.025)	2.24	(0.088)	1482	(215)	32.0	(29.1)
		12	12.0	12	0.660	(0.026)	2.46	(0.097)	862	(125)	32.7	(29.7)
		Average									32.4	(29.4)
		15	15.1	12	0.914	(0.036)	3.12	(0.123)	717	(104)	33.3	(30.3)
		15	15.1	12	0.559	(0.022)	2.21	(0.087)	993	(144)	33.7	(30.6)
		Average									33.5	(30.4)

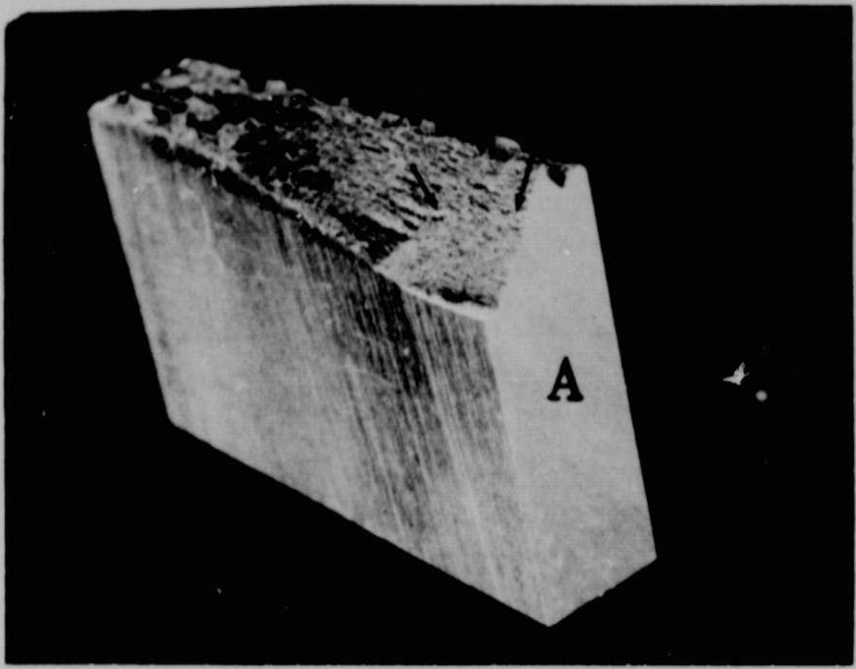

Figure IV-5
Typical Surface Flaw Fatigue-Extended Pre-Crack Showing Slant Growth (Specimen sectioned on Surface A to show slant growth)

Table IV-9
Fracture Toughness Properties of Thick, (9.04 mm) Cryogenically-Worked 17-7PH Stainless Steel

Temperature K	(°F)	Cryogenic Strain, % Normal	Actual	Aging* Time, hr	Specimen Type†	Crack Size Depth, 2 mm	(in.)	Width, 2c or 2a mm	(in.)	Fracture Stress MN/m^2	(ksi)	Fracture Toughness $MN/m^{3/2}$	(ksi $\sqrt{in.}$)
293	(70)	12	13.0	1	SF	2.23	(0.088)	9.24	(0.364)	1186	(172.0)	--	--
		12	13.8	1	SF	1.90	(0.075)	9.04	(0.356)	1127	(163.4)	--	--
		12	12.1	1	CN	--	--	6.10	(0.240)	690	(70.1)	80.1	(72.9)
		12		4	SF	2.01	(0.079)	9.14	(0.360)	1142	(161.5)	--	--
		12		4	SF	1.88	(0.074)	8.76	(0.345)	1145	(166.1)	--	--
		15	15.0	4	CN	Failed during precracking							
		15	15.2	4	CN	--	--	15.24	(0.600)	515	(75.0)	135.8	(123.6)
77	(-320)	12	12.1	1	SF	1.07	(0.042)	6.60	(0.260)	978	(141.9)	--	--
		12	12.0	1	SF	1.90	(0.075)	10.16	(0.400)	758	(110.0)	--	--
		12	12.4	4	SF	1.78	(0.070)	7.26	(0.286)	796	(115.4)	--	--
		12	12.9	4	SF	0.53	(0.021)	6.04	(0.238)	1089	(158.0)	--	--
		15	13.8	4	CN	--	--	7.37	(0.290)	375	(51.8)	62.6	(57.0)
		15	16.2	4	CN	--	--	6.60	(0.260)	419	(60.8)	69.2	(63.0)
20	(-423)	12	12.4	1	CN	--	--	5.59	(0.220)	303	(44.0)	50.3	(45.8)
		15	14.5	4	CN	--	--	9.65	(0.380)	319	(46.3)	59.9	(54.5)
		15	14.[illegible]	4	CN	--	--	9.14	(0.360)	331	(48.0)	59.8	(54.4)

*Aged at 756K (900°F).

†SF = surface flaw.

CN = center notch.

V. CONCLUSIONS

The results of this program show that cryogenic working of alloy 17-7PH develops properties that are attractive for room temperature service. The fracture properties at cyrogenic temperatures are so degraded that use as a structural material should be avoided.

Comparison of the tensile properties of 17-7PH stainless steel developed in this work showed excellent agreement with the data reported in NASA CR-72798.

At room temperature, the stress corrosion resistance of 17-7PH appears to be adequate for structural service. The fracture toughness, is at least as high as 6Aℓ-4V STA titanium. On a fracture toughness to yield strength ratio basis, the two materials are comparable, with values of approximately 0.25 $\sqrt{in.}$ From a strength-to-weight basis, the cryogenically-worked 17-7PH alloy is comparable to 6Aℓ-4V STA titanium (approximately 10^6 in.)

It appears that the properties of 17-7PH stainless steel in the cryogenically-worked condition are not adequate for low temperature service. Anticipation that qualification for such service might have been possible was based on the premise that the effect of temperature on toughness was not a major effect.

Additional characterization of compatibility with various environments is an essential requirement for this alloy to continue to be a candidate for aerospace structural service. Special consideration should be given to K_{TH} determination.

Although the tensile and fracture properties of cryo-worked 17-7PH stainless steel at room temperature are attractive, it should be noted that there are other equivalent alloys with which there is a great deal more experience. Hence, cryo-worked 17-7PH does not offer a distinct advantage.