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COMPARISON OF TENSILE PROPERTIES OF 304L AND 310S STAINLESS STEELS IN LIQUID HELIUM

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ABSTRACT

Tensile properties of 304L and 310S stainless steel were investigated in liquid helium with unnotched and notched specimens. The yield strength for 310S stainless steel was nearly twice that for 304L stainless steel. The ultimate tensile strength for 310S was about 80 percent of that for 304L stainless steel in the unnotched condition. Tensile strengths of notched unwelded and welded specimens for 310S stainless steel were significantly higher than those of 304L stainless steel.

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SUMMARY

Tensile properties of 304L and 310S stainless steel were investigated in liquid helium at -452° F (-269° C). Sheet specimens of both alloys were tested with loading applied either parallel or transverse to the sheet rolling direction using both unnotched and notched specimens. Notched specimens were tested in the unwelded and welded condition. Limited data were also obtained at -456° F (-271° C) with unnotched specimens only and no significant differences in tensile behavior were observed with either material compared to those observed at -452° F (-269° C).

In all cases the unnotched tensile strengths for both alloys were higher than their notched tensile strengths. The yield strength for 310S stainless steel was nearly twice that for 304L stainless steel. However, the ultimate tensile strength for 310S was about 80 percent of that of 304L stainless in the unnotched condition. In tests with 3-inch wide center notched specimens, the average tensile strength of 310S stainless steel was higher than that of 304L stainless steel for both unwelded and welded specimens by as much as 41 000 psi (280 MN/sq m). For 304L stainless steel the average notch-in-weld (without backing strip) tensile strength was 9000 psi (60 MN/sq m) less than that for notched unwelded specimens. For 310S stainless steel there was no significant difference in tensile strength between notch-in-weld (without backing strip) and notched unwelded specimens. X-ray diffraction studies showed that austenite in 304L stainless steel transformed to martensite during tensile tests in liquid helium. No transformation was observed with 310S stainless steel.

INTRODUCTION

Cryogenic temperatures can markedly affect the mechanical properties of containment materials for cryogenic fluids. A variety of engineering applications involve the containment of such fluids. For example, a NASA facility for high temperature plasma studies utilizes superconducting magnet coils immersed in liquid helium. To design the containment vessel for the liquid helium the tensile properties of the vessel material in a liquid helium environment was required. Design considerations indicated that 304L and 310S stainless steels were potential candidates. Unfortunately, only limited tensile data are available for most materials at liquid helium temperature. Reference 1 provides a fairly comprehensive summary of cryogenic tensile test data for several classes of materials, but most of these data were obtained at temperatures no lower than that of liquid hydrogen, -423° F (-253° C). Reference 2 included some limited tensile data for both materials of interest at -452° F (-269° C). In this reference it was also indicated that some of the austenite in the 304L stainless steel transformed to martensite below -320° F (-196° C).

An investigation was therefore conducted at the NASA Lewis Research Center to obtain more complete tensile data with both 304L and 310S stainless steel sheet specimens in a liquid helium environment. Data were obtained with notched and unnotched specimens. Several specimen configurations were used including some containing weldments. A few tests were conducted near absolute zero, at -456° F (-271° C), in an attempt to anticipate potential applications below the liquid helium lambda point (transition point between the normal liquid and the superfluid state). X-ray diffraction studies were made to determine whether irreversible martensite transformations occurred during cryogenic testing.

MATERIALS, APPARATUS, AND PROCEDURE

Materials

The materials investigated were annealed 304L and 310S stainless steel sheet, 0.063-inch (1.6 mm) thick. Chemical analyses of the as-received material are given in table I. The analyses are within nominal aerospace materials specification except for silicon in 304L stainless steel which was slightly below the minimum nominal range.

Specimens

Specimen geometries are shown in figure 1. Each specimen configuration was fabricated in two ways. In one case the loading direction was parallel to the sheet rolling direction; in the other, it was transverse to the rolling direction. Welded and notched specimen configurations were included to simulate potential fabrication situations. Welded specimens were made by butt joining sheared halves of specimen blanks with a tungsten inert gas arc weld. Specimen welds without a backing strip were made without using filler rod. Specimen welds with a backing strip were made using filler rod of the same material as the specimen. To produce a center notch in the 3-inch (7.6-cm) wide specimens, a 0.88 inch (2.23 cm) by 0.008 inch (0.20 mm) slot was made with an electrical discharge machine. The length of the notch was then increased to 1.00 inch (2.54 cm) by subjecting the specimen to axial fatigue at room temperature as suggested in reference 3.

Test Apparatus

The tensile tests were conducted in a closed loop electrohydraulically actuated universal testing machine. The cryostat and associated ducting used with this machine are schematically illustrated in figure 2. The cryostat consisted of a vacuum tight enclosure that surrounded a cylindrical specimen chamber. The chamber contained the cryogenic fluid in which the test specimen was immersed. A flanged split cylinder made of copper and attached to an annular shaped liquid nitrogen reservoir inside the vacuum jacket served as the radiation shield. The bellows permitted specimen elongation and pull-rod motion to take place without loading the cryostat. Most of the tests were conducted with the liquid helium at a pressure of approximately one atmosphere in the specimen chamber. At this absolute pressure the boiling point of liquid helium is approximately -452° F (-269° C). For those tests made at -456° F (-271° C) the absolute pressure on the liquid helium was reduced to about 24 millimeters of mercury. To reach this lower pressure the vent valve to atmosphere was closed and valve A (fig. 2) connecting the discharge line from the cryostat to a high capacity mechanical vacuum pump was opened to draw off the helium boiloff gas. When the specimen chamber was filled with liquid helium the vacuum jacketed throttling valve B (fig. 2) in the liquid helium inlet line to the cryostat was throttled to a nearly closed position. This permitted reaching a lower liquid helium boiling temperature and pressure at which the mass of liquid helium entering the specimen chamber equaled the mass of helium boiloff gas being pumped out. Although exact equilibrium was not attained, temperatures as low as -456° F (-271° C) were reached. However, during actual tests the -456° F (-271° C) temperature of the fluid could not consistently be maintained once plastic straining of the specimen test section began. Instead, the temperature of the fluid varied from -456° F (-271° C) to approximately -452° F (-269° C). This was probably due to dissipation of the specimen strain energy to the supercooled liquid helium. As a result, only the yield strength values cited can be considered as being obtained at the desired -456° F (-271° C).

Fluid test temperatures were measured with doped germanium sensors attached to the specimen with an adhesive tape. In the final stages of the investigation temperatures were measured using commercially available carbon resistors. These resistors were calibrated at cryogenic temperatures. In several tests both types of sensing elements were employed. Good agreement between indicated cryogenic fluid temperatures as determined by both techniques was obtained. The electrical resistance of the sensor or carbon resistor was determined from an accurate measurement of IR voltage when a regulated and accurately known current of 10 microamperes passed through the temperature sensor. The measured temperature was then determined from a calibration curve of temperature versus resistance.

Test Procedure

All tensile tests were conducted at controlled cross head rates of approximately 0.16 inch per minute (4 mm/min). Tests with unnotched tensile specimens were conducted with an extensometer mounted on one inch gage marks. This permitted obtaining a load versus enlongation plot so that the 0.2 percent offset yield strength could be determined. Tests at -456° F (-271° C) were conducted only with unnotched tensile specimens.

X-ray diffraction studies were made on as-received and on tested samples of both materials. The material immediately adjacent to the fracture was used to make a qualitative determination of the extent of martensite transformation during test. In addition, X-ray diffraction studies were made with a sample of 304L after immersion in liquid helium under a no load condition to observe the effect of cryogenic temperature without straining.

Tensile data obtained in this investigation with 304L and 310S stainless steel sheet specimens are summarized in tables II and III. In all cases the unnotched tensile strength for both alloys were higher than their notched tensile strengths.

Unnotched Tensile Test Data

Tensile tests at -452° F (-269° C). - Comparison of the unnotched tensile test data for the two stainless steel alloys indicates that the 0.2 percent offset yield strength for 310S is nearly twice that for 304L - approximately 116 000 psi (800 MN/sq m) versus 65 000 psi (450 MN/sq m) for specimens loaded parallel to the sheet rolling direction and approximately 118 000 psi (810 MN/sq m) versus 60 000 psi (410 MN/sq m) for specimens loaded transverse to the rolling direction. However, the ultimate tensile strength for unnotched specimens of 310S stainless steel was about 80 percent of that of 304L stainless steel - approximately 185 000 psi (1280 MN/sq m) versus 229 000 psi (1580 MN/sq m) for specimens loaded parallel to the rolling direction and approximately 187 000 psi (1290 MN/sq m) versus 228 000 psi (1570 MN/sq m) for specimens loaded transverse to the rolling direction. As will be discussed later in connection with X-ray diffraction studies, the higher ultimate tensile strengths of 304L stainless steel are probably associated with austenite to martensite transformations.

For 304L stainless steel, specimens loaded parallel to the sheet rolling direction had higher yield strengths than those loaded transverse to the rolling direction, whereas their ultimate tensile strengths were virtually the same. For 310S stainless steel, there were no significant differences in either yield or ultimate tensile strengths for the two loading orientations.

A comparison of the elongations of the tested unnotched tensile specimens indicates that the elongations for 310S stainless steel were nearly twice those of 304L stainless steel (approximately 58 percent versus 34 percent).

Figures 3 and 4 show unnotched tensile data obtained in this investigation included on plots of tensile strength versus temperature taken from the summary reference 1. The original data from which the curves of reference 1 were taken were obtained by Warren and Reed (ref. 4) and by DeSisto (ref. 5). The yield strength and to some extent the ultimate tensile strength data obtained in the present investigation for 304L stainless steel fall below the curves from reference 1. However, it should be noted that the data from reference 1 are for bar stock. For 310S stainless steel, reasonably good agreement exists between the data from this investigation and the curves taken from reference 1 except for a single point of low ultimate tensile strength which came from a specimen that failed outside the one inch (2.54 cm) gage marks.

Comparison of the data from this investigation with that of reference 2 for both alloys shows that the ultimate tensile strengths agree fairly well, but the yield strengths obtained in the present investigation are slightly higher than those of reference 2. For 310S stainless steel an ultimate tensile strength of 187 000 psi (1290 MN/sq m) and a yield strength of 100 000 psi (690 MN/sq m) were indicated in reference 2. These values compare with an average ultimate tensile strength of 186 000 psi (1280 MN/sq m) and an average yield strength of 117 000 psi (806 MN/sq m) obtained in this investigation. For 304L stainless steel, ultimate tensile strengths of 214 000 to 230 000 psi (1480 to 1590 MN/sq m) and a yield strength of 46 000 psi (320 MN/sq m) were indicated in reference 2. These values compare with an average ultimate tensile strength of 228 000 psi (1570 MN/sq m) and an average yield strength of 62 000 psi (430 MN/sq m) obtained in this investigation.

Tensile tests at -456° F (-271° C). - A few tests were conducted with unnotched tensile specimens (see table II) in liquid helium at -456° F (-271° C). Subject to the limitations of these tests described previously, there do not appear to be any significant differences in tensile behavior from those obtained at -452° F (-269° C) with either material.

Notched Tensile Test Data

Tensile tests with the 3-inch wide center notched specimens were conducted in liquid helium at -452° F (-269° C) only. The center notched tensile data are given in table III. There do not appear to be any significant differences in tensile strength obtained with specimens loaded parallel or transverse to the rolling direction for either material. However, 310S stainless steel had significantly higher tensile strengths than 304L stainless steel for both unwelded and welded specimens. For notched unwelded specimens, 310S stainless steel had a 34 000 psi (230 MN/sq m) higher average tensile strength than 304L stainless steel. For notch-in-weld (without backing strip) specimens this difference was 41 000 psi (280 MN/sq m) and for notch-in-weld (with backing strip) specimens this difference was 24 000 psi (170 MN/sq m). For 304L stainless steel the average notch-in-weld (without backing strip) tensile strength was about 9000 psi (60 MN/sq m) less than that for notched unwelded specimens. For 310S stainless steel there was no significant loss of tensile strength for the notch-in-weld (without backing strip) specimens compared to the notched unwelded specimens.

Notch-in-weld (with backing strip) tensile test specimens had strengths that were significantly higher than notch-in-weld (without backing strip) specimens and unwelded notched specimens for both mateials. For 310S stainless steel the average notch-in-weld (with backing strip) specimen tensile strength was 28 000 psi (190 MN/sq m) higher, while for 304L stainless steel it was 46 000 psi (320 MN/sq m) higher. These strengths are higher, probably because only the 0.063-inch (1.6-mm) thickness of the basic sheet specimen (excluding the backing plate thickness of 0.063 inch (1.6 mm)) was used as the load carrying area for calculating these strengths. The backing strip apparently carried a significant share of the applied load. The maximum tensile strength observed was 171 000 psi (1180 MN/sq m) with a notch-in-weld (with backing strip) specimen of 310S stainless steel.

X-Ray Diffraction Studies

X-ray diffraction studies did not reveal quantitatively the degree of martensite transformation that occurred during cryogenic tensile testing of the steels under investigation. However, the presence or absence of martensite in tested and untested samples could be determined. It was found that a transformation to martensite did occur during tensile testing of 304L in liquid helium. Immersion in liquid helium without straining the sample however, did not cause any martensite transformation to take place. There was no evidence of transformation from austenite to martensite in 310S stainless steel when tested in liquid helium.

Reference 2 reported a similar transformation taking place below -320° F (-196° C) in 304L stainless steel. The fact that 310S stainless steel is not subject to this potentially embrittling transformation under the conditions investigated suggests that it should be more amenable to structural applications at liquid helium temperatures than 304L stainless steel.

SUMMARY OF RESULTS

An investigation was conducted to determine the tensile behavior of 304L and 310S stainless steel in liquid helium at -452° F (-269° C) and to obtain limited tensile data at -456° F (-271° C). The following results were observed:

1. In all cases the unnotched tensile strengths for both alloys were higher than their notched tensile strengths.

2. For 304L stainless steel, specimens loaded parallel to the sheet rolling direction had higher yield strengths than those loaded transverse to the rolling direction, whereas their ultimate tensile strengths were virtually the same. For 310S stainless steel, there were no significant differences in either yield or ultimate tensile strengths for the two loading orientations.

3. The 0.2 percent offset yield strength for 310S stainless steel in liquid helium at -452° F (-269° C) was nearly twice that for 304L stainless steel - approximately 116 000 psi (800 MN/sq m) versus 65 000 psi (450 MN/sq m) for specimens loaded parallel to the rolling direction and approximately 118 000 psi (810 MN/sq m) versus 60 000 psi (410 MN/sq m) for specimens loaded transverse to the rolling direction. However, the ultimate tensile strength for unnotched specimens of 310S stainless steel was about 80 percent of that of 304L stainless steel - approximately 185 000 psi (1280 MN/sq m) versus 229 000 psi (1580 MN/sq m) for specimens loaded parallel to the rolling direction and approximately 187 000 psi (1290 MN/sq m) versus 228 000 psi (1570 MN/sq m) for specimens loaded transverse to the rolling direction.

4. For unnotched tensile specimens the elongations for 310S stainless steel were nearly twice those of 304L stainless steel (approximately 58 percent versus 34 percent).

5. No significant differences in tensile behavior were observed at -456° F (-271° C) from those observed at -452° F (-269° C) with either material.

6. In tests with 3-inch wide center notched tensile specimens, 310S stainless steel had significantly higher strengths than 304L stainless steel for both unwelded and welded specimens. Differences between

average values of notched tensile strengths for the two materials ranged from 34 000 psi (230 MN/sq m) for notched unwelded specimens to 41 000 psi (280 MN/sq m) for notch-in-weld (without backing strip) specimens.

7. For 304L stainless steel the average notch-in-weld (without backing strip) tensile strength was about 9000 psi (60 MN/sq m) less than that for the notched unwelded specimens; however, for 310S stainless steel there was no significant loss of tensile strength for the notch-in-weld (without backing strip) specimens compared to the notched unwelded specimens.

8. X-ray diffraction studies showed that the austenite in 304L transformed to martensite during tensile tests in liquid helium. No transformation was observed with 310S stainless steel.

CONCLUSION

The observed tensile properties suggest that 310S stainless steel should be more amenable to structural applications at liquid helium temperatures than 304L stainless steel.

REFERENCES

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2. Guntner, C. J.; and Reed, R. P.: The Effect of Experimental Variables Including the Martensitic Transformation on the Low-Temperature Mechanical Properties of Austenitic Stainless Steels. Trans. ASM, vol. 55, no. 3, Sept. 1962, pp. 399-419.

3. Anon.: Proposed Recommended Practice for Plane Strain Testing of High Strength Metallic Materials Using a Fatigue-Cracked Bend Specimen, 1968 Book of ASTM Standards, Part 31, pp. 1018-1030.

4. Warren, K. A.; and Reed, R. P.: Tensile and Impact Properties of Selected Materials from 20 to 300° K. Monograph 63, National Bureau of Standards, June 1963.

5. DeSisto, Thomas S.: Low Temperature Mechanical Properties of Base and Weld Deposits of Selected Austenitic Stainless Steels. Rep. AMRA TR 63-08, U.S. Army Materials Research Agency, July 1963.

TABLE I. - CHEMICAL ANALYSES OF AS-RECEIVED 310S AND 304L

STAINLESS STEEL SHEET

Alloy	Alloying element, wt. %								
	Nickel	Chromium	Manganese	Silicon	Phosphorus	Carbon	Sulfur	Copper	Molybdenum
[a]310S	19.0-22.0	24.0-26.0	2.00 max	0.75 max	0.04 max	0.08 max	0.030 max	0.50 max	0.50 max
[b]310S	20.78	24.60	1.77	0.46	0.027	0.076	0.006	0.25	0.22
[c]310S	21.06	25.10	1.86	0.63	0.0169	0.0462	0.0029	0.15	0.08
[a]304L	8.0-11.0	18.0-20.0	2.00 max	0.5-1.00	0.040 max	0.03 max	0.030 max	--------	--------
[b]304L	9.77	18.33	1.74	0.46	0.016	0.026	0.010	--------	--------
[c]304L	9.69	18.48	1.95	0.46	0.0166	0.0198	0.0062	--------	--------

[a]Nominal, AMS

[b]Vendors analysis

[c]Independent laboratory

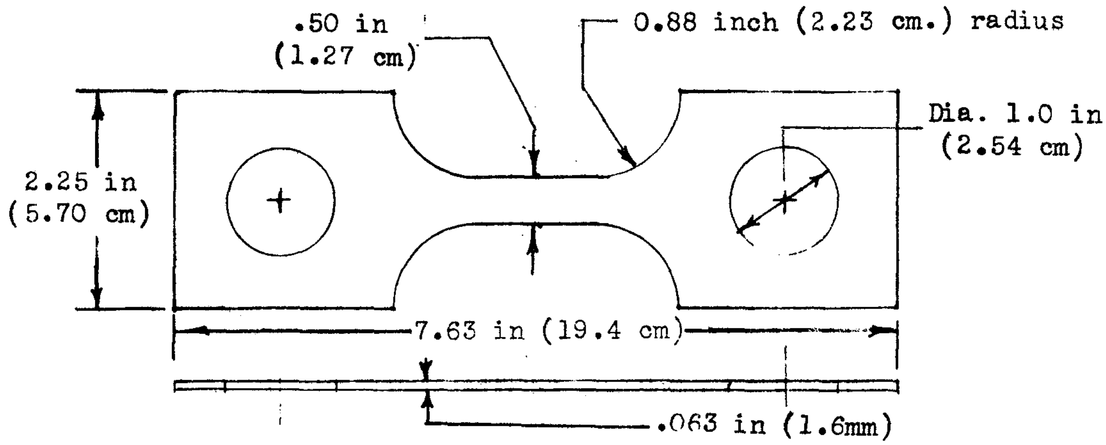
TABLE II. - SUMMARY OF UNNOTCHED TENSILE TESTS IN LIQUID HELIUM

Specimen loading with respect to sheet rolling direction	Test temp °F (°C)	304L					310S				
		Yield strength		Ultimate tensile strength		Elongation, %	Yield strength		Ultimate tensile strength		Elongation, %
		lb/in.^{2}	MN/m^2	lb/in.^{2}	MN/m^2		lb/in.^{2}	MN/m^2	lb/in.^{2}	MN/m^2	
Parallel	-452 (-269)	67 000	460	231 000	1590	34	117 000	810	180 000	1240	54
		-- ---	---	228 000	1570	32	115 000	790	190 000	1310	63
		63 000	430	229 000	1580	32					
		-- ---	---	227 000	1570	36					
	-456 (-271)	68 000	470	235 000	1620	34	107 000	740	-- ----	----	---
		58 000	400	247 000	1700	36	108 000	750	165 000	1140	(a)
Transverse	-452 (-269)	-- ---	---	226 000	1560	34	116 000	800	187 000	1290	58
		63 000	430	231 000	1590	36	119 000	820	188 000	1300	60
		56 000	390	231 000	1590	36					
		59 000	410	223 000	1540	34					
	-456 (-271)	60 000	410	203 000	1400	34	112 000	770	183 000	1260	56

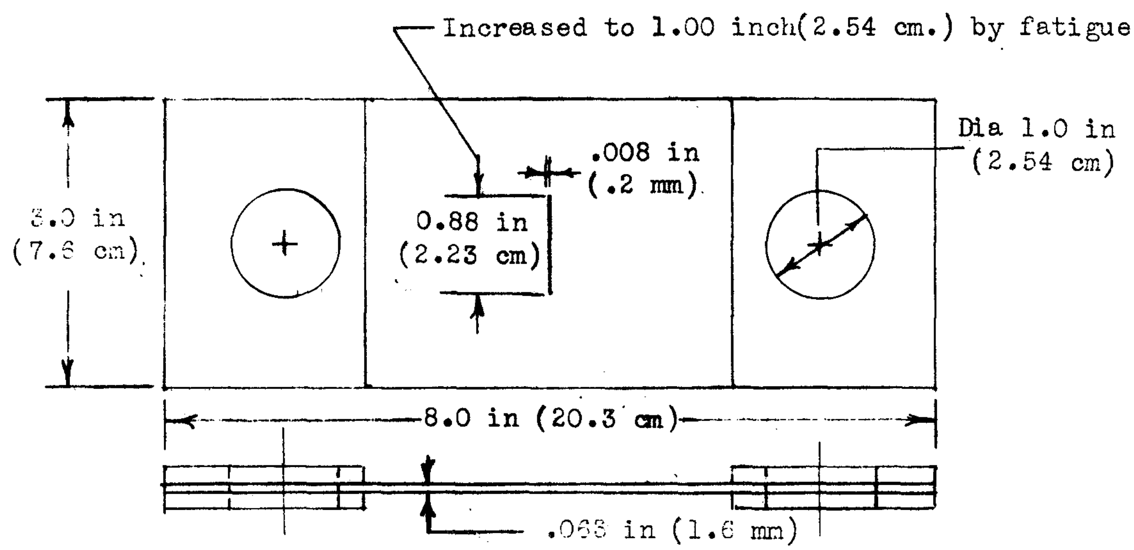
[a]Specimen failed outside test section gage marks.

TABLE III. - SUMMARY OF CENTER NOTCHED TENSILE TESTS IN LIQUID HELIUM AT -452° F (-269° C)

Specimen loading with respect to sheet rolling direction	Notched tensile strength			
	304L		310S	
	lb/in.^{2}	MN/sq m	lb/in.^{2}	MN/sq m
		Unwelded		
Parallel	103 000 103 000 105 000	710 710 720	137 000 135 000	940 930
Transverse	100 000 97 000 101 000	690 670 700	133 000 134 000	920 920
Notch-in-weld (without backing strip)				
Parallel	87 000 90 000 96 000 96 000	600 620 660 660	137 000 127 000 134 000	940 880 920
Transverse	94 000 94 000	650 650	137 000 138 000	940 950
Notch-in-weld (with backing strip) [backing strip cross sectional area excluded in stress calculations]				
Parallel	135 000 139 000 141 000	930 960 970	161 000 162 000	1110 1120
Transverse	145 000 133 000 140 000	1000 920 970	158 000 171 000	1090 1180

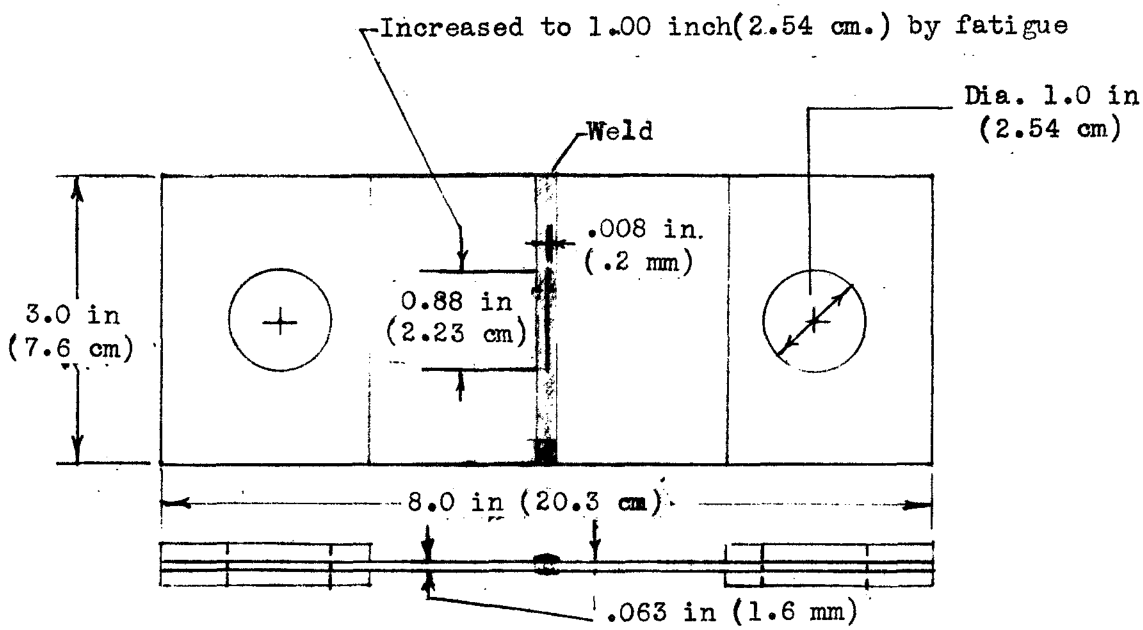


(a) Unnotched

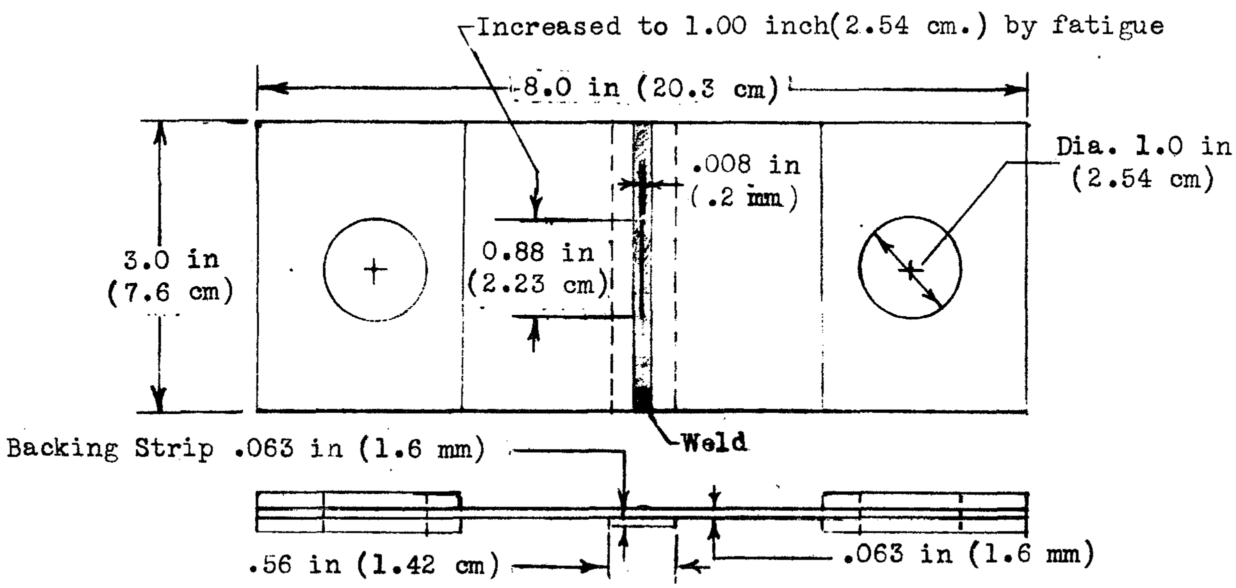


(b) Center Notched Unwelded.

Figure 1. Sheet tensile specimens



(c) Center Notch-in-Weld(Without Backing Strip)



(d) Center Notch-in-Weld(With Backing Strip).

Figure 1. Sheet Tensile Specimens (cont'd)

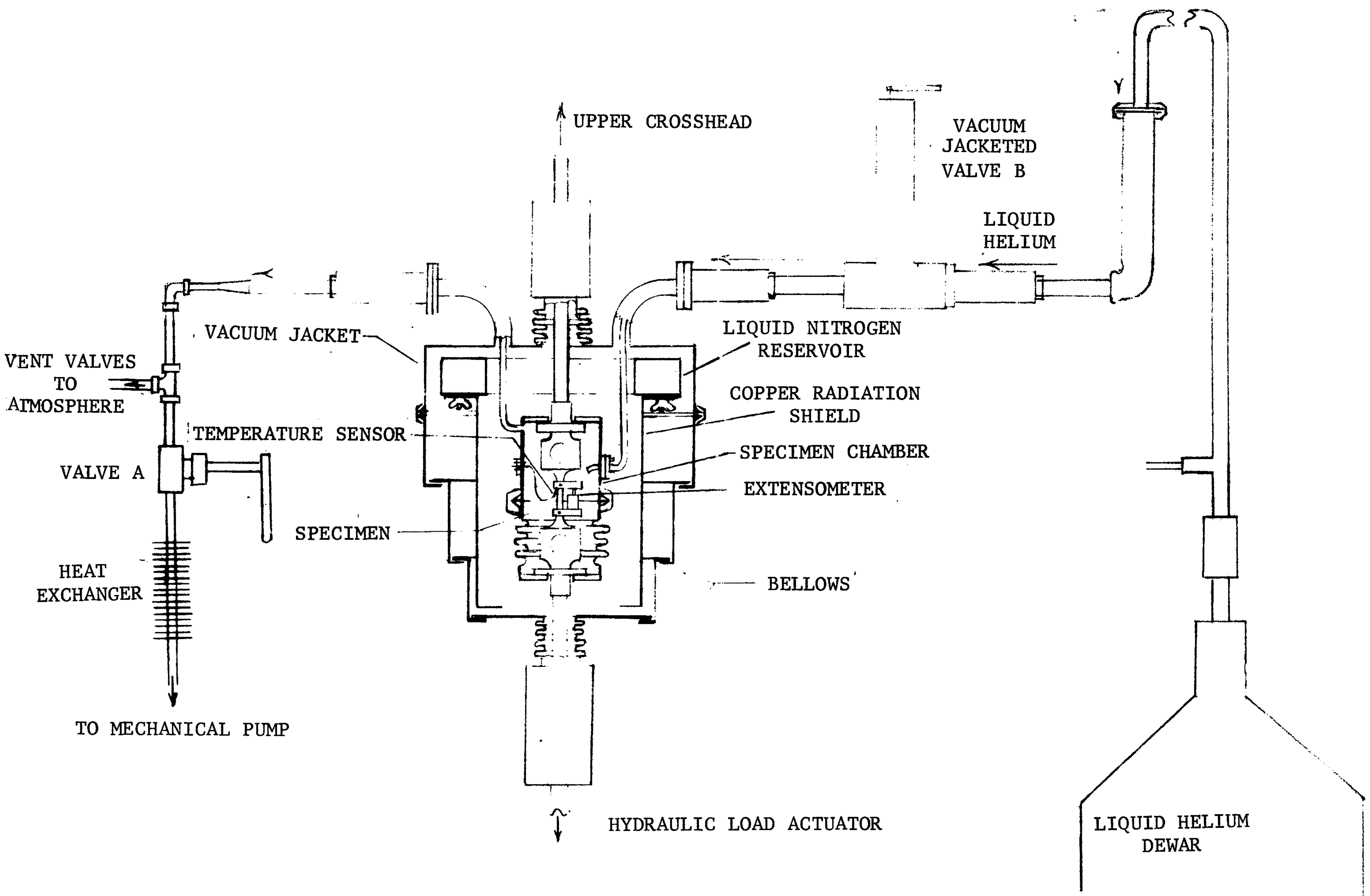
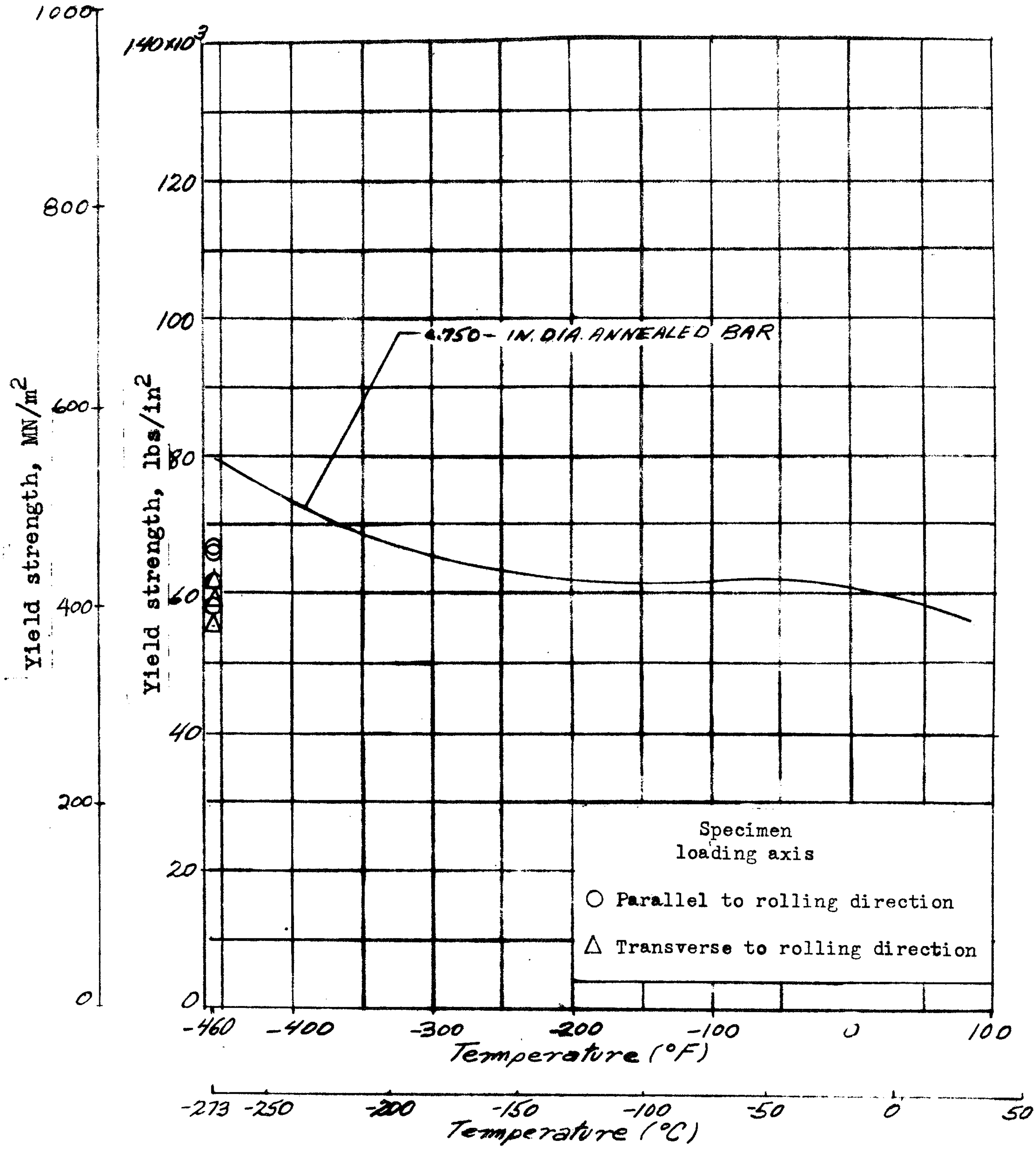
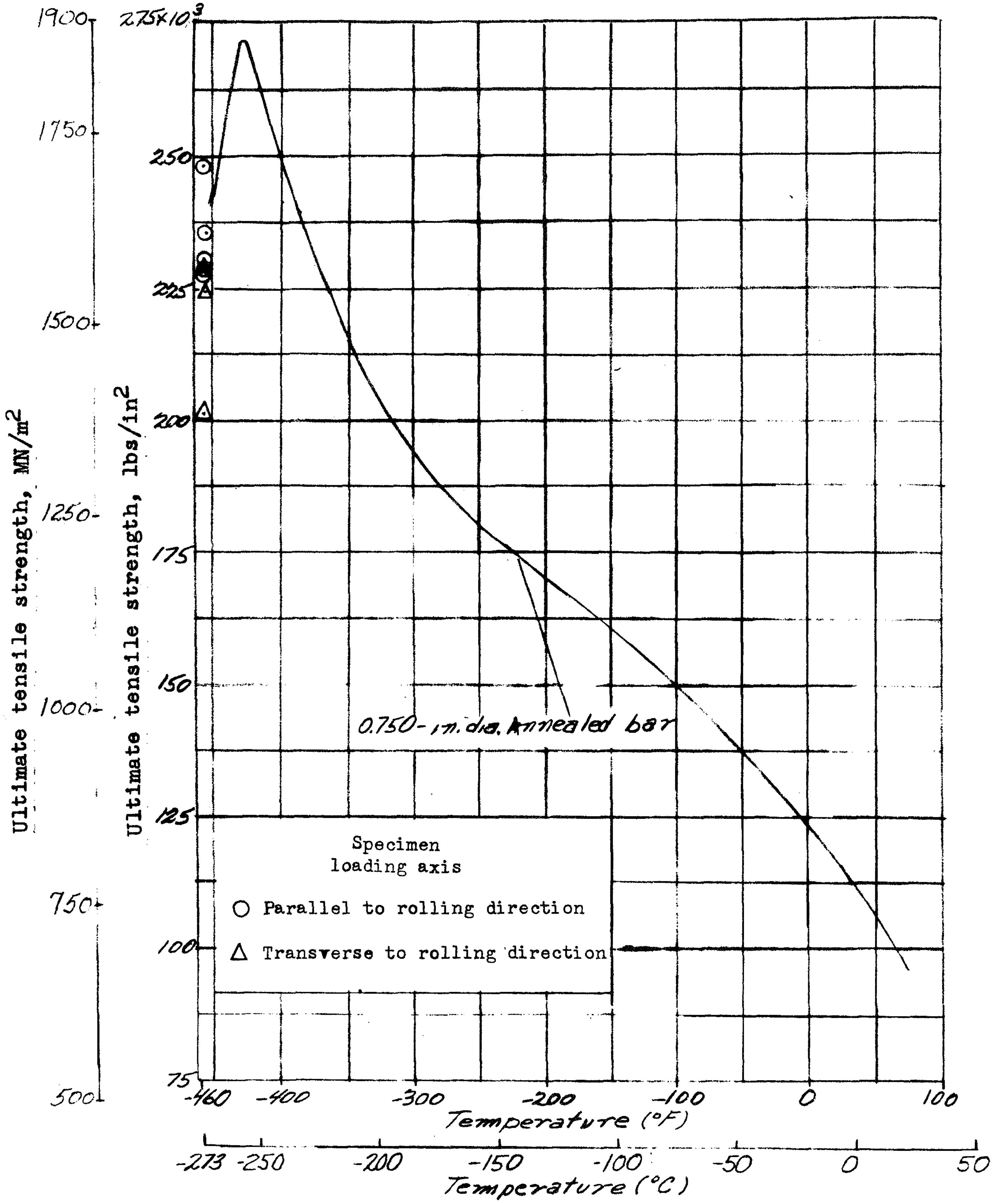


Figure 2 Liquid Helium Tensile Testing Apparatus



(a) Comparison of yield strength.

Figure 3.- Comparison of observed unnotched tensile properties of 304L stainless steel sheet (plotted points) with those of 304L stainless steel bar (plotted curves taken from reference 1).



(b) Comparison of ultimate tensile strength.

Figure 3.--Comparison of observed unnotched tensile properties of 304L stainless steel sheet (plotted points) with those of 304L stainless steel bar (plotted curves taken from reference 1).

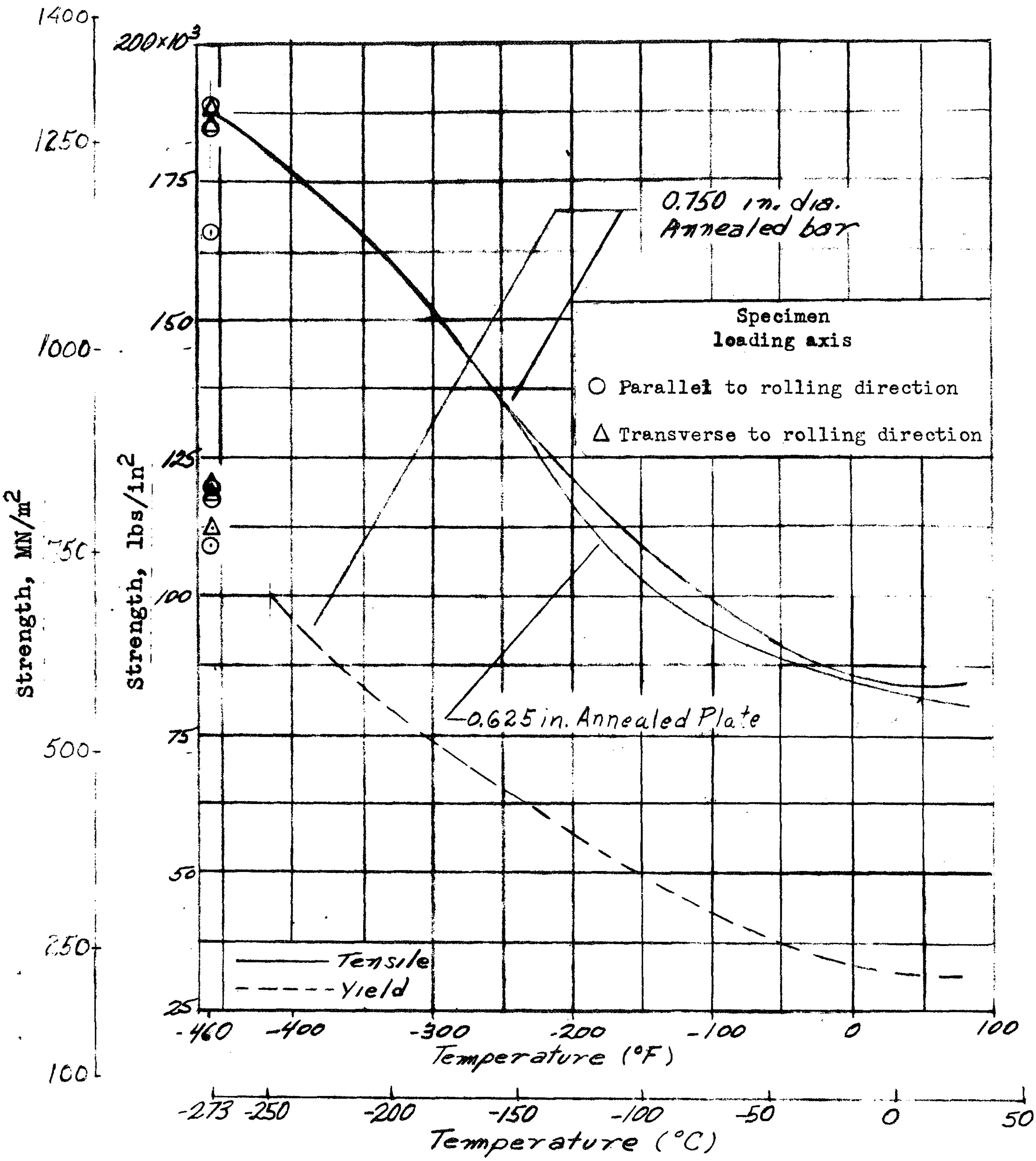


Figure 4.- Comparison of observed unnotched ultimate tensile strength and yield strength of 310S stainless steel sheet (plotted points) with those of 310S stainless steel bar and plate (plotted curves taken from reference 1).