ASD-TDR-62-258

PHYSICAL AND MECHANICAL PROPERTIES OF PRESSURE VESSEL MATERIALS FOR APPLICATION IN A CRYOGENIC ENVIRONMENT

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-62-258
MARCH 1962

Prepared For
DIRECTORATE OF MATERIALS AND PROCESSES
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE COMMAND
Wright-Patterson Air Force Base, Ohio

45
SAPPHIRE ANNIVERSARY
YEARS OF MATERIALS PROGRESS

PROJECT NO. 7381, TASK NO. 738103

(PREPARED UNDER CONTRACT NO. AF 33(616)-7719 BY
GENERAL DYNAMICS | ASTRONAUTICS, SAN DIEGO, CALIF.)
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NOTICES

ASD-TDR-62-258

AD 284293

FOREWORD

This report was prepared by General Dynamics/Astronautics, a Division of General Dynamics Corporation, under Contract No. AF 33(616)-7719. This contract was initiated under Project No. 7381, "Materials Application", Task No. 738103, "Data Collection and Correlation". The work was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division with Mr. Marvin Knight and Mr. C. L. Harmsworth acting as project engineers.

The program at General Dynamics/Astronautics was performed under the direction of Dr. H. F. Dunholter, Director of Research and Development, Dr. V. A. Babits, Manager of Research, and Mr. A. Hurlich, Chief of Materials Research, with Mr. J. L. Christian acting as the Astronautics project engineer.

This report covers the work performed during the period from December 1960 to January 1962.

The author wishes to acknowledge the assistance of his associates who contributed to this study and, in particular, to Mr. A. Hurlich and Dr. J. F. Watson who supplied technical counsel throughout the course of this investigation.

This report was prepared as General Dynamics/Astronautics Report AE62-0102.

ABSTRACT

The primary objective of this program has been to develop simple laboratory-type tests to evaluate the toughness of high strength sheet alloys and their complex welded joints at cryogenic temperatures. Another objective of this program has been to obtain useful engineering data on the mechanical properties of a number of materials currently being used or proposed for use in cryogenic-fueled missiles and space vehicles.

The tests employed for evaluating the toughness of sheet materials included notched tensile tests having stress concentration factors of 3.2, 6.3, and 19, cross-tension and tensile shear tests of individual resistance spot welds, and tensile tests of simple fusion welds. These tests were conducted at 78°, -100°, -320°, and -423° F. These data, as well as data obtained from tensile tests of the base metal, percent martensite determinations, and metallographic examinations of fractured coupons, were correlated with low-cycle, high-stress fatigue data obtained on complex welded joints at 78°, -320°, and -423° F. The most consistent index of toughness was found to be the notched (K_t = 6.3)/unnotched tensile ratio. The test data are presented in tabular and in graphical form to aid metallurgical and design engineers in the selection of materials for structural applications at cryogenic temperatures.

The test data were reduced by statistical methods and analyzed. The results of the statistical analysis, which included means, standard deviations, and statistical values, are presented and their importance discussed.

A description of the test equipment and experimental procedures for tensile and fatigue testing at room and cryogenic temperatures is given. This report also includes conclusions, recommendations for future work, and references.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

FOR THE COMMANDER:

W. P. Conrardy

W. P. CONRARDY
Chief, Materials Engineering Branch
Applications Laboratory
Directorate of Materials and Processes

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LIST OF SYMBOLS

K_t	=	stress concentration factor, $\sqrt{a/r}$
a	=	one half of the width between notches in notched tensile specimens.
r	=	radius at the root of the notches.
K	=	fracture toughness $(\frac{lb}{in.^2}\sqrt{in.})$.
σ	=	gross stress, $(\frac{lb}{in.^2})$.
K_c	=	fracture toughness at critical crack length, $(\frac{lb}{in.^2}\sqrt{in.})$.
G_c	=	crack extension force at critical crack length, $(\frac{in.-lb}{in.^2})$.
F_{ty}	=	0.2 percent yield strength, $(\frac{lb}{in.^2})$.
F_{tu}	=	tensile strength, $(\frac{lb}{in.^2})$.
ksi	=	1000 psi.
CR	=	cold rolled.
CRT	=	cold rolled and tempered.
ELC	=	extra low carbon.
s	=	standard deviation.
N	=	number of test values.
X_i	=	test values.
$\bar{X}$	=	mean.
k	=	probability tolerance factor.
TS	=	tensile strength.

1 INTRODUCTION[1]

Due to the increasing use of cryogenic propellants such as liquid oxygen and liquid hydrogen (boiling points of -297° and -423°F respectively) in current and proposed missiles and space vehicles, the properties of engineering materials at these extreme sub-zero temperatures are of prime importance. Therefore it was the purpose of this program to evaluate the mechanical properties and toughness of a number of high strength structural materials at a series of temperatures from 78° to -423°F. The need for a simple and inexpensive laboratory-type test for evaluating the toughness or resistance to brittle fracture is evident since there are hundreds of high strength alloys which have been proposed for service at cryogenic temperatures. Therefore it was the primary objective of this program to develop a simple and inexpensive test for "screening" purposes to evaluate the toughness of structural materials and their welded joints.

Notched tensile tests, cross-tension and tensile-shear tests of individual resistance spot welds, and tensile tests of fusion welds were included in this program to evaluate the toughness of the materials. Toughness is a property of vital importance in missile design because missile structures are subject to shock-type loads which occur during hydraulic hammering, vibration due to rocket engine firing, action of quick closing valves, etc. Also the structures will contain built-in stress concentrations of varying degrees of intensity due to welding defects, tool marks, assembly eccentricities, random defects in the metal, etc. These conditions all favor brittle failure, and they become even more severe at low temperature in that brittle fracture is more prone to occur at reduced temperatures.

The severest type of toughness test combines high strain rates, sharp notches, and low temperature as typified by the Charpy V-notch test conducted at low temperature. Notched/unnotched tensile tests, rather than Charpy V-notch tests, were used in this investigation as an index of toughness since all of the data reported herein were obtained on relatively thin sheet material and no fully reliable impact test has yet been devised for thin sheet materials. The notched tensile sample allows use of sharp notches and low testing temperatures, but it does not normally permit the high strain rates available in the Charpy V-notch impact test. The initial strain rate at the root of the notch is greater than that encountered in tests of smooth tensile specimens because of the stress concentration effect of the notches.

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[1] Manuscript released by the author (January 1962) for publication as an ASD Technical Documentary Report.

Notched tensile specimens with stress concentration factors (K_t) of 3.2, 6.3, and 19.0 were selected for use in this investigation. These specimens were chosen because of their use by other investigators and because they offered a wide range of notch acuity. Besides the notched tensile tests, specimens which incorporated resistance spot welds and fusion welds were used to evaluate resistance to brittle fracture.

The need for studies of this type is demonstrated by the paucity of published literature pertaining to this topic, especially in the welded joint configuration (for "state of the art" surveys, see References 1 through 12). The problem is further complicated by the fact that existing theories of metallic deformation and fracture are not sufficiently far advanced to warrant the extrapolation of data downward from higher temperatures (References 13, 14, and 15). For example, the Cr-Mn stainless steels were once considered to possess good cryogenic properties until tests at -320°F proved them to be quite brittle (References 16, 17, and 18); even 301 cold-rolled stainless steel has been found to exhibit some tendencies toward brittle behavior in welded joints at -423°F; although this grade of steel is usually considered to have excellent low-temperature properties (Reference 19). The lack of understanding of these and other effects illustrates the need for programs to determine the properties of high-strength structural materials at cryogenic temperatures.

Since this program was aimed primarily at missile and space vehicle applications, primary attention was focused on sheet alloys in thicknesses ranging from 0.012 inches to 0.125 inches because large propellant tanks are fabricated from thin gauge sheet. In addition, since weldability is of prime importance in the fabrication of these vehicles, the sheet alloys were tested in both the base metal and welded joint configurations. The materials selected for investigation represent a number of different alloy systems and include stainless steels and aluminum and titanium base alloys. These alloys were selected for investigation because they exhibited one or more of the following characteristics which suited them for missile and space vehicle application: high strength/density ratios; good toughness (i.e., resistance to brittle fracture); adequate weldability; retention of properties at moderately high temperatures; corrosion resistance; and good formability. In order to obtain optimum strength levels, the particular alloys selected for study were either cold worked (i.e., cold-rolled) or heat treated (e.g., age-hardened, or quenched and tempered) to their highest strength levels commensurate with adequate toughness.

2 TEST PROGRAM

The test program consisted of the determination of the tensile properties of parent and weld metal and the fatigue properties of complex welded joints of several high-strength sheet materials from 78° to -423° F. Test materials included stainless steels and aluminum and titanium base alloys which are of interest for application in long-range missiles and space vehicles employing cryogenic propellants.

Test conditions included tensile and notched tensile testing of the base metal, both longitudinal and transverse to the direction of rolling, at 78°, -100°, -320°, and -423° F. Three notched tensile specimens, having K_t values of 3.2, 6.3, and 19.0 were used for evaluation of the materials' toughness. Also included as evaluation tests were cross-tension and tensile-shear testing of individual resistance spot welds and tensile testing of fusion welds at 78°, -100°, -320°, and -423° F. Fatigue tests of complex welded joints were conducted at 78°, -320°, and -423°F to develop a portion of the S-N diagram (stress level versus cycles to failure) for each material in the high-stress, finite-life range. Magnetic, metallographic, hardness, and chemical tests were performed to determine mechanisms and origins of fractures, to observe microstructural details, and to provide information on low temperature embrittlement phenomena and fracture characteristics. References 20 through 23 give complete details of the test program.

Upon completion of the test program, the test data were statistically reduced and analyzed, and the results presented in graphical and tabular form. In order to satisfy the primary objective of the program, which was to develop simple and inexpensive laboratory-type tests to evaluate the toughness of high strength sheet materials at cryogenic temperatures, the data were analyzed to show any correlations between the evaluation tests and the fatigue data. The fatigue data were considered to be indicative of the service behavior of the alloys investigated (References 20 and 25). Data from the evaluation tests, which included notched tensile tests and resulting notched/unnotched tensile strength ratios, fusion-welded tensile tests, and tensile-shear and cross-tension tests of individual resistance spot welds, were analyzed to see which test or tests best predicted the fatigue life of the materials investigated.

A secondary objective of the test program was to provide useful engineering data on the mechanical properties and toughness of a number of high strength sheet materials. Therefore five or more replicate tests were performed and the data statistically reduced to provide information on the tensile and weld tensile properties from 78° to -423°F. Results obtained from the fatigue and evaluation tests were analyzed to determine the materials' toughness at each of the testing temperatures. From these results recommendations concerning the use of each material for pressure vessel applications were made. The criteria used for determining the materials' toughness at each testing temperature were: adequate fatigue life of welded joints, a notched/unnotched tensile strength ratio of near unity or above, tensile/shear ratio of 0.25 or above as obtained from individual resistance spot welds, an increase in tensile strengths of notched specimens and fusion welded specimens with a decrease in testing temperature, and a consistency in the tensile and fatigue data (a large amount of scatter in the test data indicates possible embrittlement).

3 MATERIALS

The materials selected for testing in this investigation included cold-rolled 301, 304ELC, and 310 stainless steels, cold-rolled and tempered AM-355 stainless steel; 2014-T6, 5052-H38, and 5456-H343 aluminum alloys; and annealed 5Al-2.5Sn titanium alloy. The history and chemical analysis of these materials are presented in Table 1.

These alloys were selected for the following reasons. They are representative of materials which are currently being used or are proposed for use for structural applications in missile and space vehicle systems. The alloys represent two fundamentally different methods of obtaining high strengths. These are cold rolling (301, 304ELC, and 310 stainless steels and 5052 and 5456 aluminum alloys) and heat treating (AM-355 stainless steel and 2014 aluminum alloy). Also, annealed material is represented by the Ti-5Al-2.5Sn alloy. These alloys cover a wide range of resistance to brittle failure, particularly at cryogenic temperatures. Previous data have indicated that the cold-rolled stainless steels at -423°F have decreasing toughness in the order 310, 304ELC, and 301. Also previous data indicated that 2014 and 5052 are tough, whereas 5456 is relatively brittle at -423° F. The AM-355 stainless steel in the CRT condition was expected to have the least resistance to brittle fracture of the alloys investigated at cryogenic temperatures.

The notched tensile data and notched/unnotched tension ratios obtained early in the investigation indicated that the particular heat of Type 301 stainless steel (heat No. 49061) was more brittle at -320° and -423° F than previous heats which had been evaluated at General Dynamics/Astronautics (References 19, 24, and 25). Therefore, another heat of 301 steel (heat No. 57644) was included in the test program. For the same reason, two heats of the Ti-5Al-2.5Sn alloy were evaluated. Heat M-8394 was the original titanium test material evaluated. This heat was purchased to commercial specifications which allows interstitial (C, O_2, N_2, and H_2) and iron contents to be too high for adequate toughness at extreme sub-zero temperatures. Since the initiation of this investigation it has been found that the amount of the interstitials and iron must be limited to moderately low values in the Ti-5Al-2.5Sn alloy to retain adequate resistance to brittle failure at -423° F (References 26 and 27). A special Astronautics specification (GD/A-0-71010) which limits the interstitial elements and iron contents was prepared for the purchase of Ti-5Al-2.5Sn alloy. Heat 3930131 was purchased to this specification. Tensile and fatigue property data obtained on this heat are reported.

The materials were tested in the as-received condition (as shown in Table 1) with no further cold working or heat treatment. Physical properties and chemistry met the specifications for which they were purchased for each of the alloys investigated.

4 TEST SPECIMENS

The test specimens used in this investigation included a standard flat tensile specimen, three different notched tensile specimens, cross-tension and tensile-shear spot-welded specimens, and a number of large fatigue specimens (38 inches long) containing complex-welded joints. A drawing of the flat tensile specimen used for base metal and fusion weld tensile testing is shown in Figure 1. A photograph of typical specimens is shown in Figure 8. Drawings of the notched tensile specimens are shown in Figures 2 and 3. Figure 3 presents those notched specimens having stress concentration factors of 3.2 and 6.3. Figure 4 shows the drawing of the notched tensile specimen with a K_t of 18.7. A photograph of typical notched specimens is shown in Figure 9. There are several methods for determining the stress concentration factor of a notched specimen. The stress concentration factors referred to throughout this report were determined by means of the equation: $K_t = \sqrt{a/r}$ where K_t is the stress concentration factor, a is one half of the distance between the notches and r is the radius at the root of the notches. Stress concentration factors as determined by Peterson's equation (Reference 28) and by Neuber's concept (Reference 29) are presented below:

	Notch "B"	Notch "A"	Sharp Notch
Total Width (Inches)	0.4	0.4	1.0
Width between Notches (2a) (Inches)	0.2	0.2	0.7
Radius (r) (Inches)	0.01	0.0025	0.001
K_t ($\sqrt{a/r}$)	3.2	6.3	18.7
K_t (Peterson)	3.8	7.2	21.0
K_t (Neuber)	3.9	7.5	--

Dimensional tolerances for machining of the test specimens (see Figures 2 and 3) allow stress concentration factors which may vary as much as 15 percent; therefore, the K_t was calculated by means of $\sqrt{a/r}$ for each notch specimen tested and is presented in parenthesis with the notched tensile data in Tables 5 through 12. The cross-tension and tensile-shear resistance spot-welded specimens are shown in Figures 4 and 10. Drawings of the fatigue specimens are given in Figures 5, 6, and 7, and photographs of typical specimens are shown in Figures 11, 12, and 13. Figure 5 gives the print used for machining the stainless steel and titanium longitudinal fatigue specimens. Figure 6 gives the machining print for the transverse fatigue specimens for stainless steels and titanium alloys. The print shown in Figure 7 was used for both the longitudinal and transverse fatigue specimens of the three aluminum alloys. The joints referred to in Tables 18 through 25 are as follows:

For Stainless Steels and Titanium:

Longitudinal Joint No. 1 refers to the complex-welded fatigue specimens with a doubler sheet attached by four rows of spot welds on each side of the fusion weld joint (shown in Figures 5 and 11).

Longitudinal joint No. 2 refers to the complex-welded fatigue specimens with two rows of spot welds on each side of the fusion weld (same as joint No. 1 except the outer two rows of spot welds on each side of the fusion weld are deleted). Figure 11 shows a typical specimen having a joint No. 2 configuration.

Longitudinal joint No. 3 (titanium only) refers to the welded fatigue specimen with no doubler attached. This specimen is machined per the print given in Figure 5; however, the joint consists of only a fusion weld with no doubler. Figure 13 shows a typical fatigue specimen having a joint No. 3 configuration.

Transverse joint No. 1 refers to the complex welded joint which is composed of an overlapping joint welded by resistance roll seam welding with one row of resistance spot welds on each side of the roll seam weld. The print for this specimen is given in Figure 6 and a typical specimen is shown in Figure 11.

Transverse joint No. 2 (310 stainless steel only) is the same joint as longitudinal joint No. 1; however, the material is tested in the transverse direction.

For Aluminum Alloys:

Longitudinal and transverse joint No. 1 refers to the fusion-welded fatigue specimens as shown in the print in Figure 7. The longitudinal and transverse specimens have the same joint configuration. A typical specimen is shown in Figure 12. Also shown is the fatigue specimen with a thicker area at the joint accomplished by machine milling on both sides of the fusion weld.

Longitudinal joint No. 2 refers to a complex joint containing a doubler sheet fusion welded to the specimen at the fusion-weld area. This joint contains no spot welds. A typical specimen is shown in Figure 12 (center specimen).

The procedure for specimen preparation was as follows. Specimen layout and identification was made on the sheet materials. Specimen blanks were then sheared and those specimens requiring fusion or resistance roll seam welding were welded. The fusion-weld, spot-weld, and roll-seam-weld schedules are given in Tables 2, 3, and 4. All the welds were visually inspected and some were inspected by means of an x-ray examination. Typical radiographic prints of welded joints of fatigue specimens are shown in Figures 15 and 16. The specimen blanks were then machined and surfaces prepared for testing and then inspected. Any specimens which were not within the dimensional tolerances of the machining prints were discarded. Doublers were then spot welded on the fatigue specimens. Notched tensile specimens were measured by means of an optical comparator. Smooth tensile and fatigue specimens were measured to 0.0001 inch by means of a micrometer.

A few crack propagation tests were made during this investigation. The specimens used for this testing are shown in Figure 14.

5 APPARATUS AND PROCEDURE

The tensile specimens were tested on a 30,000-pound Tinius-Olsen or a 50,000-pound Baldwin-Emery universal testing machine equipped with continuous stress-strain recorders and strain pacers. Specially constructed cryostats were used for testing at sub-zero temperatures. Small, open cryostats were used for tests at -100° F by immersion of the specimens in a bath of dry ice and alcohol and at -320°F by immersion in liquid nitrogen. Cryostats which were specially designed for tensile testing in liquid hydrogen were used for tensile tests conducted at -423°F.

The liquid-hydrogen cryostats, pull rods, grips and other accessories are constructed from 321 stainless steel. The liquid-hydrogen chambers are insulated by a concentric vacuum space, a liquid-nitrogen bath, and foamed polyurethane insulation. Lids provided with ports for the pull rods, exhaust vents, and extensometers are gas-tight fits to the chambers by means of mechanical clamps and Teflon O-ring seals. Temperature measurement is accomplished by means of copper-constantan thermocouples. Liquid-level indicators, using carbon-resistor sensors, are used to monitor the amount of liquid hydrogen present in the test chambers. Immersion type heater elements are used to boil off the liquid hydrogen upon completion of each test. A heater was chosen over other means of removing the liquid hydrogen because it permits rapid testing, is simple in design, is easy to use, and allows for greater safety. Figures 17, 18, and 19 show views of the two liquid-hydrogen cryostats used for tensile testing in this investigation. Figure 17 shows the pull rod with universal joint, stainless steel flex line for exhaust of hydrogen gas, the lid clamped into position and electrical leads to the heater, liquid-level indicator, thermocouples, and extensometer. Figure 18 shows a specimen being loaded into the liquid-hydrogen cryostat. The dewar at the right contains liquid nitrogen which is used as an insulation jacket. Figure 19 shows the transfer of liquid hydrogen from a 50-liter dewar to the test chamber through a vacuum-insulated transfer line. A gas analyzer is being used to determine the amount of hydrogen gas escaping into the laboratory. Also shown in Figure 19 is a view of one of the cryogenic laboratories equipped for liquid-hydrogen testing. The ceiling is gas tight and tapers to the center of the room where three explosion-proofed motors and fans create a circulation of air in the laboratory at the rate of four changes per minute. All lights and electrical connections and equipment higher than three feet above the floor are explosion proofed. All equipment which could not be explosion proofed was placed inside the operator's room, shown in Figure 19.

Continuous recordings of stress-strain curves were accomplished by means of standard extensometers for the room temperature tests and specially designed cryo-extensometers for the sub-zero temperature tests. An assembly view of a cryo-extensometer, clamps, and a tensile specimen is shown in Figure 20. The cryo-extensometer used to measure strain in the gauge length of the specimen uses two knife edges clamped to the specimen. The knife edges are attached to tubes extending outside the liquid-hydrogen chamber. Thus strain in the specimen results in differential movement of the two tubes which protrude above the cryostat. This differential movement, which is proportional to strain, is used as the input (through a lever) to a differential-transformer-type transducer. The output of this transducer is an electrical signal which is used to control the abscissa (strain axis) of an automatic recorder that produces a continuous stress-strain curve.

Figure 20 shows how both the extension tubes and transducer are attached to a frame and connected to each other through a lever system.

The knife edges are attached to the specimen with the help of a precision gage block which ensures that the knife edges are parallel and separated by the gage length desired (two inches in this case). The extensometer is designed to withstand severe shock without damaging the equipment so that strain can be recorded until specimen fracture. The sensitivity of the extensometer system is 0.0001 inch. The extensometers as well as the strain pacer, stress-strain recorder, and the load cells are periodically standardized and their accuracy checked.

The sequence of operations in performing the tensile tests is as follows. The specimens are checked for surface defects, measured by means of a micrometer, and gage marked for total elongation determination. The specimens are placed in the equipment and brought to the proper temperature by means of dry ice and alcohol (-100° F), liquid nitrogen (-320° F), or liquid hydrogen (-423° F). The temperature of the test specimen is measured by means of copper-constantan thermocouples. The specimens are loaded in tension until failure at the following rates: 0.001 in./in./min until 0.2-percent yield followed by 0.15 in./min until failure for the parent metal and fusion-welded tensile tests; 0.001 in./in./min as determined by an extensometer (about 0.01 to 0.02 in./min) for the notched tensile tests; 0.1 in./min for the spot-welded cross-tension and tensile-shear tests. Upon failure the specimen is removed and another prepared for test. Each test is assigned a run number, and all data, including specimen number and measurements, test temperature, loads, stress-strain curve, strain rate, elongation, and special remarks, are recorded. The results, as reported in Tables 5 through 12, are then determined.

A thorough description of the liquid-hydrogen cryostats, cryo-extensometers, and accessory equipment, as well as the safety features, rapidity of testing, and sequence of operations may be found in Reference 30.

The high-stress, low-cycle fatigue tests were conducted on a series of hydraulic test beds. Figure 21 shows a static tensile test being performed on a 301 stainless steel fatigue specimen at room temperature. Figure 22 shows the same type of test being performed at -320° F. These specimens are being static tested on a 200,000-pound Tinius-Olsen universal testing machine. Figure 23 shows a view of the outdoor liquid-hydrogen testing area where the fatigue tests are performed. The dewar trailers shown in Figure 23 contain liquid nitrogen and liquid hydrogen. The test console is shown in the foreground. The test beds are located in the small building (center of photo). The building is equipped with blower fans which circulate the air during the test. Gaseous hydrogen may be seen escaping to the atmosphere at the top of the exhaust stack. Figure 24 shows the hydraulic rams which are used on one of the four test beds. Test gages, such as shown in Figure 24, are located at the test beds and at the test console (located about 20 yards from the test beds). Automatic cycling apparatus equipped with counters is used to monitor the fatigue tests with minimum operators' attendance. One of the test beds is shown in Figure 25. The specimen, which is shown loaded in the test bed, may be tested at room temperature or at -320°F (by filling and maintaining the insulated test chamber with liquid nitrogen). A photo of a fatigue specimen being prepared for testing at -423°F is shown in Figure 26. The liquid-hydrogen cryostat, also shown in Figures 27 and 28, is positioned on the fatigue specimen. The specimen is then mounted in the test bed which is filled with liquid nitrogen. The liquid-hydrogen cryostat is then filled and maintained with liquid hydrogen. After the specimen has come to temperature, the fatigue test is conducted. Shown in Figure 26 is the vacuum-insulated fill line, exhaust line, and electrical leads to a liquid-level sensor and thermocouple.

The sequence of operations for fatigue testing is as follows. The specimens are inspected and area determinations made. The specimens are placed in the test bed and brought to test temperature. Loads are set by means of a test gage and a four-way, solenoid operated, hydraulic control valve. The test is operated automatically with the number of cycles determined by an electrical counter. The fatigue tests are conducted at the rate of six cycles per minute. Static tests are performed at 0.001 in./in./min until failure.

In addition to the tensile and fatigue tests, a few crack propagation tests were made during this study. The cryostat used for these tests is shown in Figure 29. Observation of the specimen (shown in Figure 14) and the extension of the crack upon loading is made by means of a simple optical system. More information on the crack propagation testing apparatus and procedure may be found in Reference 31.

The failed tensile and fatigue specimens were visually observed, hardness and magnetic (for steels) measurements were made; and fractured edges mounted for metallographic examination. These tests were made to help determine the mechanism and origins of fractures, to observe microstructural details, and to provide information on low-temperature embrittlement phenomena and fracture characteristics. Hardness measurements were performed on a Rockwell Superficial hardness tester using the 15-N scale. Magnetic measurements were made by means of a Magne-Gage which had been calibrated to read directly in terms of percent martensite present in stainless steels (Reference 32). Metallographic studies were made with conventional equipment. Figure 30 is a view of the metallography laboratory showing metallurgical microscopes, metallograph, and electron microscope.

6 EXPERIMENTAL RESULTS

Mechanical property data on base metal tensile tests are given in Tables 5 through 12, 25, and 26 for the materials tested in this investigation. These tables include yield (0.2 percent offset) and tensile strengths at each testing temperature. These data are plotted as a function of temperature in Figures 31 through 38. Total elongations are reported in the tables and plotted in Figures 39 and 40. Notched tensile strengths, notched/unnotched tensile ratios, fracture toughness and stress concentration factors are given in Tables 5 through 12. The notched data are shown graphically in Figures 41 through 58. The stress concentration factor (K_t) of each individual notched specimen is reported in parenthesis with the notched tensile data. The fracture toughness values were calculated from the equation $K^2 = \pi a \sigma^2$ where K is the fracture toughness, a is one half of the initial crack (notch) length and σ is the gross stress (Reference 33). It should be noted that the fracture toughness values reported in Tables 5 through 12 were calculated from initial crack (notch) lengths and not the critical crack lengths. Therefore, the values reported are K values, not K_c values, and as such may be conservative. Some K_c and G_c data are reported for Type 301 stainless steel (reported in Section 8). Tensile data obtained on single fusion welds are reported in Tables 5 through 12, 26, and 27. Tensile strengths, joint efficiencies, and elongations of the welds are shown as a function of test temperature in Figures 59 through 64. Hardness values and magnetic measurements of fractured tensile specimens are reported in Tables 5 through 12.

Cross-tension and tensile-shear data obtained on individual resistance spot welds are reported in Tables 13 through 17. These data are shown graphically as a function of temperature in Figure 65.

The high-stress, low-cycle fatigue data are reported in Tables 18 through 26 and Table 28. S-N (stress level versus number of cycles to failure) curves were plotted from the fatigue data and are shown in Figures 66 through 103.

Photographs were made of typical tensile and fatigue specimen fractures. Figures 104 through 107 show typical failures of base metal and simple fusion-weld tensile specimens. Typical fractures of the fatigue specimens are shown in Figures 118 through 128. Photomicrographs were made on fractured edges of tensile specimens and are shown in Figures 108 through 115. Photomicrographs of resistance spot welds are shown in Figures 116 and 117.

Results of a statistical reduction and analysis of the tensile data of base metal, fusion welds and cross-tension and tensile-shear data of resistance spot welds are given in Table 30 and Figures 129 through 138.

7 STATISTICAL ANALYSIS OF DATA

A statistical analysis was performed on each of the alloys tested in this investigation. Results of the statistical analysis are reported for F_{ty}, F_{tu}, and weld tensile strengths for both the longitudinal and transverse directions, and cross-tension and tensile-shear strengths of individual resistance spot welds. The data for each of the test temperatures were analyzed.

Mean values, standard deviations, and 90- and 99-percent probability (with 95-percent confidence) values were obtained for the particular heats and coils of materials tested. The 90- and 99-percent levels employed herein statistically correspond, respectively, to the "B" and "A" values as discussed in MIL-HDBK-5, March 1959 (Reference 34). The "B" and "A" values are not considered to be material design allowables because only one heat and coil of each material was tested which probably would not be fully representative of all material produced to the same specifications. Therefore, the 90- and 99-percent levels may be considered to be "B" and "A" design allowables only for the particular coils tested.

For the purposes of this report, an "A" value will be considered to be that level which would be exceeded by at least 99 percent of the population; i.e., the confidence is 95 percent that 99 percent of all the test data, for each test condition obtained from the tested heat and coil of material, would exceed the "A" value. The "B" value is similarly defined for 90-percent probability and 95-percent confidence. The material property data were analyzed independently for each test condition. For F_{ty}, F_{tu}, and weld tensile strength, five test values were analyzed for each combination of eight materials, two grain directions, and four temperatures. For spot-weld tensile and shear strengths, twenty test values were analyzed for each combination of five materials and four temperatures. In each case the sample standard deviation (s) was calculated from the following equation:

$$s = \sqrt{\frac{\sum_{i=1}^{N} (X_i - \bar{X})^2}{N - 1}}$$

Where N = number of test values,

X_i = test values, and

$$\bar{X} = \frac{1}{N} \sum_{i=1}^{N} X_i \, .$$

The "A" and "B" values were evaluated by subtracting from $\overline{X}$ the product ks, where k is the applicable probability tolerance factor as follows:

$$X_B = \overline{X} - k_B s$$

$$X_A = \overline{X} - k_A s$$

Reference 35 contains tables of the one-sided tolerance factors for the normal distribution at the desired levels of probability and confidence. The assumption of normality in the analyses is justifiable on the basis of the small sample sizes. Previous investigations of strength properties having large sample sizes indicate that the distribution functions are often slightly non-normal (Reference 36). In many cases, the log-normal distribution best describes the total population due to the influence of specification minimum requirements, quality control, etc. However, the use of non-normal distribution functions with small sample sizes where the population distribution function is not definitely known may lead to erroneous results. The normal or Gaussian distribution function was therefore adopted for the analysis of the data herein.

The data were coded for and analyzed on an IBM 7090 digital computer. The results of the statistical analysis are presented in Table 29. Included in Table 29 are the means, standard deviations, and "A" and "B" values. An effort was made to indicate possible misleading values resulting from the statistical study. In general, for mechanical property data of engineering materials, the "A" value should exceed 80 percent of the mean. Those "A" values given in Table 29 which did not exceed 80 percent of the mean are indicated by means of an asterisk. There are several possible explanations for the large standard deviations, and thus low design allowable values, for the cases noted. There may have been too few of a number of test values, in which case additional testing would have to be performed to obtain better estimates of the population parameters. It may be that even with additional testing the dispersion of the data would remain large, in which case, it is possible that the data are not definitive enough to permit a reasonable statistical evaluation. Large standard deviations may also be a result of the material, fabrication of the test specimen, or testing equipment and procedure. A more thorough study of the standard deviations as a function of test temperature was made. The results are plotted in Figures 129 through 138. In general, the standard deviations increase with decrease in testing temperature, and the standard deviations are larger for the tensile strengths of welds than for the base metal. The explanation for the latter case is that the welding process has introduced other factors which would tend to increase the amount of scatter in the tensile data. These factors include porosity, lack of fusion, gas absorption, thinning, mismatch, presence of intermetallics in the heat affected zone (which tends to decrease the resistance to brittle fracture), etc. Although the welds were found to be radiographically sound and acceptable per industrial standards, it is felt that the added factors introduced by the presence of the welds may be responsible for those cases in which the dispersion of the tensile data was greater for the weld metal than for the parent metal.

The general increase of standard deviations with decrease in testing temperature is felt to be due to several reasons. The values of the test data generally increase with decrease in testing temperature; therefore, a larger standard deviation (actual value, not percent of standard deviation with respect to mean value, i.e. $s/\overline{X}$) would be expected. Graphs of $s/\overline{X}$ versus temperature were plotted to determine the validity of this explanation. It was found that the $s/\overline{X}$ values when plotted versus temperature did not increase as much with decrease in test temperature as for the s versus temperature plots. This would indicate that the effect of increasing test values with decreasing temperatures was to increase the standard deviation at the lower test temperatures. However, this does not totally explain the increase of standard deviation with decrease in temperature because, in general, the values of the standard deviations divided by the means ($s/\overline{X}$) also increased with decrease in temperature. A possible explanation for the increased scatter of test data at sub-zero temperatures is the greater likelihood of experimental error at the lower temperatures due to the necessary increase in complexity of the test equipment. It is believed that a more likely explanation, however, is that some of the materials tested in this investigation become less tough with decrease in temperature and that decreased toughness (embrittlement) is directly proportional to increased scatter in the test data. Previous data have indicated that a greater spread of test values is obtained for the more brittle materials than for tough materials (Reference 25). As may be seen in Table 29 and Figures 129 through 138, those materials with large standard deviations and low "A" and "B" values (as compared to the mean values), for a particular test condition (temperature, grain direction), appear to be less tough as determined by notched tensile tests, spotweld tensile and shear tests, and fatigue tests. An exception to this is the weld tensile data which was discussed previously, and is felt to be due to the presence of the weld. It is believed that a statistical analysis (particularly $s/\overline{X}$ versus temperature) of tensile test data can be used in the evaluation of the toughness of a material, and it is suggested that further efforts be made in the development of this method of evaluating candidate materials for structural applications at cryogenic temperature.

It is again emphasized that the "A" and "B" values as given in Table 29 are not intended as design allowables for the materials but are, as defined previously, probability values based upon tests from one coil of one heat of each material.

8 DISCUSSION OF RESULTS

Each of the alloys tested in this investigation will be discussed individually to provide maximum clarification and interpretation of the experimental results. This is necessary due to the large amount of data obtained in this study. Several correlations between the data of one alloy and another, however, are noted and graphs of tensile and fatigue properties of all the alloys are shown in Figures 31 through 65, 78 through 86, 94 through 99, and 137 and 138.

8.1 301 STAINLESS STEEL. Base metal tensile, notched tensile, and fusion-weld tensile data at 78°, -100°, -320°, and -423° F are presented for one heat of 60-percent cold-rolled Type 301 stainless steel in Table 5 and Figures 31 through 64. Table 13 and Figure 65 present cross-tensile and tensile-shear data on individual resistance spot welds of this alloy at the same temperatures. High-stress, low-cycle axial fatigue data obtained on complex-welded joints are presented in Table 18 and Figures 66 through 68 and 78 through 86. Results of a statistical analysis of these data are given in Table 29 and Figures 129, 137, and 138. Photographs of typical fractures of base metal and welded tensile specimens are shown in Figure 104 with photomicrographs of the fractured edges shown in Figure 108. Fractures of fatigue specimens were similar at each testing temperature and are typified by those failures shown in Figure 118. Figure 119 shows a failure in the base metal, indicating 100-percent joint efficiency.

As may be seen in Tables 1 and 5, the 301 material meets Specification GD/A-0-71004 with respect to chemistry and room temperature base metal mechanical properties (minimum F_{ty} of 160 ksi; minimum F_{tu} of 200 ksi; minimum elongation of 2.0 percent). There are, however, several notable differences between this particular heat (49061) of material and those which have been tested previously (References 19 and 24), and it was for this reason that another heat of Type 301 stainless steel was included in the test program in addition to the initial one. The tensile and fatigue property data obtained on the second heat (57644) are presented in Table 26. The differences in heat 49061 and previous heats, as mentioned above, include: greater directionality effects (F_{ty} and F_{tu} at 78° F) than normal; very low notched tensile strengths (K_t = 6.3) and reduced notched/unnotched tensile ratios in the transverse direction at all testing temperatures and in the longitudinal direction at -320° and -423° F; low joint efficiencies; low elongations in the base metal and fusion-weld joints; greater amounts of martensite in the base metal (75 to 80 percent as compared to the normal 60 to 65 percent); a larger amount of stringers present in the microstructure (see Figure 108); low static joint efficiencies of complex-welded joints at -423° F (about 60 percent); and decreased resistance to fatigue failure of the complex joints at -423° F.

Examination of the notched/unnotched tensile ratios (Table 5) shows the following. The notched/unnotched tensile ratios obtained from the notched specimen with a K_t of 3.2 indicate a decrease in toughness at -320° F for the longitudinal direction and a decrease in toughness at -423° F for the transverse direction. With a K_t of 6.3, the ratios indicate a decrease in toughness for both rolling directions at -320° and -423° F. With a K_t of 19, the ratios also indicate low-temperature embrittlement for both directions at -320° and -423° F. The notched/unnotched tensile ratios obtained from each of the notched specimens (K_t of 3.2, 6.3, and 19) indicate that the transverse rolling direction is less tough than the longitudinal direction.

Fusion-weld joint tensile strengths, elongations, and joint efficiencies indicate a large resistance to brittle failure from 78° to -320° F with a decrease in the resistance to brittle failure at -423° F. The test on resistance spot welds is employed in Specification MIL-W-6858A, "Welding, Aluminum, Magnesium, Non-Hardening Steels or Alloys, and Titanium Spot, Seam, and Stitch". As required by the specification, the tensile/shear ratio must not be less than 0.25 for satisfactory spot weldability. Previous data (References 19 and 24) have indicated that when this test is employed at cryogenic temperatures, the results may correlate with fatigue resistance of complex-welded joints (incorporating resistance spot welds).

The results of the notched/unnotched tensile ratios and tensile/shear ratios of individual spot welds seem to indicate that this particular heat of 301 stainless steel is much less resistant to brittle failure at -320° F than at 78° or -100° F, and that the material is as tough at -423° F as it is at -320° F. A cursory examination of the notched tensile data and the tensile behavior (fracture characteristics of the parent metal tensile tests), however, reveals the following information. The notched (K_t = 3.2) tensile strengths continue to increase from 78° to -423° F for the longitudinal direction and continue to increase from 78° to -320° F with a decrease from -320° to -423° F for the transverse direction. The notched (K_t = 6.3) tensile strengths increase significantly from 78° to -320° F with very little increase from -320° to -423° F for both rolling directions. The notched (K_t = 19) tensile strengths remain about the same for both directions at all testing temperatures. An examination of the fractured unnotched tensile specimens and the tensile data show that at -320° F the material serrated (References 24 and 37) and work hardened but did not fracture until very high tensile strengths were reached. Large increases in the tensile strengths and elongations at -320° F are to be noted. The extraordinary high tensile strengths at -320° F cause the notched/unnotched tensile ratios to be quite small (this explains the decrease in the notched/unnotched tensile ratio with the K_t = 3.2 specimens at -320° F). Serrations and work hardening also occur at -423° F; however, the specimens fracture in a "premature" failure at one of the serrations before high loads are reached, resulting in a rather small increase in tensile strength (F_{tu}) from -320° to -423° F. Note the very large decrease in elongation from -320° to -423° F and the large increase in yield strength as compared to tensile strength from -320° to -423° F. The notched/unnotched tensile ratios are therefore significantly decreased at -320° F and not at -423° F as a result of this alloy's tensile behavior at cryogenic temperatures.

Critical fracture toughness (K_c) data were obtained at 78° and -320°F on this heat of material. Specimens used were 10 inches long by 4 inches wide and centrally cracked by means of electrical discharge machining. It has been found that reliable and consistent data can be obtained by use of this coupon and that 0.001-inch crack tips can be machined by the electrical discharge method without altering the microstructure of the material. The data obtained are given below:

Test Temperature (°F)	Direction	K_c	G_c
78	Longitudinal	204	1642
78	Transverse	206	1432
-320	Longitudinal	142	747
-320	Transverse	109	385
-423	Longitudinal	146	718
-423	Transverse	105	355

The fatigue data show a high degree of resistance to failure at 78°F. An average of 420 cycles to failure were obtained for the longitudinal joint configuration No. 1 (typical joint as used in the Atlas and Centaur vehicles) at a stress level of 95 percent of the material's yield strength. Also, the large number of cycles required to fail the specimen after detection of the first leak indicates a high degree of resistance to crack propagation. Fatigue data on longitudinal joint No. 2 (containing two rows instead of four rows of spot welds on each side of the fusion weld for attachment of a doubler sheet) were nearly the same as for longitudinal joint No. 1 at 78°F. The number of cycles to failure was somewhat less for the transverse joint than for the longitudinal joints at the same stress level/yield strength ratio. Also, there was a fewer number of cycles from the first leak to failure. The evaluation tests (notched data, notched/unnotched tensile ratios, fusion-weld data and crack propagation tests) indicated that the transverse direction was less tough than the longitudinal direction.

At -320°F, the number of cycles to failure at the highest stress level (95 percent of F_{ty} at -320°F) was much less than for the same test conditions at 78°F. However, at the stress level corresponding to 85 percent of F_{ty} the number of cycles to failure was about the same and at the 75 percent of F_{ty} stress level there was an average of 1029 cycles to failure at -320°F as compared to 862 at 78°F. Longitudinal joint No. 2 was less resistant to fatigue failure than longitudinal joint No. 1 at -320°F. Also, the number of cycles to failure for the transverse joints was less than for the longitudinal joints at the same ratios of stress levels to F_{ty}. Although there was a fewer number of cycles to failure at the higher stress levels at -320°F than at 78°F, it is apparent from the fatigue data that this material is still quite tough and resistant to fatigue failure at -320°F. Some of the evaluation tests indicate embrittlement at

-320° F (i.e. tensile/shear ratio of spot welds, notched/unnotched tensile ratios for all notched configurations, and crack propagation data). However, the notched tensile values and fusion-weld tensile properties indicate very little, if any, decrease in toughness at -320° F.

The fatigue data at -423° F show a severe decrease in resistance to brittle failure for both the longitudinal and transverse joints. In fact, the impairment of toughness was so severe that stress levels of 40 to 65 percent of the yield strengths (at -423° F) were used in the fatigue tests. The lower stress levels were mandatory due to the low joint efficiencies (about 60 percent) in static tension tests. The transverse joint was less resistant to fatigue failure than the longitudinal joints. All of the evaluation tests indicate decreased toughness at -423° F; however, the severe embrittlement as shown by the fatigue data was not apparent except for the simple fusion-weld tensile data. In general, it was not felt that the evaluation-type tests provided an adequate quantitative description of the toughness of this particular heat of 301 stainless steel; however, as screening tests, they did indicate a qualitative decrease in toughness at cryogenic temperatures.

This particular heat (49061) of 301 stainless steel was rejected for use in cryogenic tankage and another heat (57644) of material which is more representative of 60-percent cold-rolled 301 stainless steel was evaluated. The tensile and fatigue data obtained on heat 57644 are given in Table 26. It may be seen from the data presented that this heat of 301 retains a much greater resistance to brittle failure at -423°F than did heat 49061.

8.2 <u>304 ELC STAINLESS STEEL.</u> The tensile and fatigue properties of 50-percent cold-rolled 304 ELC stainless steel are given in Tables 6, 14, and 19 and Figures 31 through 65, 69, 70, and 78 through 86. Photographs of fractured tensile and fatigue specimens and microstructures are shown in Figures 104, 109, 116, and 120.

Base metal yield and tensile strengths increased about 50 percent upon reducing the testing temperature from 78° to -423° F but were 26 to 30 percent at -320° F, a result which had been noted in previous tests (References 19 and 24). The elongations at 78°, -100°, and -423° F are primarily due to "necking" whereas at -320° F the elongations are of a uniform nature over the entire reduced section of the tensile specimen. Magnetic measurements indicate that the reduced section of coupons tested at -320° F contains nearly 100-percent martensite whereas reduced sections of coupons tested at 78°, -100°, and -423° F show very little austenite transformation. Fusion-weld joint efficiencies are quite low at 78° F but continuously increase with reduction in testing temperature to values in excess of 90 percent at -423° F. All fractures occurred in the weld or heat-affected zone. Elongations of the weld joints were low at all testing temperatures but continuously increased with reduction in testing temperature. The weld tensile data indicate that the 304 ELC material does not decrease in toughness to -423° F.

In general, the notched (K_t of 3.2, 6.3, and 19) tensile data and notched/unnotched tensile ratios indicate that the 50-percent cold-rolled Type 304 ELC stainless steel is quite tough from 78° to -423° F. For the notched specimen with a K_t of 3.2, the notched tensile strengths and notched/unnotched tensile ratios continuously increased from 78° to -423° F. For the notched specimens with a K_t of 6.3, the notched tensile strengths continuously increased from 78° to -423° F and the notched/unnotched tensile ratios were considerably above unity at all testing temperatures. With a K_t of 19, the notched tensile strengths continuously increased from 78° to -423° F in the longitudinal direction but decreased from -320° to -423° F for the transverse specimens. Also, the notched/unnotched tensile ratios were much less for the transverse than the longitudinal direction at 78°, -100°, and -423° F. Interpretation of the notched tensile data obtained from specimens with a K_t of 3.2 and 6.3 indicate that this heat of 304 ELC is quite tough at all testing temperatures. The notched (K_t = 19) data indicate a high degree of resistance to brittle failure in the longitudinal direction from 78° to -423° F, but a lesser degree of toughness in the transverse direction at 78°, -100°, and -320°F with an indication of embrittlement at -423°F.

Table 14 gives the cross-tensile and tensile-shear properties of individual resistance spot welds at 78°, -100°, -320°, and -423°F. The tension/shear ratios are quite large at all testing temperatures as compared to the 0.25 which is specified as a minimum in MIL-W-6868A. The spot-weld data indicate that the 50-percent cold-rolled 304 ELC material has a high degree of resistance to brittle fracture from 78° to -423° F.

Table 19 presents the fatigue data on complex-welded joints of the 304 ELC stainless steel. As would be expected from the results of notched tensile tests, notched/unnotched tensile ratios, fusion-weld joint efficiencies and tension/shear ratios of resistance spot welds, the number of cycles to failure upon repeated loadings are quite high at all testing temperatures. As may be seen in the table, the stress levels for both longitudinal (parallel to the direction of rolling) and transverse directions were about 85 percent of typical base metal yield strength at each corresponding temperature. Static joint strengths continuously increased from 78° to -423° F with resulting joint efficiencies of nearly 100 percent at all testing temperatures. The number of cycles to failure for the transverse direction is greater than for the longitudinal direction. Although the transverse joint is different than the longitudinal joint, it is believed that the fatigue data show that the 304 ELC material is quite tough to -423° F in both the longitudinal and transverse direction.

It would appear from the data obtained in this investigation that all of the evaluation tests [notched (K_t = 3.2 and 6.3) tensile tests, fusion-weld tensile tests, and spot weld tests] , with exception of the notched (K_t = 19) data for the transverse direction, properly evaluated the 50-percent cold-rolled Type 304 ELC stainless steel.

8.3 310 STAINLESS STEEL. Mechanical property data on 75-percent cold-rolled Type 310 stainless steel are given in Table 7. Yield and tensile strengths for both the longitudinal and transverse directions increased more than 60 percent from 78° to -423° F. Base metal elongations were greater at all cryogenic temperatures than at room temperature. Fusion-weld joint efficiencies increased from about 45 percent at 78°F to about 70 percent at -423° F, while elongations remained about the same (two percent). Results of the notched tensile testing and notched/unnotched tensile ratios indicate no degree of embrittlement at temperatures down to -423° F for notched specimens with K_t of 3.2 and 6.3. The notched tensile strengths continued to increase from 78° to -423° F and the notched/unnotched tensile ratios were well above unity at all testing temperatures for those specimens with a K_t of 3.2 and 6.3. For the specimens with a K_t of 19, the notched tensile strengths decreased from -320° to -423° F in the longitudinal direction with a resultant decrease in the notched/unnotched tensile ratio at -423° F. Also, the notched (K_t = 19) data indicate that the transverse direction is much less resistant to brittle fracture than the longitudinal direction at all testing temperatures.

Cross-tension and tensile-shear strengths of individual resistance spot welds are given in Table 15. As was the case for 304 ELC stainless steel, the 310 material exhibits high tension/shear ratios at all testing temperatures.

The static tensile and fatigue properties of complex-welded joints are presented in Table 20. As may be seen, the static tensile strength continues to increase from 78° to -423° F for both the longitudinal and transverse joints. The fatigue specimens were repeatedly loaded from zero to a stress level of 75, 85, and 95 percent of typical base metal yield strengths at each corresponding temperature. The number of cycles to failure indicate that Type 310 stainless steel is resistant to fatigue failure at all testing temperatures. Longitudinal joint No. 2 (doubler attached by two rows of spot welds on each side of the fusion weld) was somewhat less resistant to fatigue failure than longitudinal joint No. 1 (doubler attached by four rows of spot welds on each side of the fusion weld) at each testing temperature. Also the transverse joints, both No. 1 (overlap roll seam weld with one row of spot welds on each side) and No. 2 (same as longitudinal joint No. 1 except for material direction) joints failed at a lower number of cycles than the longitudinal joints. The fatigue tests were run on transverse joint No. 2 to determine if the material was much less tough for the transverse than for the longitudinal direction. Although there were a fewer number of cycles to failure for the transverse direction, it is believed that the fatigue test data show that the 310 material retains a high degree of resistance to brittle failure for both directions to -423° F.

In general, it is felt that all of the evaluation tests, with the possible exception of the notched (K_t = 19) tensile tests, properly evaluated this particular heat of 310 stainless steel.

8.4 AM-355 STAINLESS STEEL. The tensile properties of AM-355 stainless steel, cold-rolled and tempered, are given in Table 8. There is a rather small increase in tensile and yield strengths from 78° to -100° F and then a decrease at -320° and -423° F. Tensile properties of fusion welds indicate poor toughness at -320° and -423° F by the decrease in joint efficiencies and elongations. Notched (K_t = 6.3) tensile data indicated a definite decrease in toughness at -320° and -423° F.

The tension/shear ratios of resistance spot welds indicate a lack of toughness at -100°, -320°, and -423° F.

The fatigue data are given in Table 21. The static tensile and fatigue data show that this alloy is relatively brittle even at 78° F. Note that the static tensile failure of the transverse joint was 10,000 psi below the base metal yield strength and that the number of cycles to failure for both the longitudinal and transverse joints was quite small at stress levels of 85 percent of typical yield. The static tensile strengths decreased at -320° and -423°F with resultant joint efficiencies as low as 19 percent. Therefore the fatigue tests had to be run at stress levels of 85 percent of the static joint strengths (or from 17 to 38 percent of the base metal yield strengths) and, even at these low stress levels, only a small number of cycles were obtained prior to failure.

This alloy was included in the investigation to show the correlation of evaluation tests with the axial fatigue (simulated service) data. It was expected that the AM-355 would be quite brittle at cryogenic temperatures due to its high carbon and martensite contents.

The notched tensile strengths, notched/unnotched tensile ratios, tensile properties of the fusion welds, and tension/shear ratios of individual resistance spot welds indicated severe embrittlement of this heat of material at cryogenic temperatures. The low-temperature embrittlement was evidenced by the static tensile and fatigue data of complex-welded joints.

8.5 2014-T6 ALUMINUM ALLOY. The mechanical properties of 2014-T6 aluminum alloy are given in Table 9. Yield and tensile strengths, elongations, proportional limits, and elastic moduli of the base metal continuously increase with decrease in testing temperatures. Hardness values obtained on the reduced sections and fractured edges remain nearly constant over the range of testing temperatures. Tensile strengths of fusion welds (with 2319 aluminum filler) increased from 78° to -423° F with resulting joint efficiencies of 70 to 80 percent. Elongations (over a two-inch gage length) of the welds were small at all testing temperatures and decreased from 78° to -423° F. Typical fractures of base metal and welded tensile specimens are shown in Figure 106.

All fractures of the welded tensile specimens occurred at the edge of the weld in the heat-affected zone. The cored structure of the weld (tested in the "as-welded" condition) may be seen in the photomicrographs of fractured edges shown in Figure 112.

Tensile strengths obtained from the notched tensile specimens having a K_t of 3.2 and 6.3 continuously increased with reduction in testing temperature; however, the notched/unnotched tensile ratios decreased slightly. Notched (K_t = 19) tensile strengths decreased from 78° to -320°F and then increased at -423°F for the longitudinal direction, and decreased from 78° to -100° F and then increased at -320° and -423°F for the transverse direction. The notched (K_t = 19)/unnotched tensile ratios decreased from 78° to -423° F. The notched tensile and weld tensile tests indicate that there may be a slight decrease in toughness of the 2014-T6 material from 78° to -423° F; however, the decrease would be expected to be quite small.

The fatigue properties of welded joints at 78°, -320°, and -423° F are given in Table 22. Typical fractures of the fatigue specimens are shown in Figures 124 and 125. Longitudinal and transverse joints No. 1 are simple fusion-welded joints made with 2319 aluminum filler metal. Weld schedules are given in Table 2. Originally it was intended to machine or chemically mill the aluminum fatigue specimens on each side of the weld (such as is shown in Figure 12) to provide a thicker weld area and thus 100-percent joint efficiency; however, a few such specimens were tested with no resulting failures in the weld area. Therefore, the aluminum fatigue specimens were tested without milling in order to obtain failure at the weld and thus provide data on the weld joint. In the design and fabrication of missiles and space vehicles, a thickened weld area would probably be used to provide 100-percent joint efficiency. In this case, the stress on the base metal would be higher than that given in Table 22 (stress range in ksi); however the stress in the weld area would be nearly the same as that given in Table 22. Longitudinal joint No. 2 refers to a joint in which a 0.063-inch doubler sheet (or backing sheet) was fusion welded to the 0.063-inch skins of the specimens (References 20 and 21). A single fusion weld was used to join the skins as well as attach the doubler (no spot welds). This joint was included in the study because of its proposed use as a method of increasing the joint efficiency.

The static tensile strengths of the fatigue specimens increased with decrease in testing temperatures; however, they were smaller than the simple fusion-weld tensile strengths with resulting lower joint efficiencies (60 to 70 percent as compared to 70 to 80 percent for the weld tensile strengths). The fatigue tests were made at stress levels of about 75, 85, and 95 percent of the static joint strengths. These values correspond to about 60 to 70 percent of the base metal yield strengths at each corresponding test temperature. The number of cycles to failure was quite large for the No. 1 joints at 78°F. In fact, nearly all of the specimens either did not fail after 2000 or more cycles or failed in the end plate. Failures in the end plate were a result of the nature of the test equipment which was actually designed to test thinner gage materials having end doublers for extra strength and bearing surface. All of the test runs are reported in Table 22 and it is believed that the fatigue data show a large resistance to fatigue failure for the No. 1 joints at 78° F. The data obtained on the longitudinal No. 2 joints show poor joint efficiency and poor resistance to fatigue failure at 78° F as well as at -320° and -423° F. Fatigue data on the simple fusion-welded joints (No. 1 joints) at -320° F show a high degree of resistance to fatigue failure at the lower (41.2 and 46.7 ksi) stress levels, but not at the higher stress level (52.2 ksi). Examination of those specimens which fractured at a very low number of cycles (specimens 28L, 26T, 29T, and 30T) showed a fairly large amount of porosity and lack of fusion in the welds which may have been responsible for the poor resistance to fatigue loading. It is believed, however, that the data signify some degree of embrittlement in the weld joint. Fatigue data at -423° F similarly show some degree of embrittlement in the weld joint.

The notched tensile tests and notched/unnotched tensile ratios indicated a slight decrease in toughness from 78° to -423° F and the weld tensile tests showed very little ductility, as determined by elongation, in the welds. As was indicated by the evaluation tests, a partial embrittlement of the fusion welds was evidenced from the fatigue tests at -320° and -423° F. The apparent embrittlement of the 2014-T6 fusion welds seems to be a characteristic of the material. This problem is solved in the design and fabrication of cryogenic pressure vessels by providing a thicker section at the weld and thus reducing the operating stress in the weld area. As may be seen from the data in Table 22, the 2014-T6 welds had a high degree of resistance to fatigue failure at the lower stress levels.

Although the notched tensile tests had previously been used to evaluate the fatigue resistance of complex joints containing spot welds, it is believed that in general, the evaluation tests used (notched and weld tensile) in this investigation performed satisfactorily in properly evaluating the toughness or fatigue resistance of 2014-T6 fusion welds at cryogenic temperatures.

8.6 <u>5052-H38 ALUMINUM ALLOY</u>. The mechanical properties of 5052-H38 aluminum alloy at 78°, -100°, -320°, and -423° F are given in Table 10. The yield and tensile strengths, elongations, proportional limits, and elastic moduli of the parent metal continuously increased with reduction in testing temperature. There was a small increase in the hardness of the reduced sections and fractured edges with decreasing temperature indicating that some work hardening was probably occurring at cryogenic temperatures.

The notched (K_t = 6.3) tensile strengths continuously increased from 78° to -423° F, but the notched/unnotched tensile ratios decreased slightly. The tensile strengths, elongations, and joint efficiencies of the fusion-welded tensile specimens continuously increased with reduction in temperature. The evaluation tests indicate that 5052-H38 should remain quite tough to -423° F and that the fatigue resistance of weld joints should be quite high at cryogenic temperatures.

The results of static tensile and axial fatigue testing of fusion-welded (with 5356 aluminum filler) joints of 5052-H38 are given in Table 23. The static tensile strengths continuously increased from 78° to -423° F resulting in joint efficiencies of 70 to 80 percent. Axial fatigue tests were made at stress levels of 85 percent of the static joint strengths. The stress level for the fatigue tests at 78° F corresponded to about 75 percent of the base metal yield strength at the same temperature. At -320° and -423° F the stress levels were 95 to 105 percent of the base metal yield strengths at the corresponding temperatures. Even at these high stress levels, nearly all of the specimens were subjected to 2000 cycles or more without failure. The fatigue data show that 5052-H38 is very tough to -423°F, as would be expected from the notch tensile and weld tensile evaluation tests.

8.7 5456-H343 ALUMINUM ALLOY. Table 11 presents the mechanical properties of 5456-H343 aluminum alloy at 78°, -100°, -320°, and -423° F. Yield and tensile strengths of the base metal continuously increased from 78° to -423° F. Elongations of the base metal increased from 78° to -320° F and then decreased from -320° to -423° F. Proportional limits and elastic moduli increased very little from 78° to -320° F but increased significantly from -320° to -423° F. Hardness values taken at the reduced sections and near the fractured edge remained about the same for specimens tested over the temperature range from 78° to -423° F. Notched ($K_t = 6.3$) tensile strengths increased from 78° to -423° F; however, the notched/unnotched tensile ratios decreased from -100° to -320° F and were considerably less than unity at both -320° and -423° F. Tensile strengths, elongations, and joint efficiencies of fusion welds (with 5356 aluminum filler metal) increased from 78° to -320° F but decreased from -320° to -423° F. The evaluation tests indicate a possible decrease in toughness at -320° F and a definite decrease in toughness at -423° F.

The results of static tensile and axial fatigue tests of large (4-inch by 20-inch test section) fusion-welded specimens are presented in Table 24 and Figures 92 and 93. The No. 2 joint had the same configuration as the No. 2 joint for 2014-T6, and, as was typical for this joint in 2014-T6, proved to be quite poor in fatigue resistance both at room and cryogenic temperatures for the 5456-H343 material. The poor fatigue resistance of this welded joint is believed to be due to the joint configuration and not the material.

The static strengths of the No. 1 joints increased from 78° to -320° F and then decreased at -423° F. The joint efficiencies were 82 percent at 78° F, 84 percent at -320° F, but only 63 to 69 percent at -423° F. The axial fatigue tests were cycled from zero stress to a stress of 85 percent of the base metal yield strength at 78° F (about 90 percent of static joint strength) with no failure occurring after being subjected to 2000 cycles (other than for two end plate failures). At -320° F, the stress level was 85 percent of the static tensile strength or 93 to 104 percent of the base metal yield strengths at -320° F. There were several fatigue failures in the weld at -320° F; however, the number of cycles to failure was quite large with respect to the high stress level. The stress level was reduced from 53.7 ksi at -320° F to 47.9 ksi at -423° F due to the decrease in static tensile strength. The 47.9 ksi stress level is 85 percent of the static tensile strength and 75 to 85 percent of the base metal yield strength at -423° F. Except for one specimen (15L), the 5456-H343 fatigue specimens did not fail after being repeatedly cycled from 0 to 47.9 ksi for 2000 cycles at -423° F.

Although there was a decrease in the static tensile strengths and therefore a decrease in the stress levels for the fatigue tests at -423° F, the fatigue data show the 5456-H343 fusion-welded joints are actually quite tough and resistant to fatigue failure at cryogenic temperatures. Further studies, such as crack propagation testing, have been recommended on this alloy to determine if the notched and weld tensile tests have improperly evaluated the material or if the alloy is actually more brittle at -423° F than the fatigue data indicate.

8.8 5Al-2.5Sn TITANIUM ALLOY. The mechanical properties of one heat of annealed Ti-5Al-2.5Sn alloy which was tested at 78°, -100°, -320°, and -423°F are given in Table 12. The yield and tensile strengths of the base metal increase about 100 percent from 78° to -423°F. Elongations decreased with reduction in testing temperature. Proportional limits and elastic moduli continuously increased from 78° to -423° F. Hardness of the reduced sections and fractured edges remained uniform over the range of testing temperatures. Typical fractures and photomicrographs of typical fractures of tensile specimens are shown in Figures 107 and 115.

Notched (K_t = 3.2) tensile strengths continuously increased from 78° to -423° F. Although there was a decrease in the notched (K_t = 3.2)/unnotched tensile ratios over the same temperature range the values were well above unity even at -423° F. From the mild notched (K_t = 3.2) tensile data it would seem that this heat of Ti-5Al-2.5Sn alloy was quite tough from 78° to -423° F. However, the notched tensile data obtained from those specimens with a K_t of 6.3 indicate embrittlement at -423° F, and the notched tensile data obtained from the specimens with a K_t of 19 indicate embrittlement at -320° and -423° F. The notched (K_t = 6.3) tensile strengths continuously increase from 78° to -320° F and then decrease from -320° to -423° F. The notched (K_t = 6.3)/unnotched tensile ratios are well above unity at 78°, -100°, and -320° F but are significantly decreased at -423° F. Notched (K_t = 19) tensile strengths increased from 78° to -100° F but decreased from -100° to -320° F and from -320° to -423° F. The notched (K_t = 19)/unnotched tensile ratios were considerably less than unity at -320° and -423° F.

Tensile strengths of fusion-welded (no filler metal) tensile specimens increased from 78° to -423° F with resulting joint efficiencies of 98 to 100 percent at all testing temperatures. Elongations of the welded tensile specimens, however, decreased slightly from 78° to -320° F and then decreased sharply from -320° to -423° F. The results of the weld tensile data indicate nearly 100 percent joint efficiency from 78° to -423° F but with some degree of embrittlement of the weld at -423° F as witnessed by the decrease in ductility at this temperature and the fact that fractures occurred in the weld area at -423° F (see Figure 107), but in the base metal at 78°, -100°, and -320° F.

The results of cross-tension and tensile-shear tests of individual resistance spot welds are given in Table 17. It may be seen that the shear values are large at all testing temperatures but that the cross-tension values are quite small even at 78° F and decrease at cryogenic temperatures. Therefore, the tension/shear ratios are small at all testing temperatures. The tension/shear ratio is 0.26 at 78° F (a minimum of 0.25 is specified as acceptable in MIL-W-6858A) and 0.16 to 0.19 at cryogenic temperatures. Based on the results of these tests, it would be expected that complex joints, containing resistance spot welds, of this alloy would have marginal fatigue resistance at 78° F and rather poor fatigue resistance at cryogenic temperatures.

The results of static tensile and axial fatigue tests on complex-welded joints of Ti-5Al-2.5Sn alloy are given in Table 25. Static tensile strengths of longitudinal joint No. 1 (doubler attached by four rows of spot welds on each side of the fusion weld) are 120 kis, or 97-percent joint efficiency, at 78°F; 188 ksi, or 95-percent joint efficiency, at -320° F; and 167 ksi, or 67-percent joint efficiency at -423° F. Static tensile strengths of transverse joint No. 1 (overlap of skins with roll-seam weld and one row of resistance spot welds on each side of the seam weld) are 112 ksi, or 91-percent joint efficiency, at 78° F; 158 ksi, or 80-percent joint efficiency, at -320° F; and 159 ksi, or 64-percent joint efficiency at -423° F. The results of the static tensile tests on complex-welded joints show a slight decrease in joint efficiency from 78° to -320° F and a large decrease in joint efficiency from -320° to -423° F. Also, the joint efficiencies for transverse joint No. 1 are less than for longitudinal joint No. 1 at all testing temperatures. The decrease in static tensile strengths and joint efficiencies of the complex-welded joints from -320° to -423° F is felt to be due to the embrittlement of this heat of Ti-5Al-2.5Sn at -423° F and to the poor tensile properties of resistance spot welds. An explanation for the lower joint efficiencies of the transverse joints than for the longitudinal joints is believed to be due to difference in the design of the joints. The transverse joints contain only resistance welds (spot and roll-seam) which were found to have marginal properties at 78° F and inferior properties at cryogenic temperatures, whereas the longitudinal joints contain fusion welds as well as resistance spot welds.

The longitudinal and transverse joints No. 1 were repeatedly loaded from 0 to 87 ksi, 0 to 99 ksi and 0 to 110 ksi at 78 °F. These stress levels represent 75, 85, and 95 percent of typical base metal yield strength at 78 °F. Also, longitudinal joint No. 2

(doubler attached by two rows of spot welds on each side of the fusion weld) was fatigue tested at 78° F at a stress level of 85 percent of the base metal yield strength, and longitudinal joint No. 3 (simple butt fusion weld with no filler metal, no post weld treatment and no doublers attached) was fatigue tested at stress levels of 85 and 95 percent of the base metal yield strength. Results of these fatigue tests show that each of the joints has a high resistance to fatigue failure at 78° F. Based on the few tests that were made on the butt fusion-welded joint (longitudinal No. 3), it seems that this joint is superior in fatigue resistance to the other joints. This is in accordance with what would be expected from the results of the cross-tension and tensile-shear tests of individual resistance spot welds.

At -320° F the fatigue tests were made at stress levels of 0 to 140 ksi, 0 to 159 ksi, and 0 to 178 ksi which correspond to 75, 85, and 95 percent of the base metal yield strength at -320° F. The results of the fatigue tests at -320° F show that those specimens which contained resistance spot welds (longitudinal joints No. 1 and No. 2 and transverse joint No. 1) were much less resistant to fatigue failure at -320° F than at 78° F (at stress levels of 75, 85, and 95 percent of base metal yield strengths at each corresponding temperature). However, the number of cycles to failure for the butt fusion-welded fatigue specimens (longitudinal joint No. 3) were about the same as for the 78°F tests. Therefore, it is believed that this heat of Ti-5A1-2.5Sn was not embrittled at -320°F, as evidenced by the fatigue data on the butt fusion-welded joints. The poor fatigue resistance of the other joints at -320°F is believed to be due to the presence of the resistance spot welds which were found to have inferior mechanical properties at -320°F.

At -423° F, the fatigue specimens containing resistance spot welds were repeatedly loaded from 0 to 129 ksi, 0 to 146 ksi, and 0 to 163 ksi which correspond to 75, 85, and 95 percent of the static strength of the complex joints or 55, 62, and 70 percent of the base metal yield strengths at -423° F. The stress levels were reduced from the normal 75 to 95 percent of F_{ty} for the fatigue tests at -423° F due to the decreased joint efficiency of the complex joints at this temperature. Even with the reduced stress levels, however, the number of cycles to failure were very small. The stress levels for those fatigue tests made on the simple fusion-welded joints were 0 to 184 ksi and 0 to 208 ksi or 80 and 90 percent of the base metal yield strength at -423° F. The number of cycles to failure was considerably less than those obtained at 78° or -320° F. Also, there was a larger amount of scatter in the fatigue data at -423° F. One fatigue specimen (85L) failed (after 35 cycles) in the base metal at the location of a small scratch. It is believed that the fatigue data indicate that this heat of Ti-5Al-2.5Sn is quite brittle at -423° F as evidenced by the decrease in complex-joint efficiencies and a lower number of cycles to failure for both the complex joints and simple fusion-welded joint.

The notched (K_t = 3.2) tensile tests indicated a high degree of toughness to -423° F which was disproved by the fatigue data. The notched (K_t = 6.3) tensile tests indicated a high degree of toughness to -320° F but embrittlement at -423° F, which is in accordance with the fatigue test data. The notched (K_t = 19) tensile tests indicated embrittlement at -320° and -423° F; however, it is believed that the fatigue data show embrittlement only at -423° F. The fusion-welded tensile tests indicated a decrease in toughness at -423° F but not at -320° F. From the results of the tests on individual resistance spot welds, a poor performance of those joints containing spot welds would be expected at cryogenic temperatures. It is believed that the notched (K_t = 6.3) tensile tests more accurately evaluated the alloy than did the other evaluation tests.

Several heats of the Ti-5Al-2.5Sn alloy have been evaluated at cryogenic temperatures and it has been shown that large amounts of interstitial alloying elements, particularly oxygen, cause this alloy to be brittle at liquid-hydrogen temperatures (References 26, 27, and 38). Therefore a special specification, GD/A-0-71010, which limits the amount of interstitial elements and iron, was prepared. The mechanical properties at 78°, -320°, and -423° F of material purchased to this specification (heat 3930131) were determined and are reported in Table 27. The base metal yield and tensile strengths increase nearly 100 percent from 78° to -423°F. Elongations are high at all testing temperatures. Notched (K_t = 6.3) tensile strengths continuously increase from 78° to -423°F and the resulting notched/unnotched tensile ratios are well above unity at all testing temperatures. Simple fusion-weld tensile strengths continuously increase from 78° to -423°F with resulting joint efficiencies of 90 to 97 percent. Elongations of welded specimens were low (1.0 to 2.0 percent) at all testing temperatures. The reason for the low elongations and lower joint efficiencies is due to the presence of a small amount of cold work in the material. All fractures of the weld tensile tests occurred in the weld. Although this heat of Ti-5Al-2.5Sn is believed to be quite tough to -423° F the tension/shear ratios of individual resistance spot welds indicate marginal properties at 78° F and inferior properties at cryogenic temperatures. The low strength of titanium spot welds in cross-tension tests appears to be a characteristic of the material.

The static tensile and fatigue data on complex joints are given in Table 28. As would be expected from the notched (K_t = 6.3) tensile data, this heat (3930131) of Ti-5Al-2.5Sn remains quite tough at -423° F as evidenced by the high static tensile strengths and joint efficiencies (81- to 85-percent joint efficiency at -423° F as compared to 64 to 67 percent for heat M-8394) and the relatively large number of cycles to failure.

9 RECOMMENDATIONS FOR FUTURE WORK

The large amount of interest in the properties of engineering materials at cryogenic temperatures is apparent from the increased number of investigations in this field, the large number of recent technical papers in the literature and technical conferences on the properties of materials in a cryogenic environment, and the increased use and growth of the Cryogenic Data Handbook. It is recommended that the work initiated in this investigation be continued to include more materials and more test conditions. The materials and tests recommended for future study are given in Table 30. The crack propagation testing is included to increase the scope of fracture mechanics testing to -423°F and to provide more quantitative data to the metallurgical and design engineers to aid them in the proper selection of materials and the design of structures for cryogenic-fueled missiles and space vehicles. It is also recommended that further investigations be made in the development of statistical analysis methods for evaluating the relative toughness of engineering materials.

10 SUMMARY AND CONCLUSIONS

The objectives of this investigation were to develop simple laboratory type tests to evaluate the toughness of high-strength sheet materials at cryogenic temperatures and to obtain useful engineering data on the properties of these materials from 78° to -423°F. Alloys investigated include Types 301, 304 ELC, 310, and AM-355 stainless steels, 2014-T6, 5052-H38, and 5456-H343 aluminum alloys and the 5Al-2.5Sn titanium alloy. The tests employed for evaluating the toughness of sheet alloys included notched (K_t = 3.2, 6.3, and 19) tensile tests, fusion-weld tensile tests, and cross-tension and tensile-shear tests of individual resistance spot welds. The results from these tests, as well as data obtained from tensile tests of the base metal, and percent martensite, hardness determinations, and metallographic examinations of fractured specimens, were correlated with low-cycle, high-stress fatigue data obtained on complex-welded joints. A total of more than three thousand tensile and fatigue tests were conducted during the investigation, and the data statistically analyzed. The results are presented in tabular and graphical form to aid metallurgical and design engineers in the selection of materials for pressure vessel applications in a cryogenic environment. Based upon the data obtained from the experimental investigation and the information contained within this report the following conclusions are made:

a. The notched tensile specimen with a stress concentration of 6.3 provided the most reliable and consistent correlation with fatigue resistance (toughness) of complex-welded joints of high strength sheet materials at cryogenic temperatures.

b. The notched (K_t = 3.2) tensile data properly evaluated 304 ELC and 310 stainless steels and 2014-T6 aluminum alloy, but failed to indicate the decreased toughness of 301 stainless steel (heat 49061) and Ti-5Al-2.5Sn alloy (heat M-8394) at -423°F. Due to the mildness of the notch, the data improperly indicated that all of the alloys investigated with the notched (K = 3.2) tensile test were resistant to brittle failure at -423°F.

c. The data obtained from the notched (K_t = 19) tensile tests improperly evaluated many of the alloys investigated. These data incorrectly predicted embrittlement of the 301 stainless steel (heat 49061) and the Ti-5Al-2.5Sn alloy (heat M-8394) at -320°F and the 304 ELC (transverse direction) and 310 (transverse direction) stainless steels at cryogenic temperatures.

d. The fusion-weld tensile data (joint efficiencies and elongation) correlated well with fatigue resistance of welded joints at cryogenic temperatures as compared to the fatigue resistance at 78°F.

e. The data obtained from cross-tension and tensile-shear tests of individual resistance spot welds provided valuable information for assessing the fatigue resistance of those complex-welded joints which contained spot welds.

f. The information obtained from a combination of the notched (K_t = 6.3) tensile, fusion-weld tensile, and spot-weld tensile and shear evaluation tests provided an accurate evaluation of the low-temperature toughness of the alloys investigated.

g. Information obtained from statistical analyses (i.e. standard deviations) may provide an index of toughness of materials at cryogenic temperatures.

h. The data obtained during this investigation are useful to metallurgical and design engineers for the proper selection of materials for, and design of, pressure vessels for application in a cryogenic environment.

The following criteria were used for determining the toughness of each alloy at cryogenic temperatures:

The number of cycles to leak and to failure of welded joints tested in axial fatigue,

Notched/unnotched tensile strength ratios,

Notched tensile strengths as a function of temperature,

Tensile strengths and resulting joint efficiencies of fusion welds as a function of temperature,

The cross-tension/tensile-shear ratio of individual resistance spot welds,

The elongations of parent metal and fusion welded tensile specimens, and

A statistical analysis of the scatter in the test data (i.e. standard deviations).

A fatigue life of 100 cycles at a stress level of 85 percent of the yield strength was considered a minimum for adequate resistance to brittle fracture. Also, a large number of cycles between first crack initiation and final specimen failure was considered desirable since rapid crack extension is a characteristic of brittle behavior. Notched/unnotched tensile strength ratios of 1.0 for a K_t of 3.2, 0.90 for a K_t of 6.3 and 0.60 for a K_t of 19 were considered as minima for acceptable toughness at each test temperature. A decrease of the notched tensile strengths with decrease in temperature was considered to indicate embrittlement; therefore the notched tensile strengths must increase or remain the same with reduction in testing temperature to insure adequate toughness. A large decrease in the tensile strength of butt fusion welds with reduction in testing temperature seemed to indicate an embrittlement of the weld metal. Therefore, only those alloys in which the joint efficiencies of fusion welds remained nearly constant or increased with reduction in temperature were recommended for cryogenic service. An evaluation of the toughness of resistance spot welds was made by the cross-tension/tensile-shear ratio. Whenever this ratio was less than 0.25 the resistance spot weld was considered to be brittle. Although of less significance than the former evaluation tests, another indication of possible embrittlement was a large decrease in the total elongation of parent or fusion welded metal with decrease in testing temperature. A large amount of scatter in the test data, or large standard deviations as obtained from a statistical analysis of the data, also indicated a lack of toughness. Based on the above criteria and the test data obtained in this program the following materials are recommended for structural applications at cryogenic temperatures.

These materials are sufficiently tough for structural applications at 100° and -320°F: 301 (heats 49061 and 57644), 304 ELC and 310 stainless steels, 2014-T6, 5052-H38, and 5456-H343 aluminum alloys, and Ti-5Al-2.5Sn alloy (heats M-8394 and 3930131).

These materials are sufficiently tough for structural applications at -423°F: 301 (heat 57644), 304 ELC and 310 stainless steels, 2014-T6 and 5052-H38 aluminum alloys, and Ti-5Al-2.5Sn alloy (heat 3930131).

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ILLUSTRATIONS

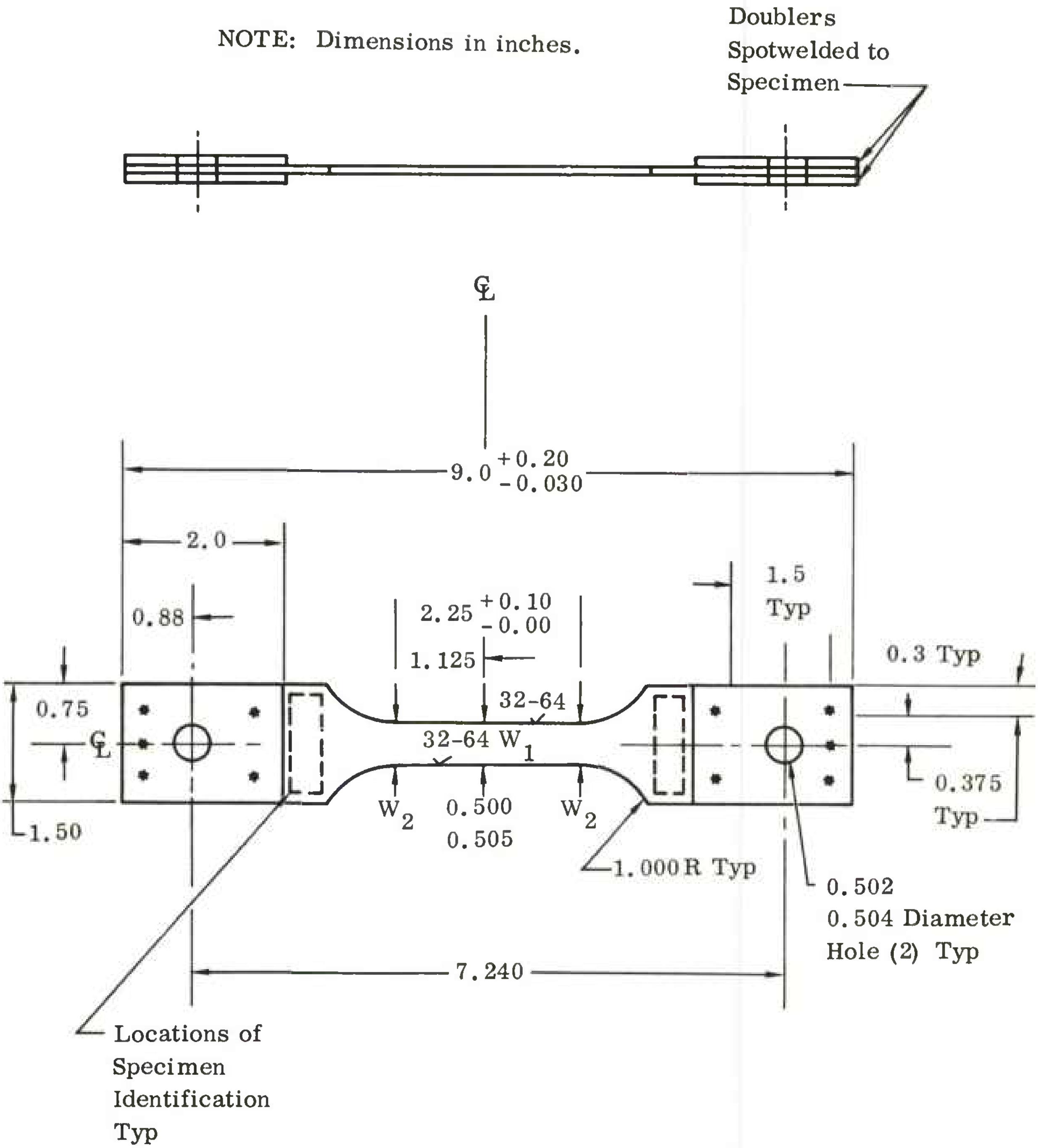


Figure 1. Flat Tensile Specimen (Standard)

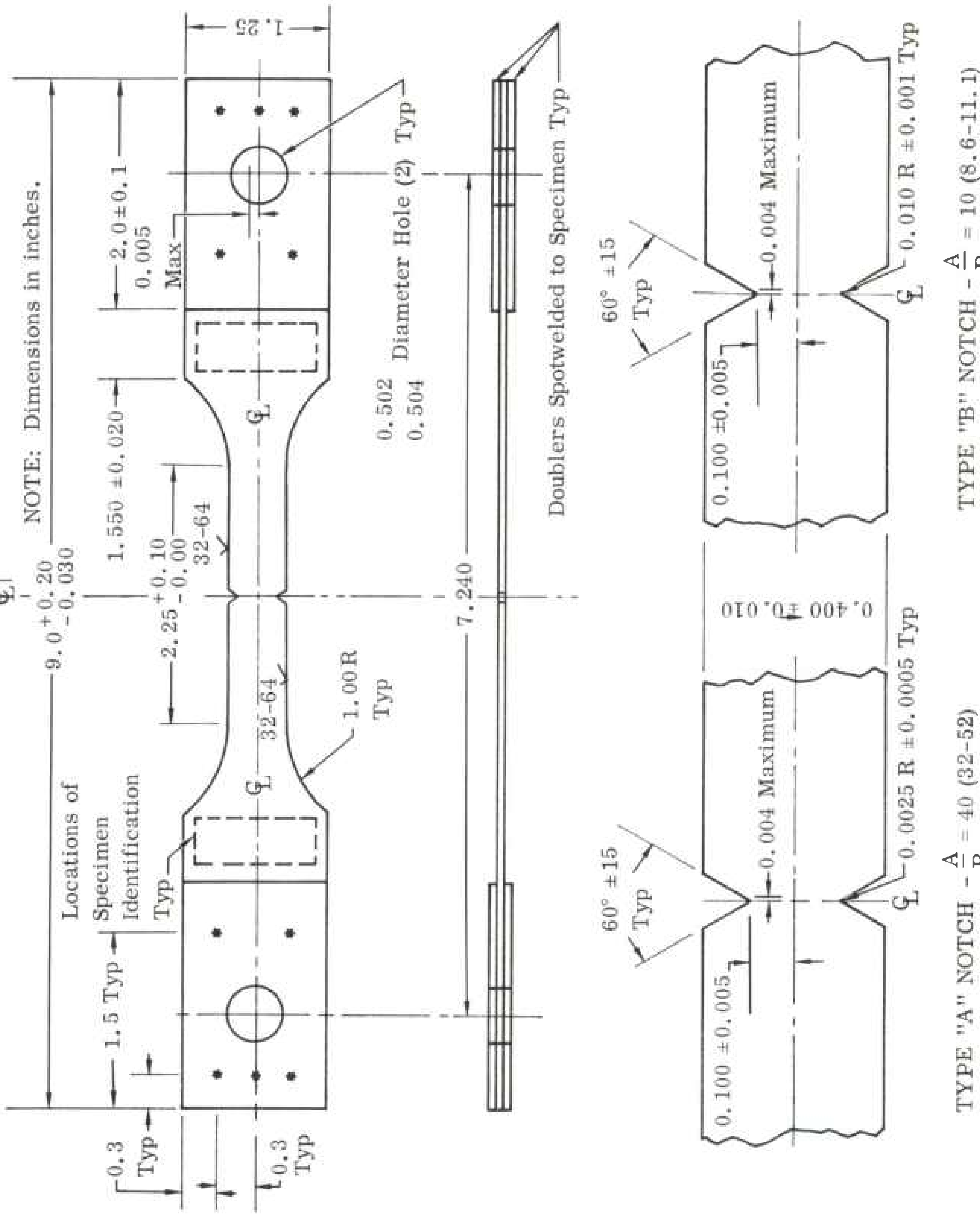


Figure 2. Notched Tensile Specimen (K_t = 3.2 and 6.3)

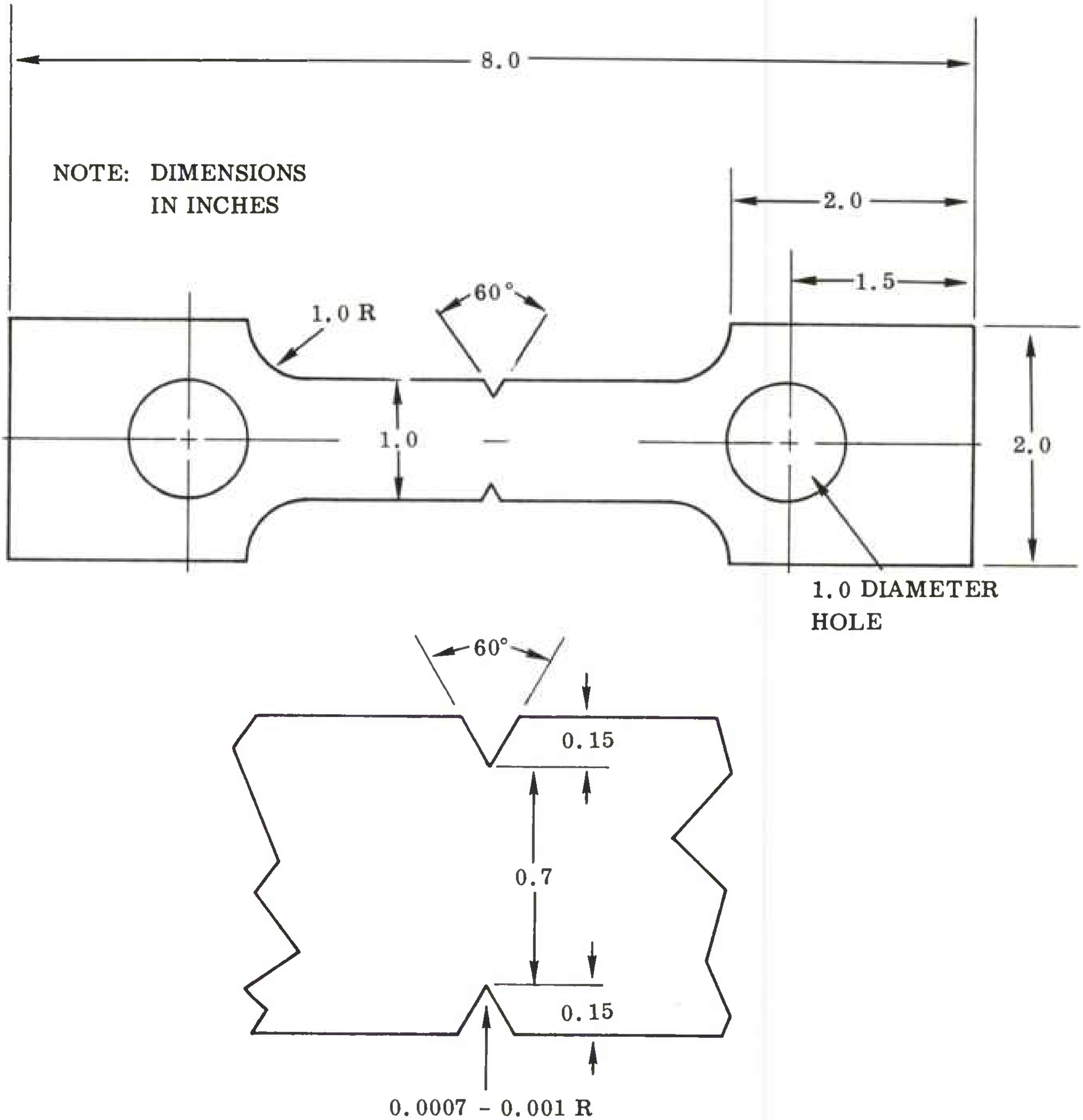


Figure 3. Notched Tensile Specimen (K_t = 19)

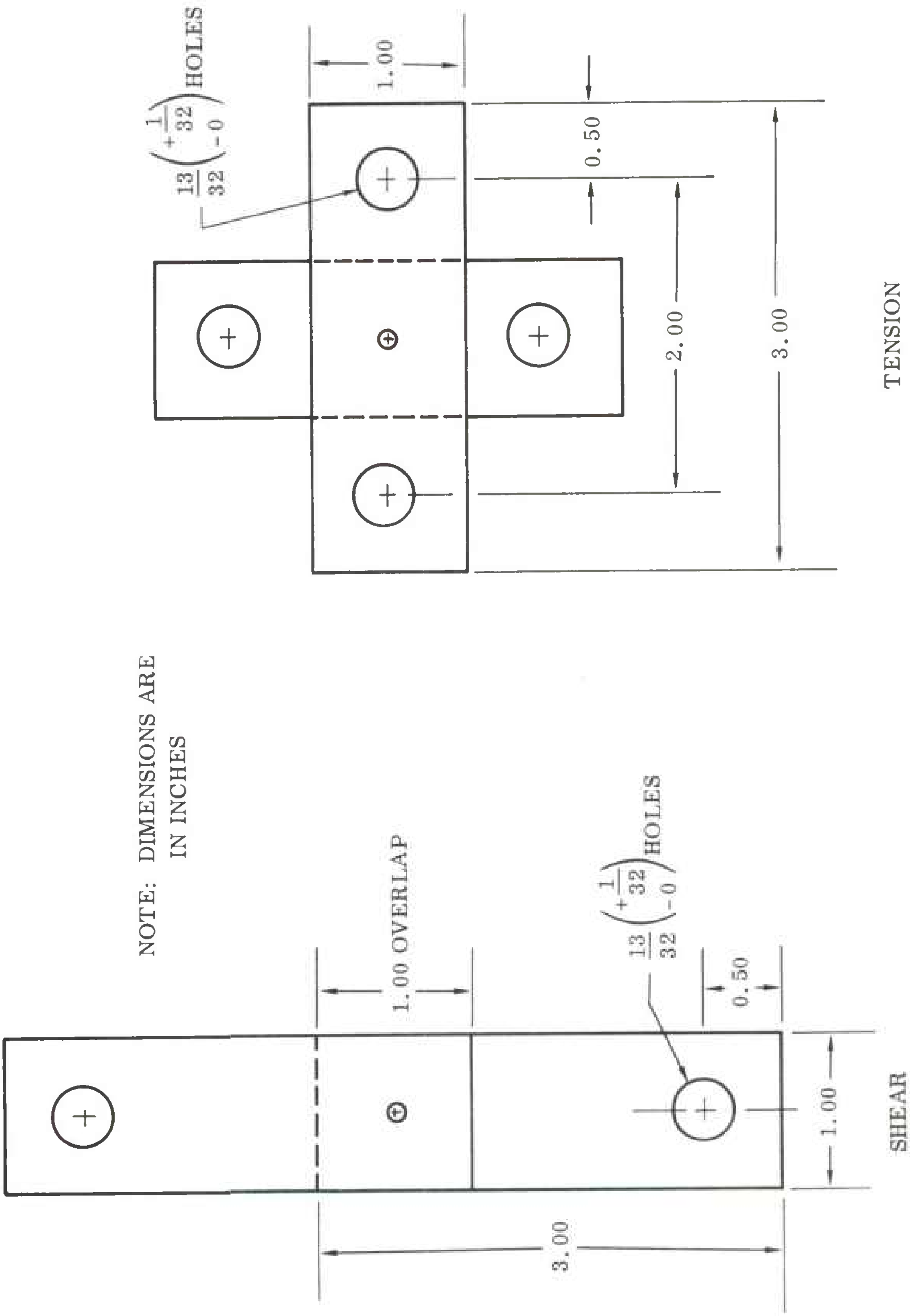
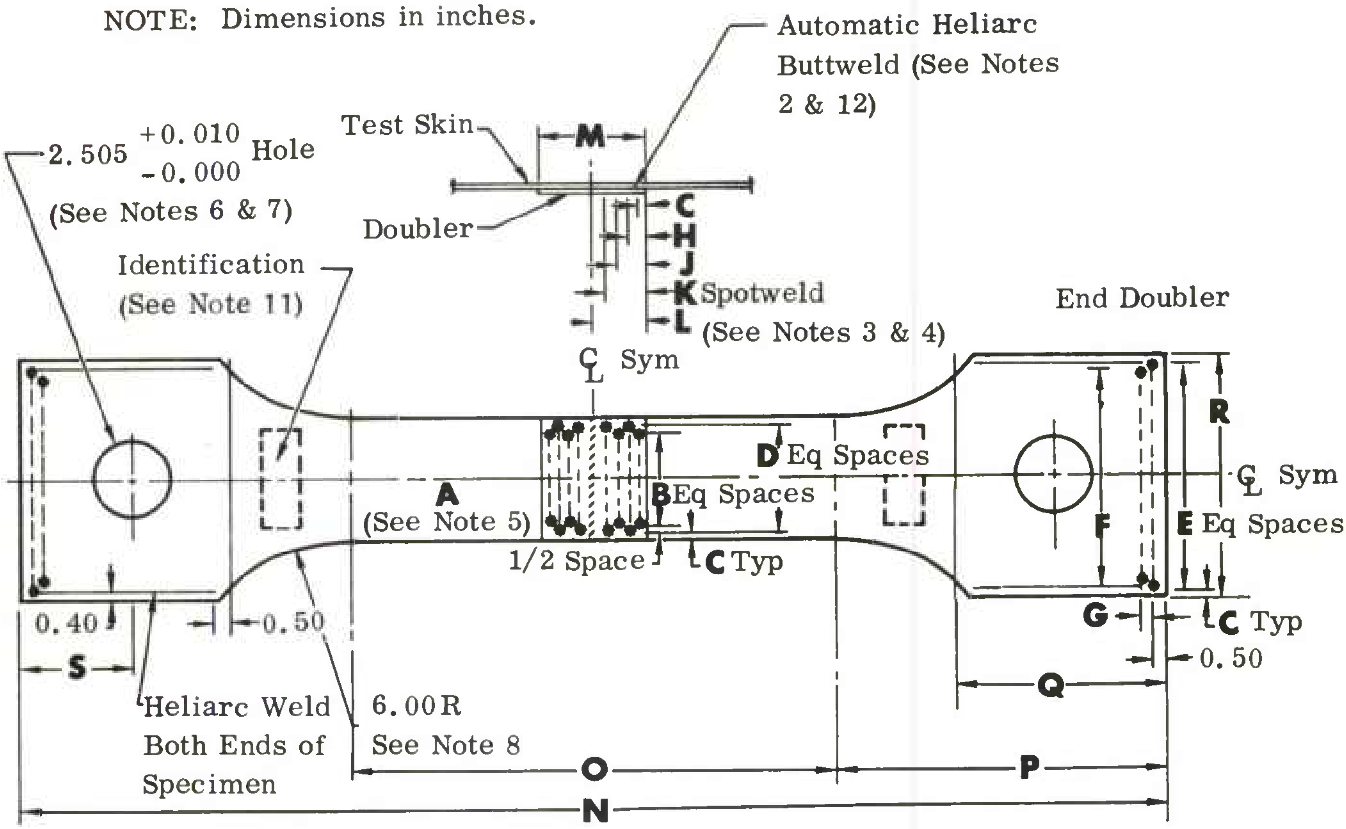


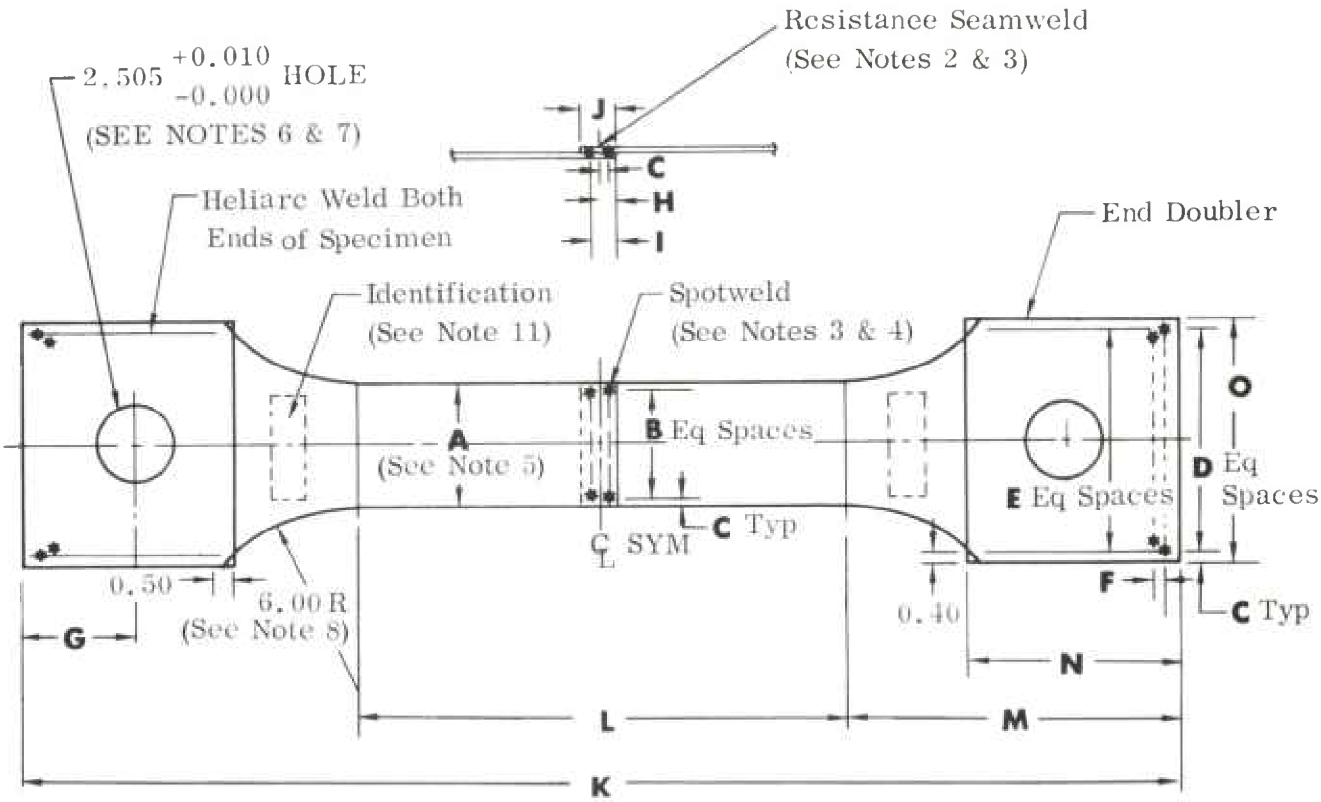
Figure 4. Spot Welded Tension and Shear Specimens



MATERIAL	ASSY	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S
301 SS	-855	4.52	7	0.32	8	11	10	0.37	0.74	1.14	1.52	2.00	3.51	38	16	11	7	8	3.75
Ti and AM-355 SS	-843	4.26	5	0.34	6	11	10	0.37	0.74	1.14	1.52	2.00	3.51	38	16	11	7	8	3.75
310 SS	-837	3.98	6	0.25	7	13	12	0.34	0.59	0.93	1.27	1.74	3.51	38	16	11	7	8	3.75
304 SS	-825	3.86	7	0.25	8	17	16	0.34	0.59	0.93	1.27	1.74	3.51	38	16	11	7	8	3.75

1. Metal stamping of parts not permitted.
2. Buttweld test skins prior to machining.
3. Spotwelds per spec MIL-W-6858A.
4. Tolerance on location of spotwelds to be ±0.06.
5. Test section width minimum at center. Total taper to be 0.010 from one end to center.
6. Edges of skin must be sharp and free from burrs.
7. Holes to be centered with test section ±0.015.
8. In radius no notches or undercuts permitted.
9. Material spec to be called out with specimen request.
10. Edges of test skin to be machined to 125✓ finish.
11. Each specimen to have gage, coil, heat, spec and specimen number.
12. Heliarc buttwelds per spec 0-75005.

Figure 5. Fatigue Specimen (Longitudinal for Steel and Titanium)

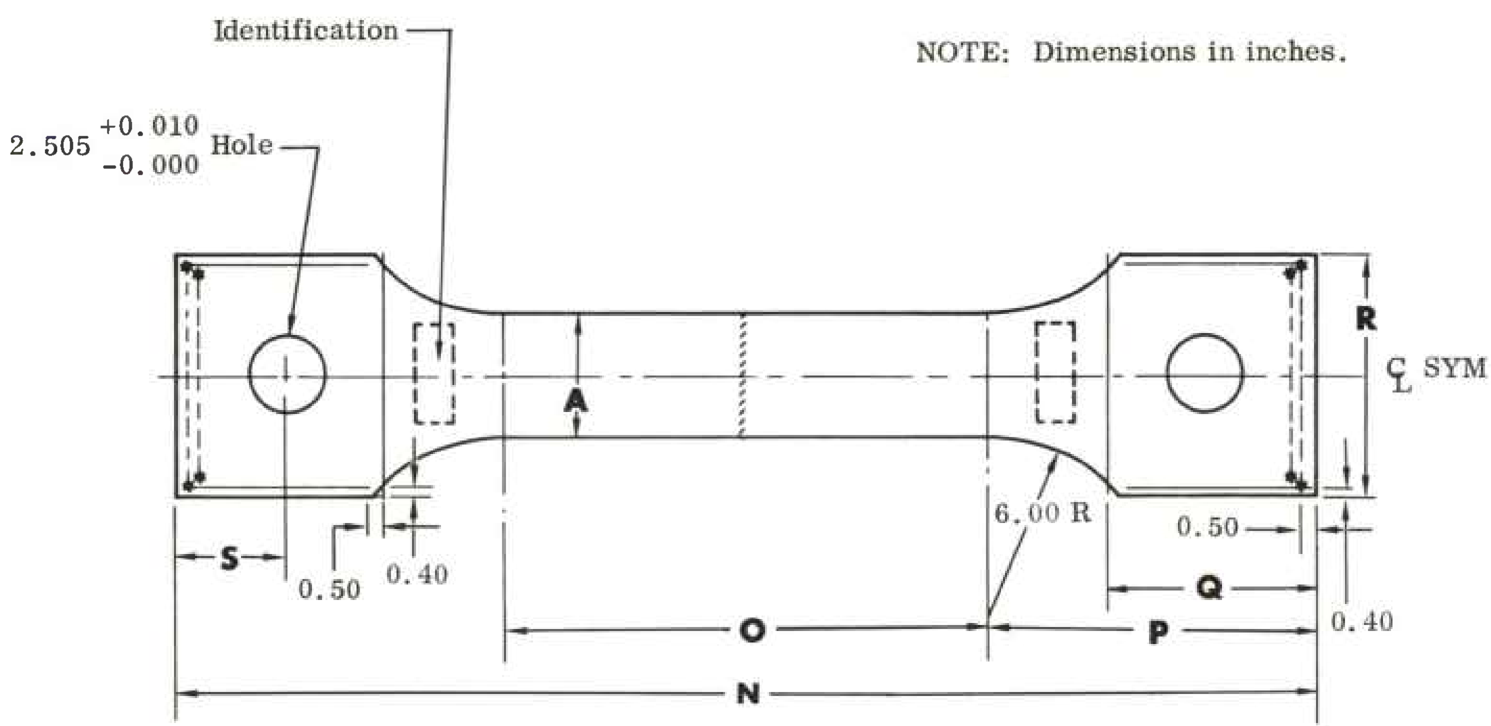


Note: Dimensions in inches.

MATERIAL	ASSY	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
304SS	-845	3.86	8	0.25	17	16	0.34	3.75	0.59	0.93	1.21	38.0	16	11	7	8
310SS	-857	3.98	6	0.25	12	11	0.34	3.75	0.59	0.93	1.21	38.0	16	11	7	8
Ti and AM-355	-859	4.12	6	0.28	13	12	0.37	3.75	0.71	1.14	1.42	38.0	16	11	7	8
301SS	-861	3.92	6	0.28	13	12	0.37	3.75	0.65	1.02	1.33	38.0	16	11	7	8

1. Metal stamping of parts not permitted.
2. Seamweld test skins prior to machining.
3. Spotwelds and seamweld per MIL-W-6858A.
4. Tolerance on location of spotwelds to be ±0.06.
5. Test section width minimum at center. Total taper to be 0.010 from one end to center.
6. Edges of skin must be sharp and free from burrs.
7. Holes to be centered with test section ±0.015.
8. In radius no notches or undercuts permitted.
9. Material spec to be called out with specimen request.
10. Edges of test skin to be machined to 125√ finish.
11. Each specimen to have gage, coil, heat, spec and specimen number.

Figure 6. Fatigue Specimen (Transverse for Steel and Titanium)



ASSY	A	N	O	P	Q	R	S
-851	4.00	38	16	11	7	8	3.75

Figure 7. Fatigue Specimen (Longitudinal and Transverse for Aluminum)

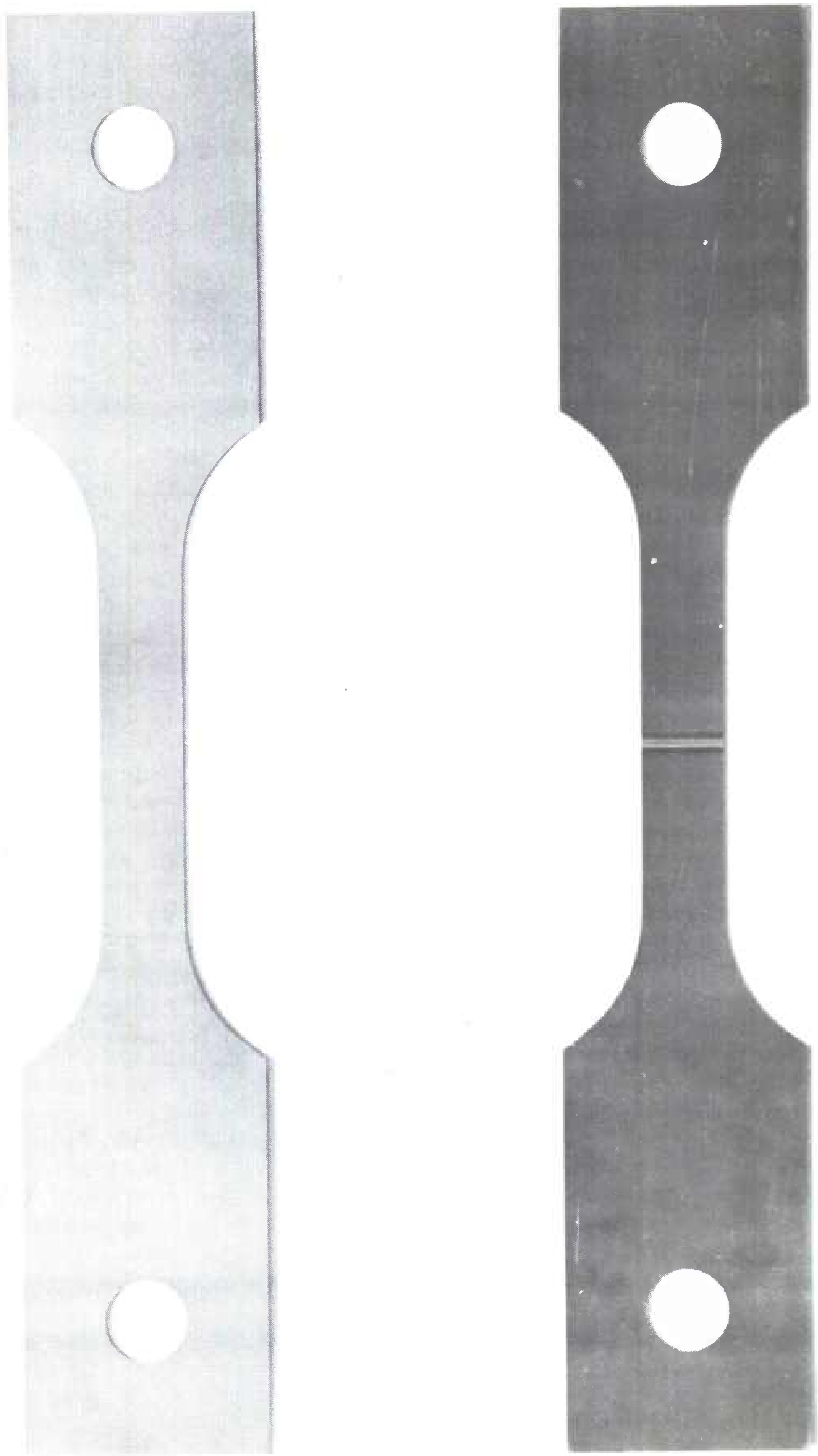


Figure 8. Photograph of Parent Metal and Welded Flat Tensile Specimens

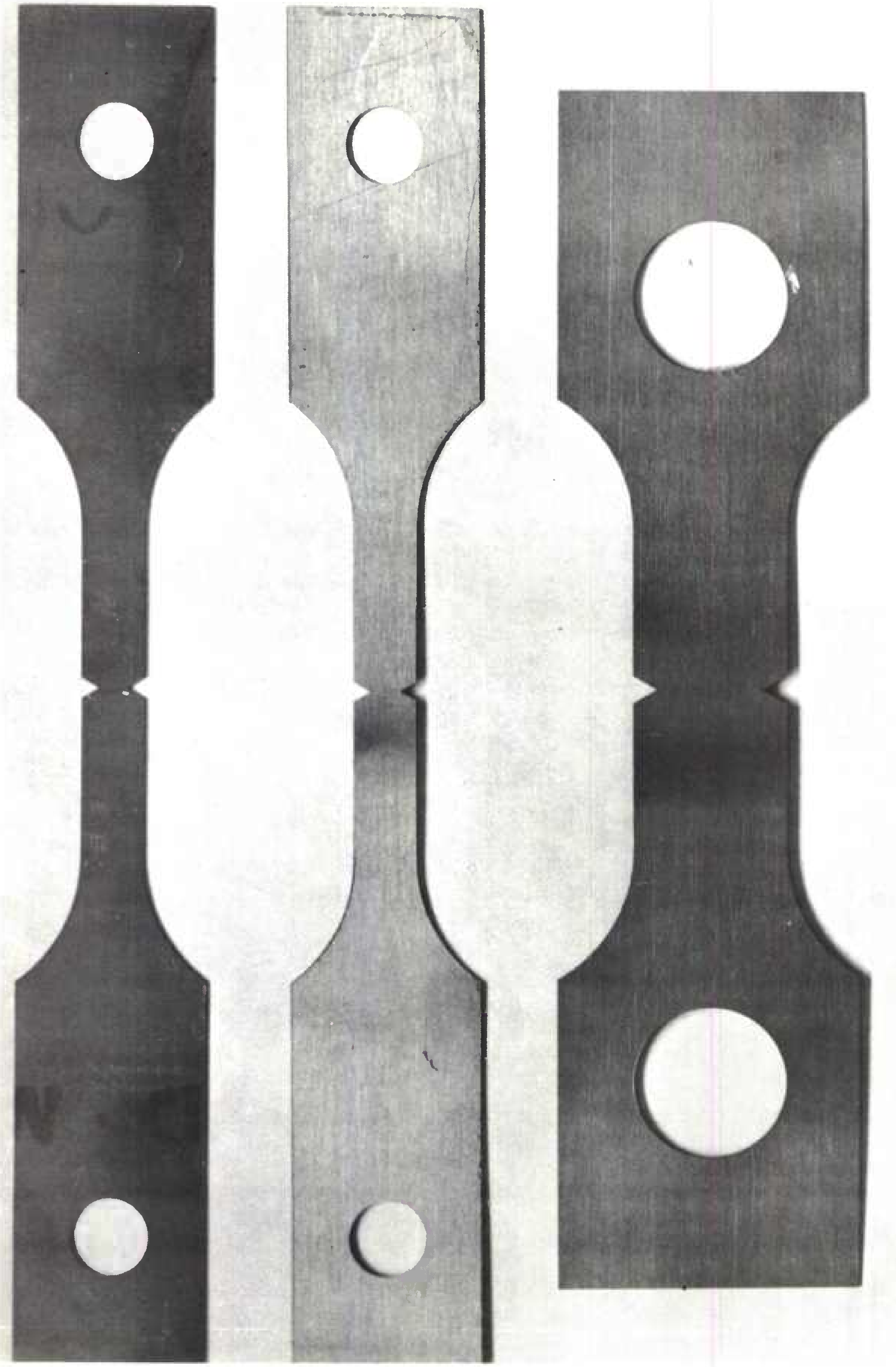


Figure 9. Photograph of Notched Tensile Specimens

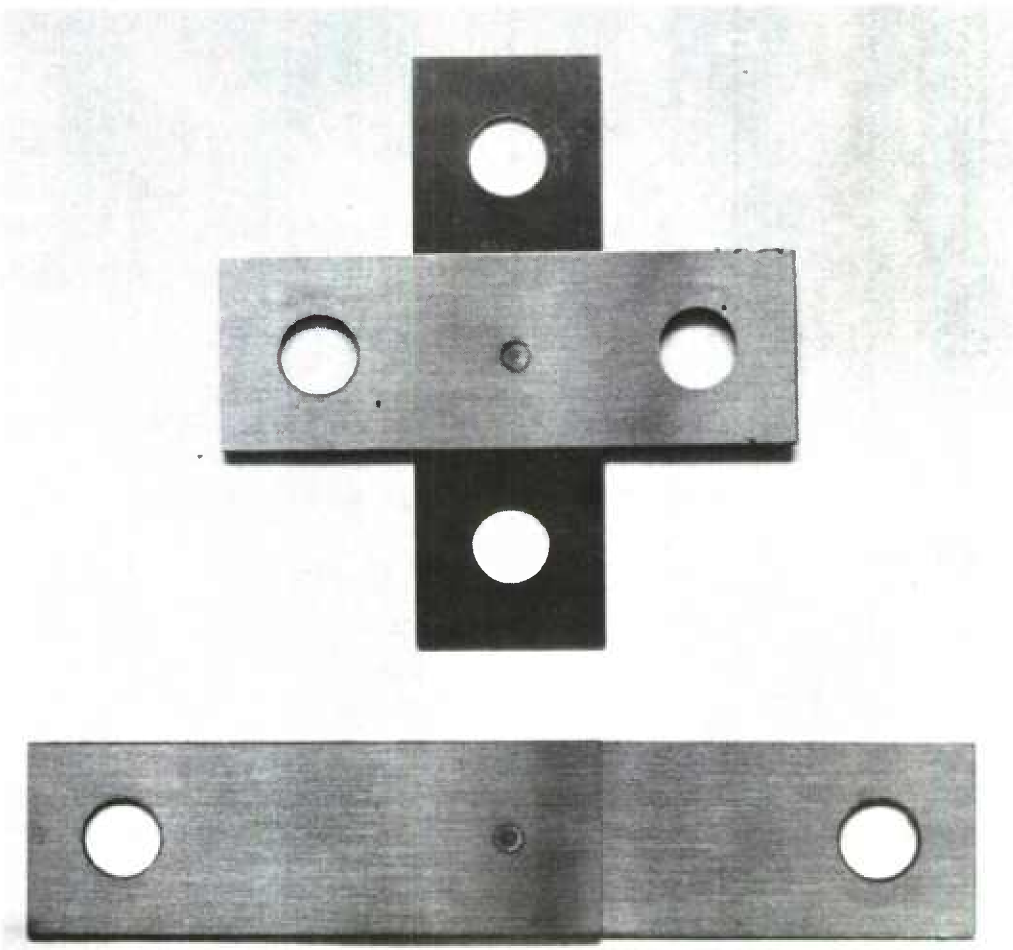


Figure 10. Photograph of Spot Welded Tension and Shear Specimens

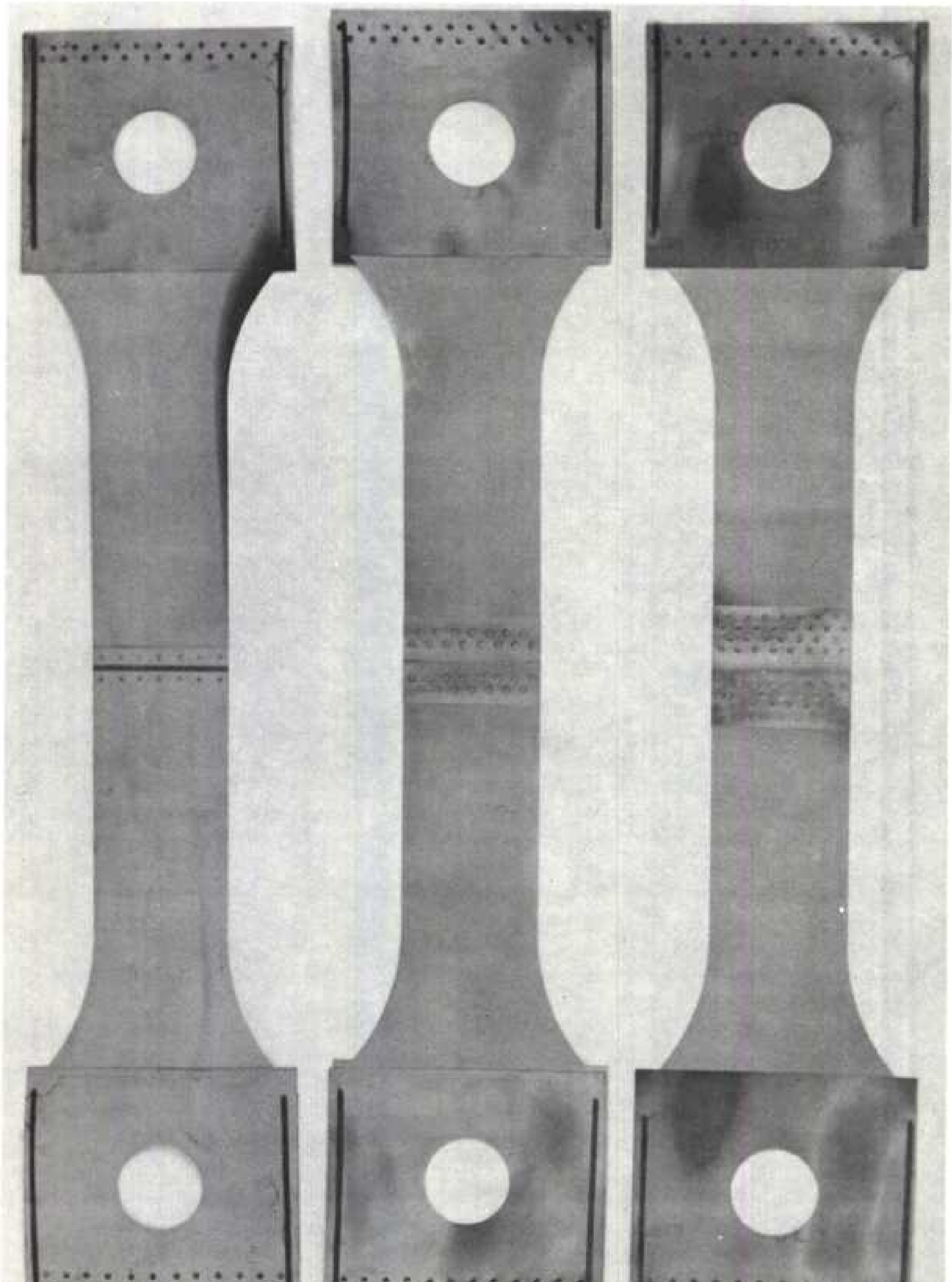


Figure 11. Photograph of Fatigue Specimens (Steel and Titanium)

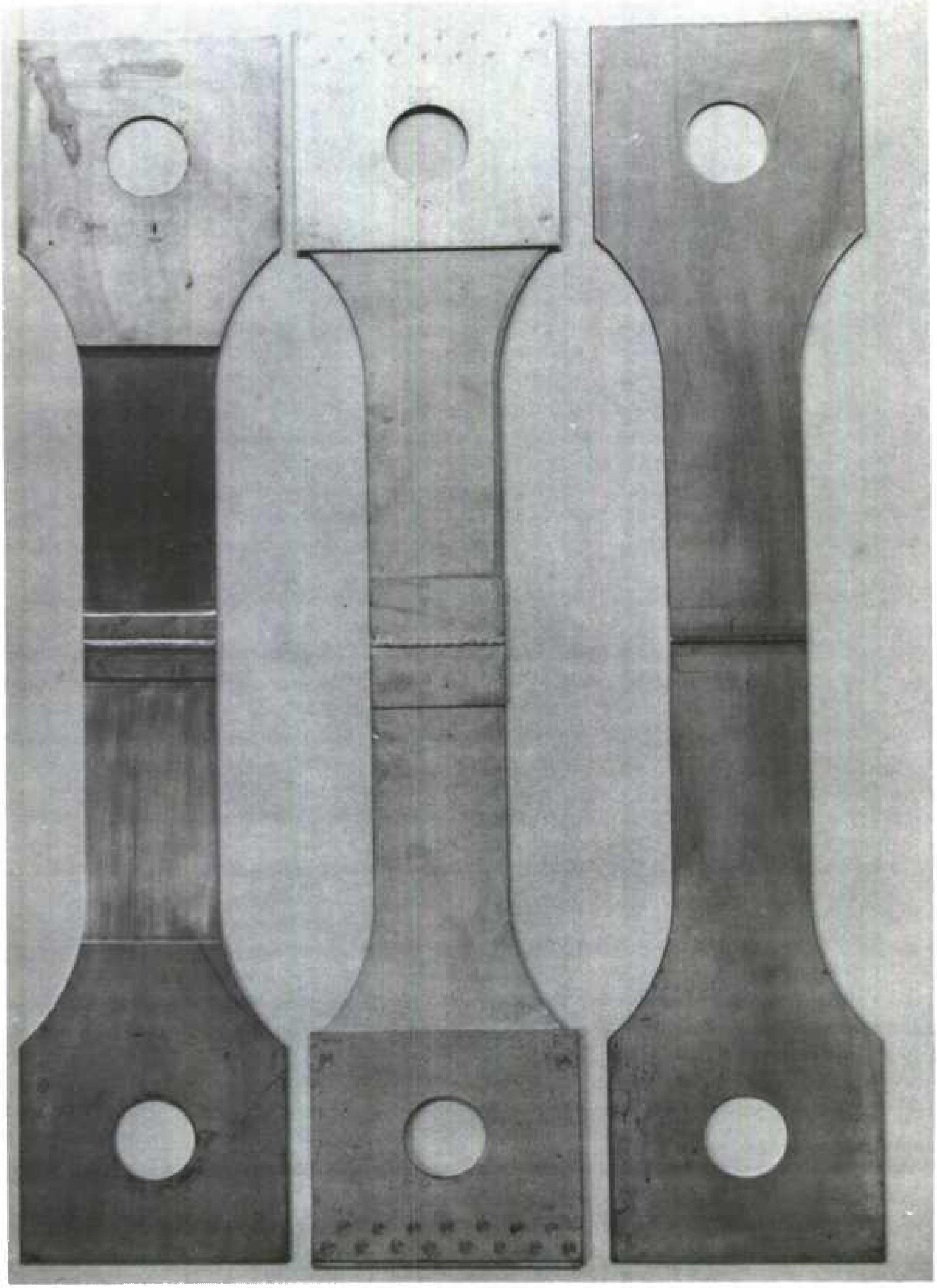


Figure 12. Photograph of Fatigue Specimens (Aluminum)

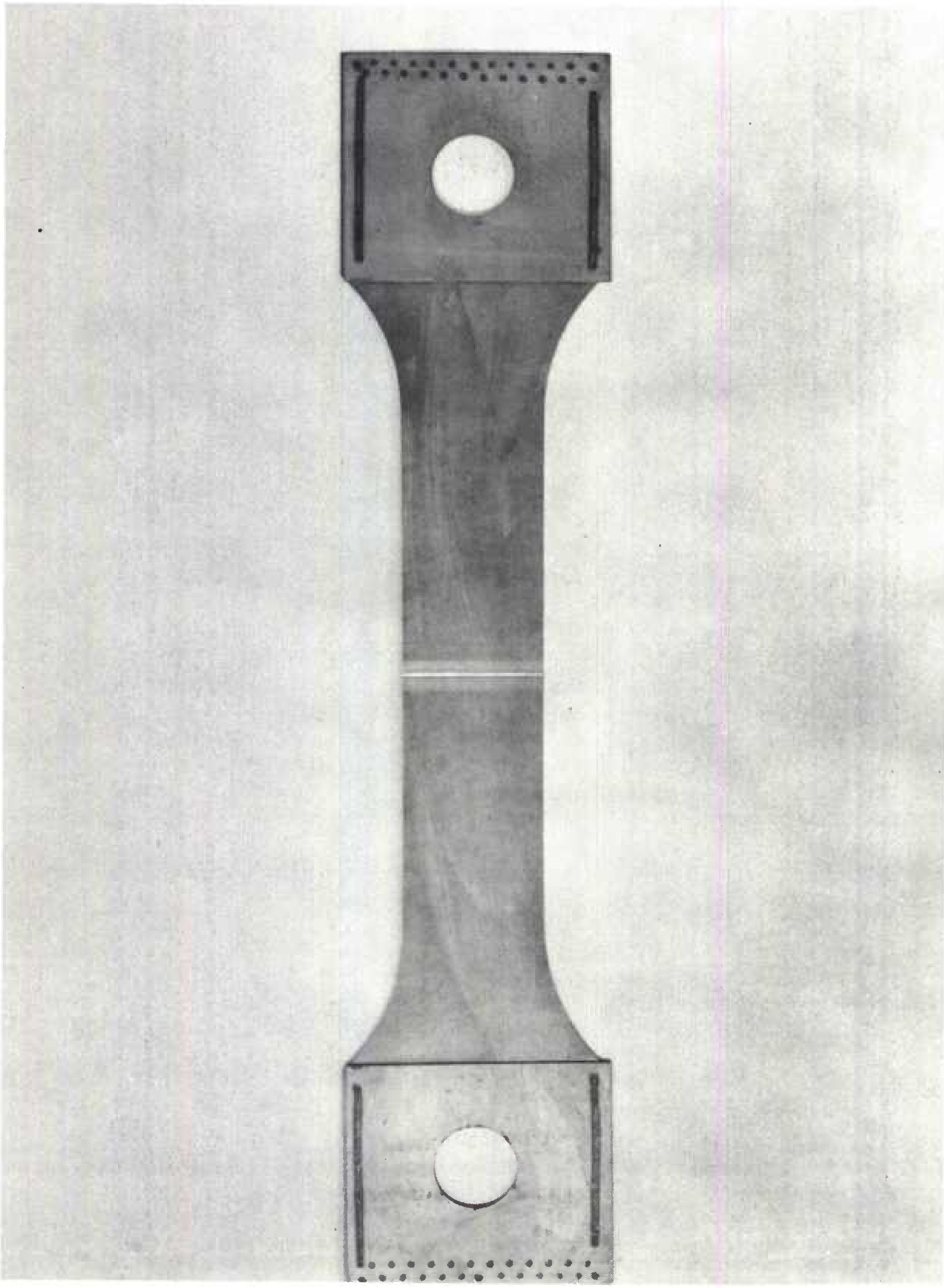


Figure 13. Photograph of Fatigue Specimen (Titanium)

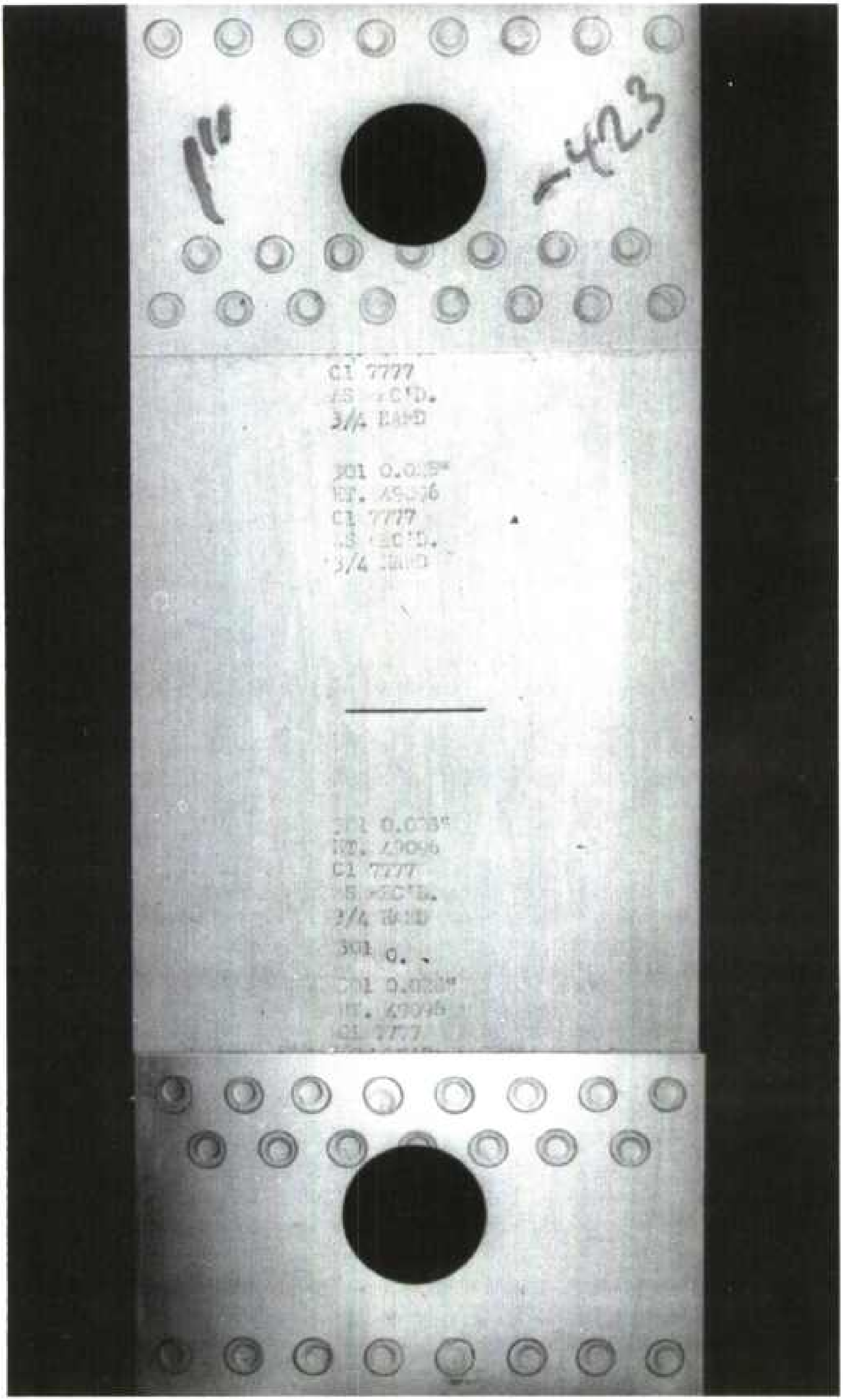


Figure 14. Photograph of Crack Propagation Specimen

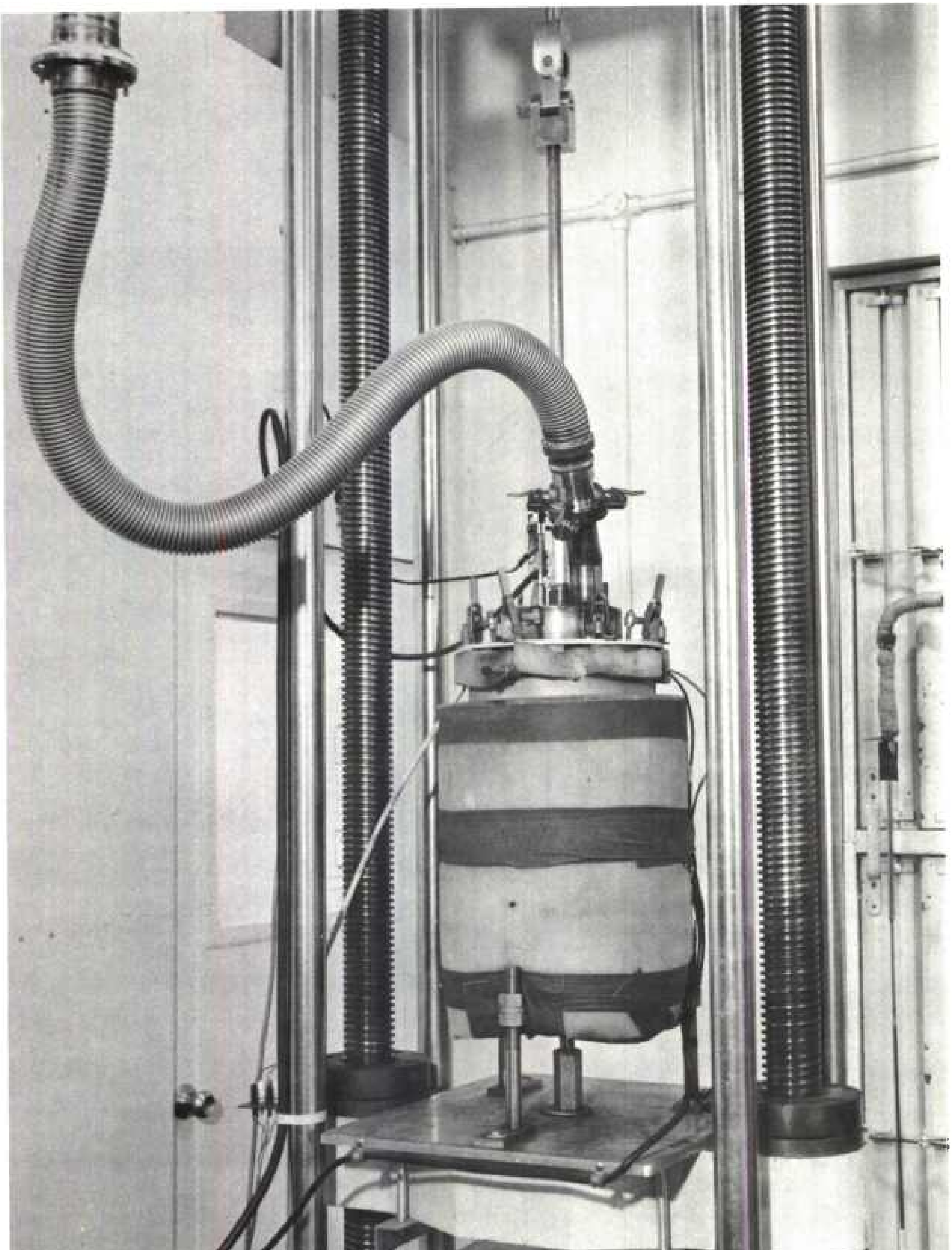


Figure 17. Liquid-Hydrogen Cryostat

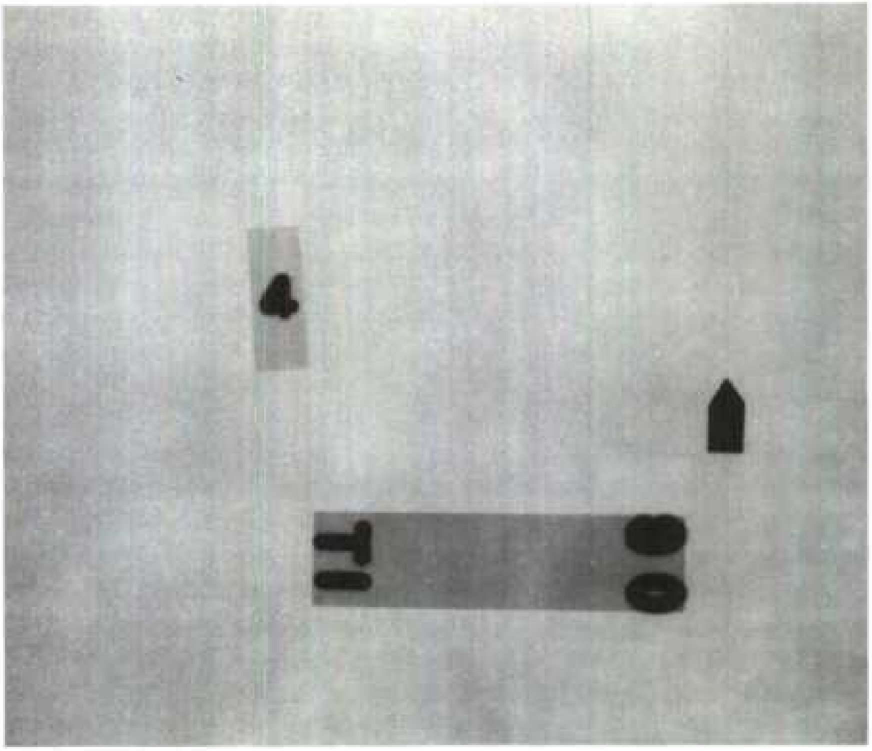


Figure 15. Radiograph of Fusion Welded Fatigue Specimen

Figure 16. Radiograph of Complex Welded Fatigue Specimen

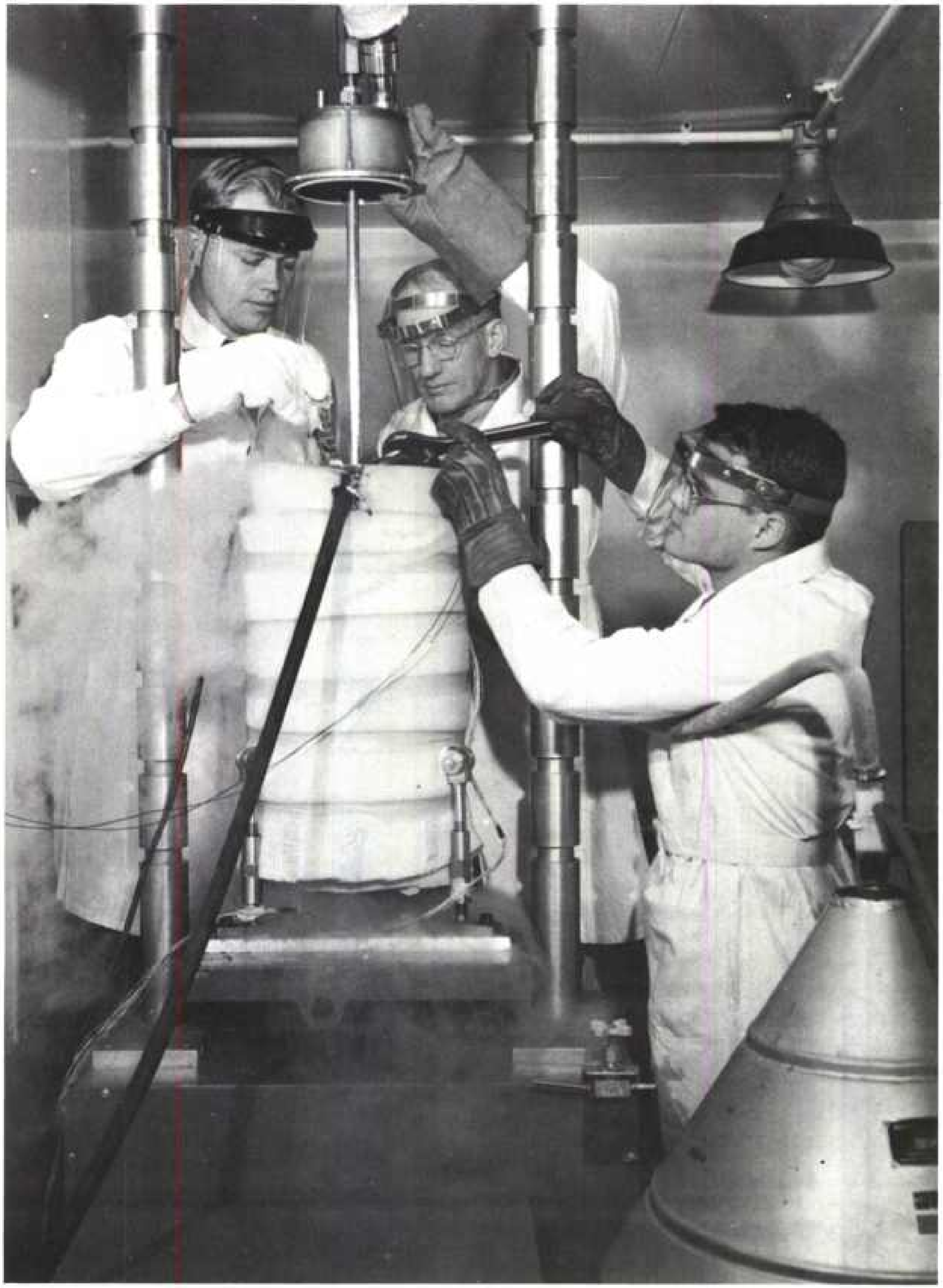


Figure 18. Liquid-Hydrogen Test Chamber Being Prepared for Test

Figure 19. Transfer of Liquid Hydrogen

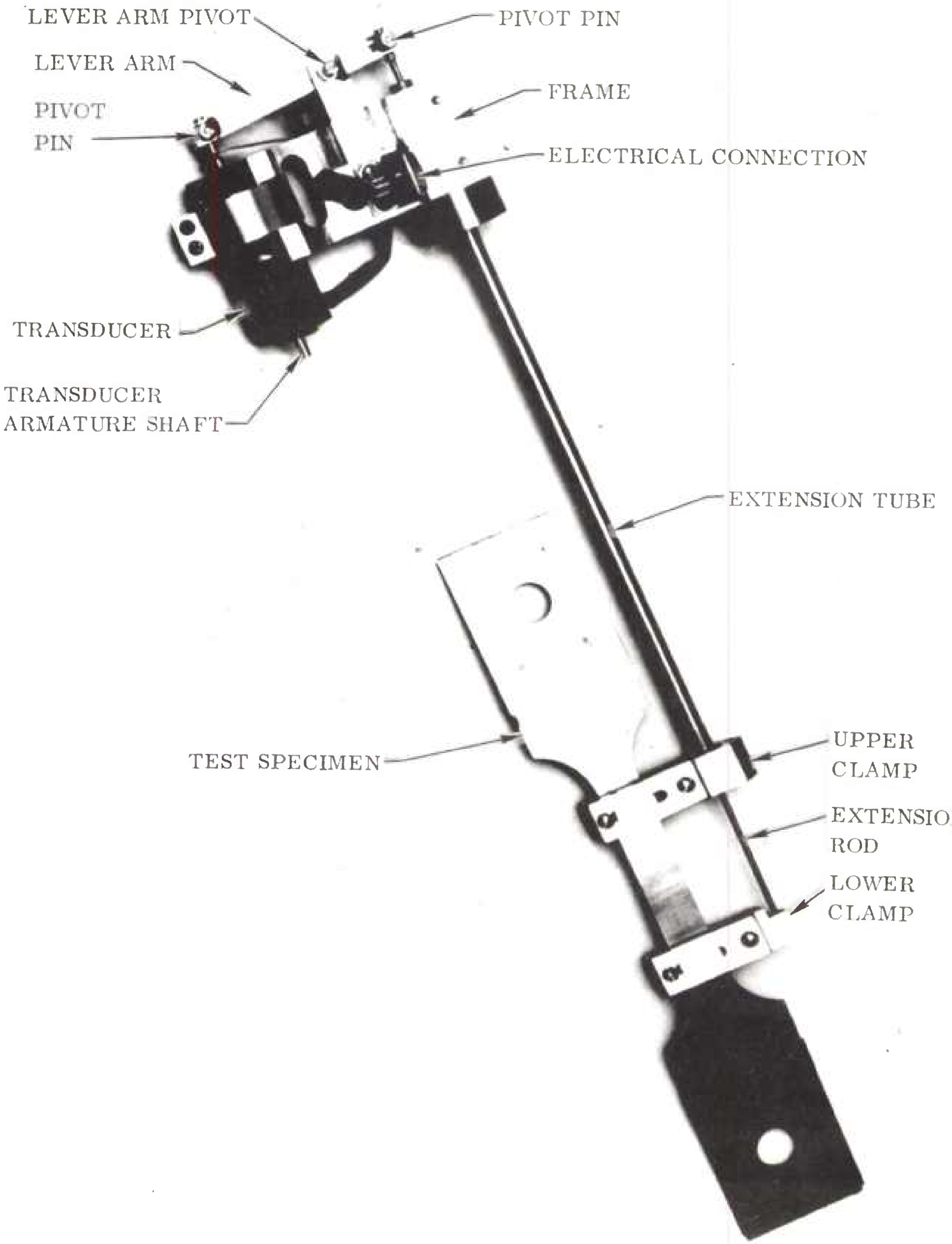


Figure 20. Cryo-extensometer

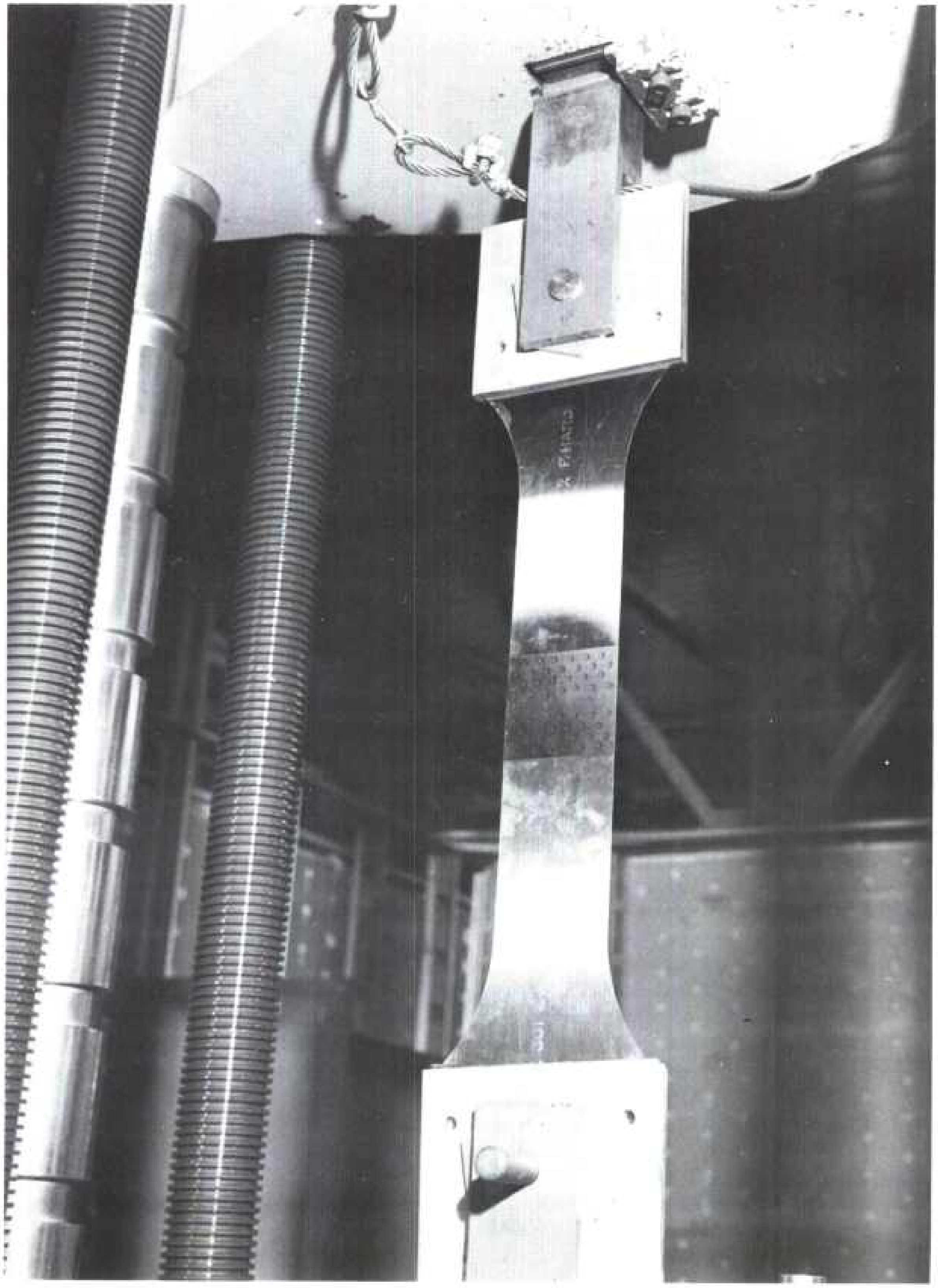


Figure 21. Fatigue Specimen in Static Test

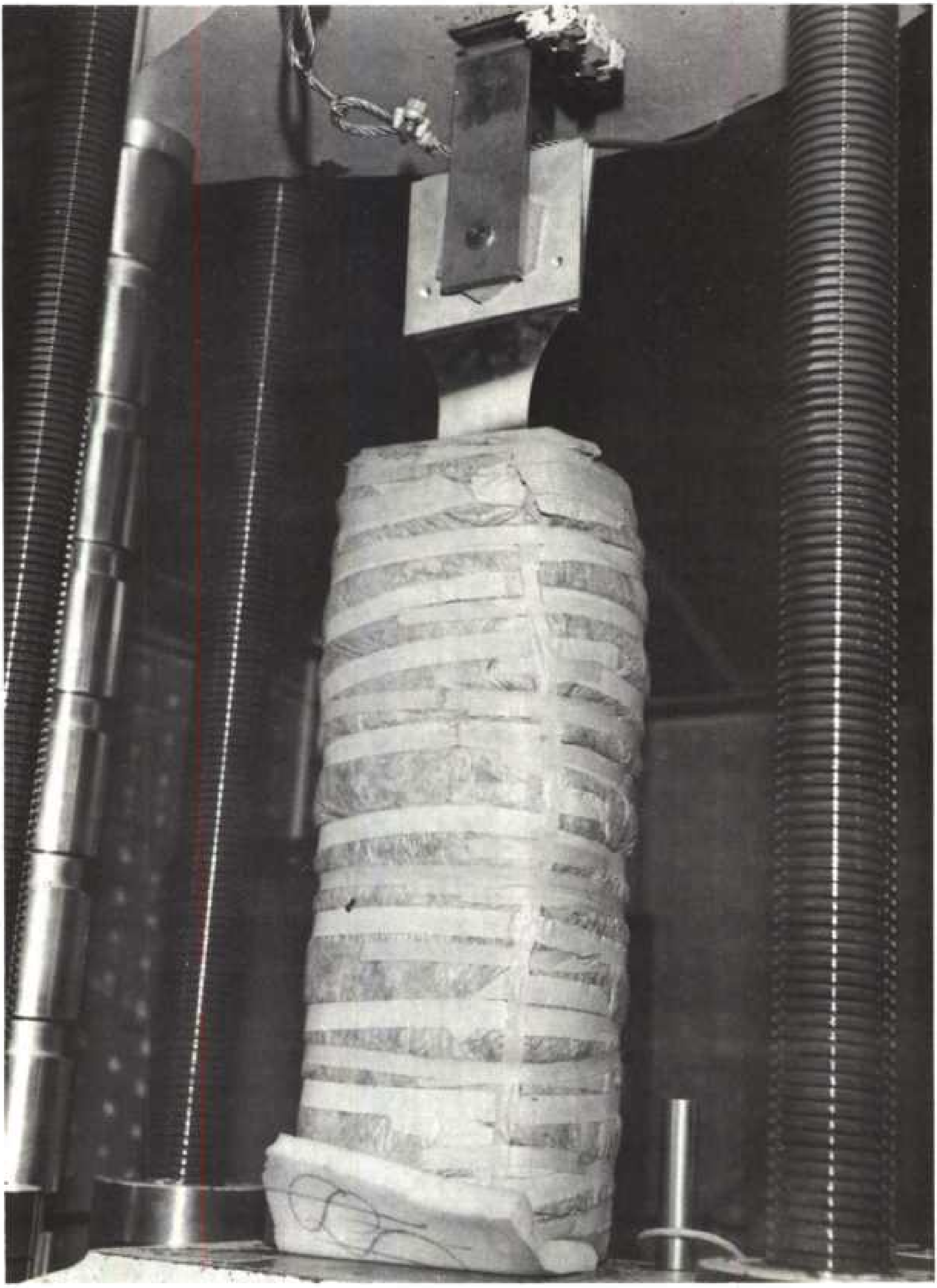


Figure 22. Fatigue Specimen in Liquid-Nitrogen Cryostat

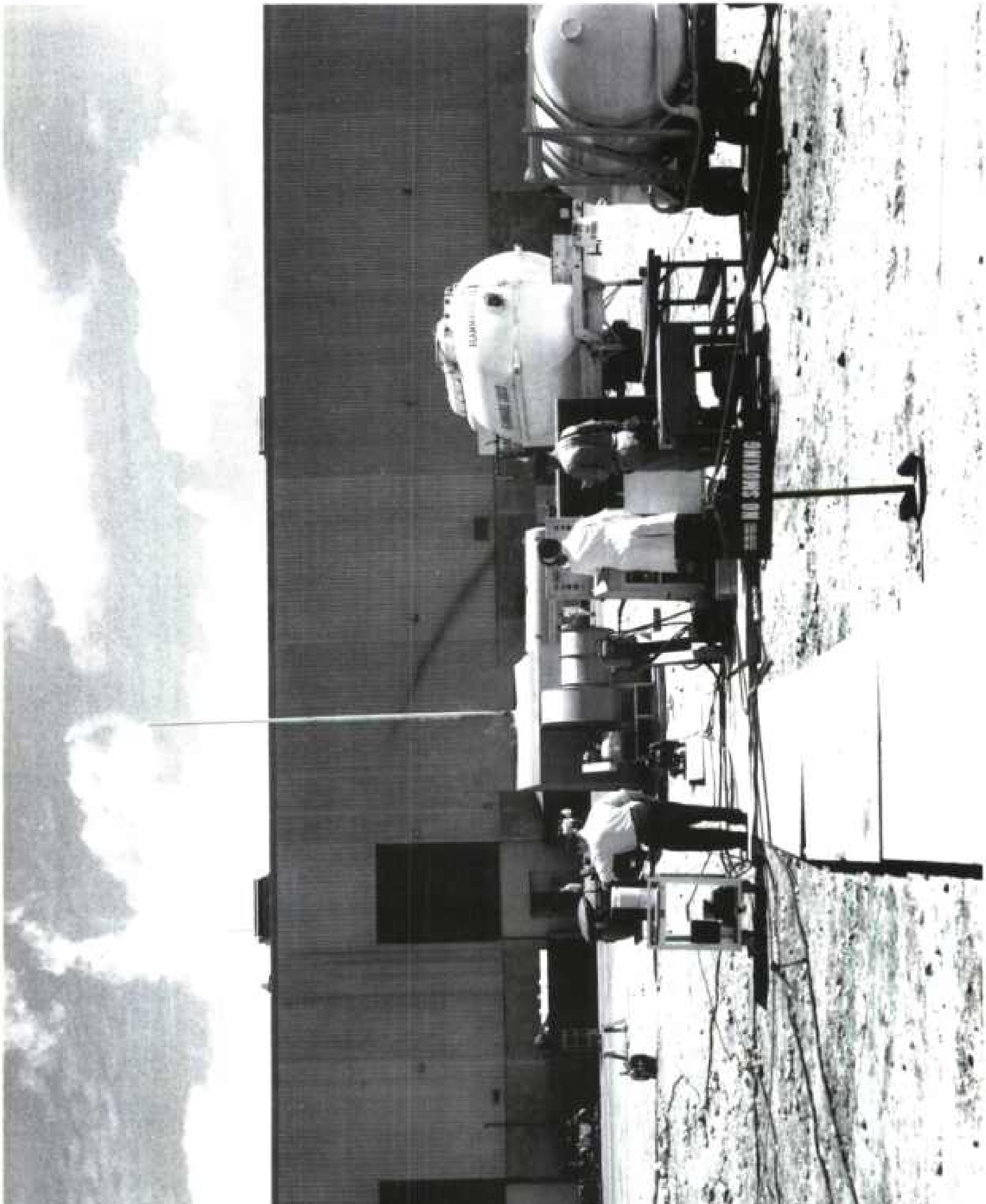


Figure 23. Outdoor Liquid Hydrogen Test Area

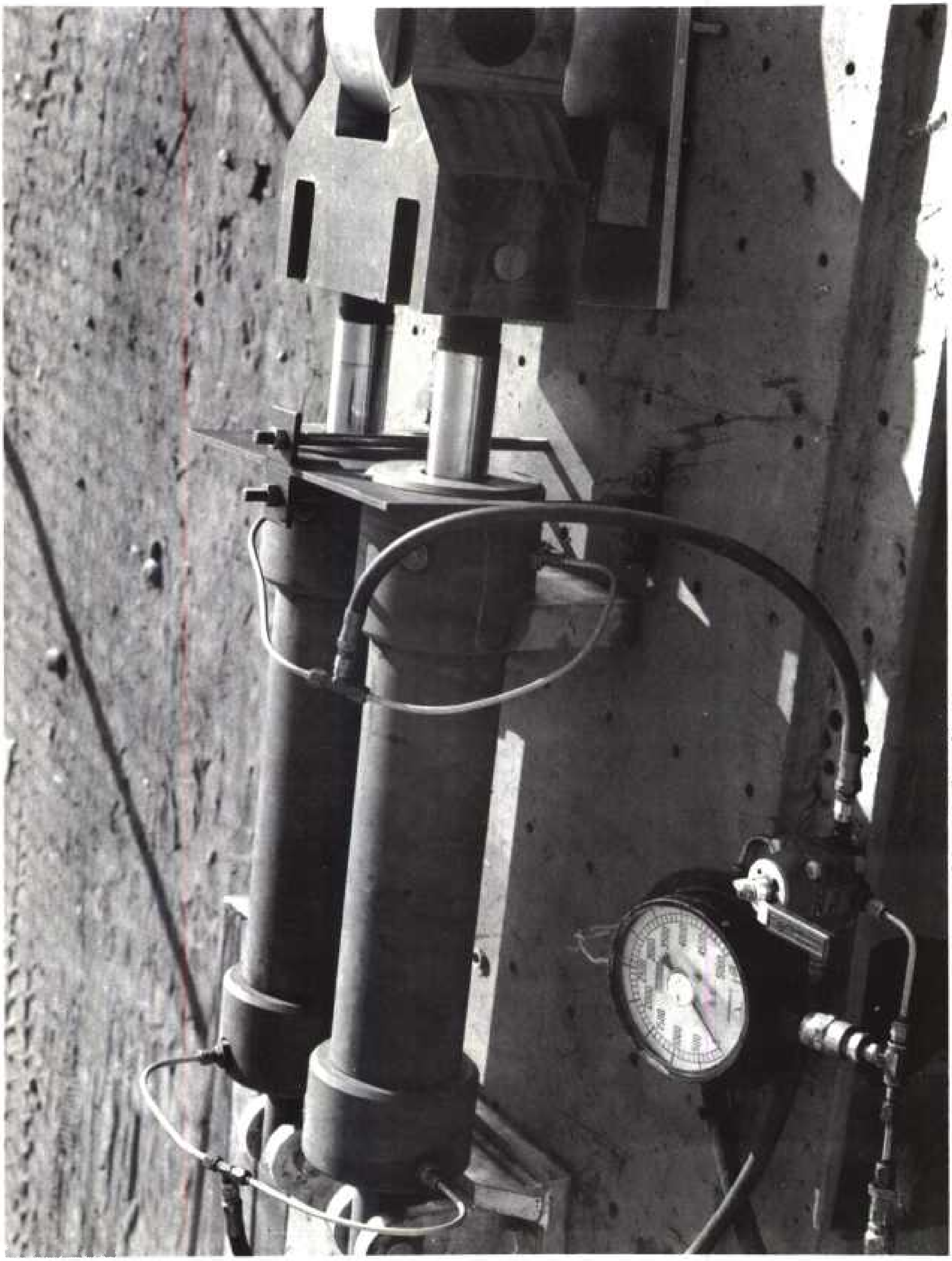


Figure 24. Hydraulic Rams - Fatigue Test Equipment

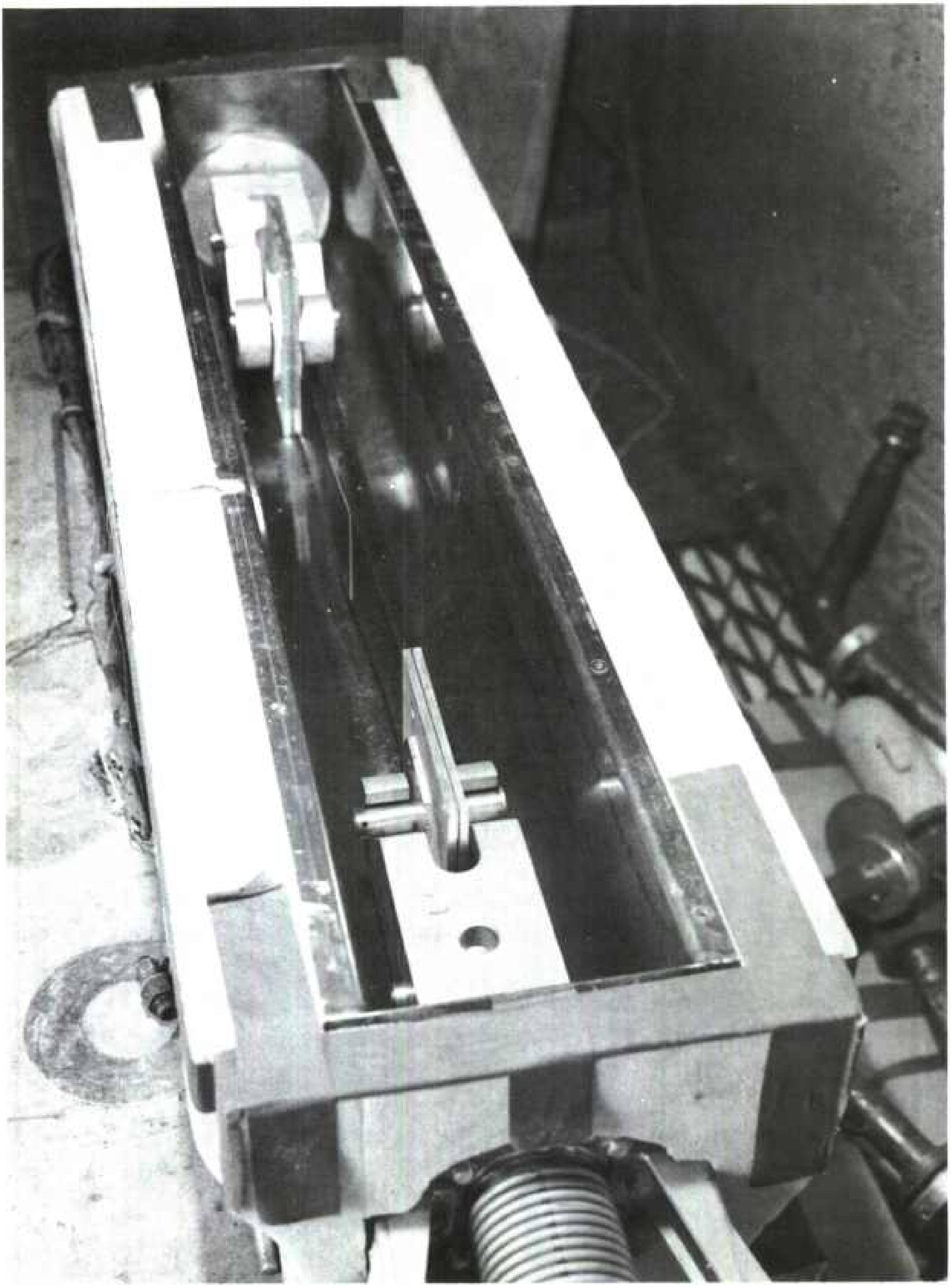


Figure 25. Fatigue Test Chamber (for Room Temperature and Liquid-Nitrogen Testing)

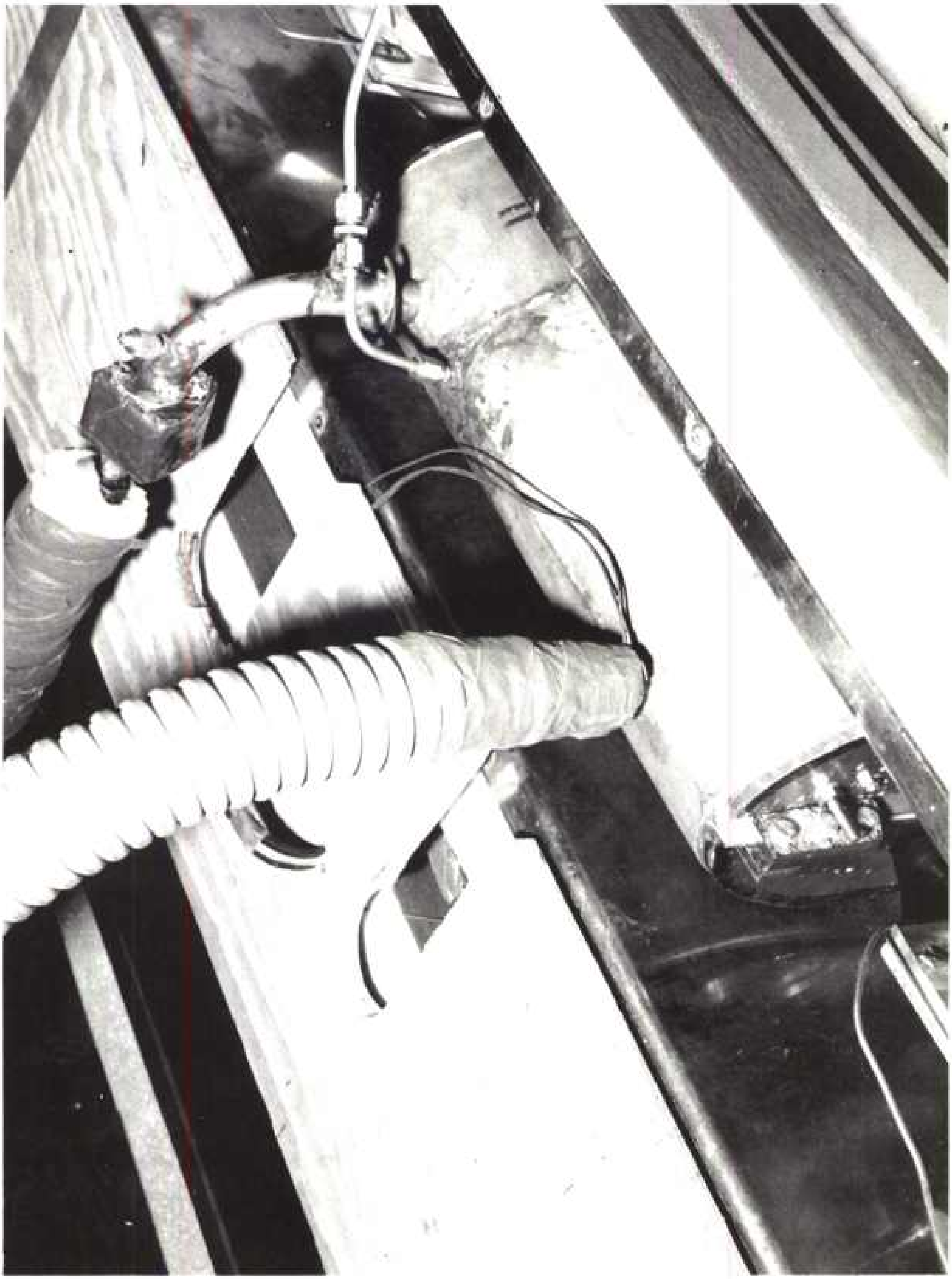


Figure 26. Fatigue Test Bed with Liquid-Hydrogen Test Chamber

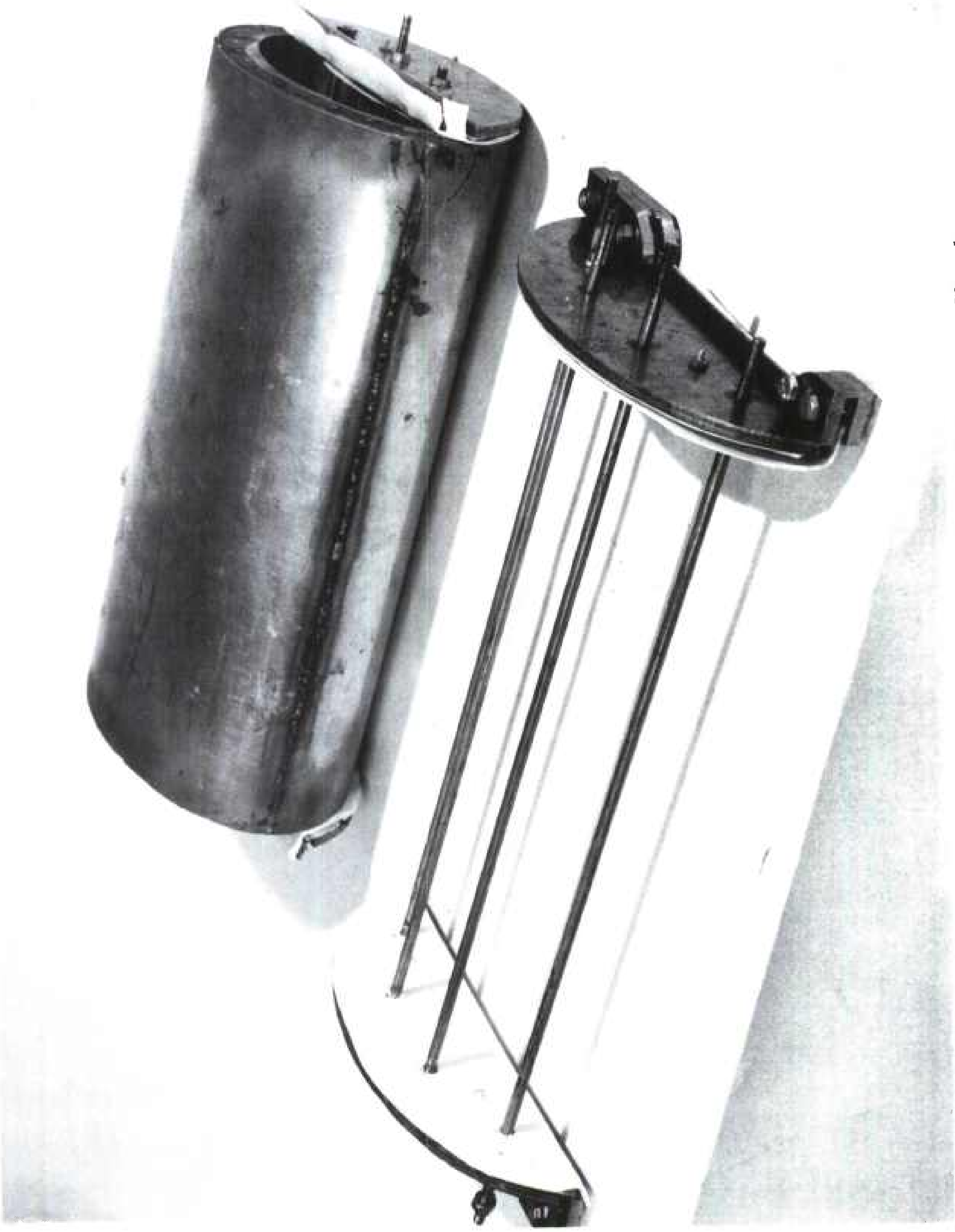


Figure 27. View of Liquid-Hydrogen Fatigue Test Chamber

Figure 28. View of Liquid-Hydrogen Fatigue Test Chamber (Assembled)

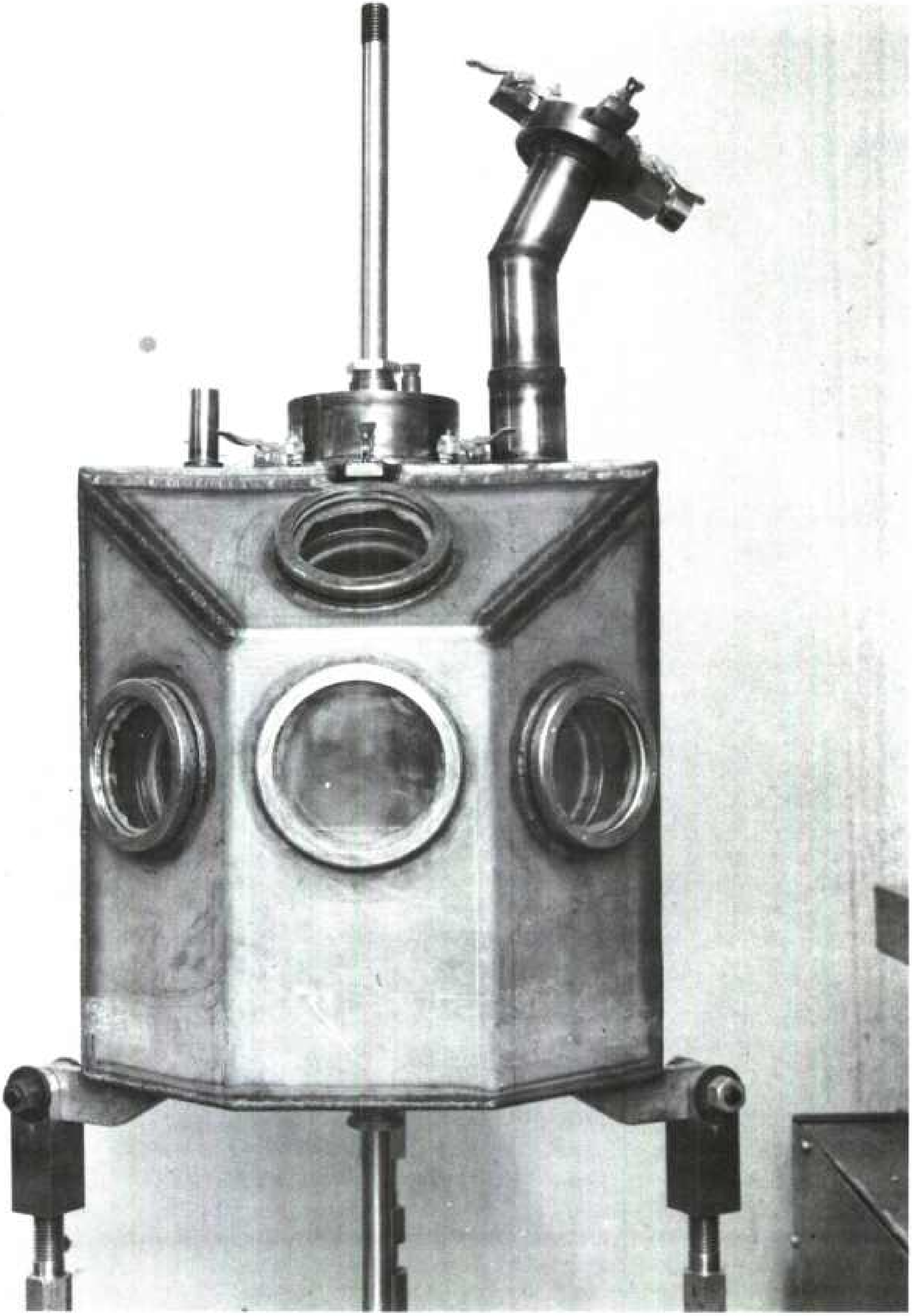


Figure 29. Liquid-Hydrogen Cryostat for Crack Propagation Testing

Figure 30. Metallographic Laboratory

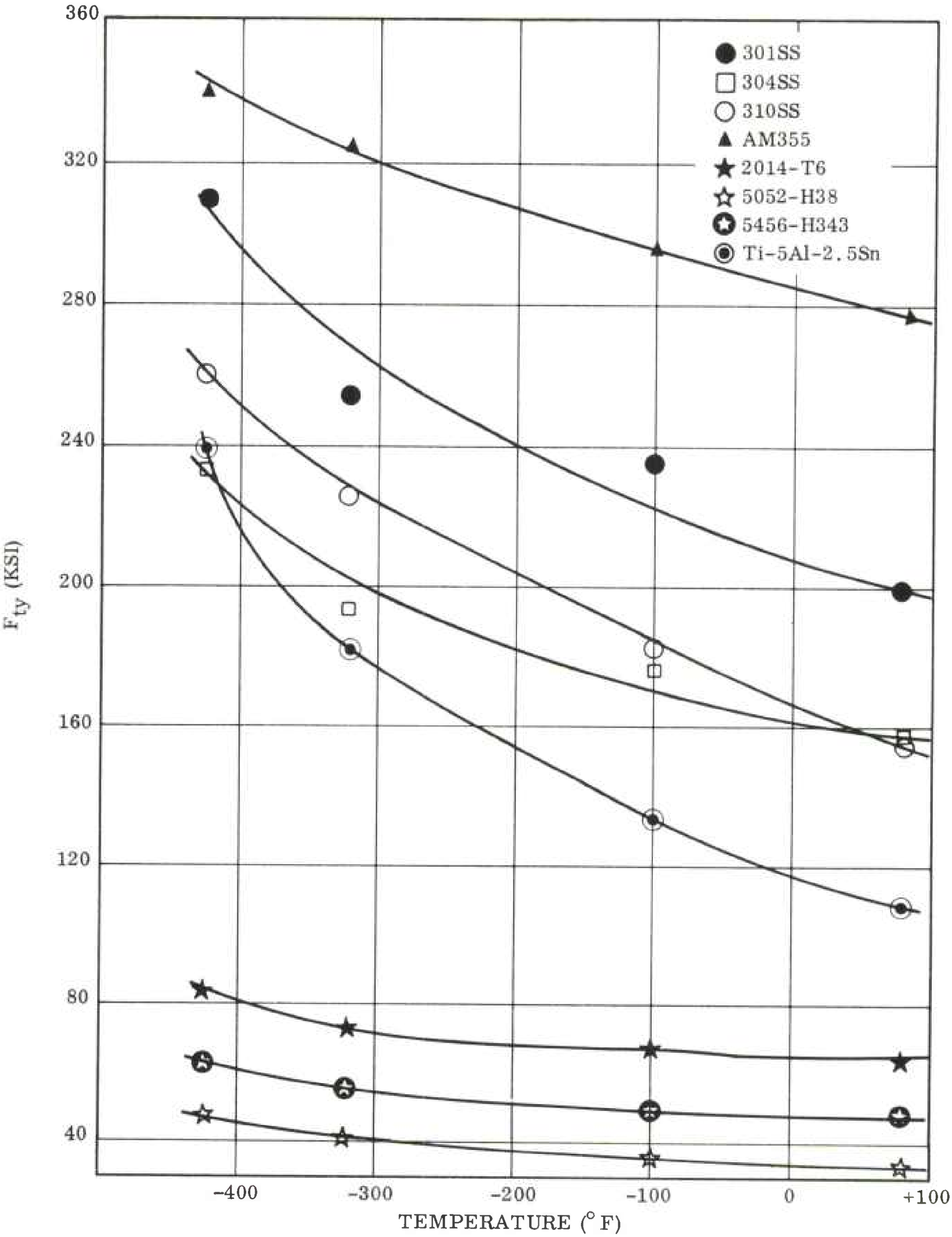


Figure 31. F_{ty} Versus Temperature (Longitudinal)

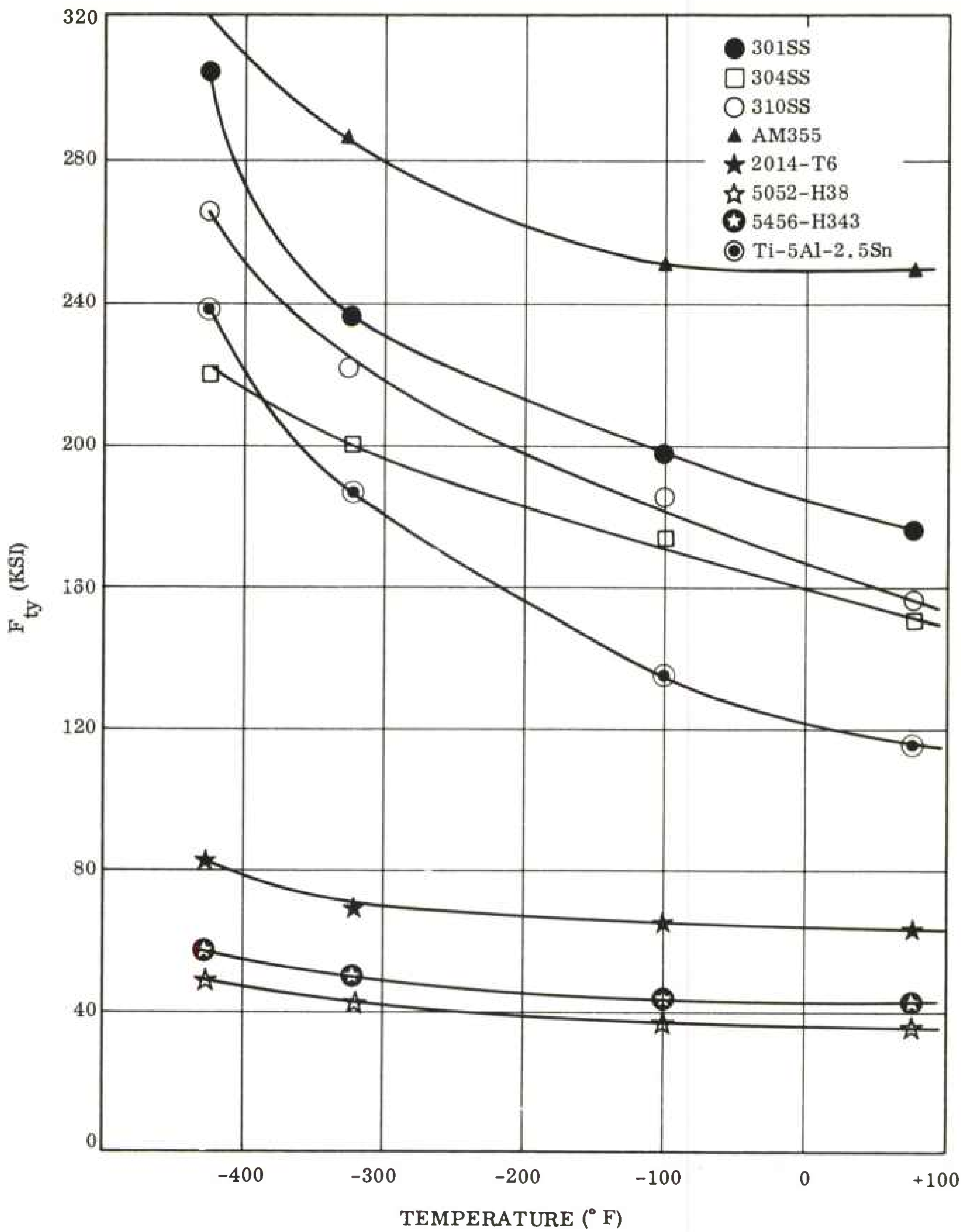


Figure 32. F_{ty} Versus Temperature (Transverse)

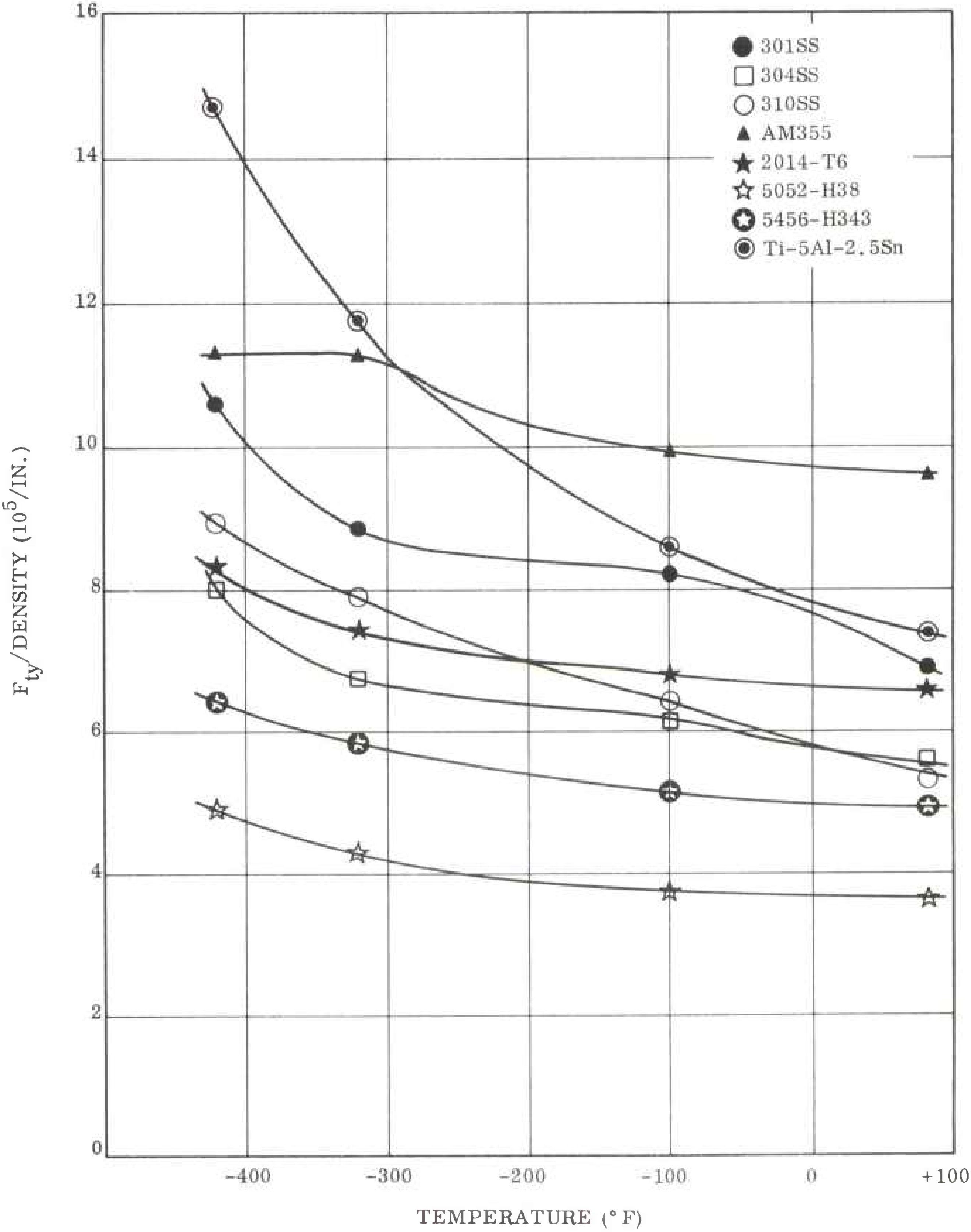


Figure 33. F_{ty}/Density Versus Temperature (Longitudinal)

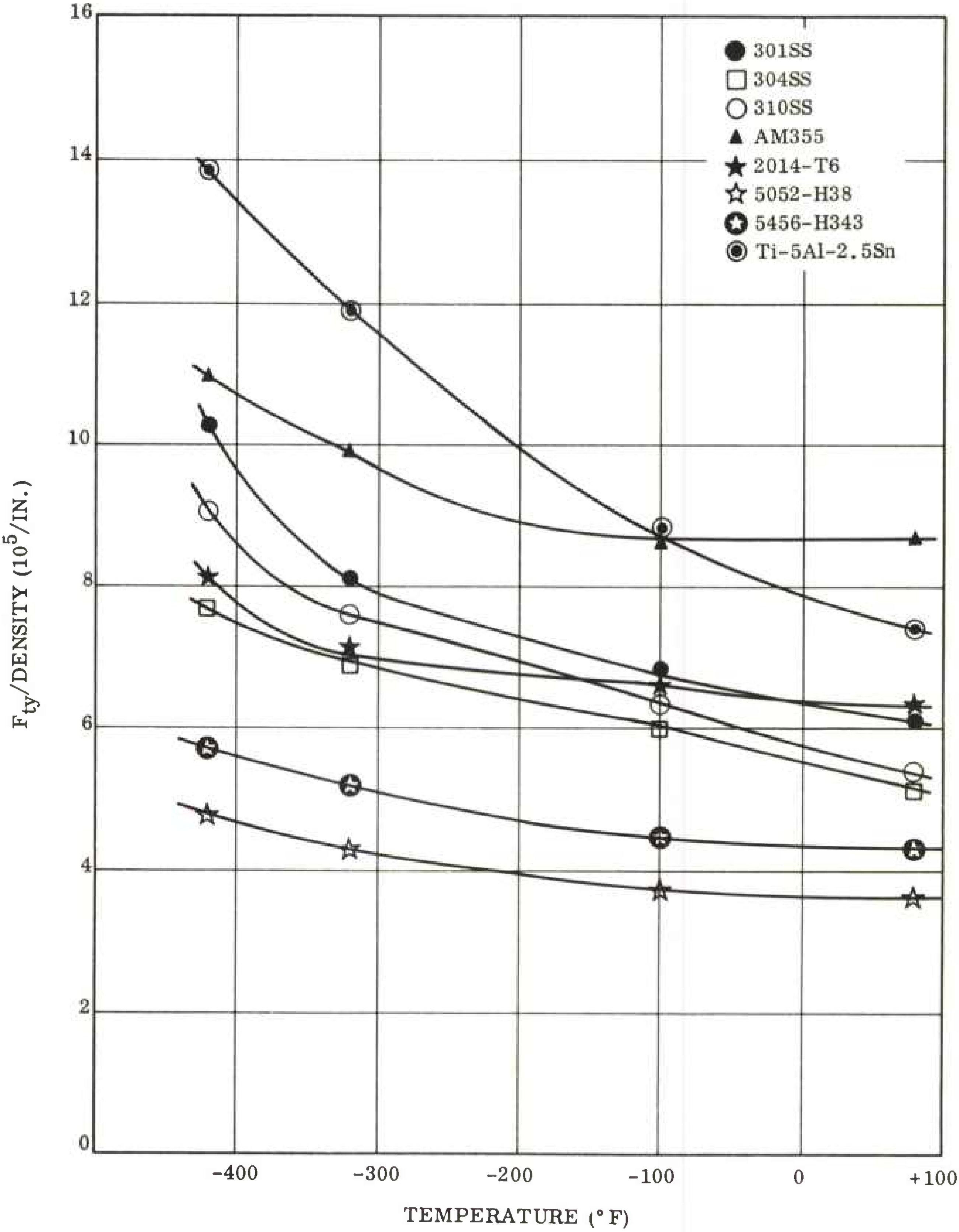


Figure 34. F_{ty}/Density Versus Temperature (Transverse)

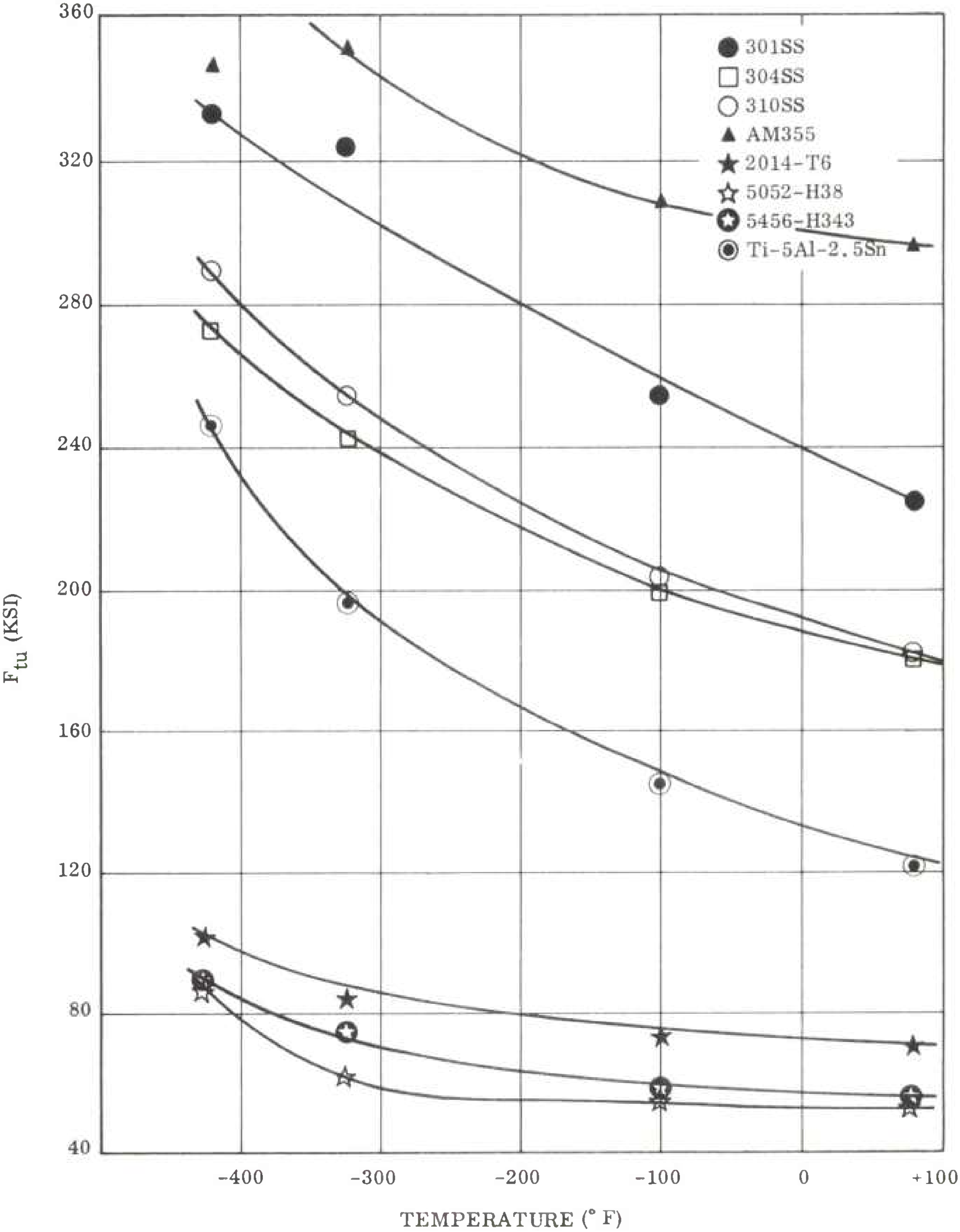


Figure 35. F_{tu} Versus Temperature (Longitudinal)

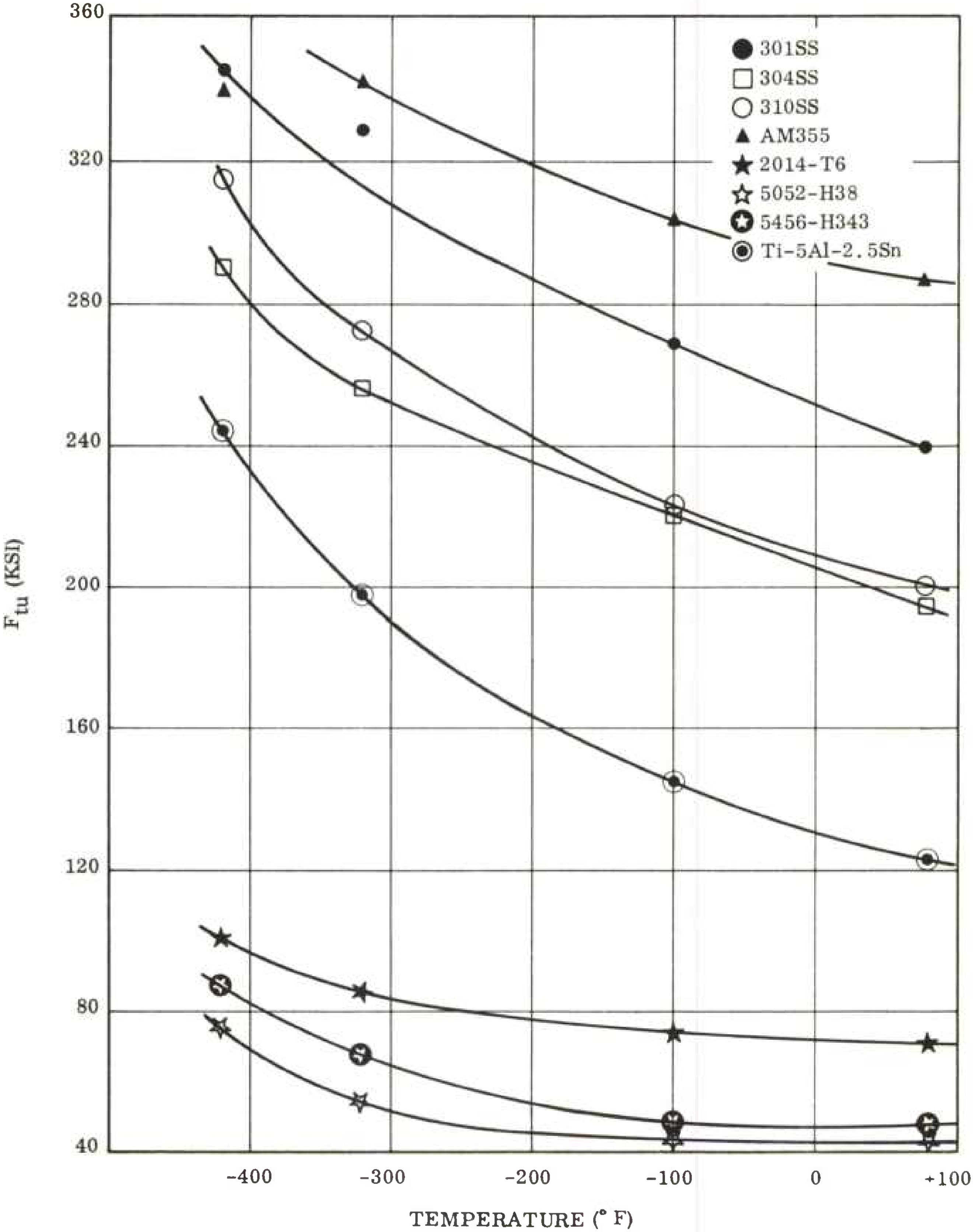


Figure 36. F_{tu} Versus Temperature (Transverse)

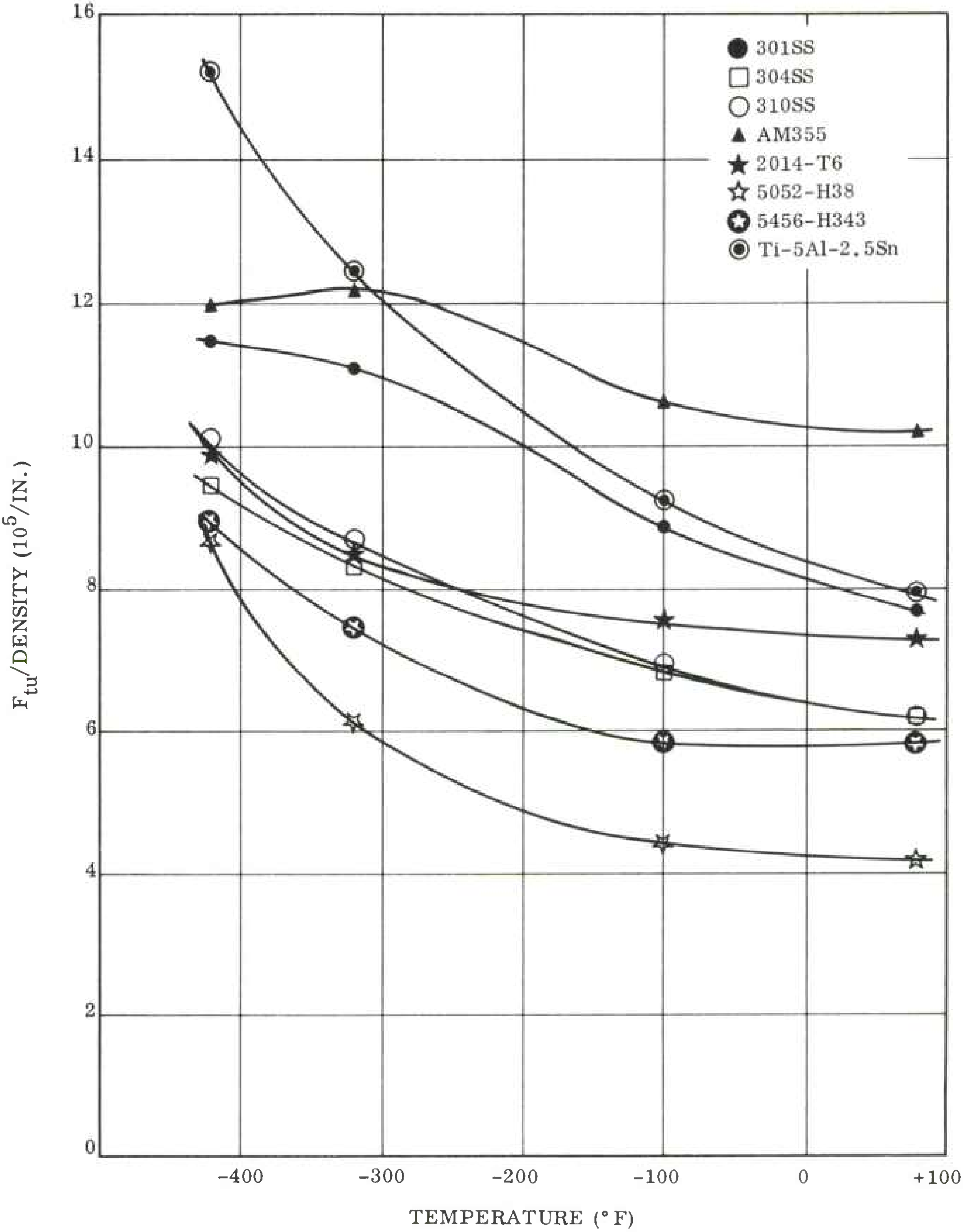


Figure 37. F_{tu}/Density Versus Temperature (Longitudinal)

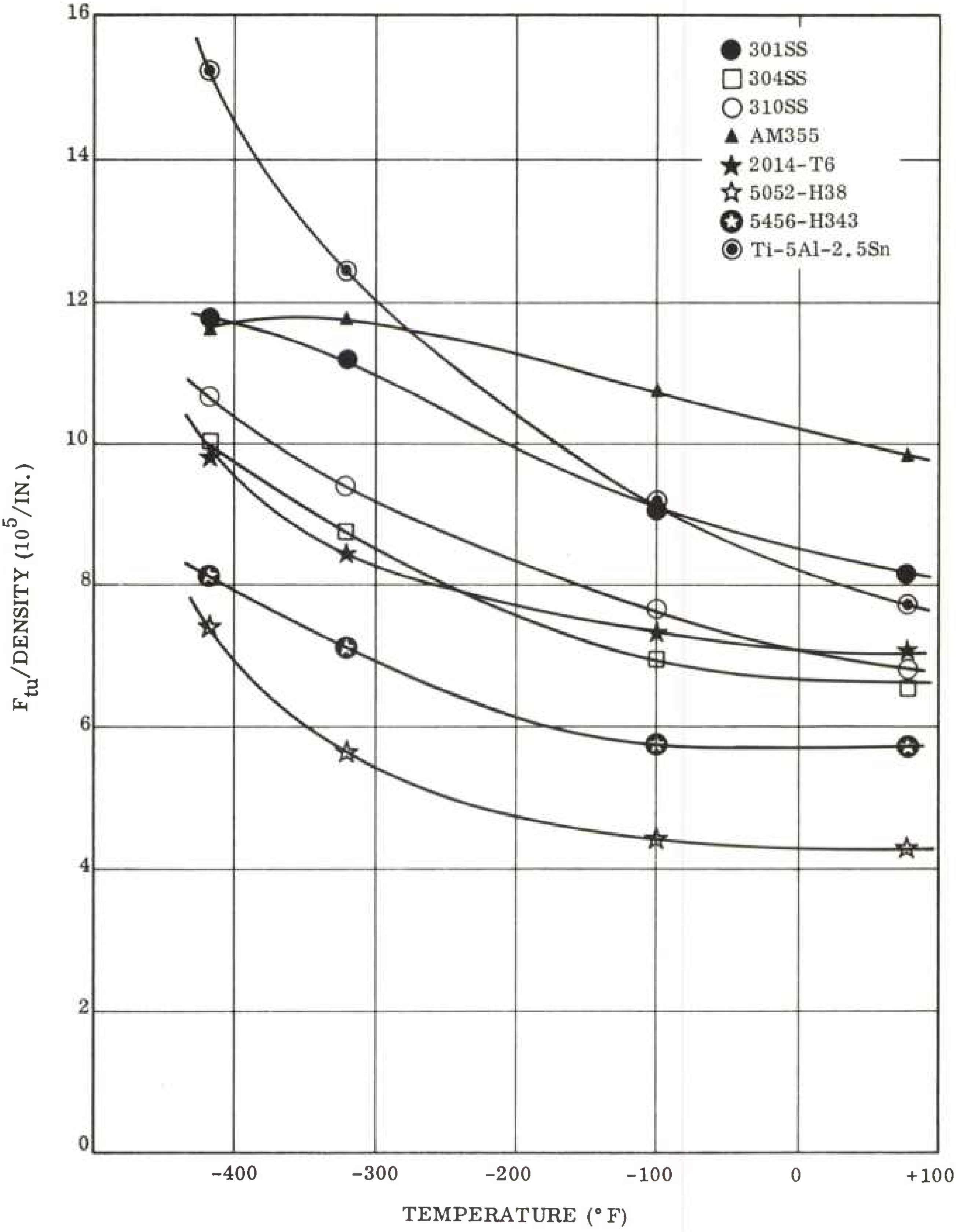


Figure 38. F_{tu}/Density Versus Temperature (Transverse)

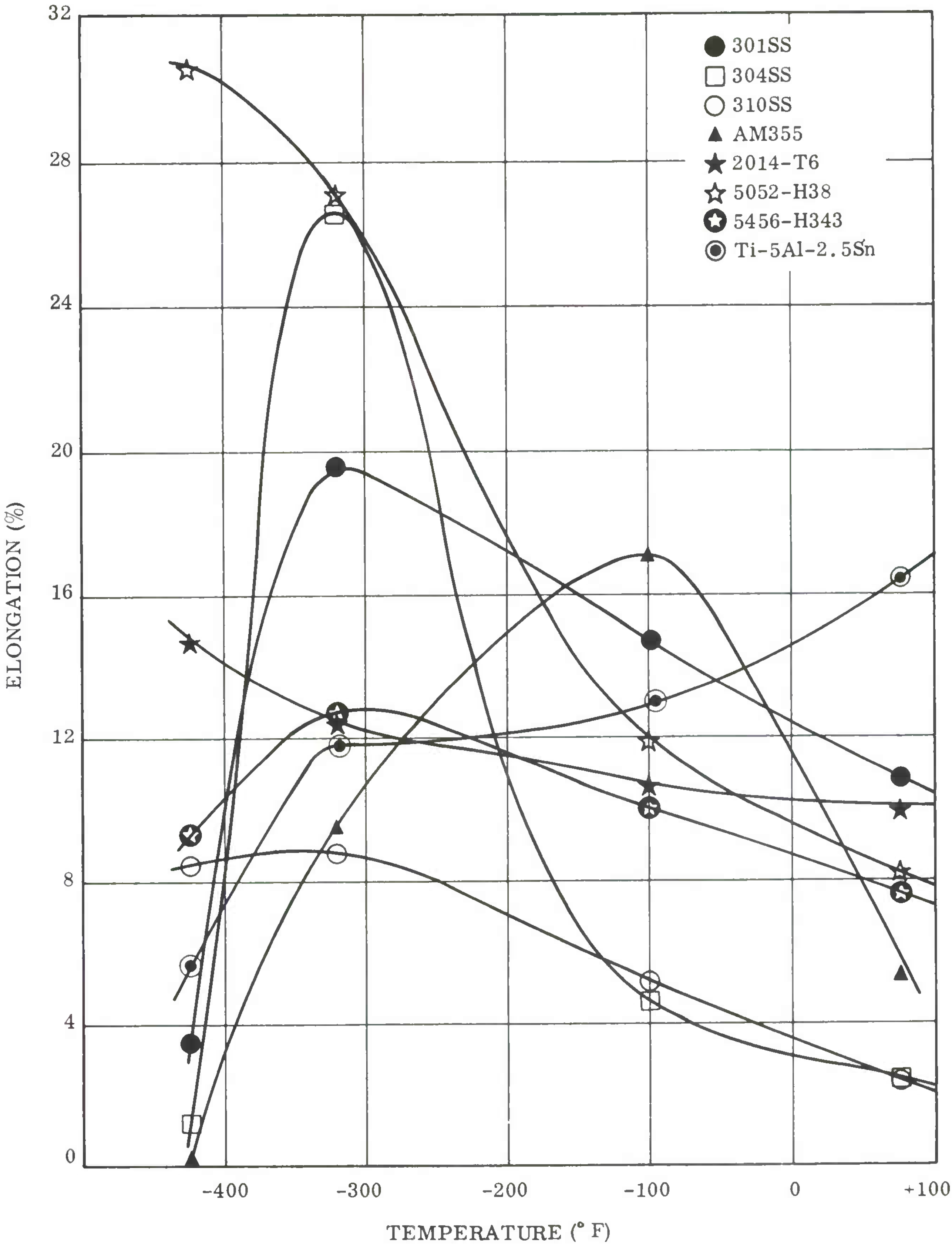


Figure 39. Elongation Versus Temperature (Longitudinal)

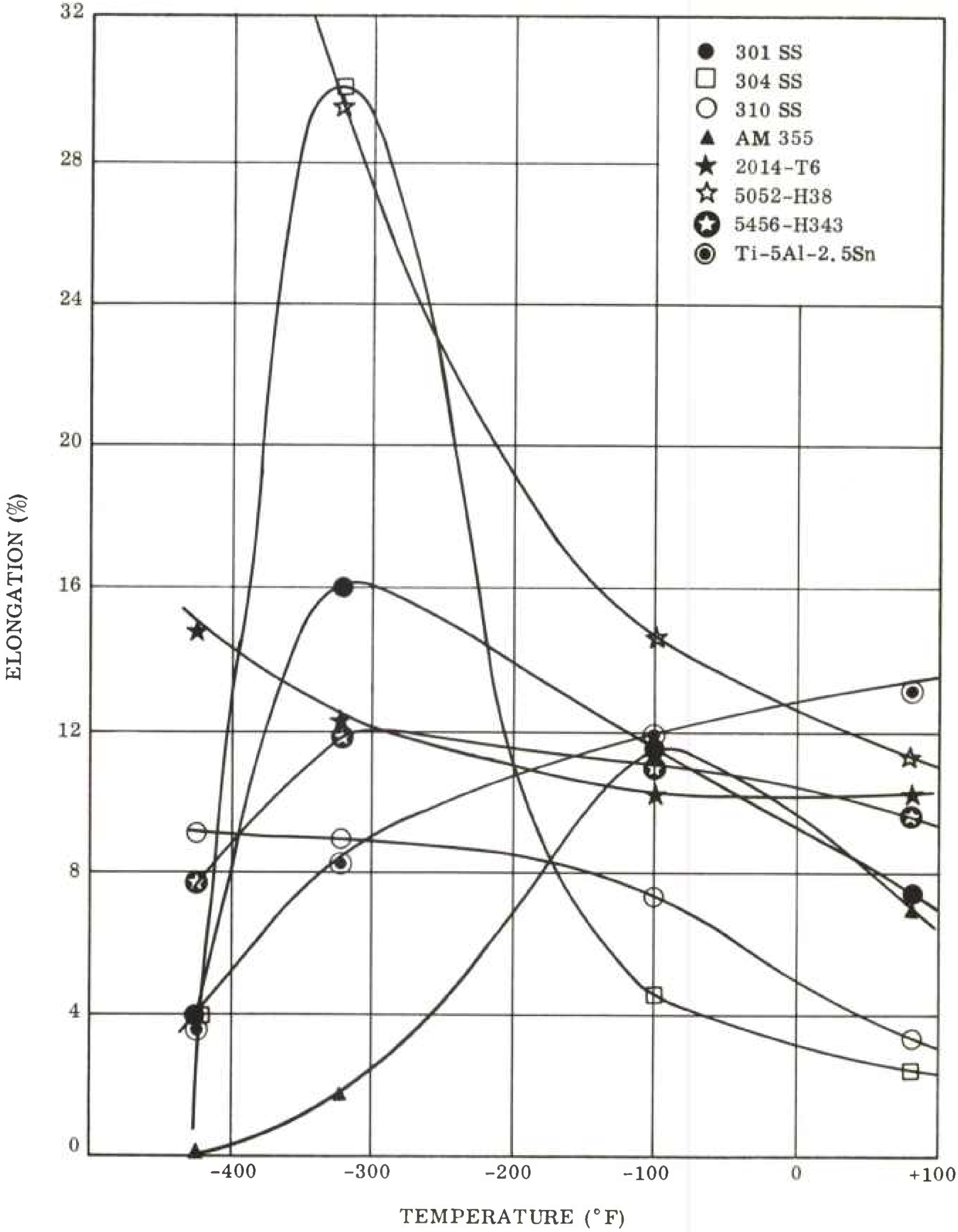


Figure 40. Elongation Versus Temperature (Transverse)

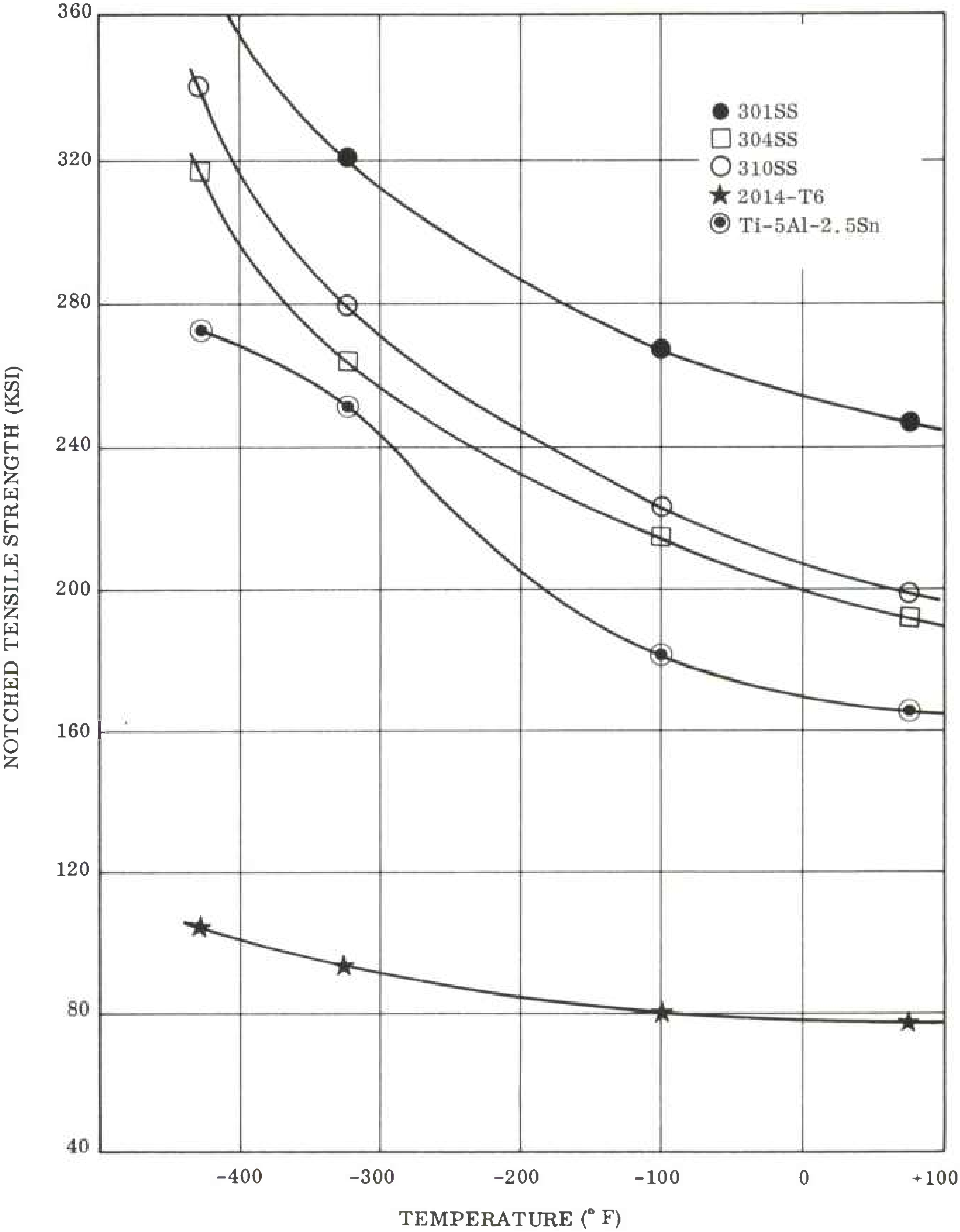


Figure 41. Notched Tensile Strength (K_t = 3.2) Versus Temperature (Longitudinal)

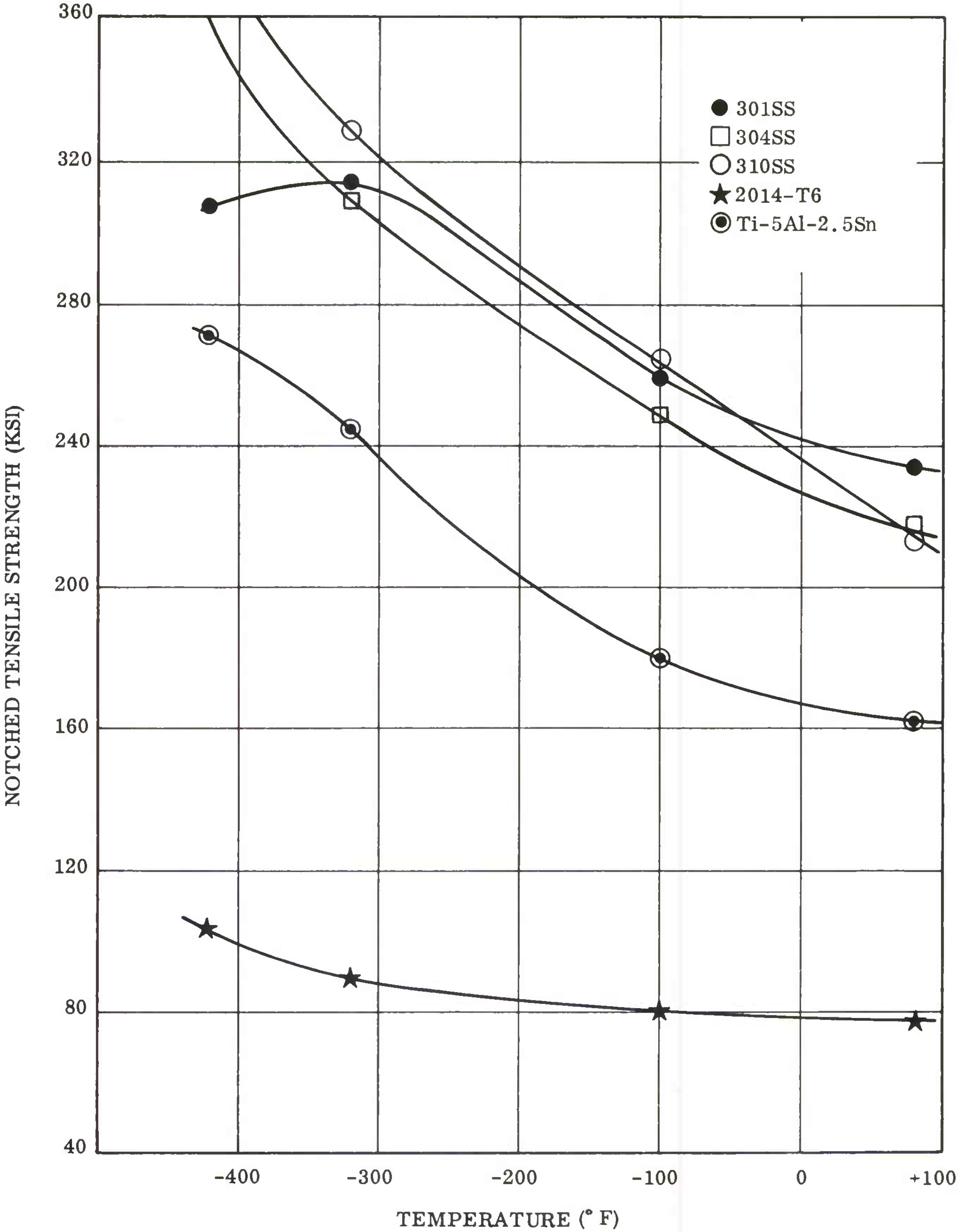


Figure 42. Notched Tensile Strength (K_t = 3.2) Versus Temperature (Transverse)

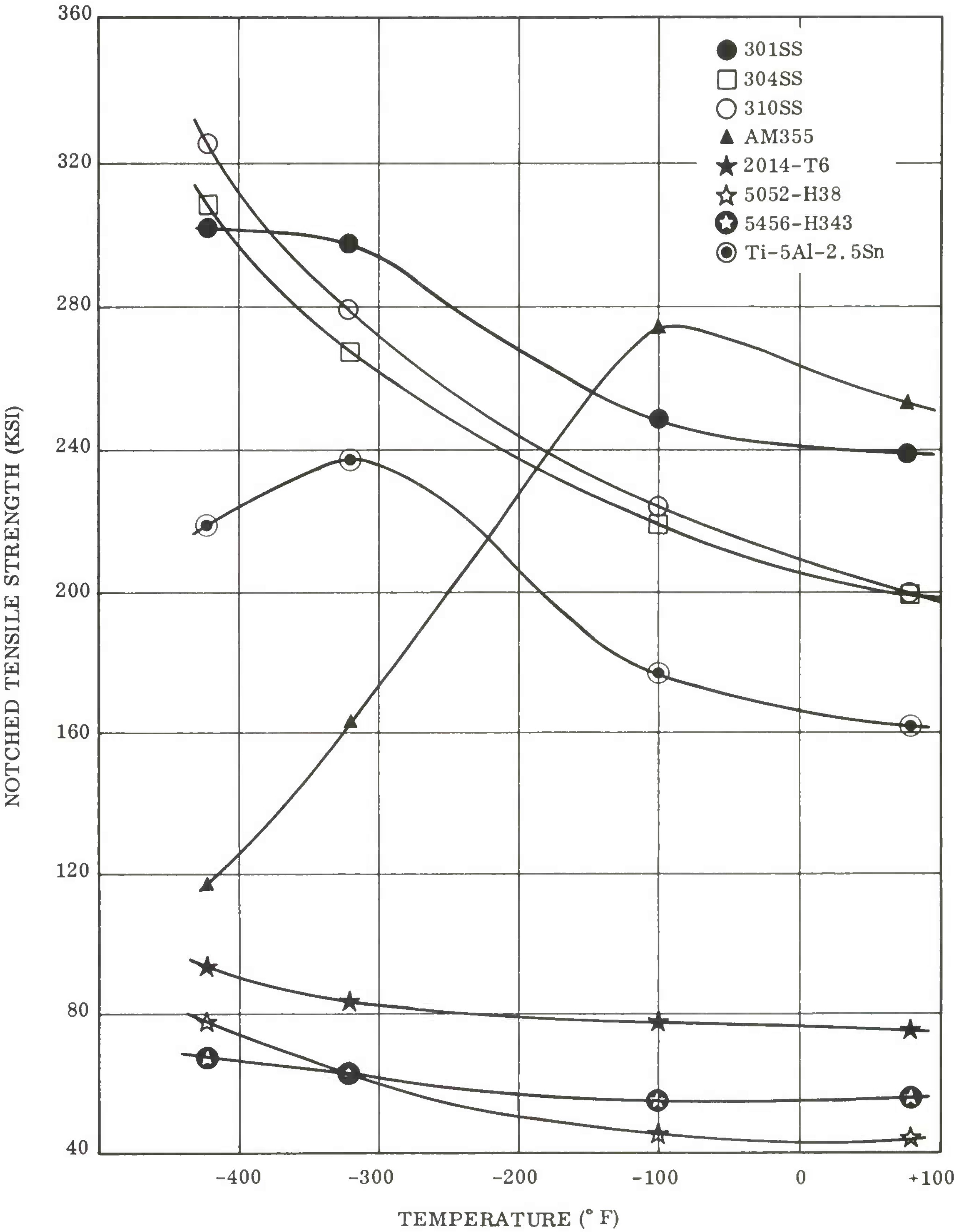


Figure 43. Notched Tensile Strength (K_t = 6.3) Versus Temperature (Longitudinal)

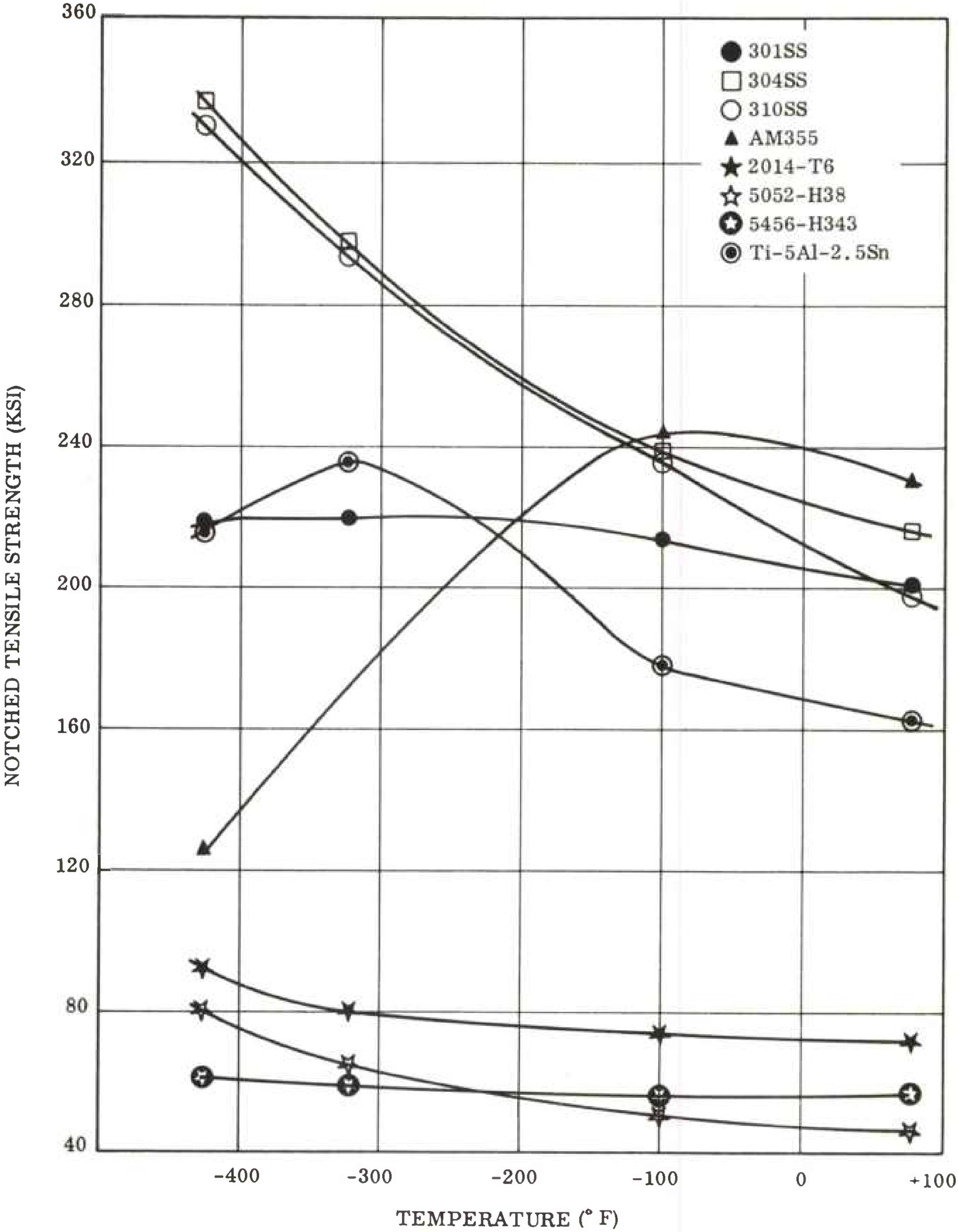


Figure 44. Notched Tensile Strength (K_t = 6.3) Versus Temperature (Transverse)

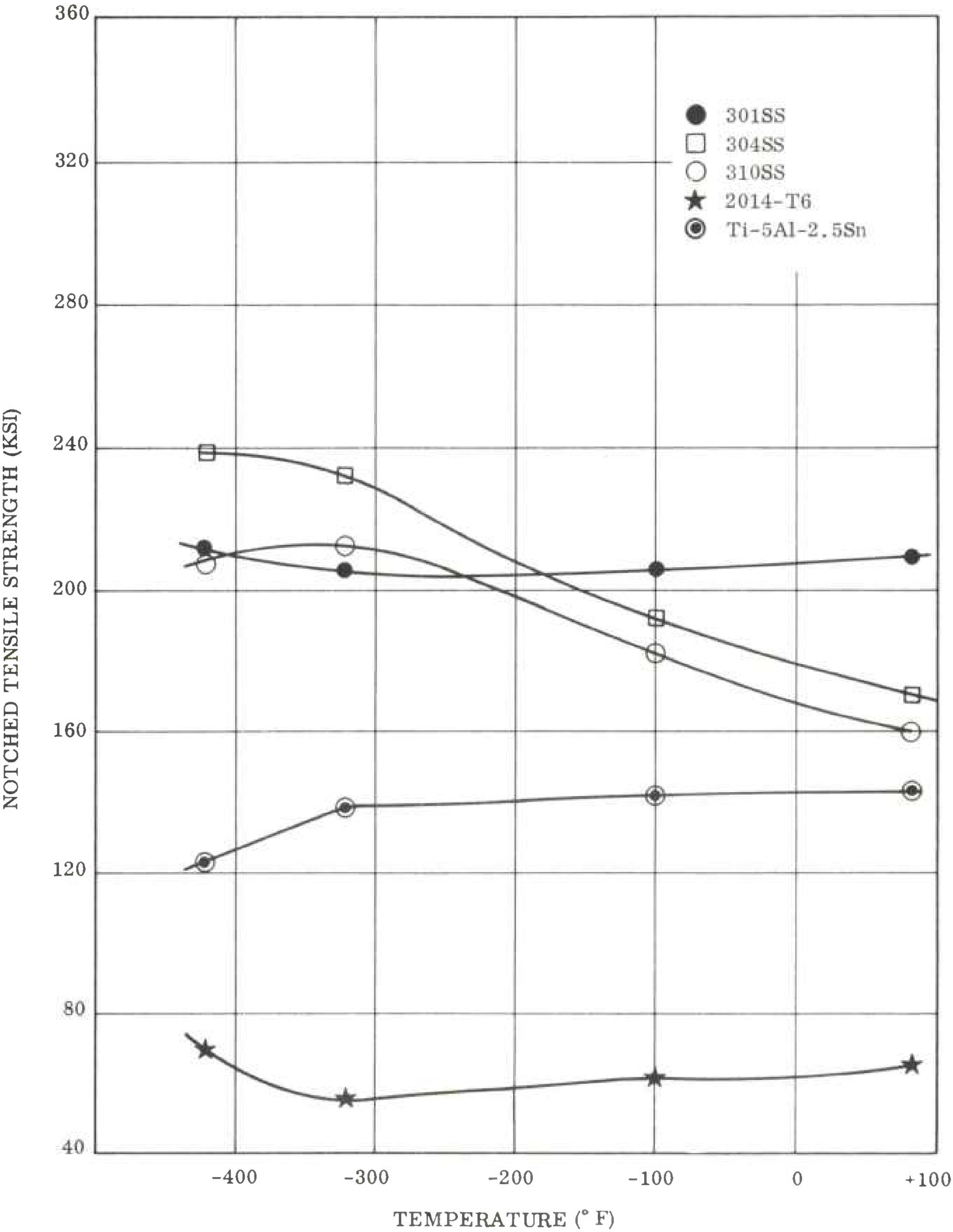


Figure 45. Notched Tensile Strength (K_t = 19) Versus Temperature (Longitudinal)

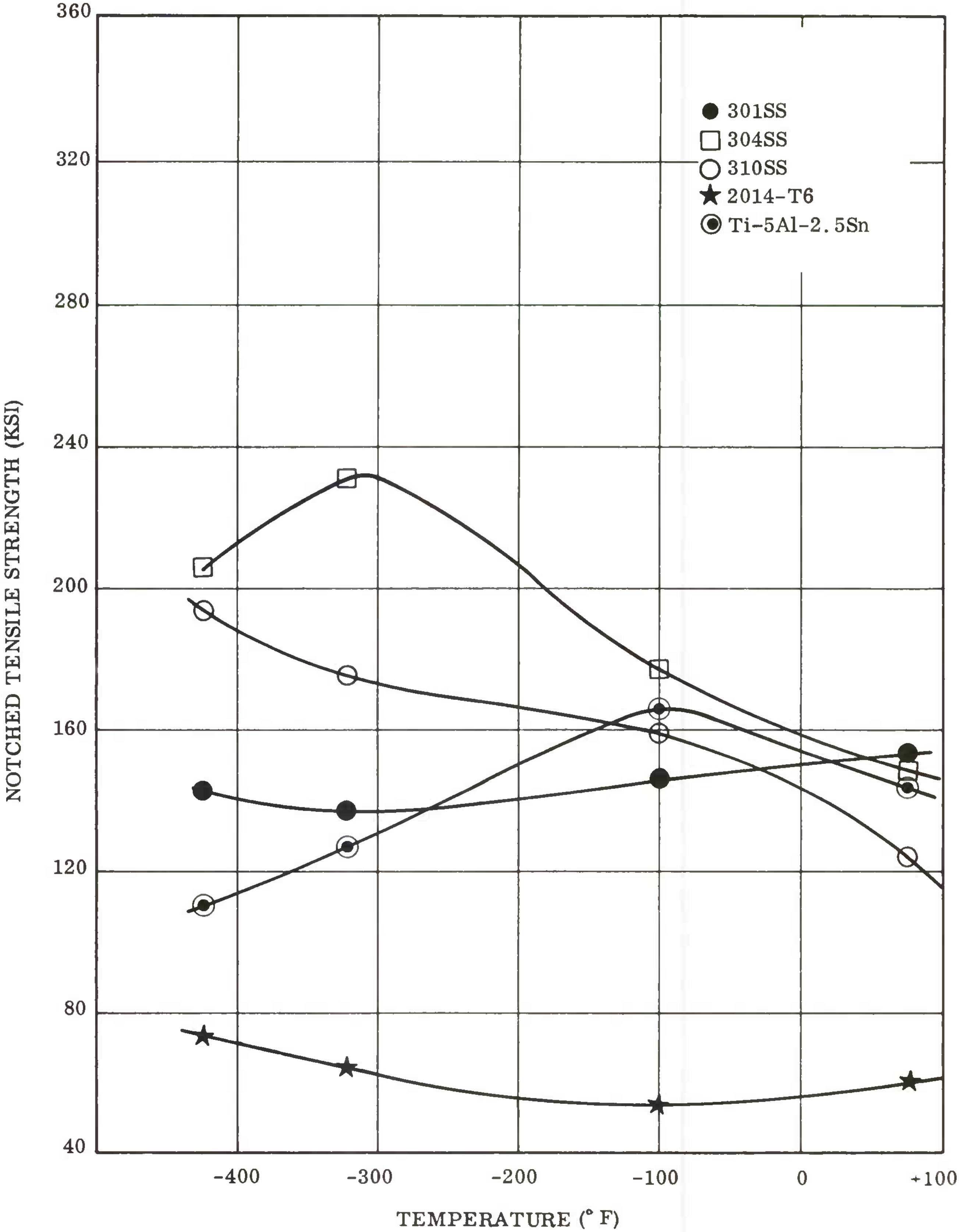


Figure 46. Notched Tensile Strength (K_t = 19) Versus Temperature (Transverse)

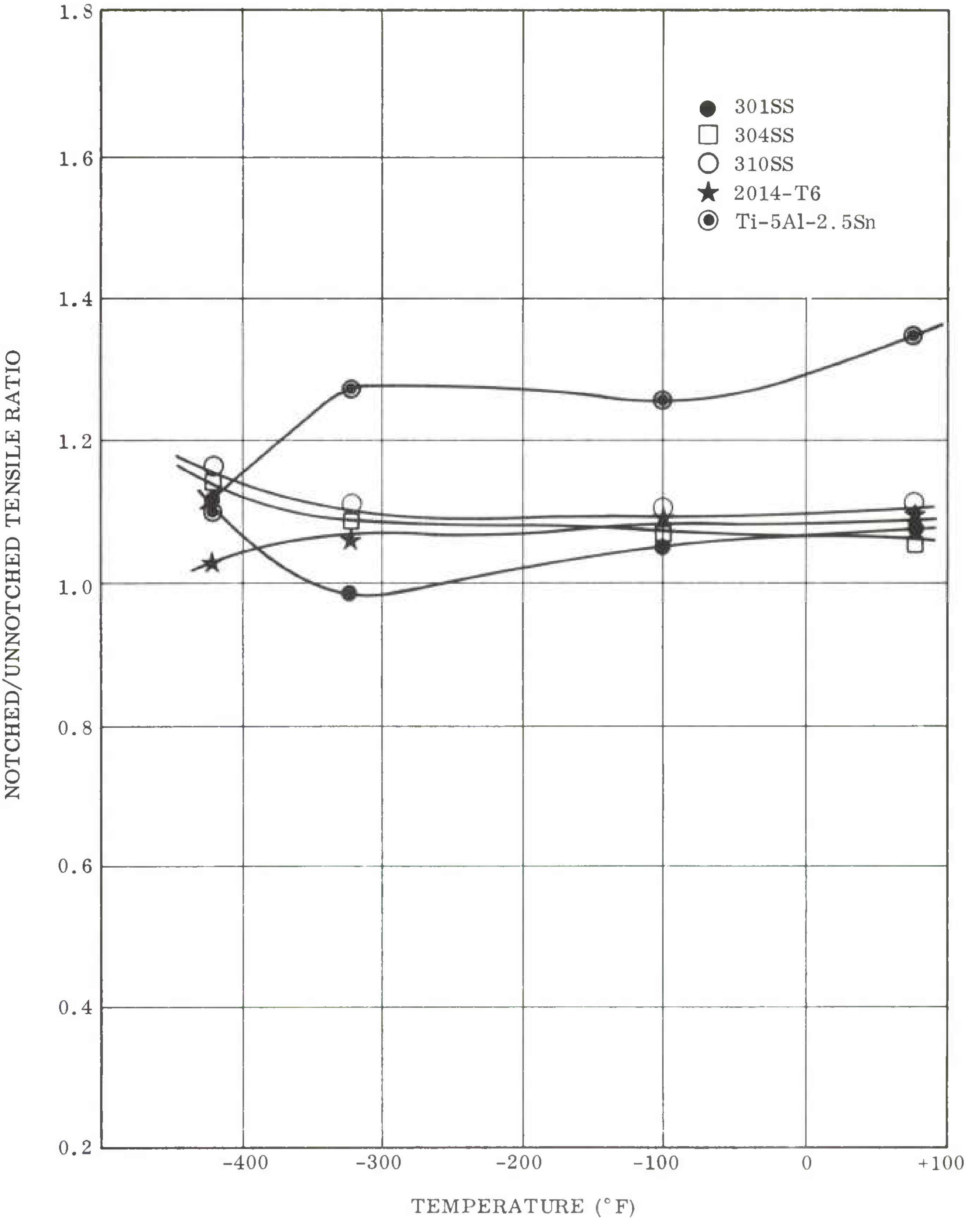


Figure 47. Notched (K_t = 3.2)/Unnotched Tensile Ratio Versus Temperature (Longitudinal)

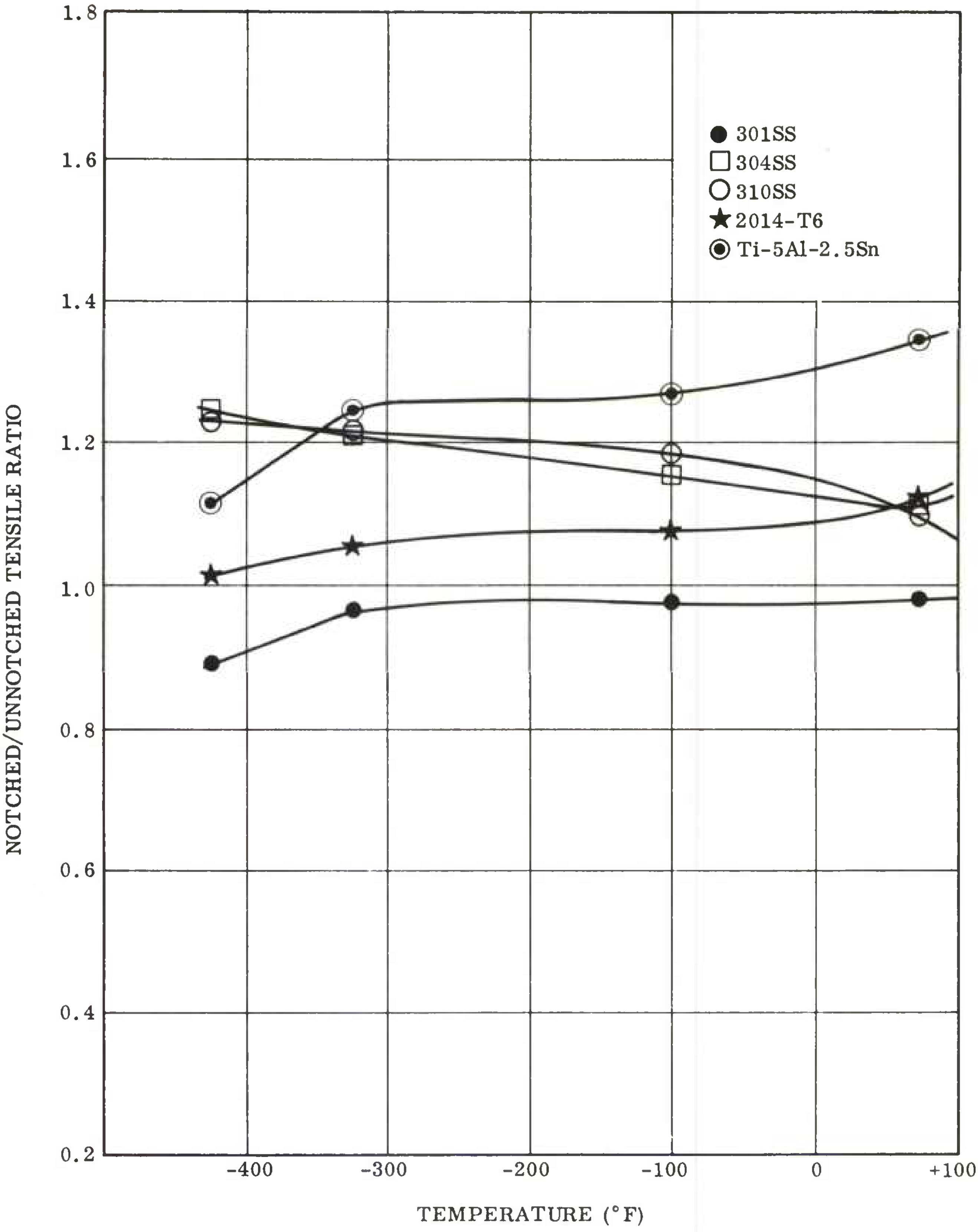


Figure 48. Notched (K_t = 3.2)/Unnotched Tensile Ratio Versus Temperature (Transverse)

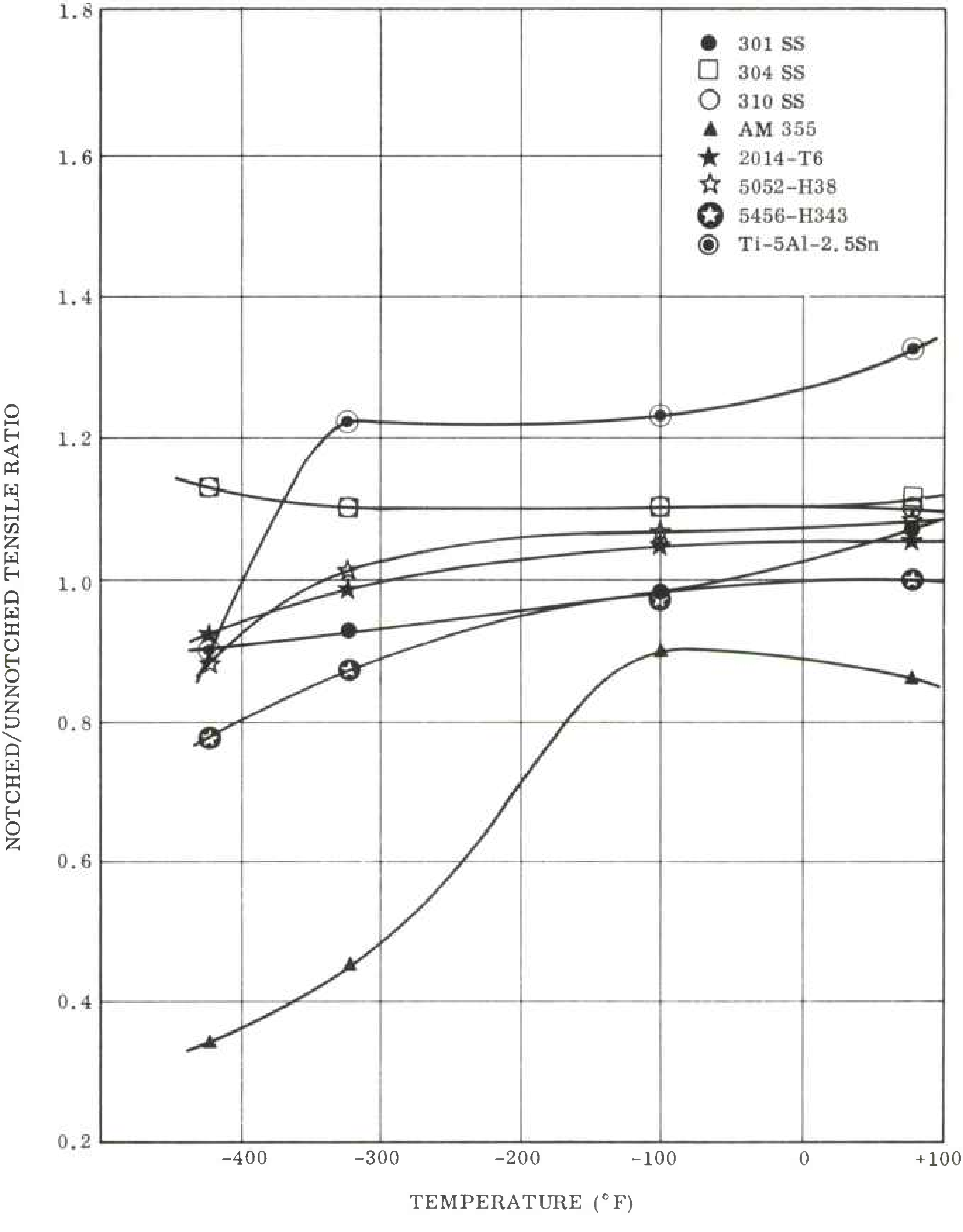


Figure 49. Notched (K_t = 6.3)/Unnotched Tensile Ratio Versus Temperature (Longitudinal)

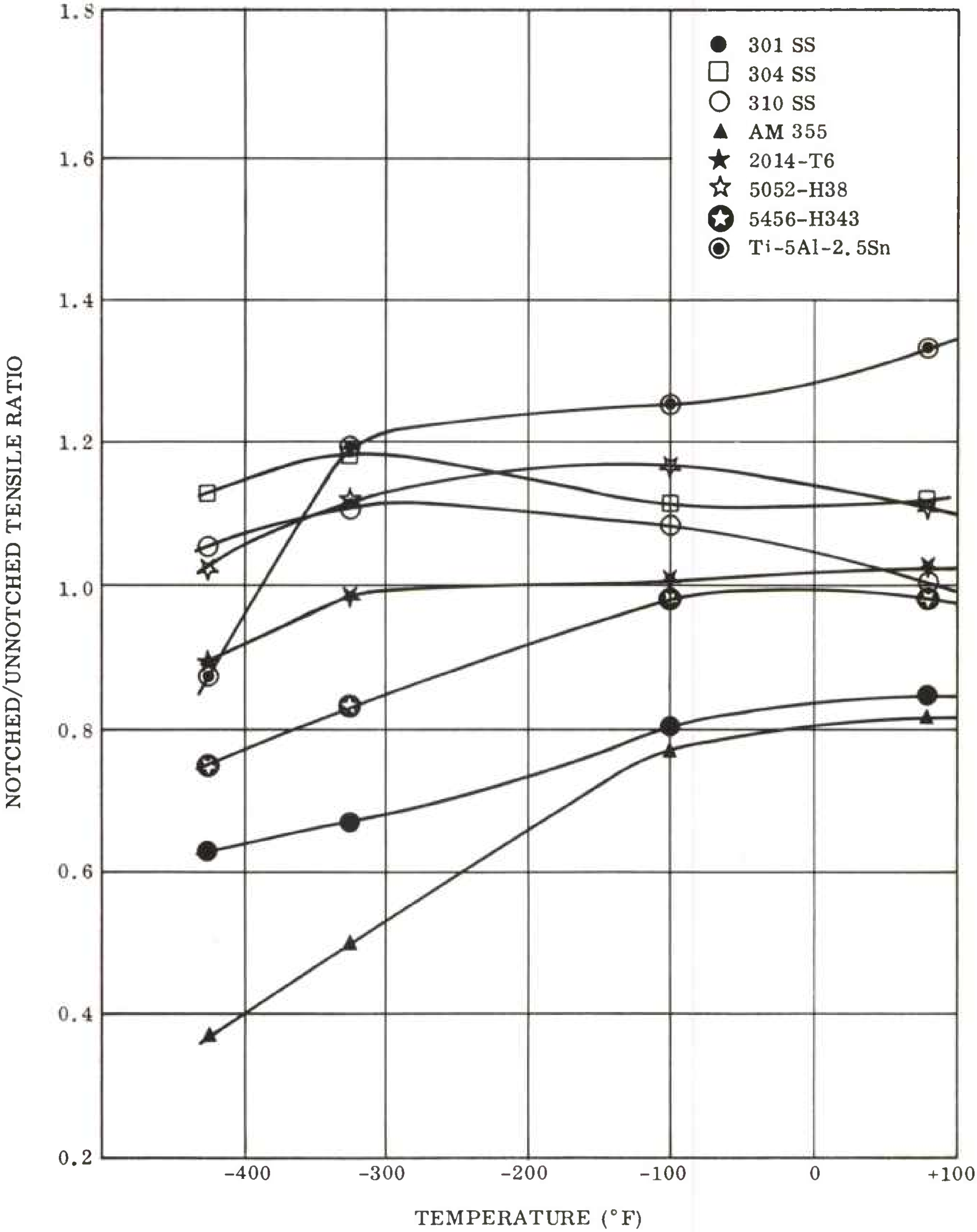


Figure 50. Notched (K_t = 6.3)/Unnotched Tensile Ratio Versus Temperature (Transverse)

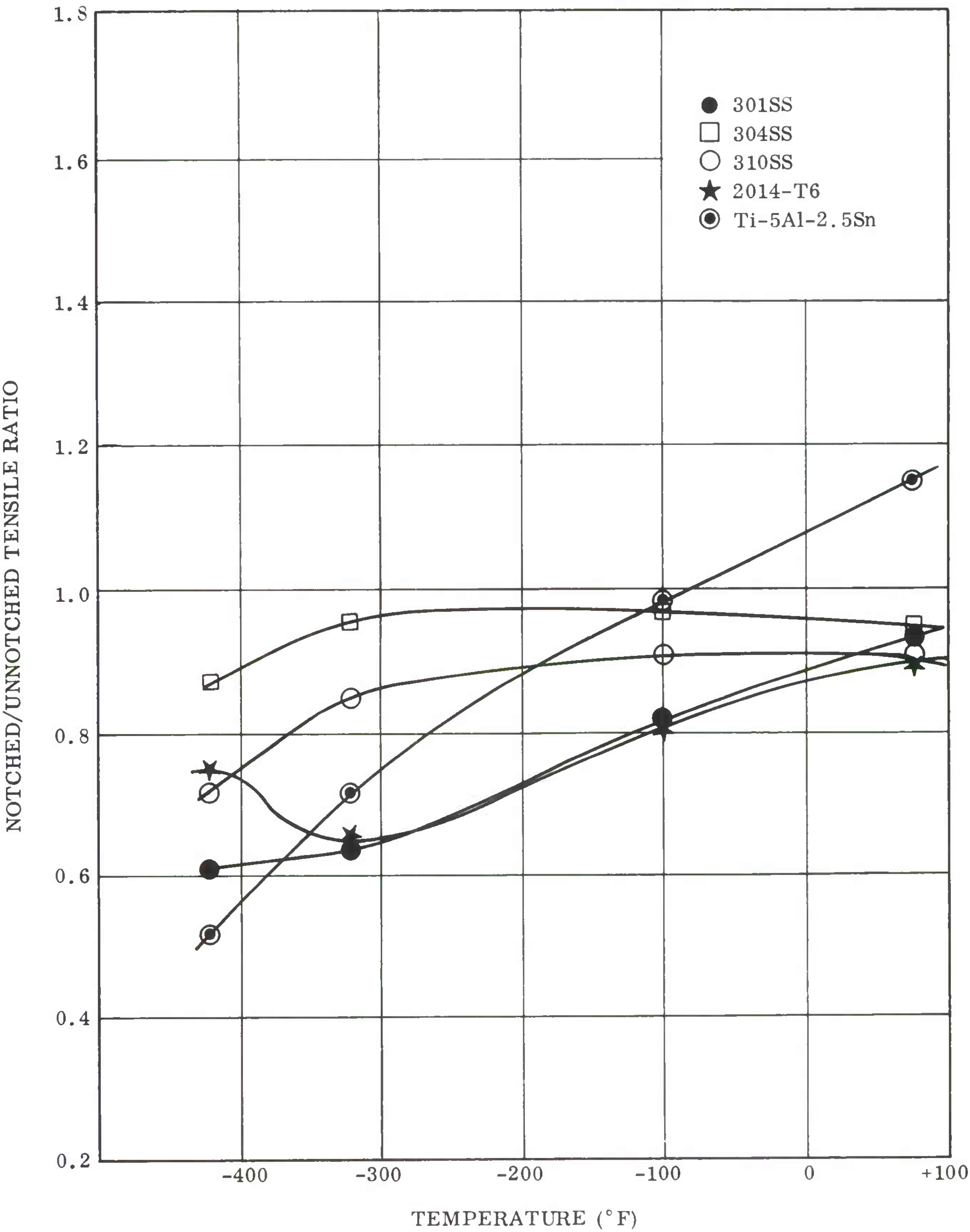


Figure 51. Notched (K_t = 19)/Unnotched Tensile Ratio Versus Temperature (Longitudinal)

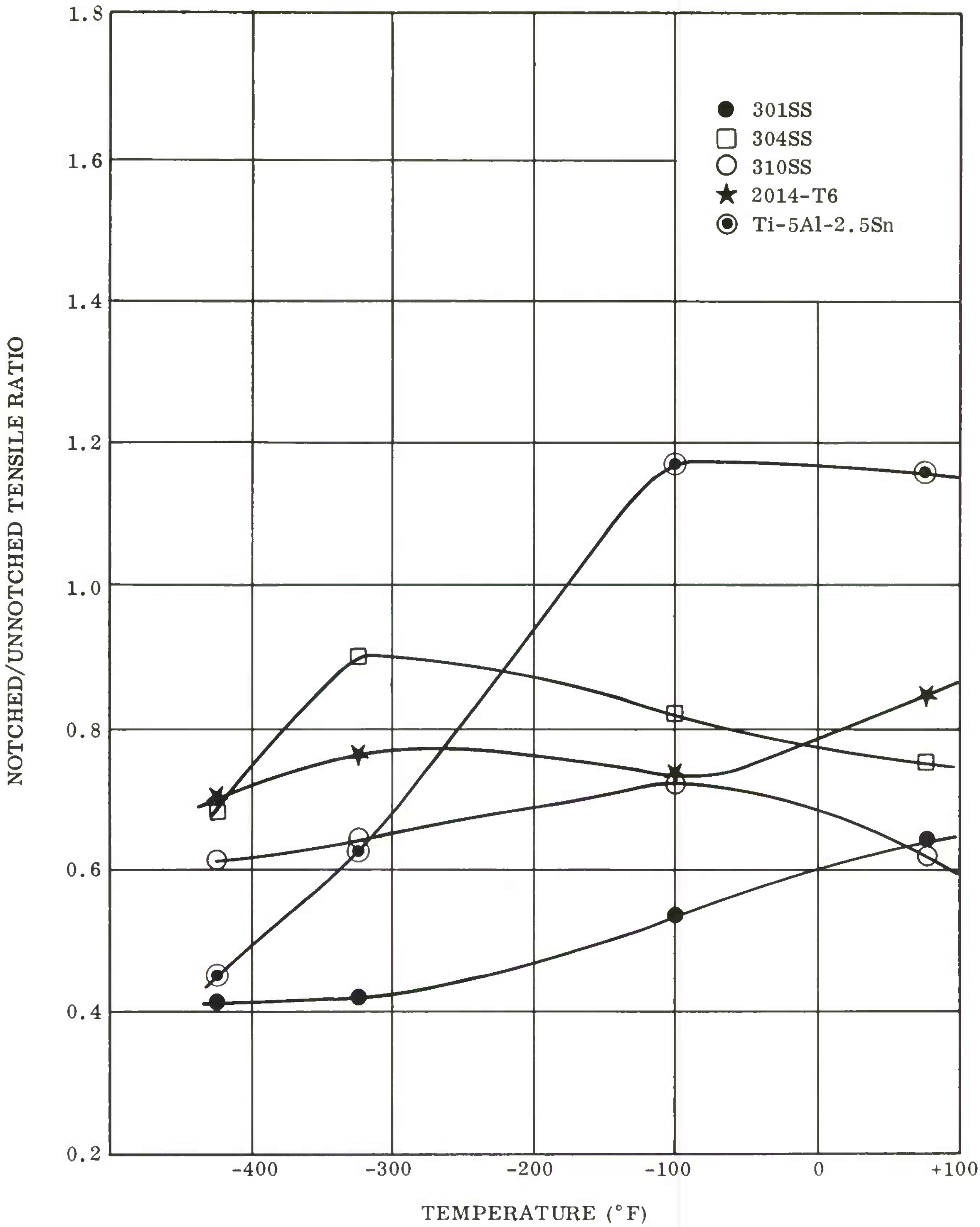


Figure 52. Notched (K_t = 19)/Unnotched Tensile Ratio Versus Temperature (Transverse)

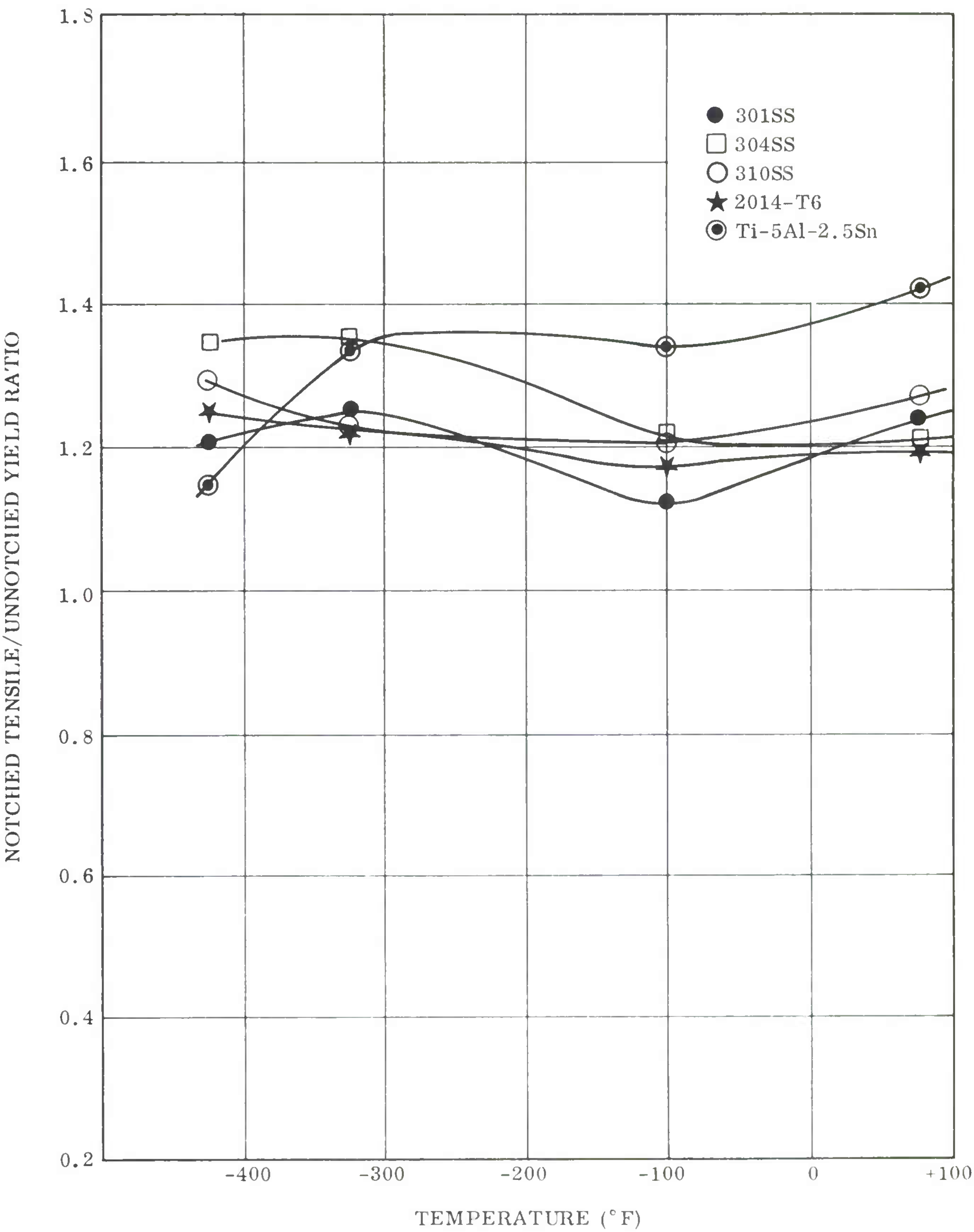


Figure 53. Notched (K_t = 3.2) Tensile/Unnotched Yield Ratio Versus Temperature (Longitudinal)

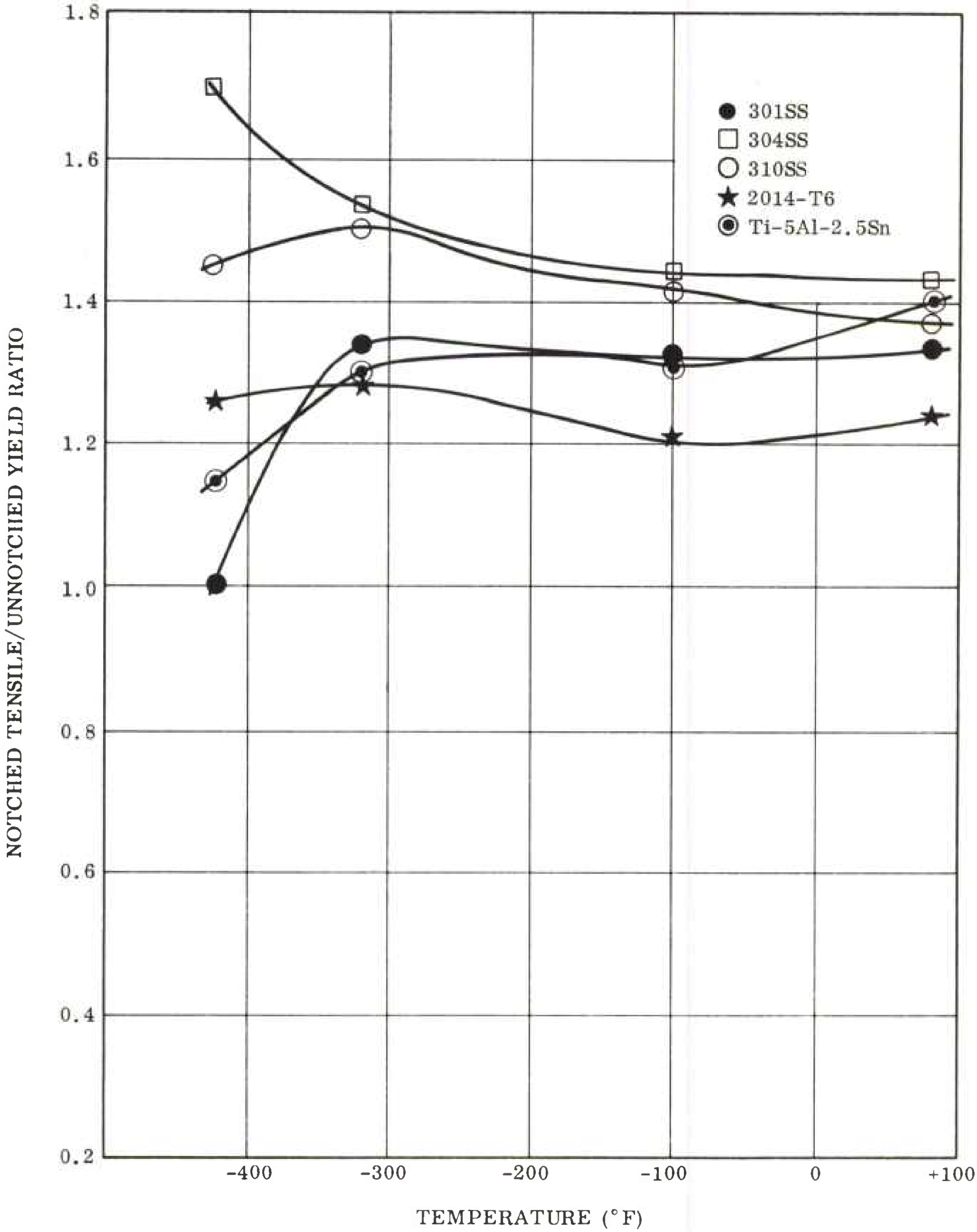


Figure 54. Notched (K_t = 3.2) Tensile/Unnotched Yield Ratio Versus Temperature (Transverse)

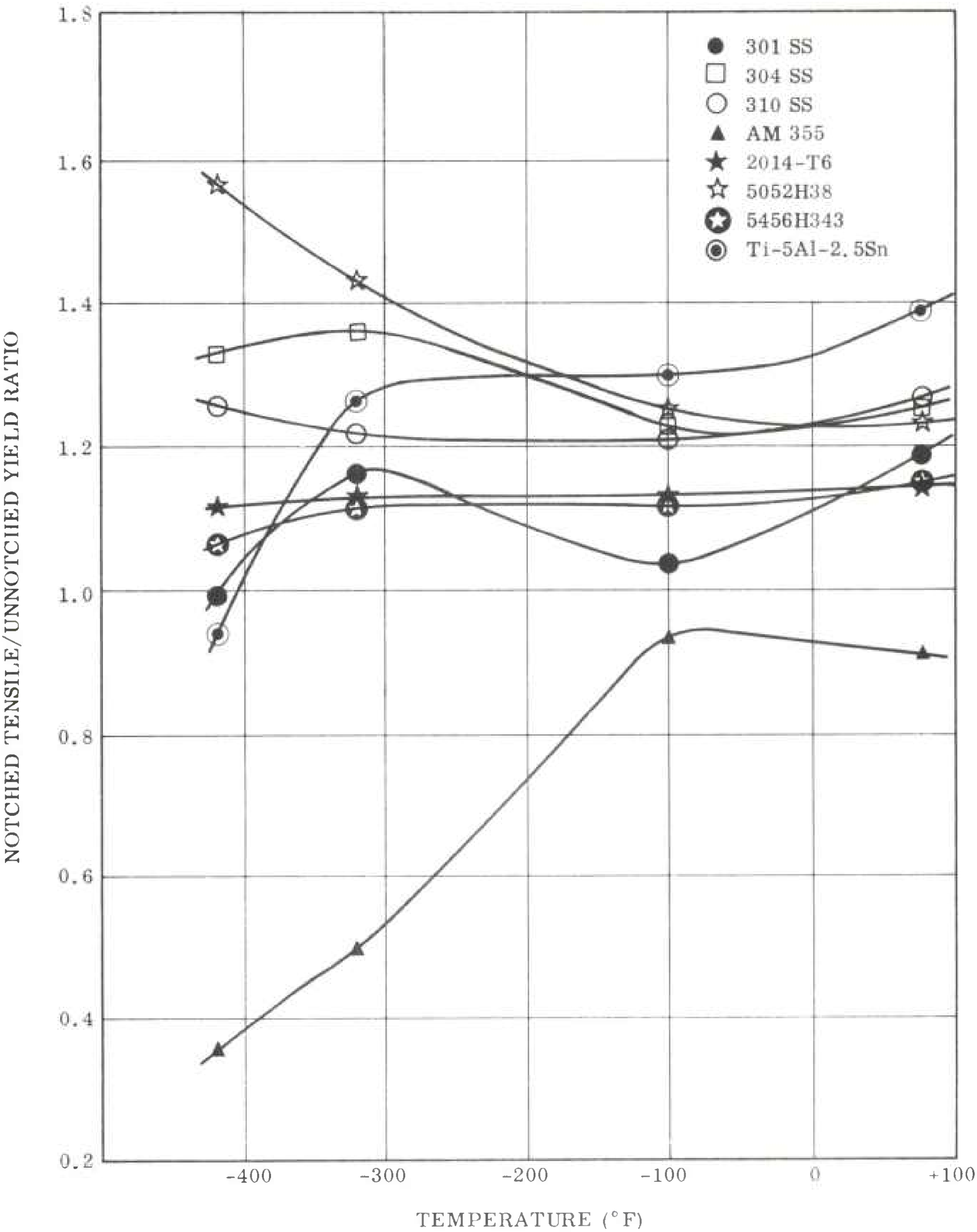


Figure 55. Notched (K_t = 6.3) Tensile/Unnotched Yield Ratio Versus Temperature (Longitudinal)

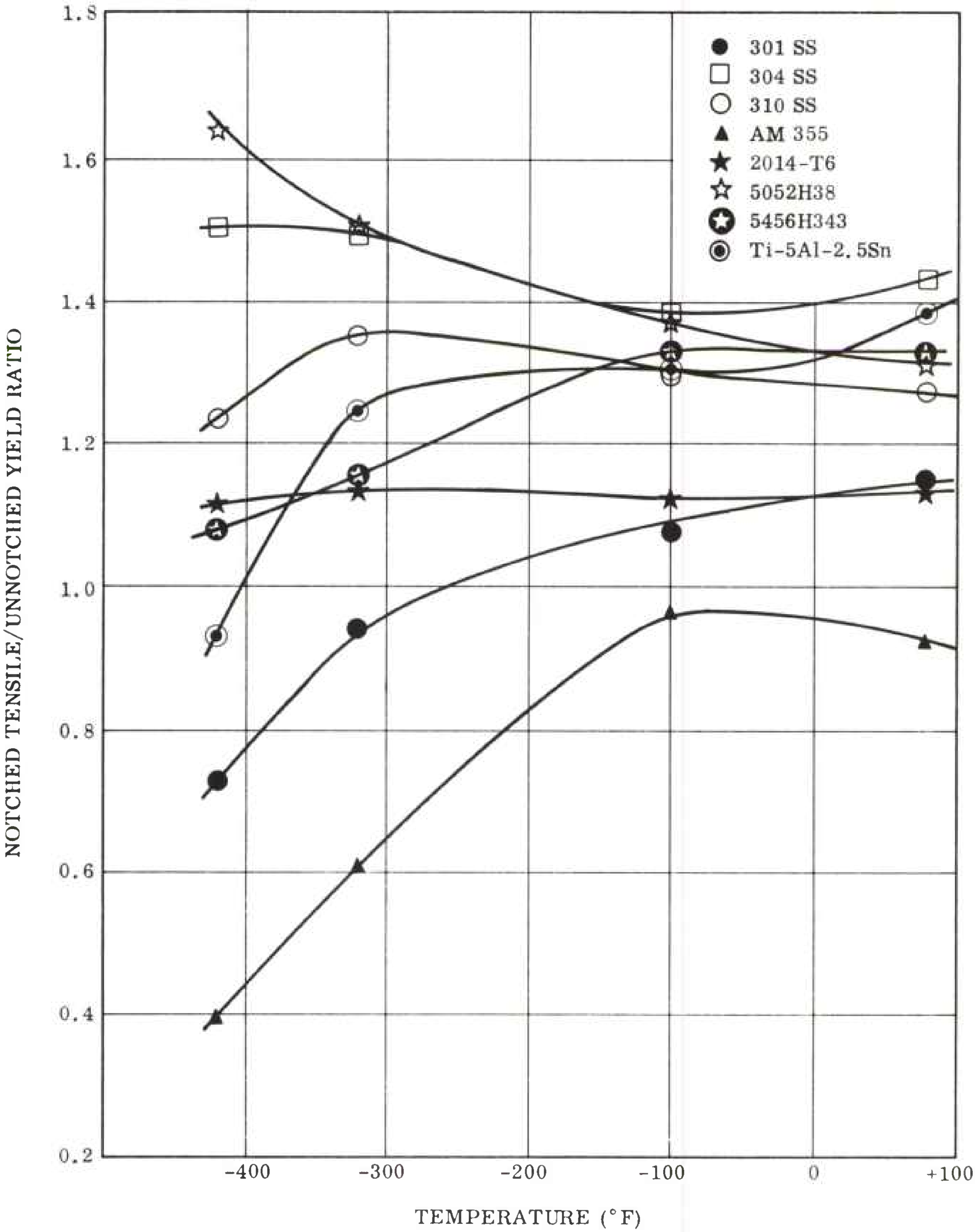


Figure 56. Notched (K_t = 6.3) Tensile/Unnotched Yield Ratio Versus Temperature (Transverse)

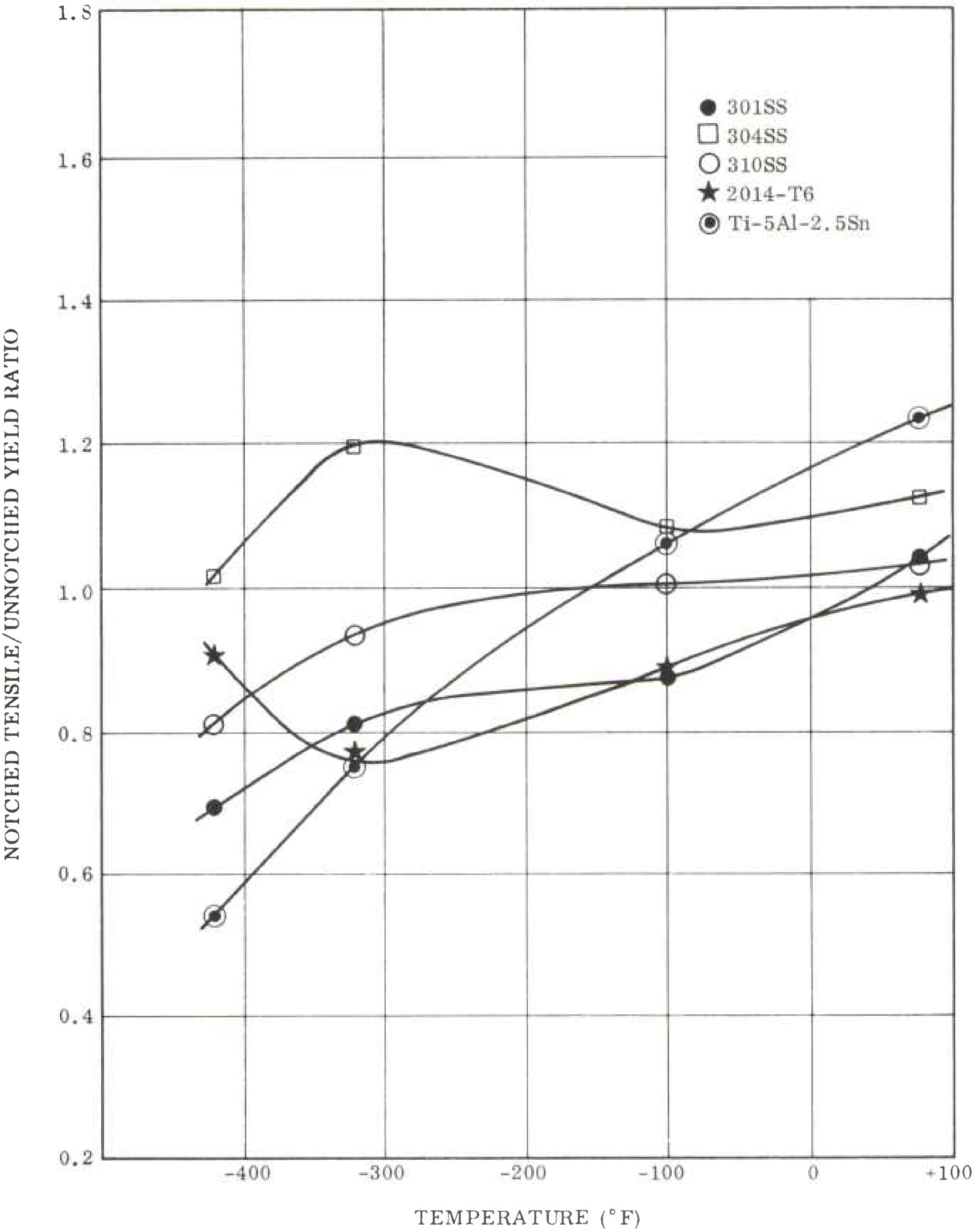


Figure 57. Notched (K_t = 19) Tensile/Unnotched Yield Ratio Versus Temperature (Longitudinal)

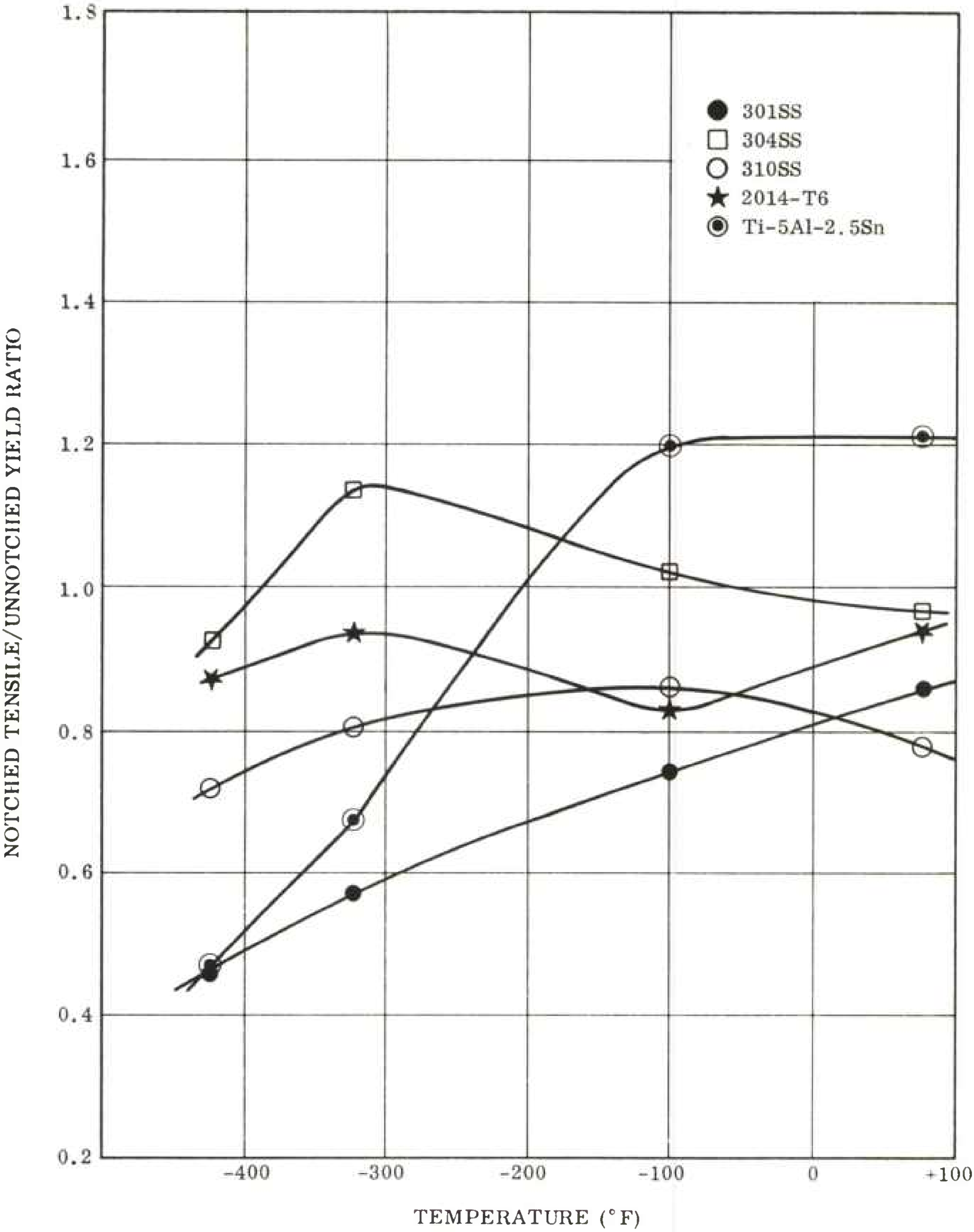


Figure 58. Notched (K_t = 19) Tensile/Unnotched Yield Ratio Versus Temperature (Transverse)

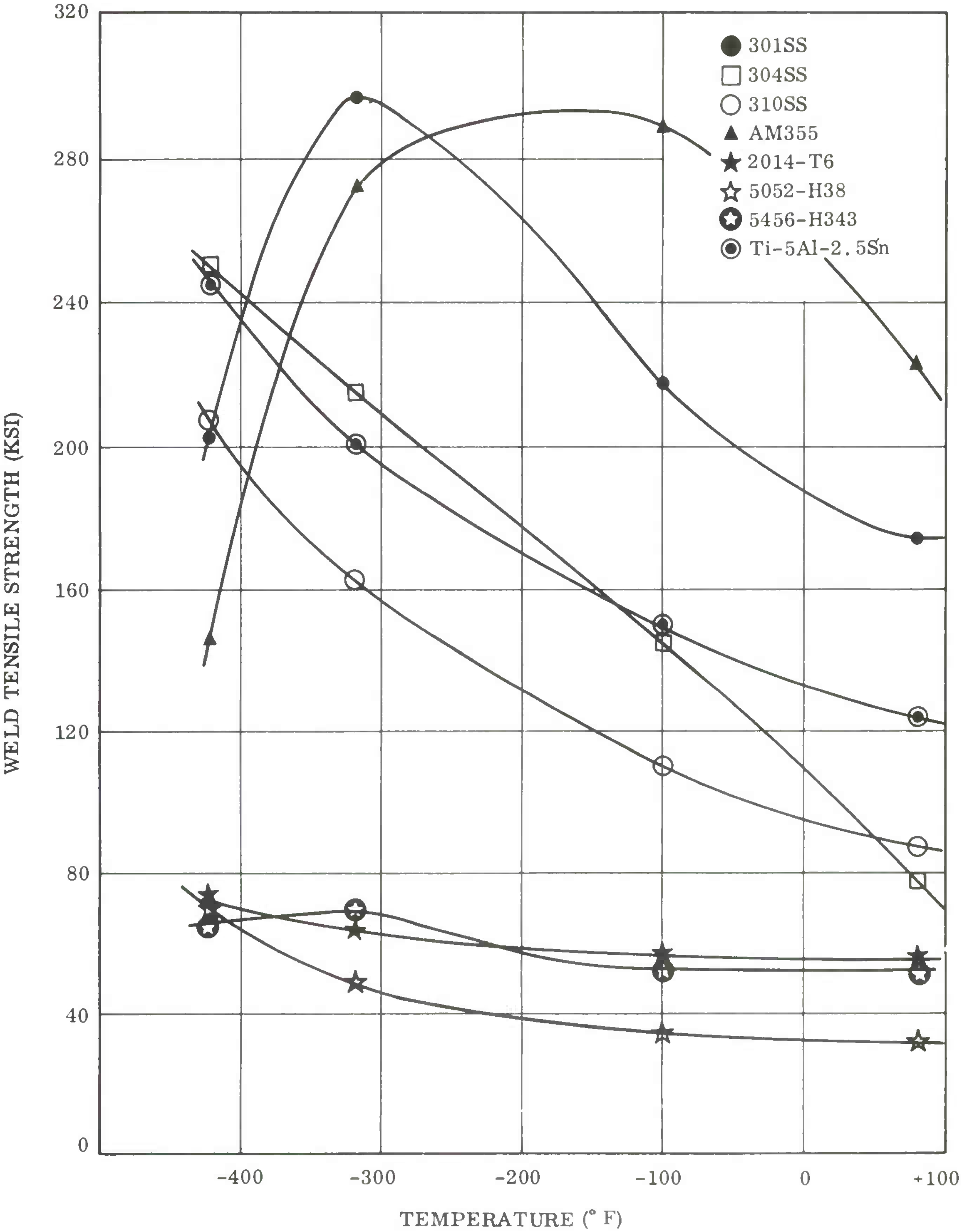


Figure 59. Weld Tensile Strength Versus Temperature (Longitudinal)

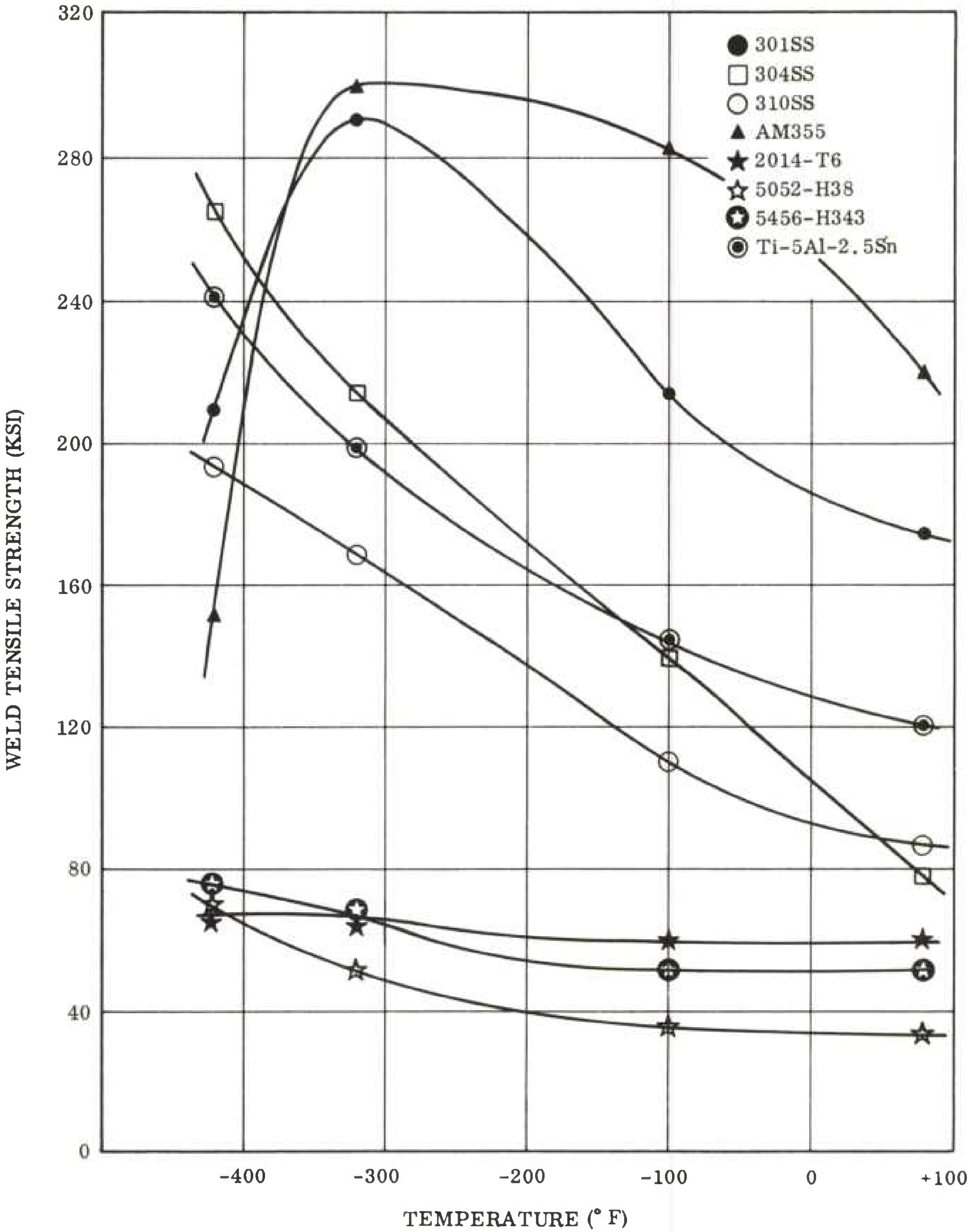


Figure 60. Weld Tensile Strength Versus Temperature (Transverse)

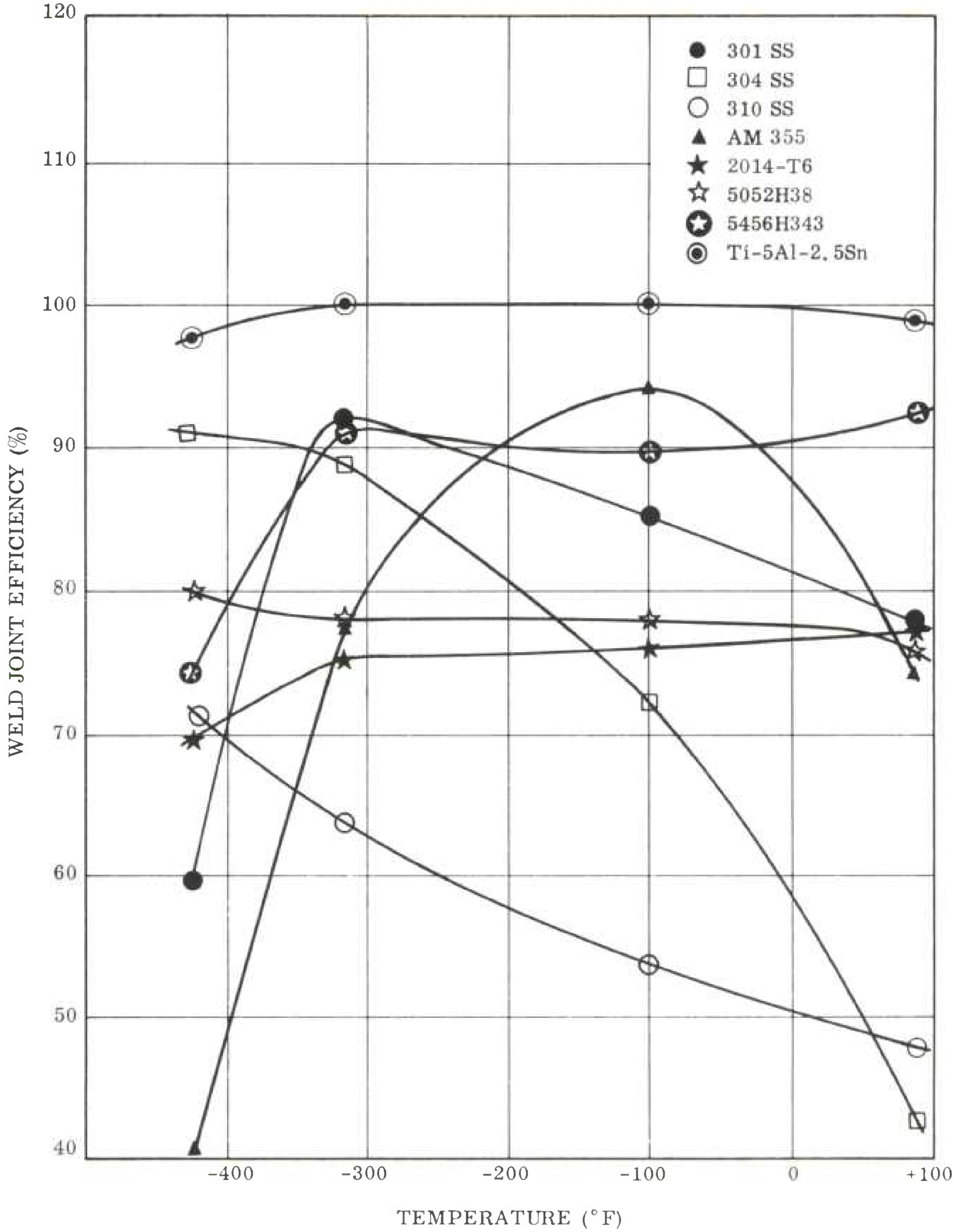


Figure 61. Weld Joint Efficiency Versus Temperature (Longitudinal)

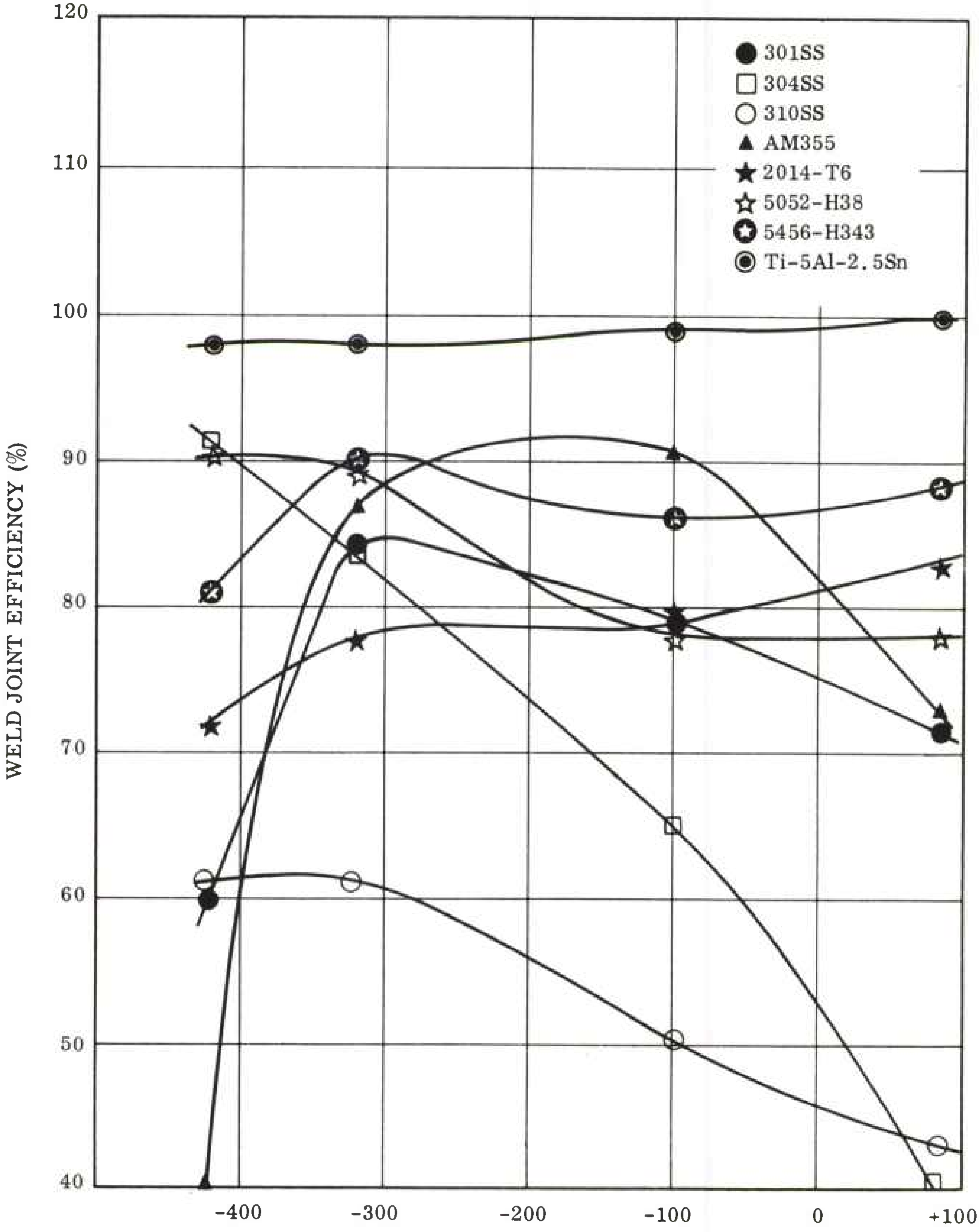


Figure 62. Weld Joint Efficiency Versus Temperature (Transverse)

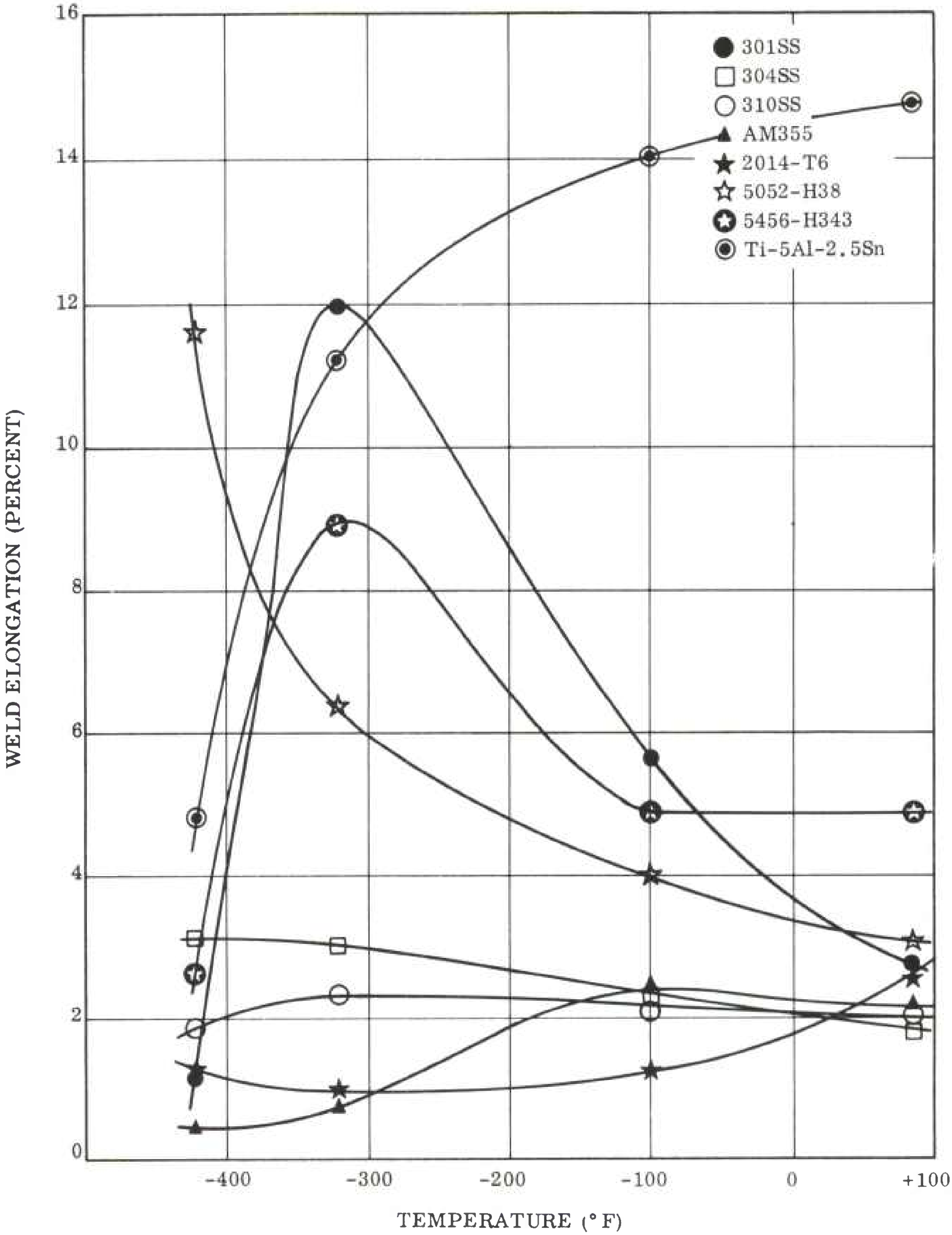


Figure 63. Weld Elongation Versus Temperature (Longitudinal)

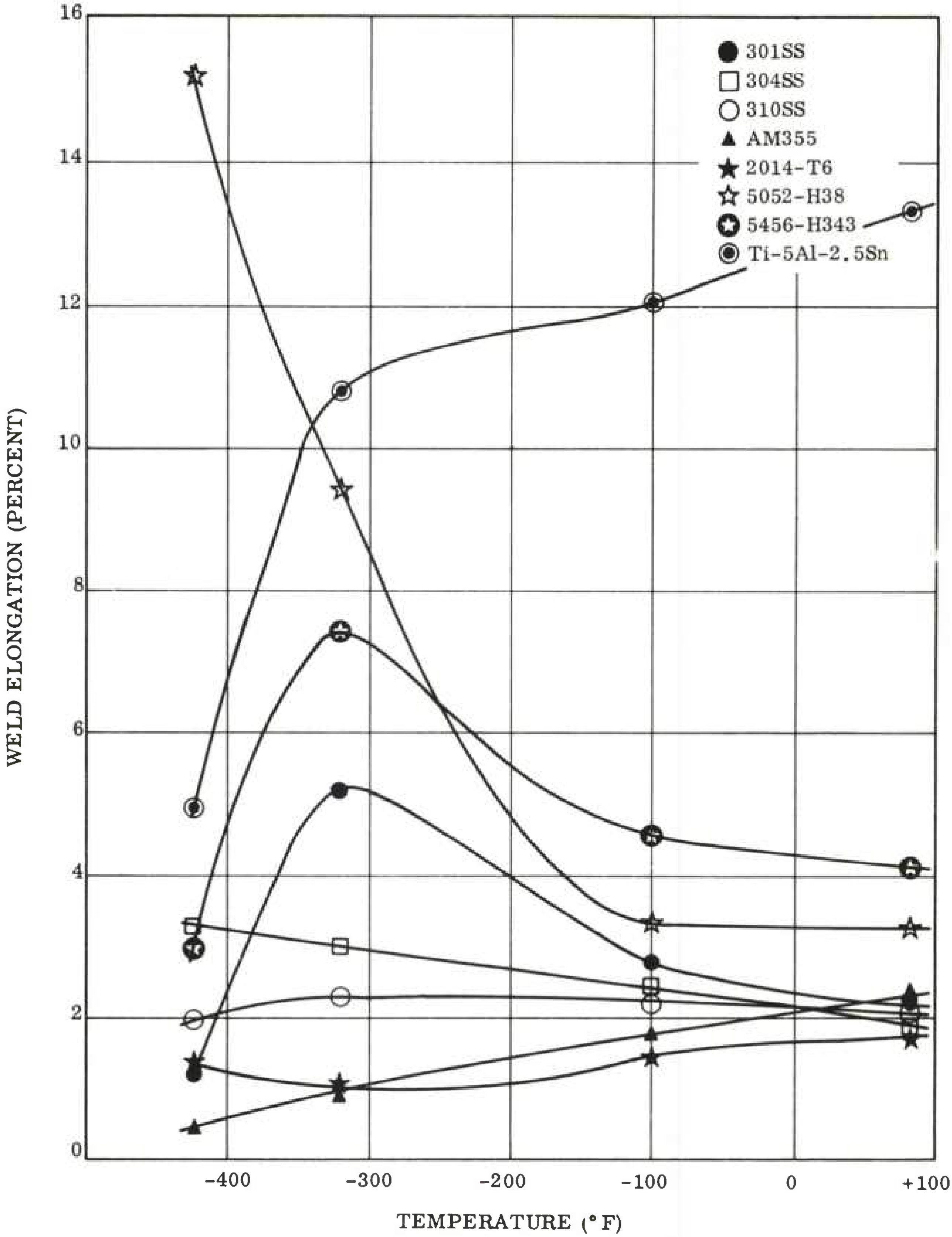


Figure 64. Weld Elongation Versus Temperature (Transverse)

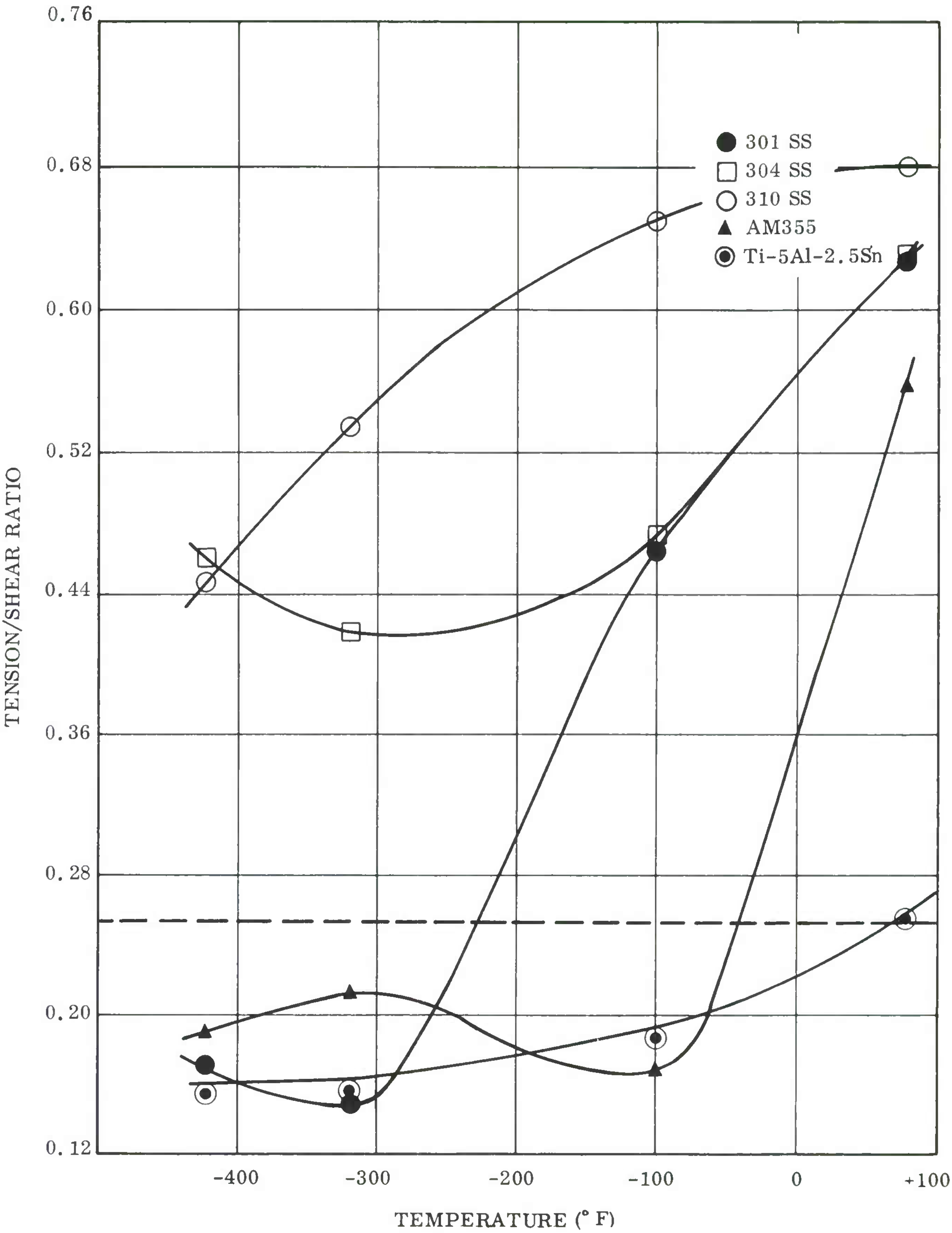


Figure 65. Tension/Shear Ratio of Spot Welds Versus Temperature

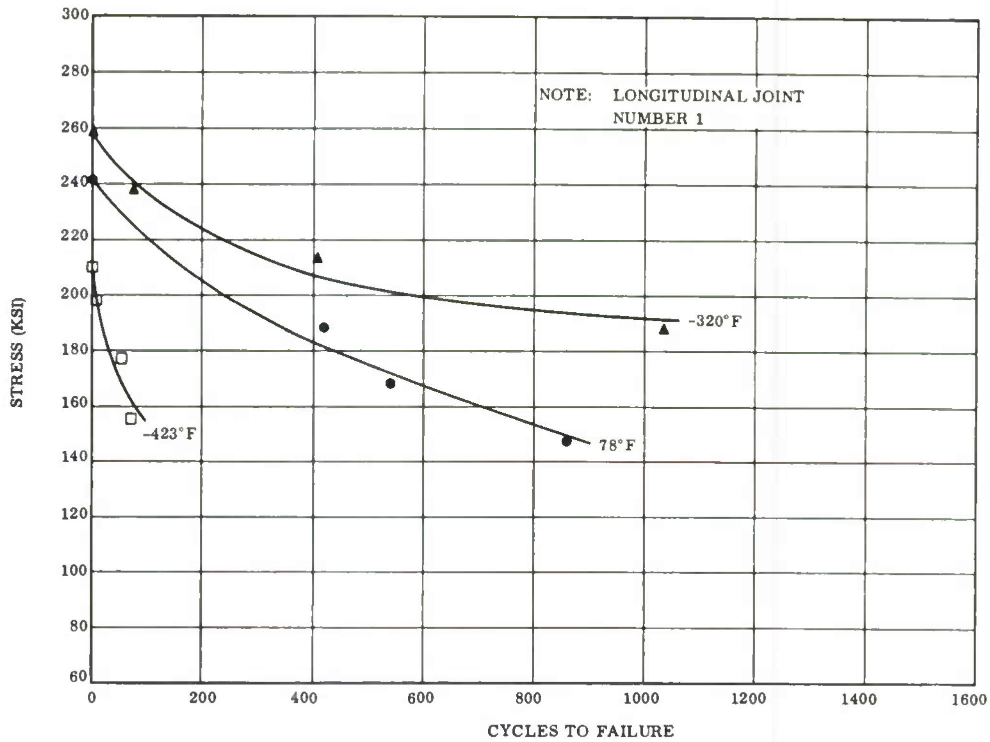


Figure 66. S-N Curve - 301 Stainless Steel (Longitudinal - Joint No. 1)

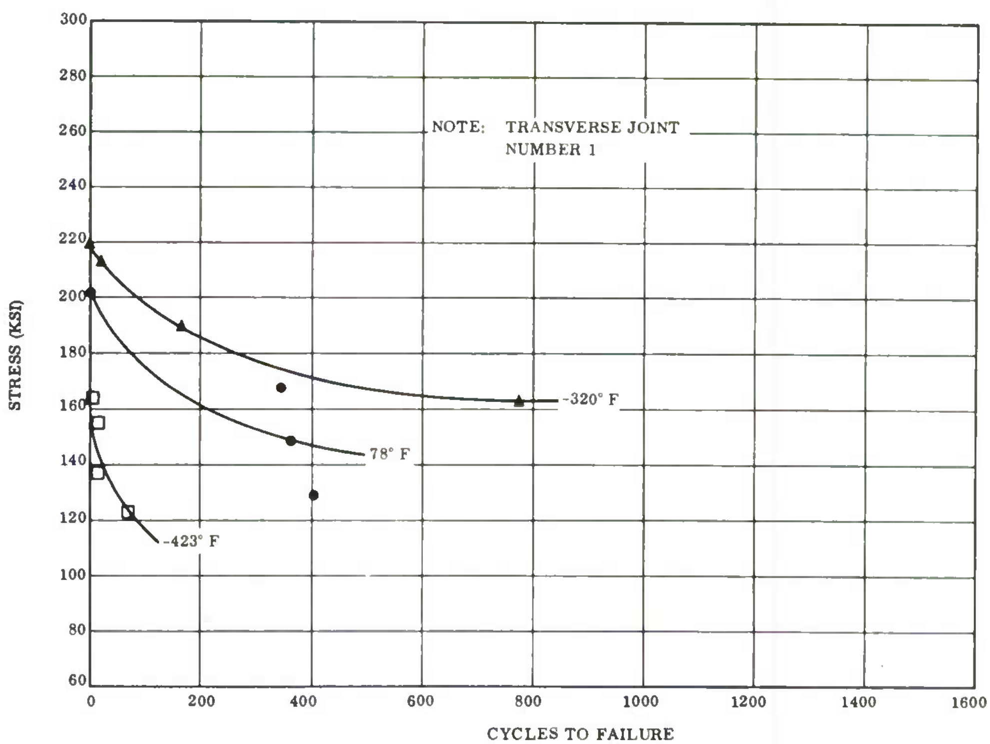


Figure 67. S-N Curve - 301 Stainless Steel (Transverse Joint No. 1)

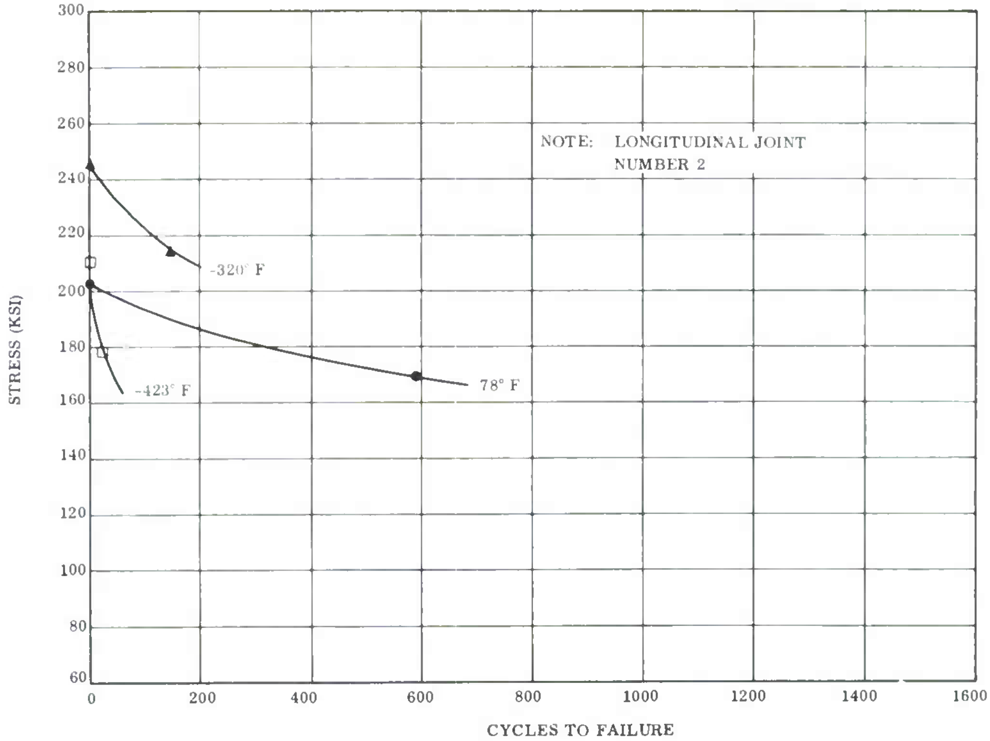


Figure 68. S-N Curve - 301 Stainless Steel (Longitudinal - Joint No. 2)

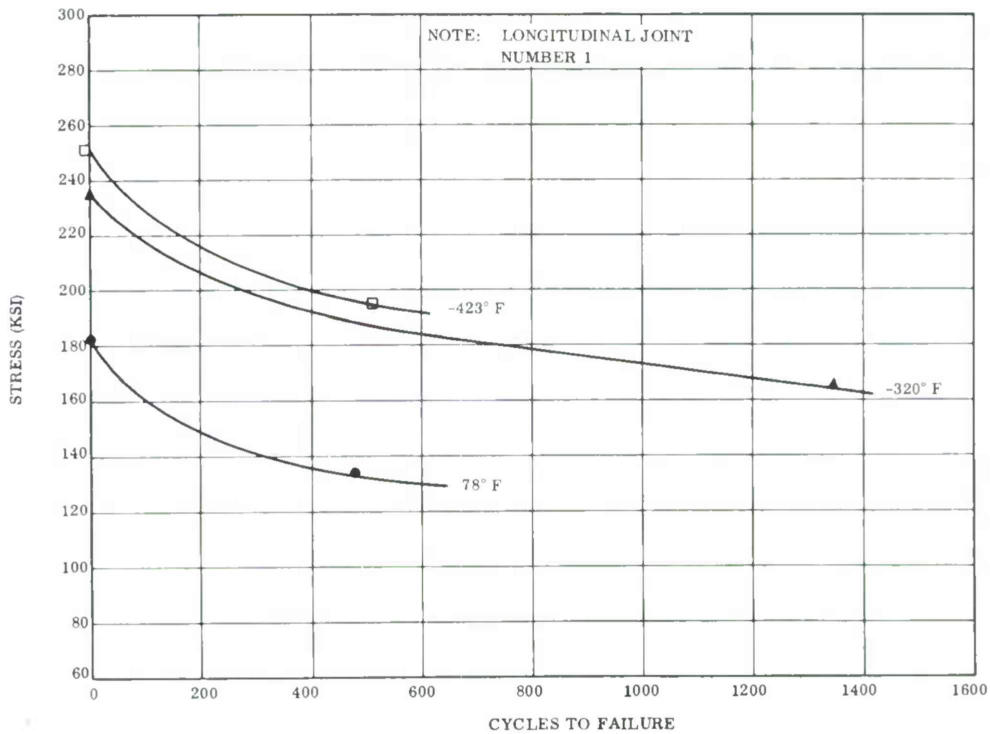


Figure 69. S-N Curve - 304 ELC Stainless Steel (Longitudinal - Joint No. 1)

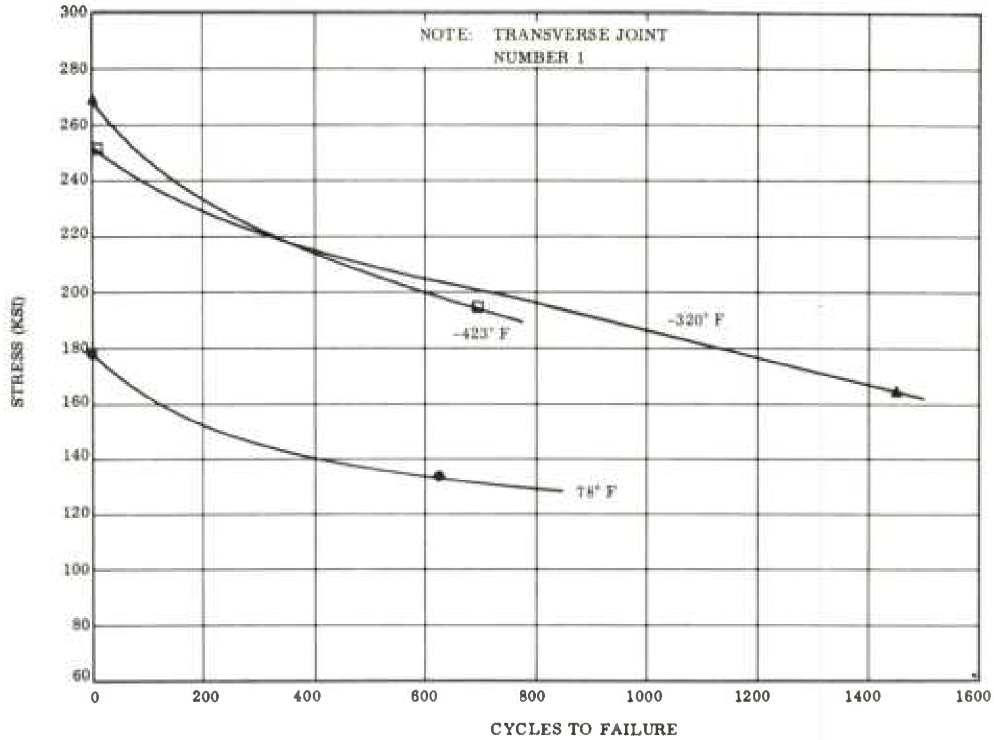


Figure 70. S-N Curve - 304 ELC Stainless Steel (Transverse - Joint No. 1)

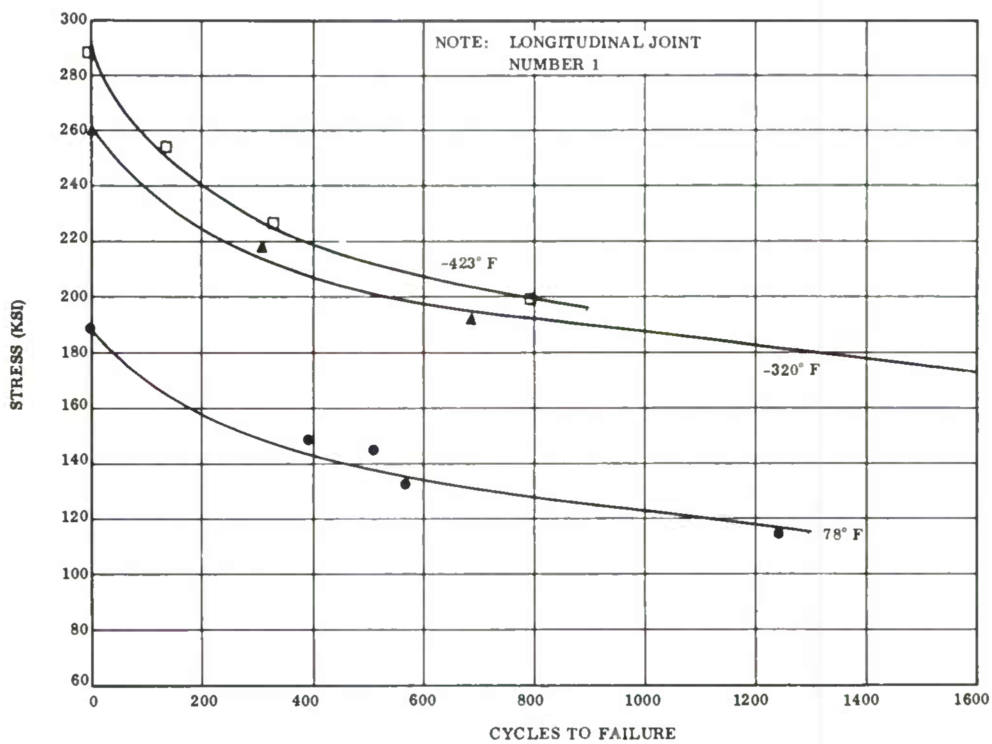


Figure 71. S-N Curve - 310 Stainless Steel (Longitudinal - Joint No. 1)

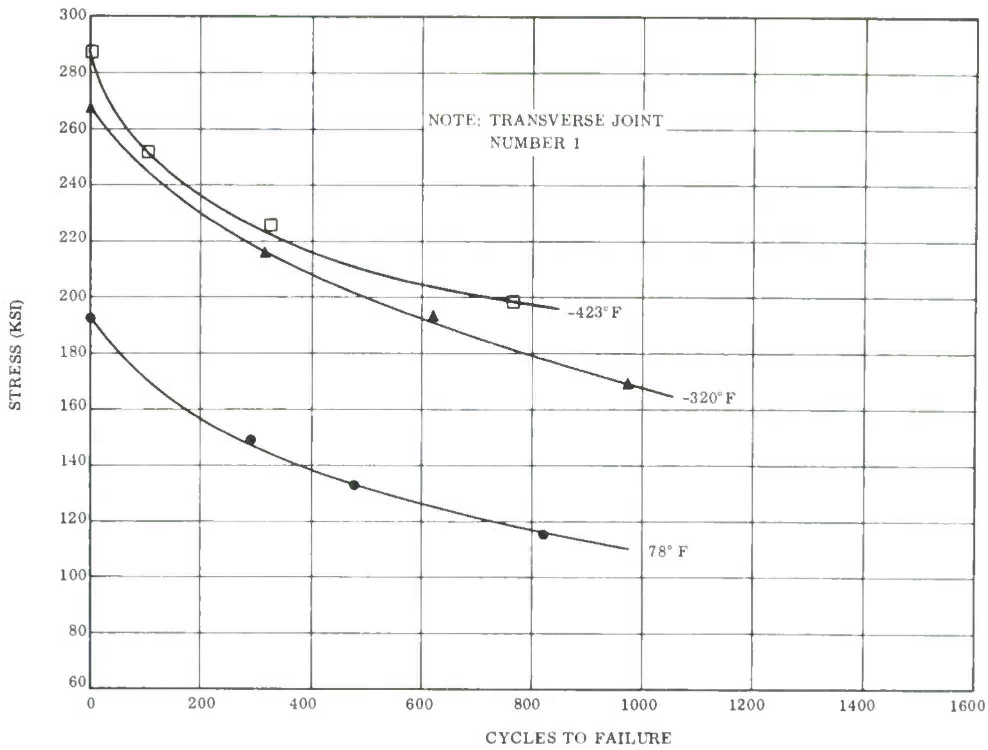


Figure 72. S-N Curve - 310 Stainless Steel (Transverse - Joint No. 1)

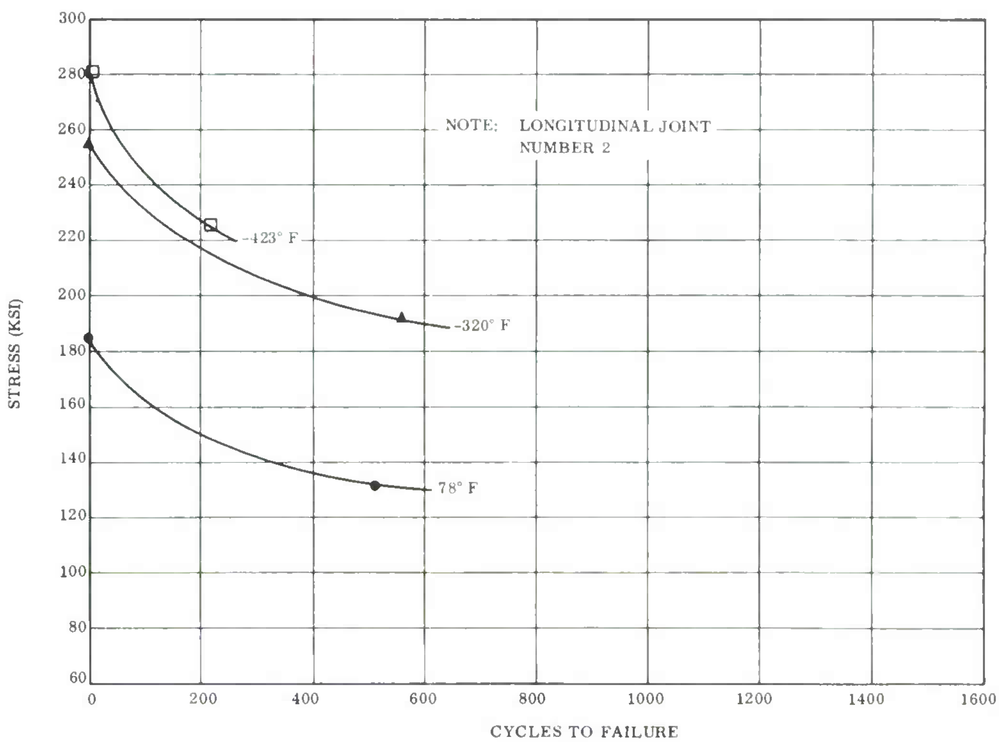


Figure 73. S-N Curve - 310 Stainless Steel (Longitudinal - Joint No. 2)

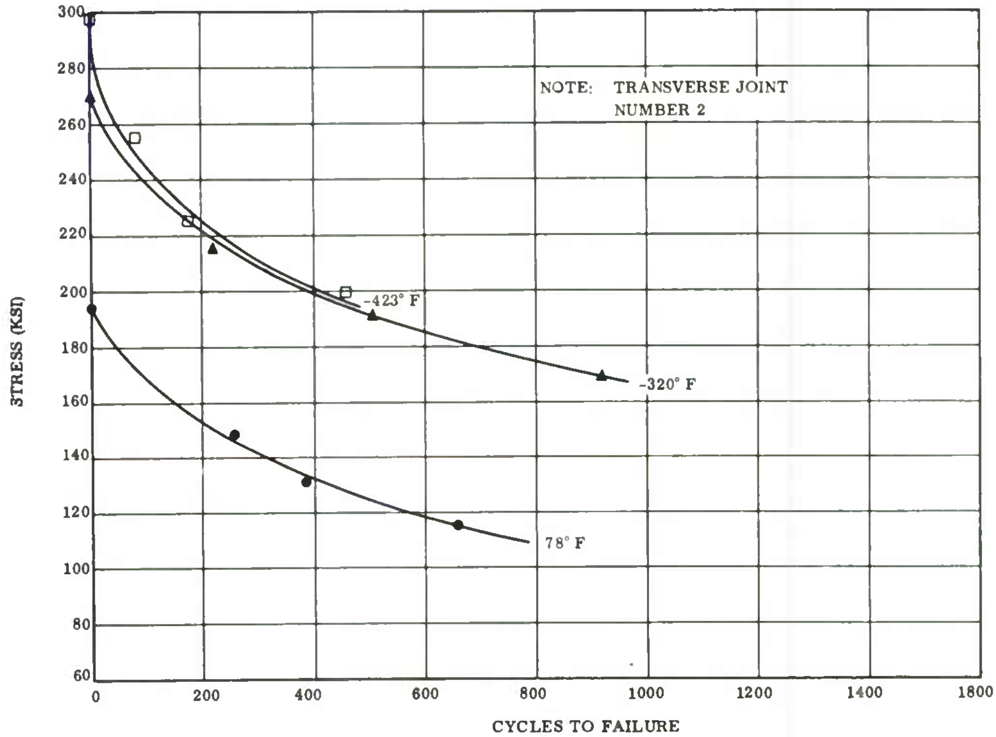


Figure 74. S-N Curve - 310 Stainless Steel (Transverse - Joint No. 2)

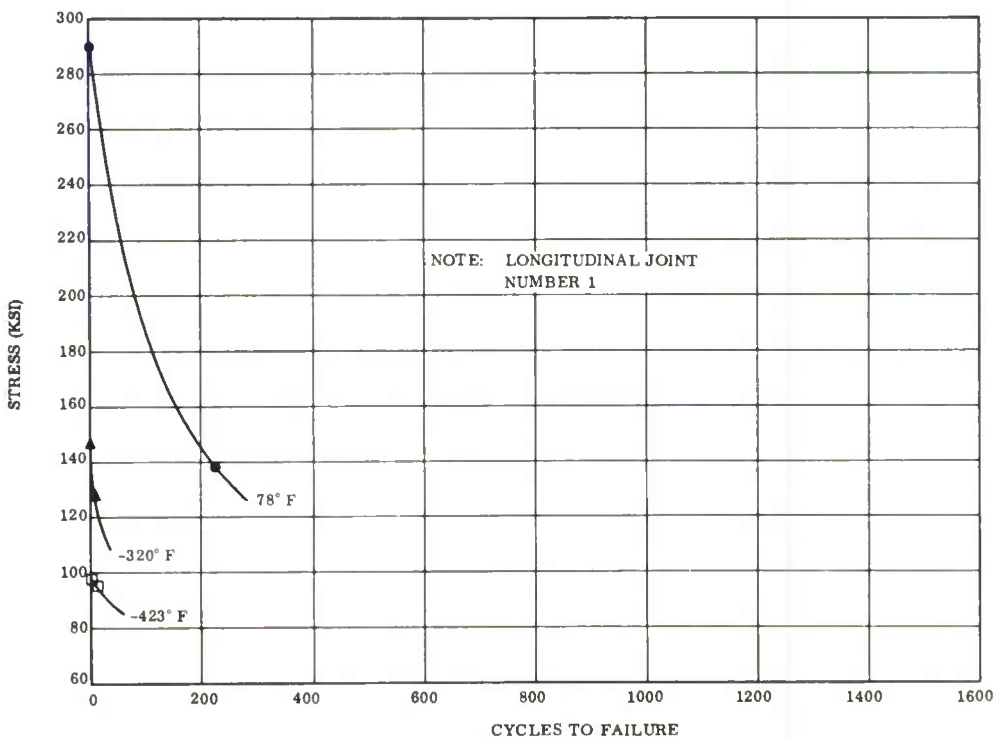


Figure 75. S-N Curve - AM-355 Stainless Steel (Longitudinal - Joint No. 1)

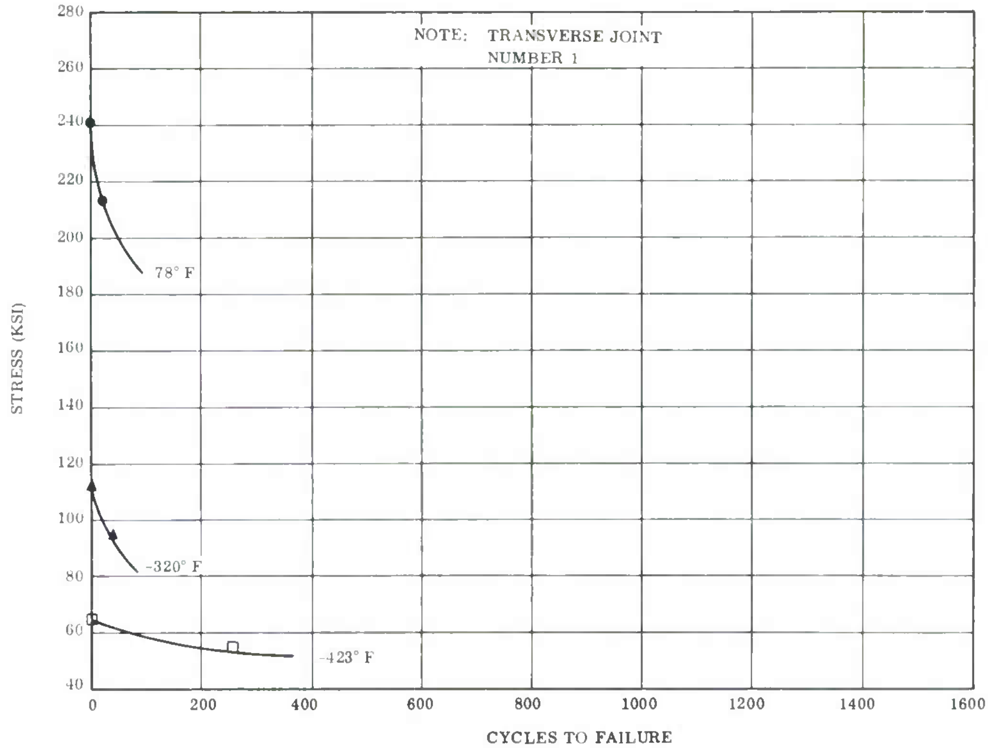


Figure 76. S-N Curve - AM-355 Stainless Steel (Transverse - Joint No. 1)

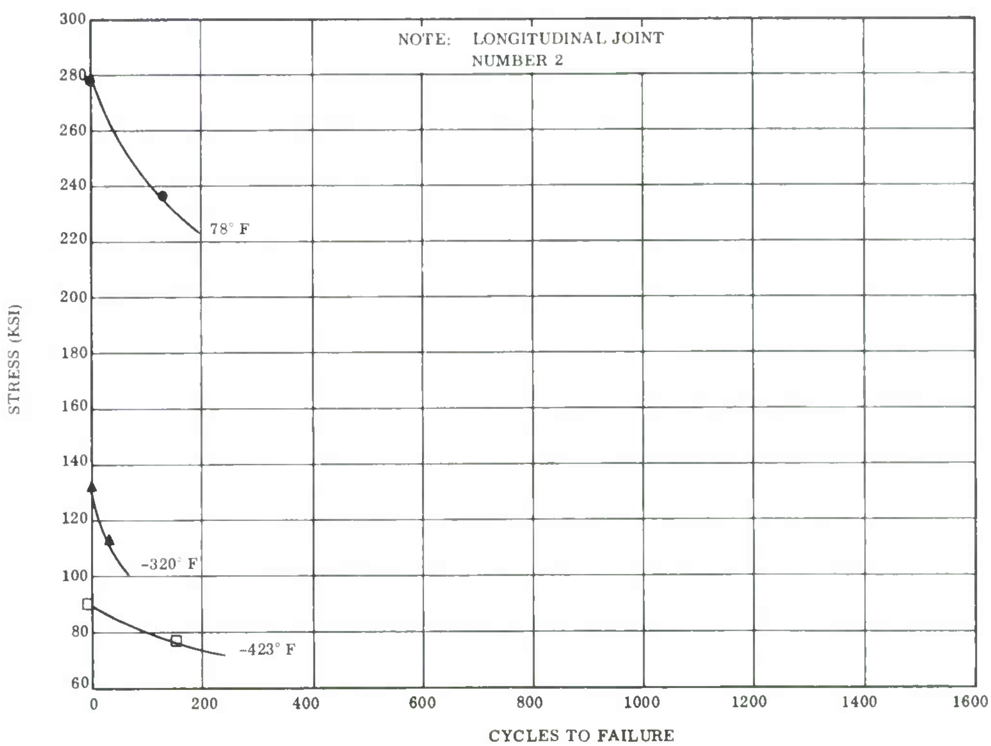


Figure 77. S-N Curve - AM-355 Stainless Steel (Longitudinal - Joint No. 2)

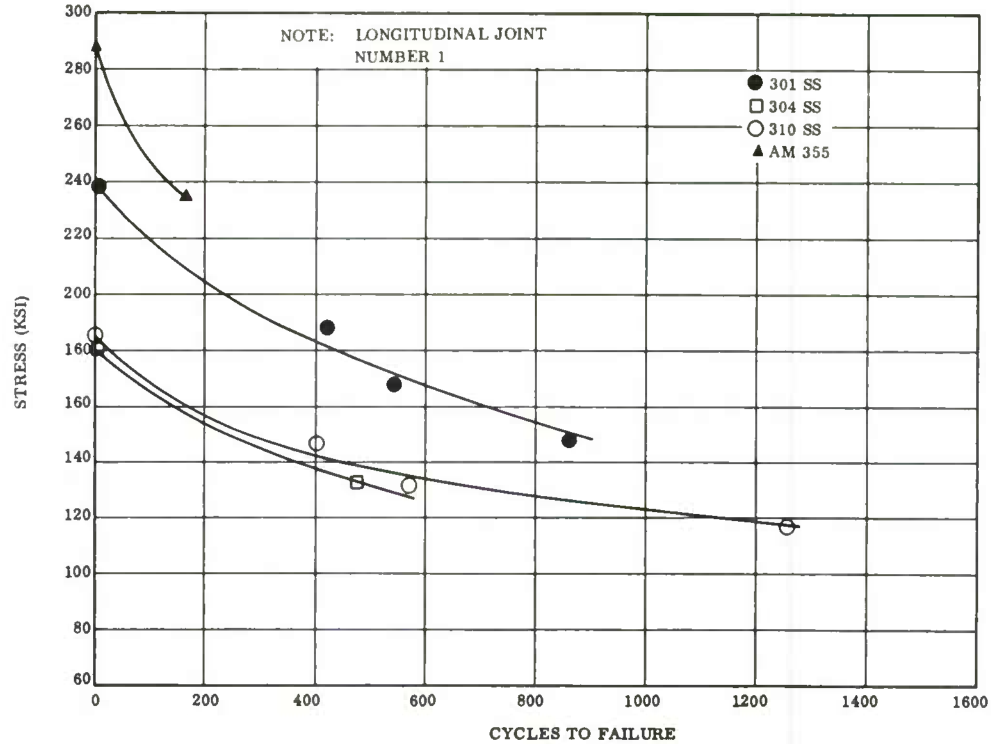


Figure 78. S-N Curve - Stainless Steels at 78°F (Longitudinal - Joint No. 1)

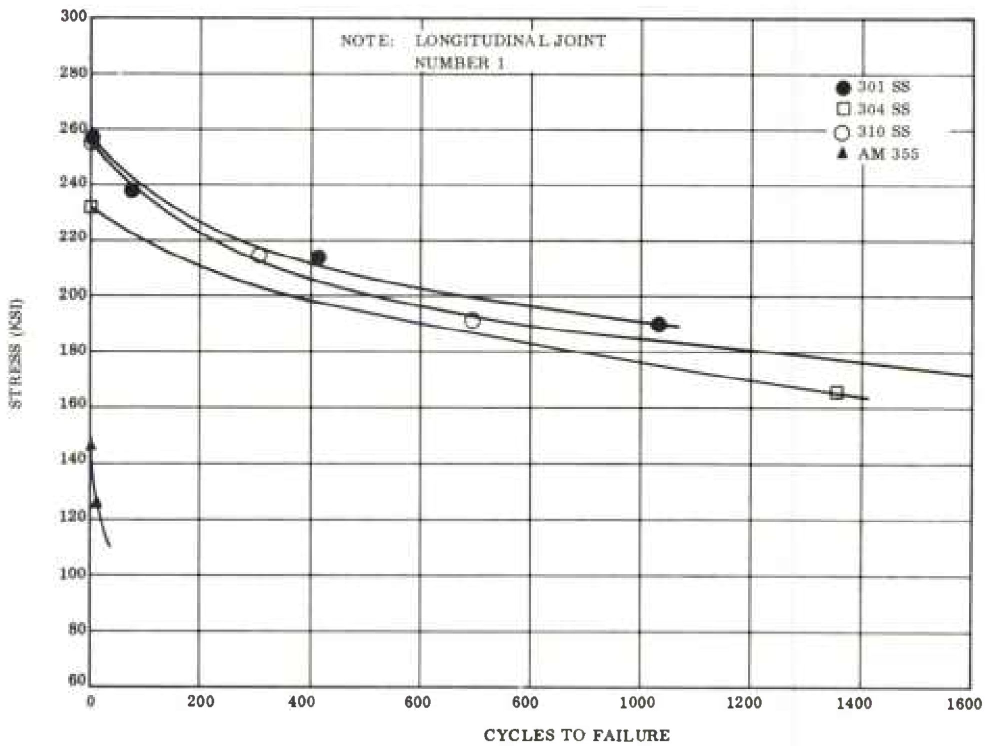


Figure 79. S-N Curve - Stainless Steels at -320°F (Longitudinal - Joint No. 1)

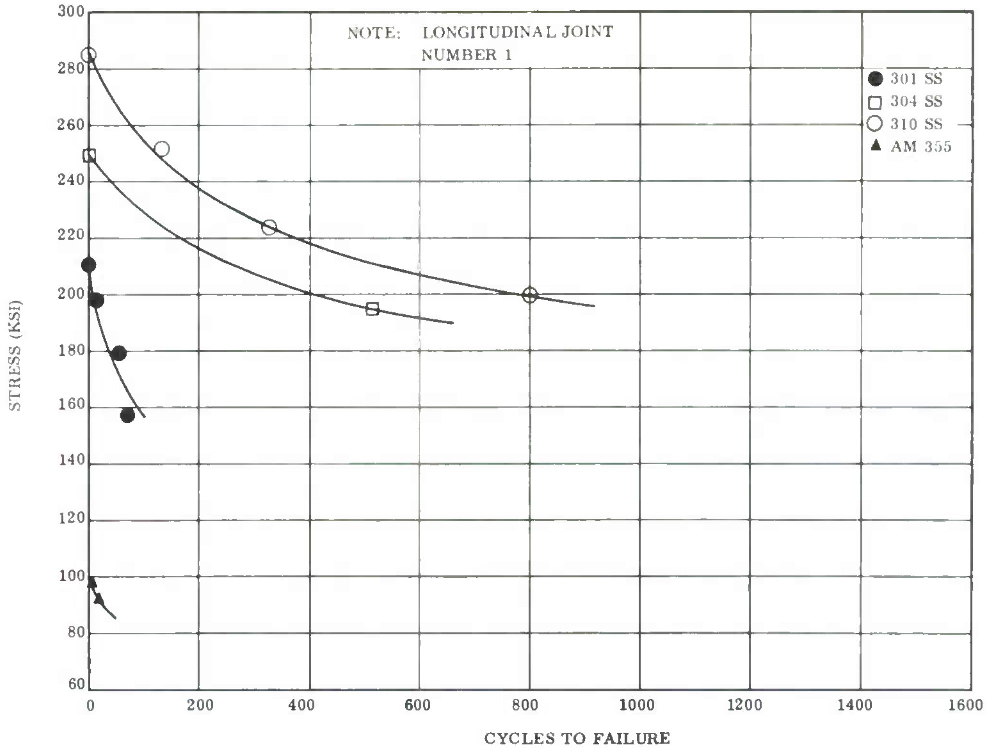


Figure 80. S-N Curve - Stainless Steels at -423°F (Longitudinal - Joint No. 1)

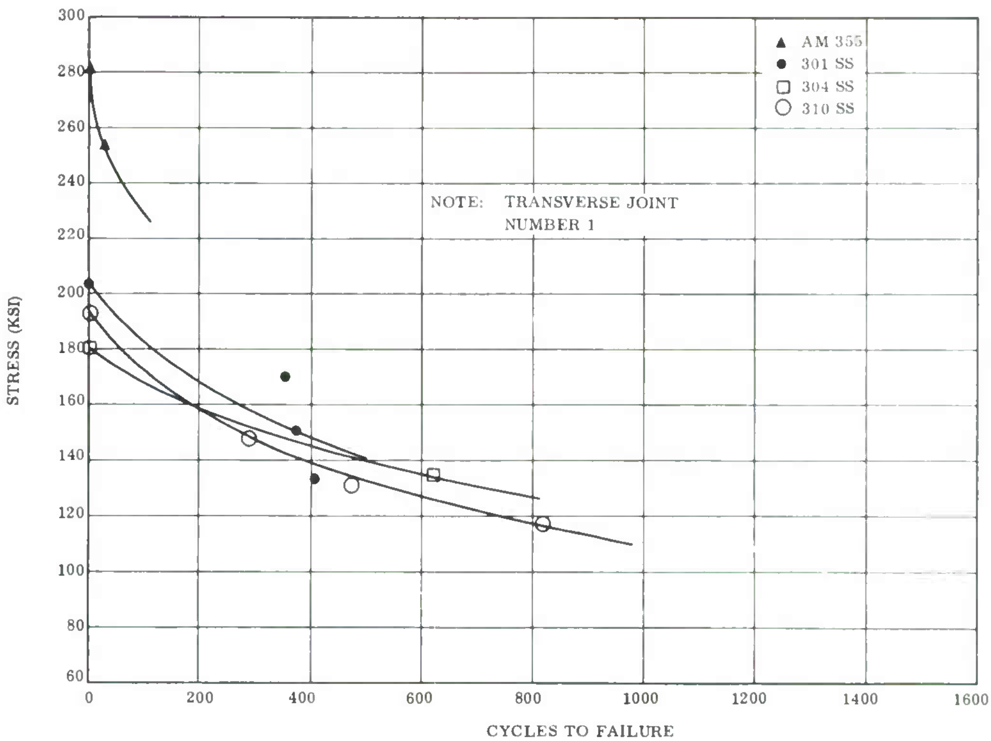


Figure 81. S-N Curve - Stainless Steels at 78°F (Transverse - Joint No. 1)

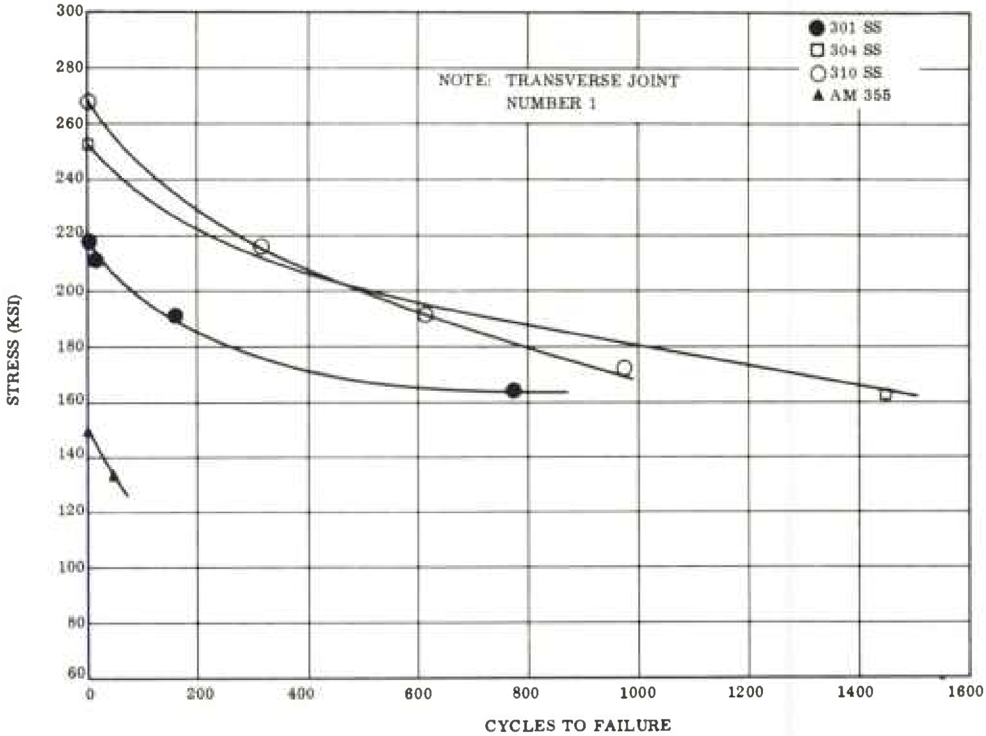


Figure 82. S-N Curve - Stainless Steels at -320°F (Transverse - Joint No. 1)

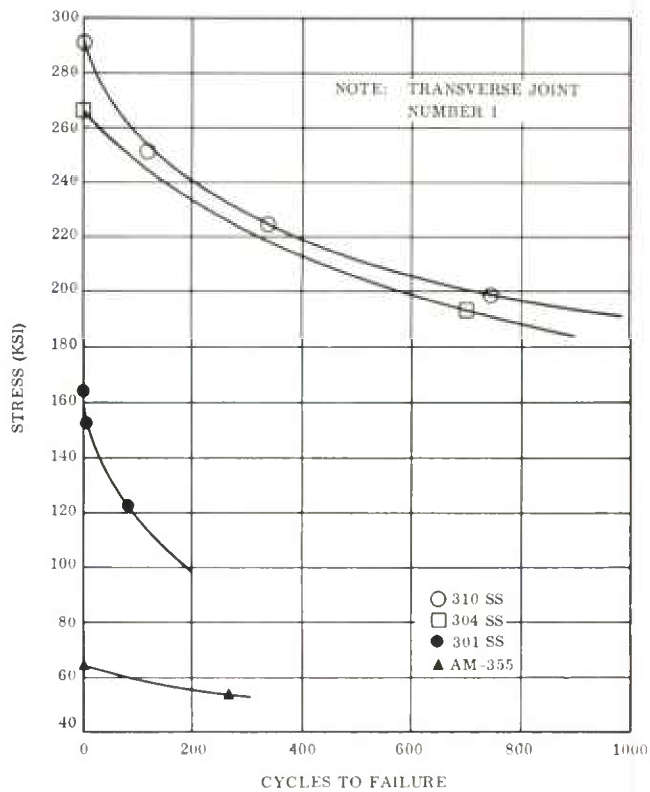


Figure 83. S-N Curve - Stainless Steels at -423°F (Transverse - Joint No. 1)

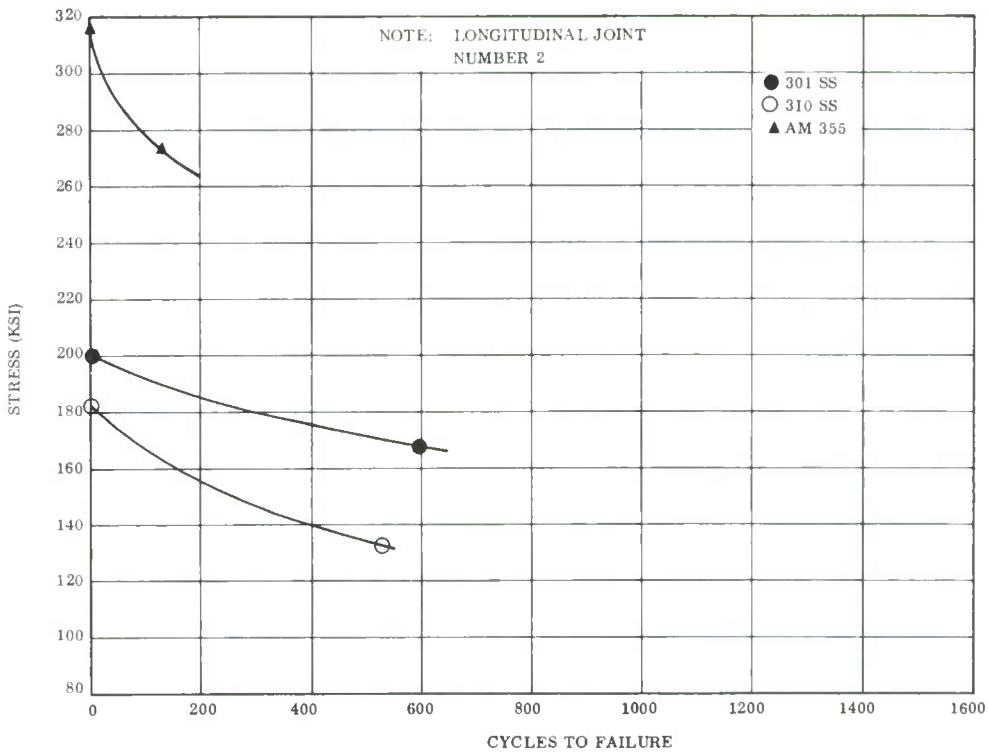


Figure 84. S-N Curve - Stainless Steels at 78°F (Longitudinal - Joint No. 2)

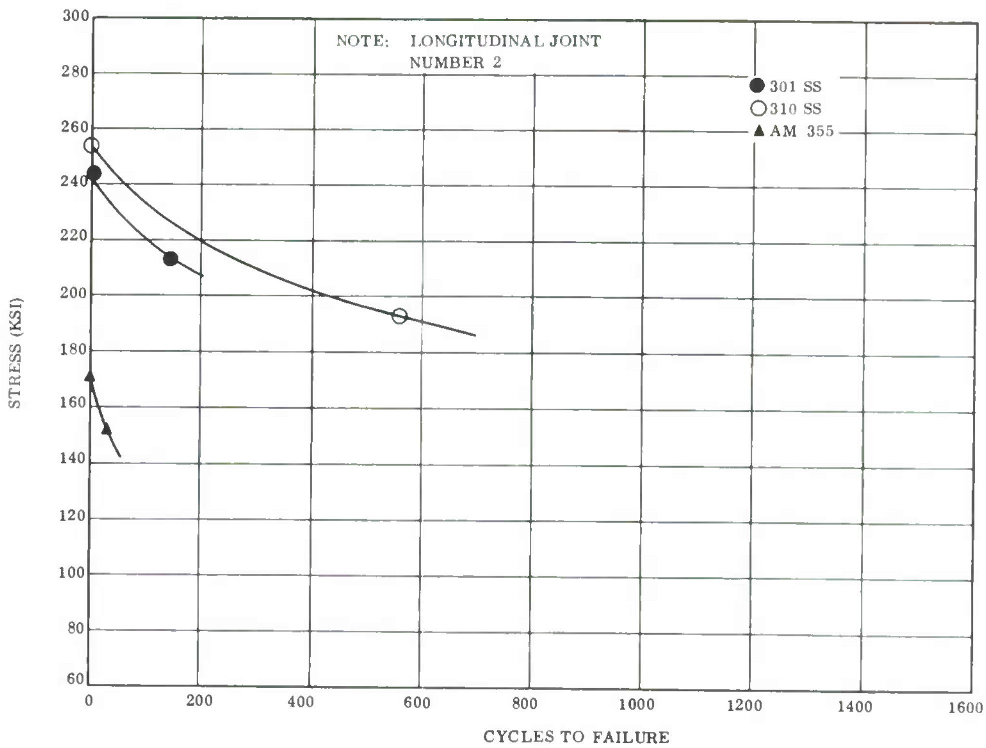


Figure 85. S-N Curve - Stainless Steels at -320°F (Longitudinal - Joint No. 2)

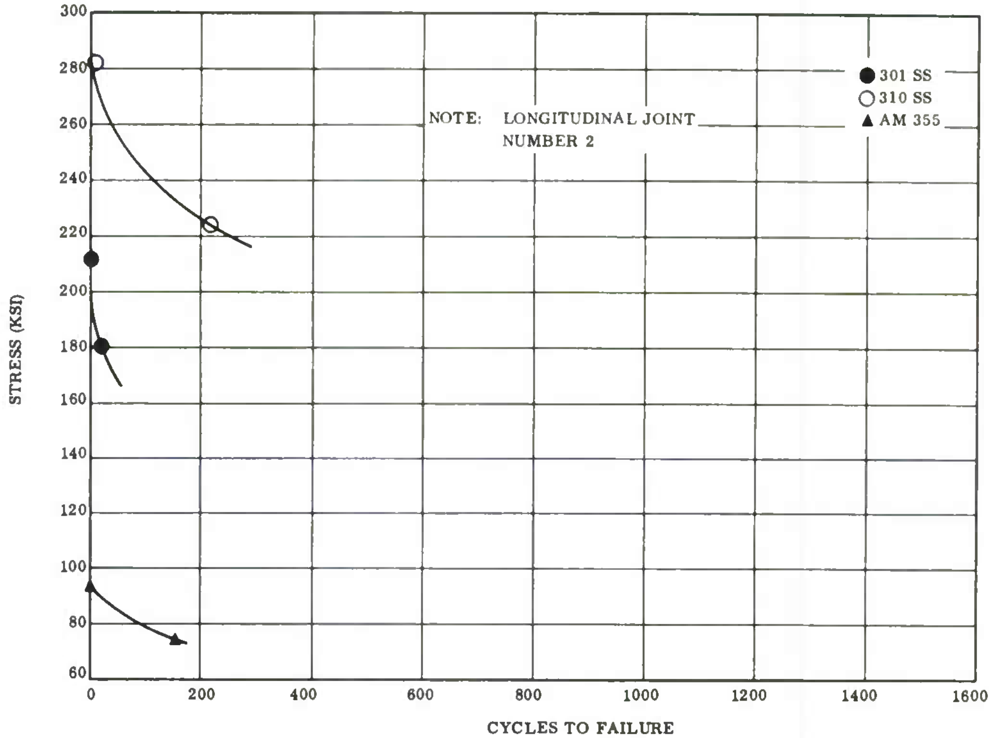


Figure 86. S-N Curve - Stainless Steels at -423°F (Longitudinal - Joint No. 2)

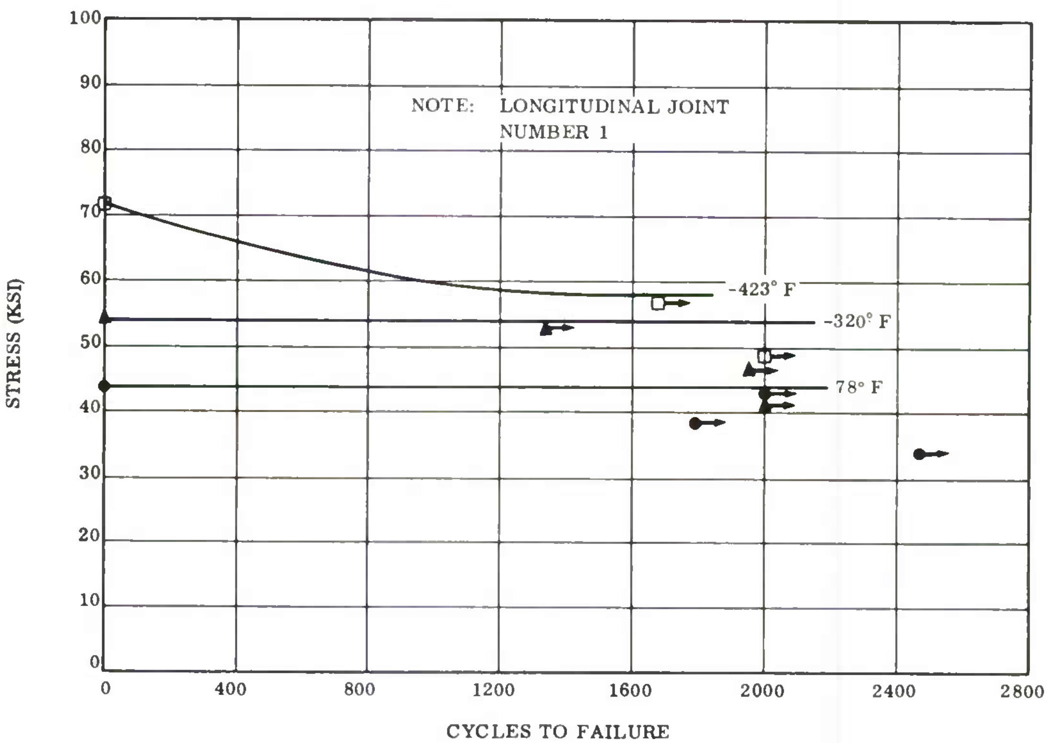


Figure 87. S-N Curve - 2014-T6 Aluminum Alloy (Longitudinal - Joint No. 1)

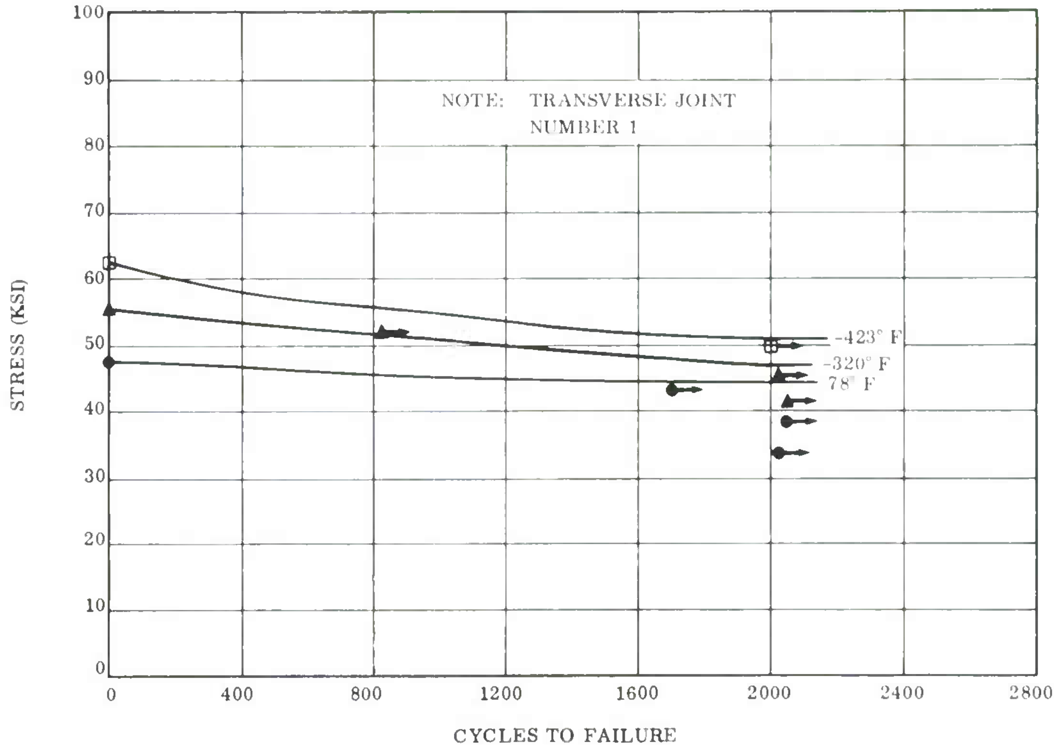


Figure 88. S-N Curve - 2014-T6 Aluminum Alloy (Transverse - Joint No. 1)

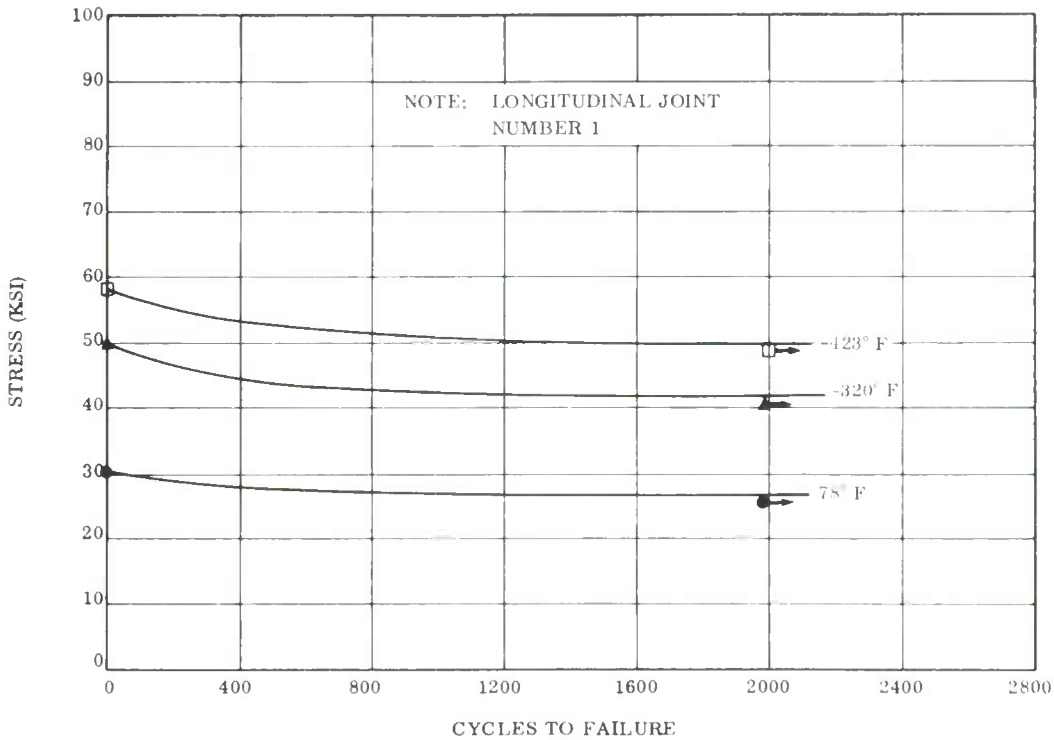


Figure 89. S-N Curve -- 5052-H38 Aluminum Alloy (Longitudinal - Joint No. 1)

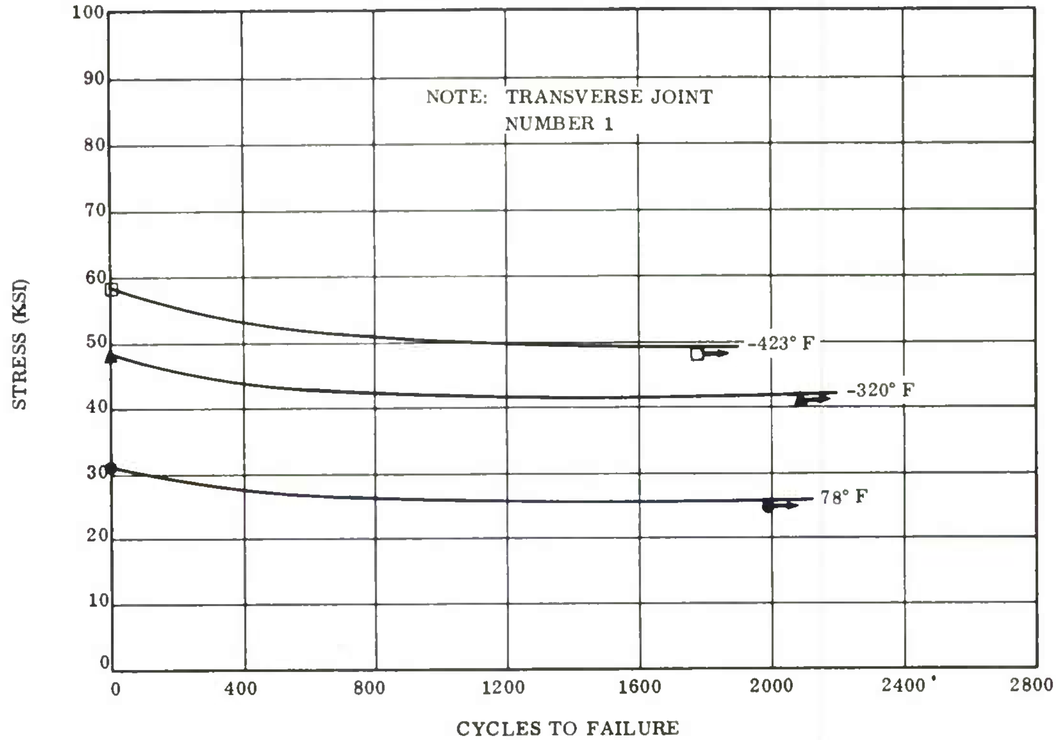


Figure 90. S-N Curve - 5052-H38 Aluminum Alloy (Transverse - Joint No. 1)

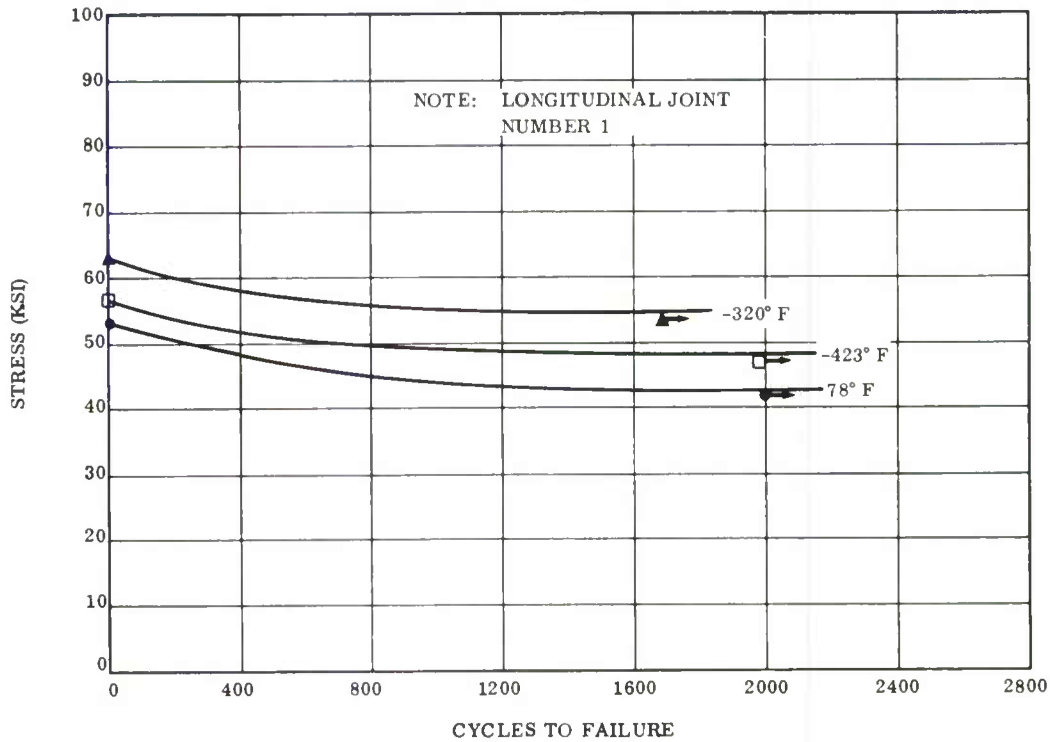


Figure 91. S-N Curve - 5456-H343 Aluminum Alloy (Longitudinal - Joint No. 1)

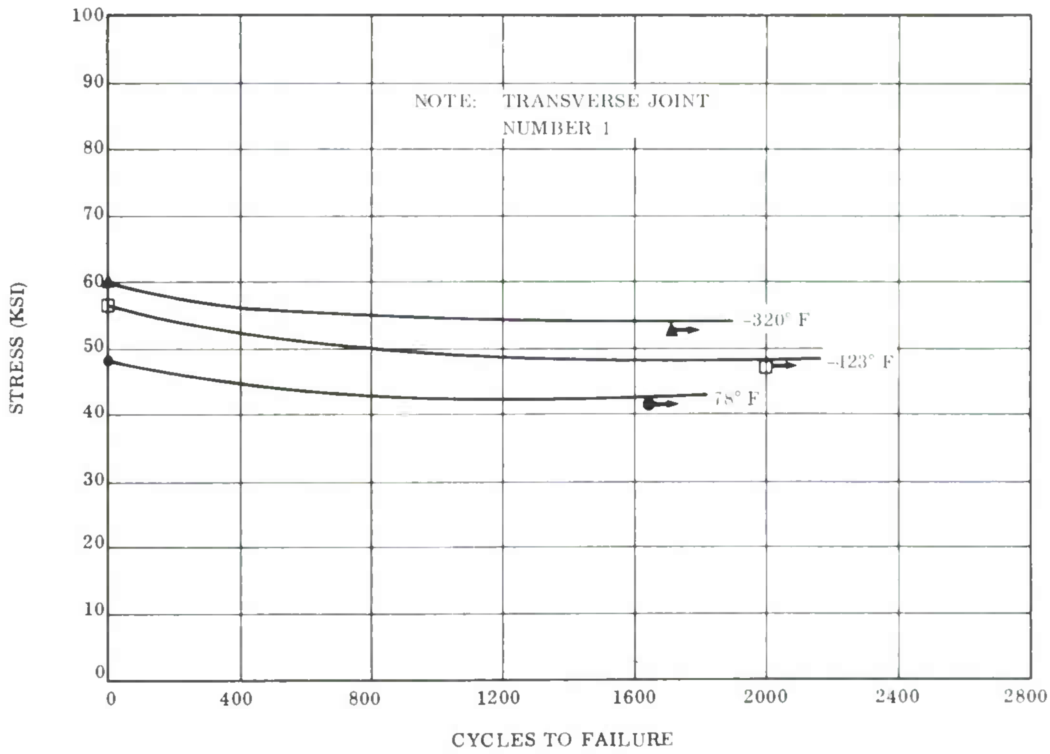


Figure 92. S-N Curve - 5456-H343 Aluminum Alloy (Transverse - Joint No. 1)

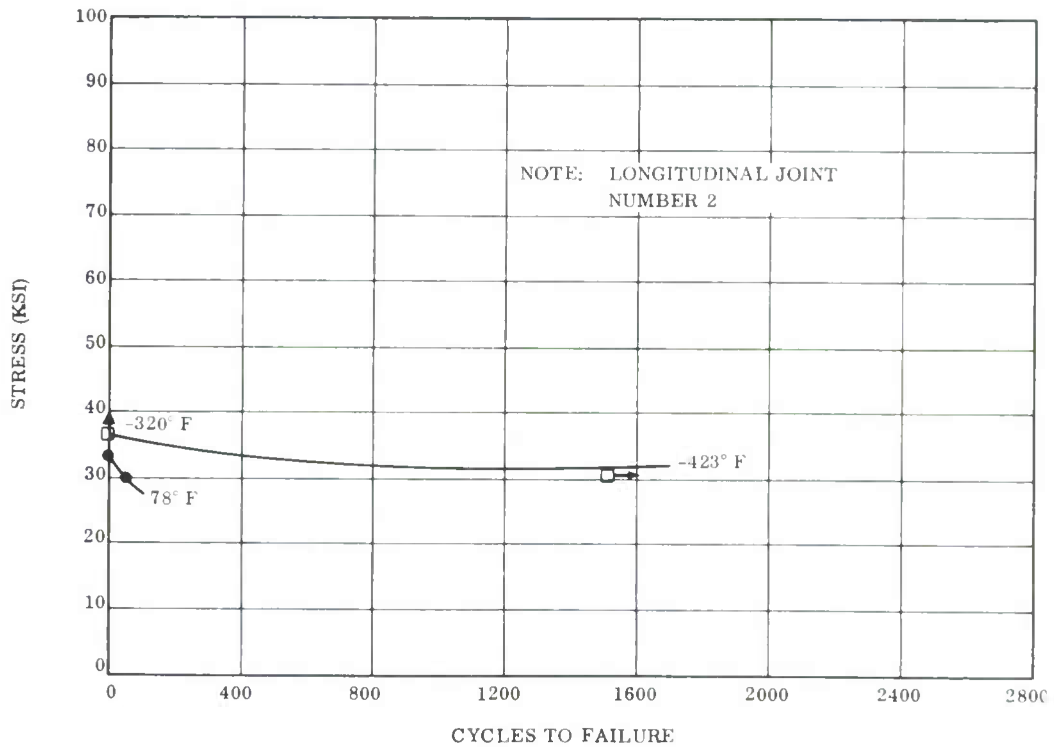


Figure 93. S-N Curve - 5456-H343 Aluminum Alloy (Longitudinal - Joint No. 2)

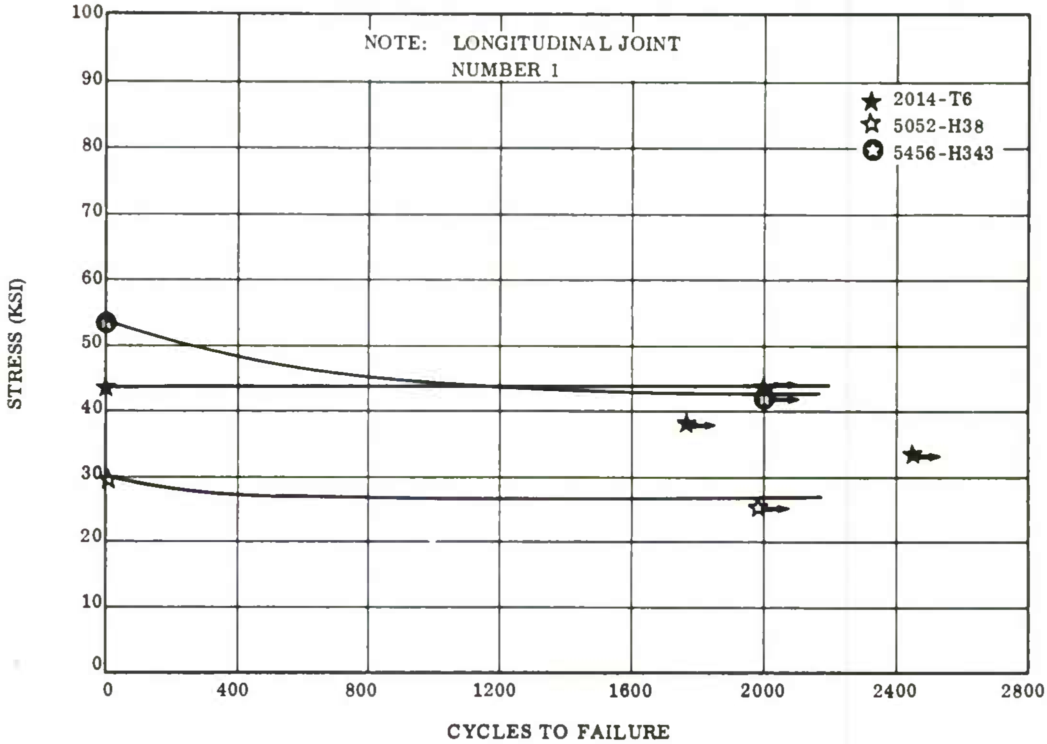


Figure 94. S-N Curve - Aluminum Alloys at 78°F (Longitudinal - Joint No. 1)

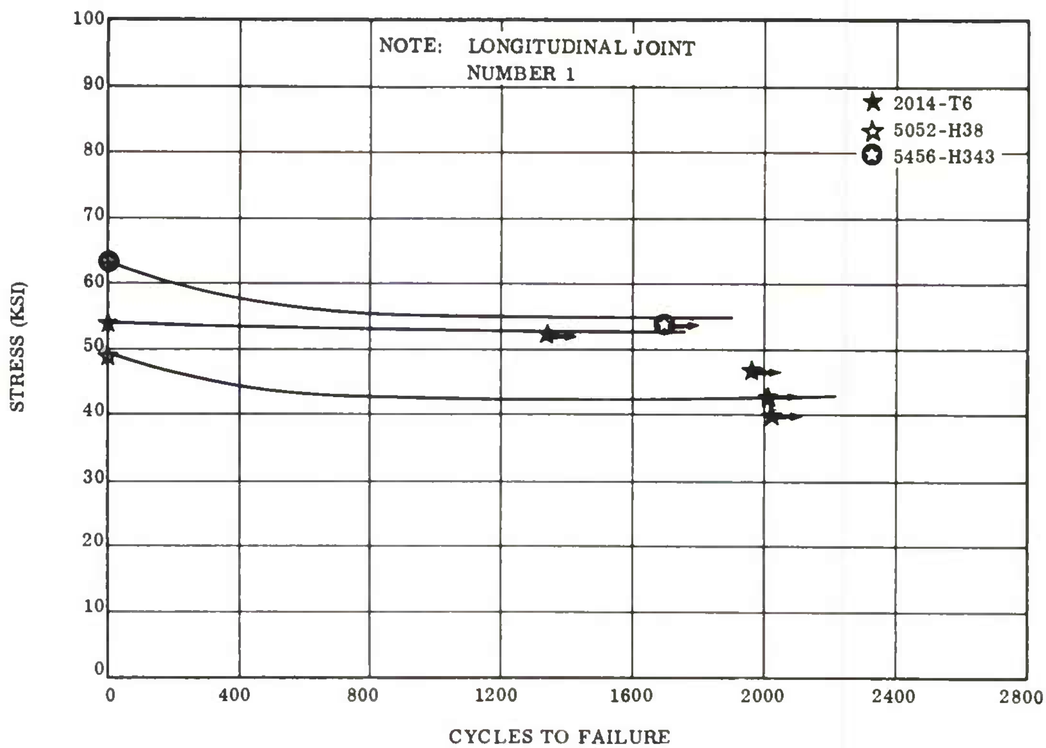


Figure 95. S-N Curve - Aluminum Alloys at -320°F (Longitudinal - Joint No. 1)

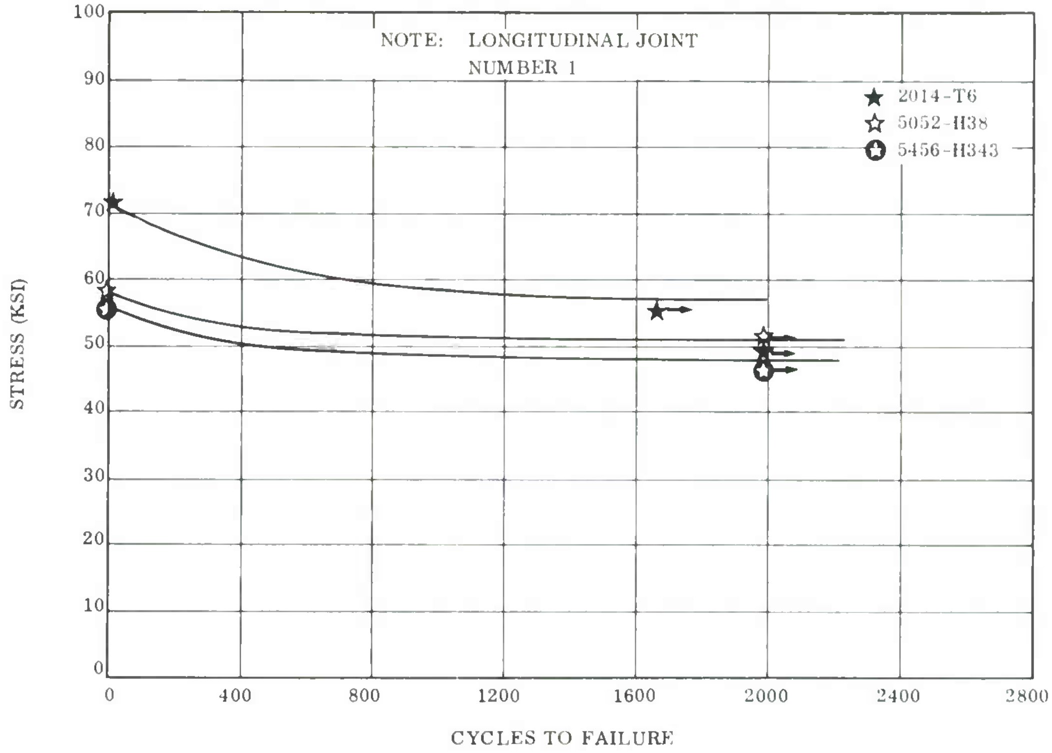


Figure 96. S-N Curve - Aluminum Alloys at -423°F (Longitudinal - Joint No. 1)

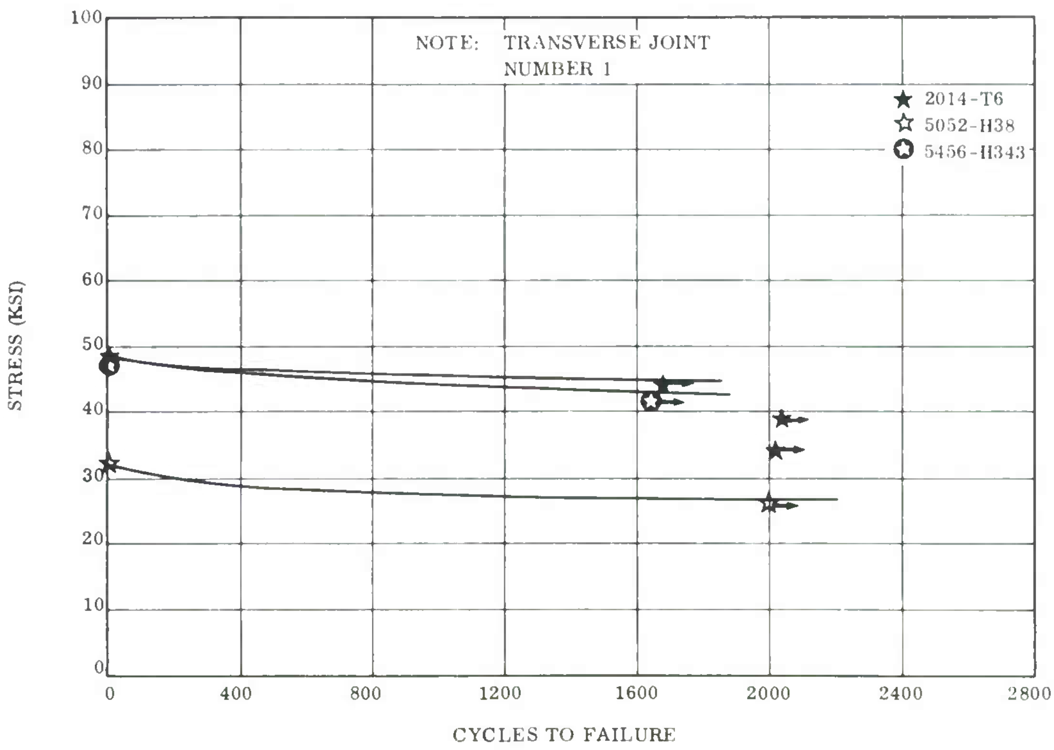


Figure 97. S-N Curve - Aluminum Alloys at 78°F (Transverse - Joint No. 1)

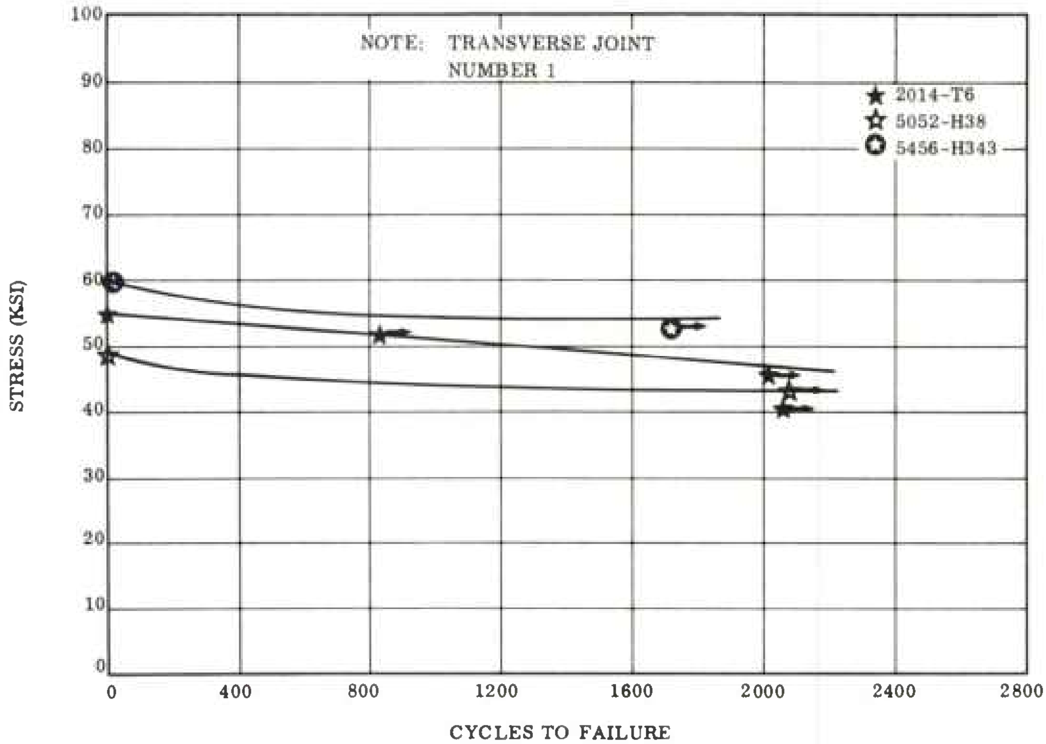


Figure 98. S-N Curve - Aluminum Alloys at -320°F (Transverse - Joint No. 1)

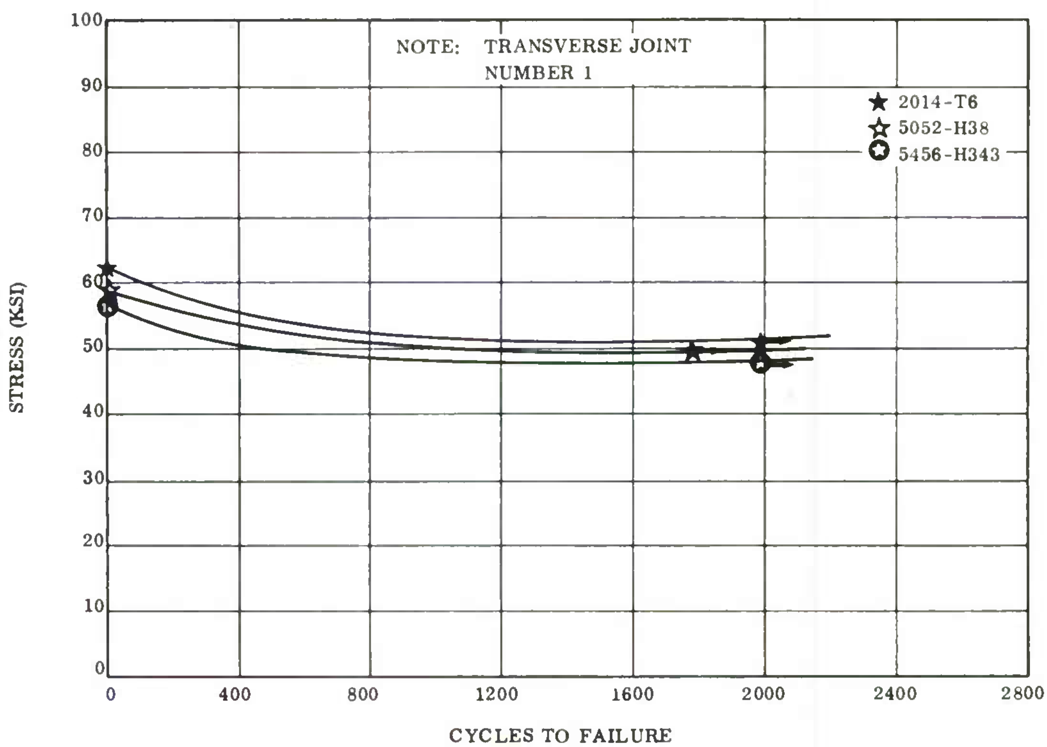


Figure 99. S-N Curve - Aluminum Alloys at -423°F (Transverse - Joint No. 1)

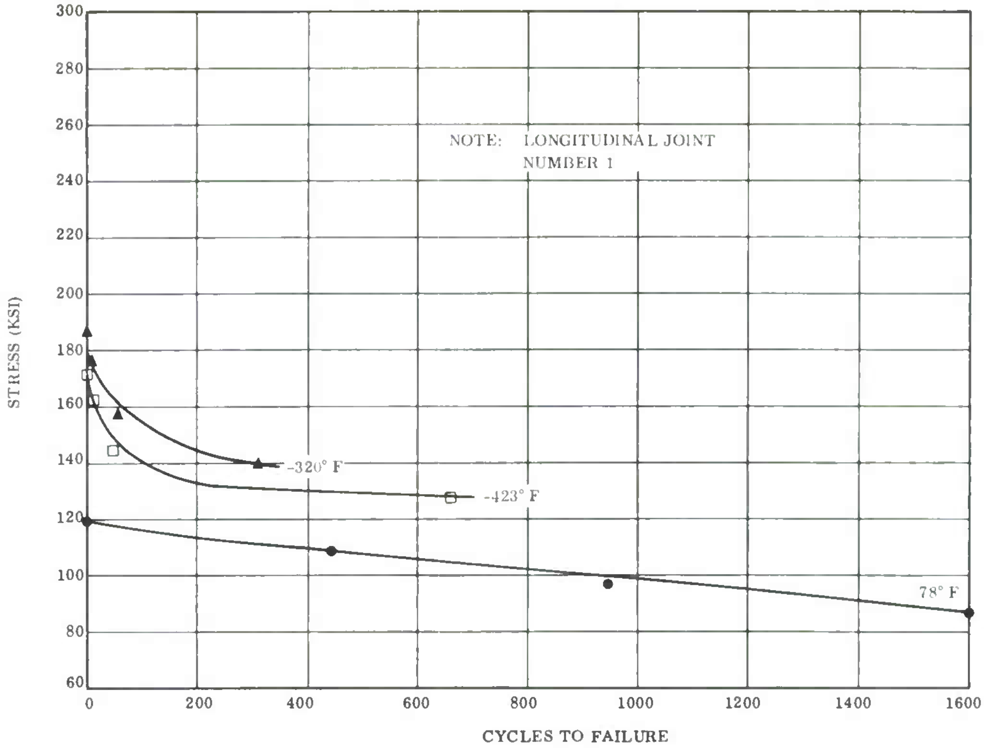


Figure 100. S-N Curve - Ti-5Al-2.5Sn Alloy (Longitudinal - Joint No. 1)

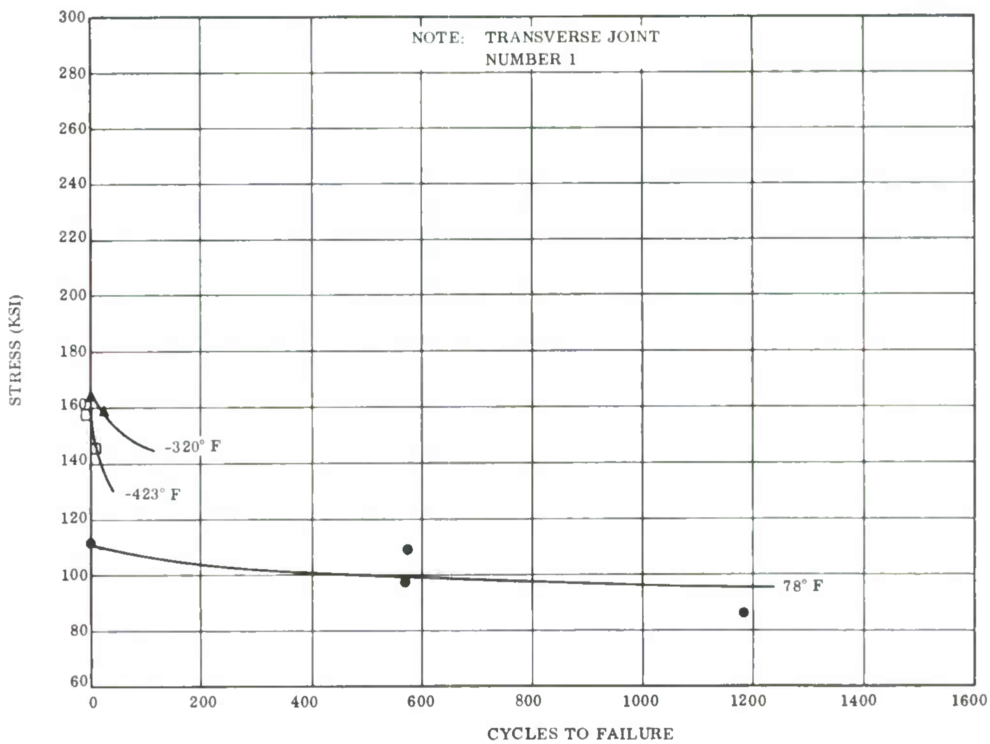


Figure 101. S-N Curve - Ti-5Al-2.5Sn Alloy (Transverse - Joint No. 1)

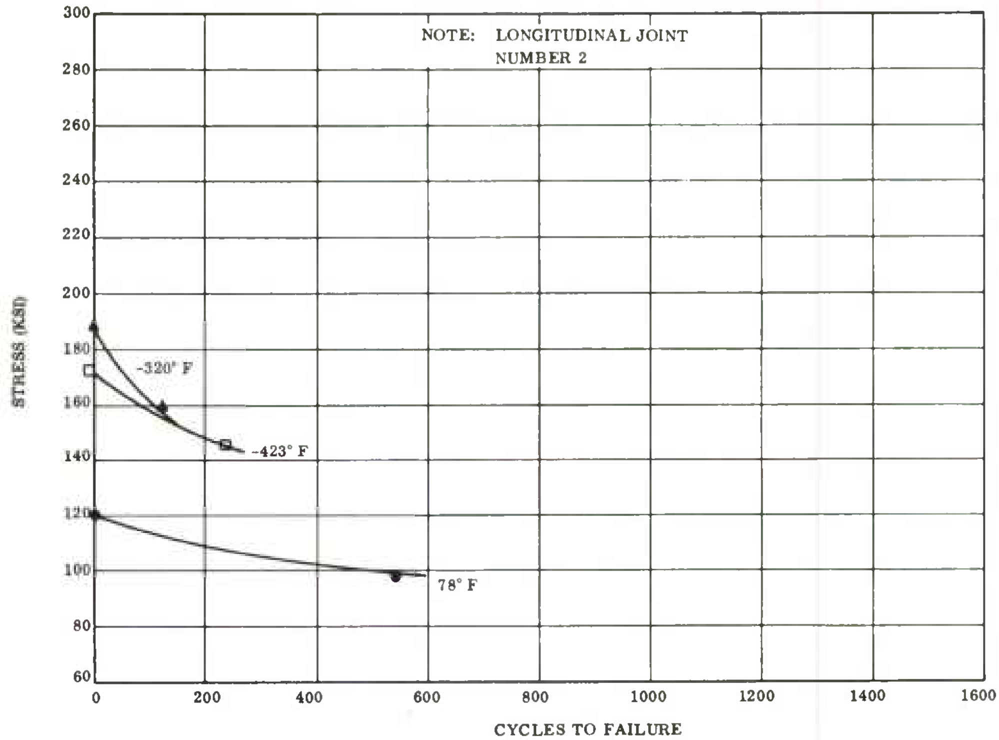


Figure 102. S-N Curve - Ti-5Al-2.5Sn Alloy (Longitudinal - Joint No. 2)

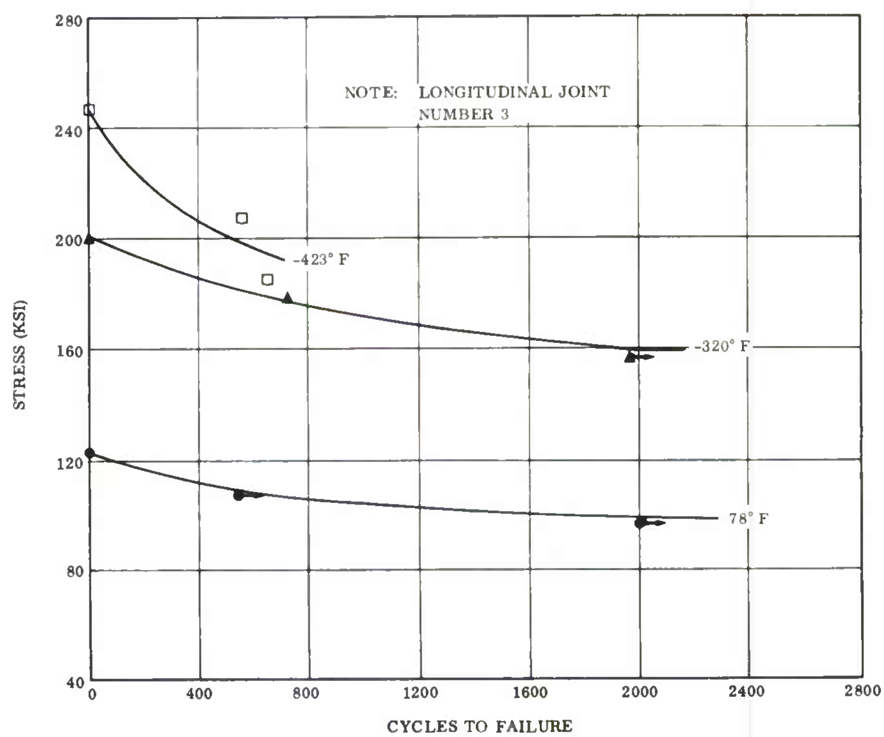
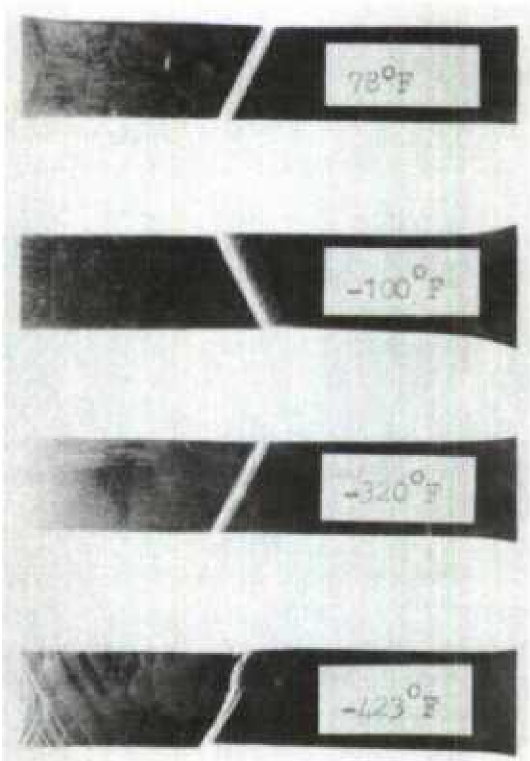
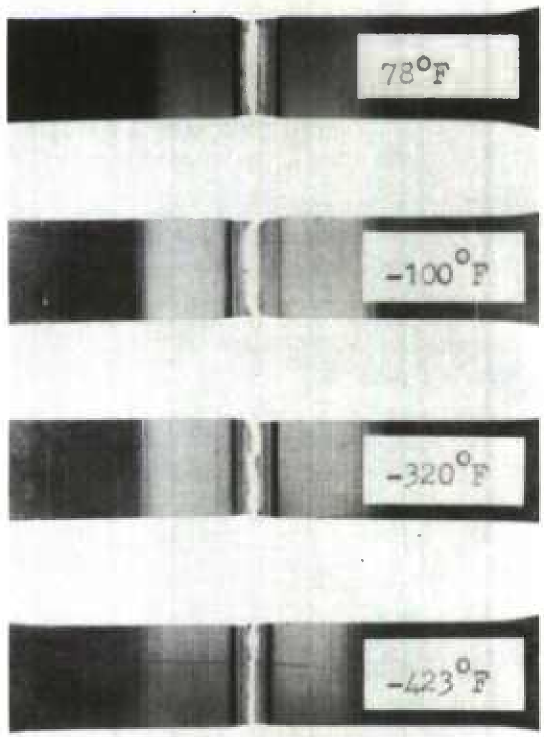


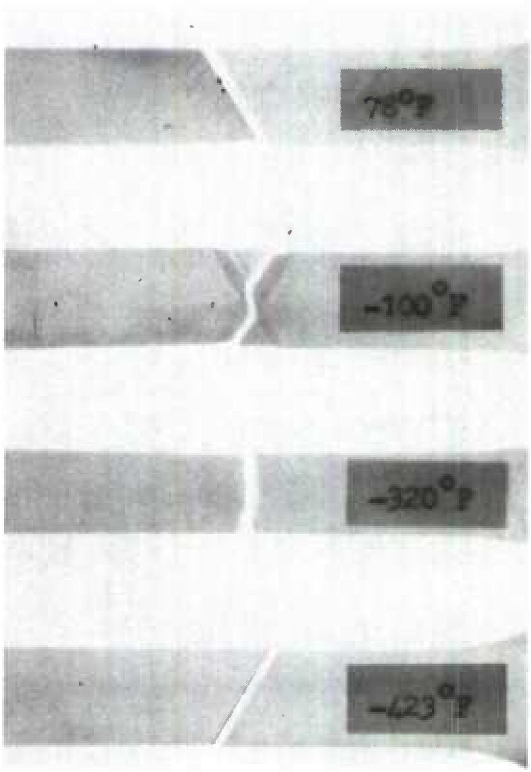
Figure 103. S-N Curve - Ti-5Al-2.5Sn Alloy (Longitudinal - Joint No. 3)



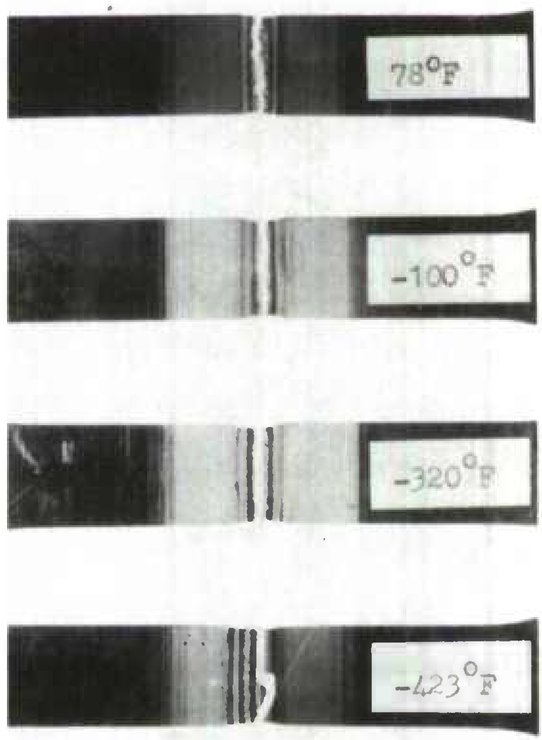
301 Stainless Steel



301 Stainless Steel Welds

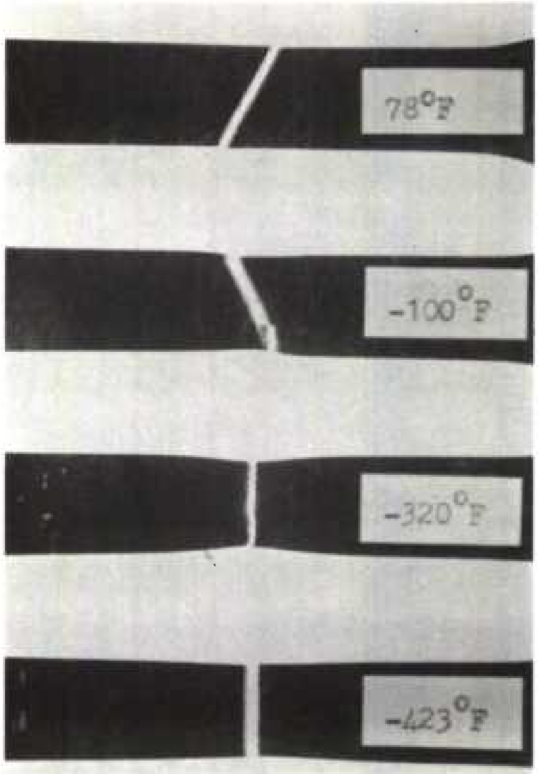


304 Stainless Steel

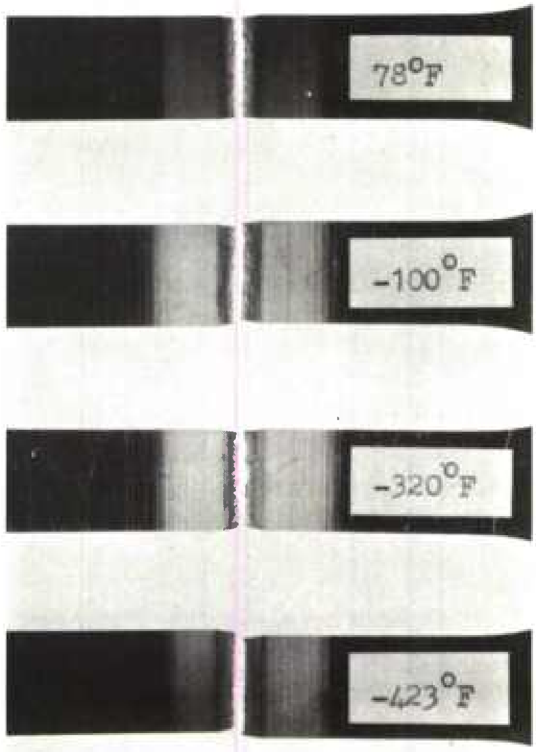


304 Stainless Steel Welds

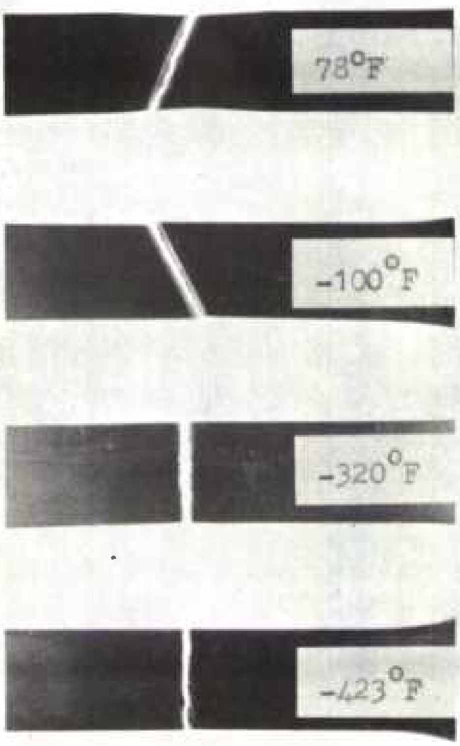
Figure 104. Photomacrographs of Fractured Tensile Specimens (301 and 304 Stainless Steels)



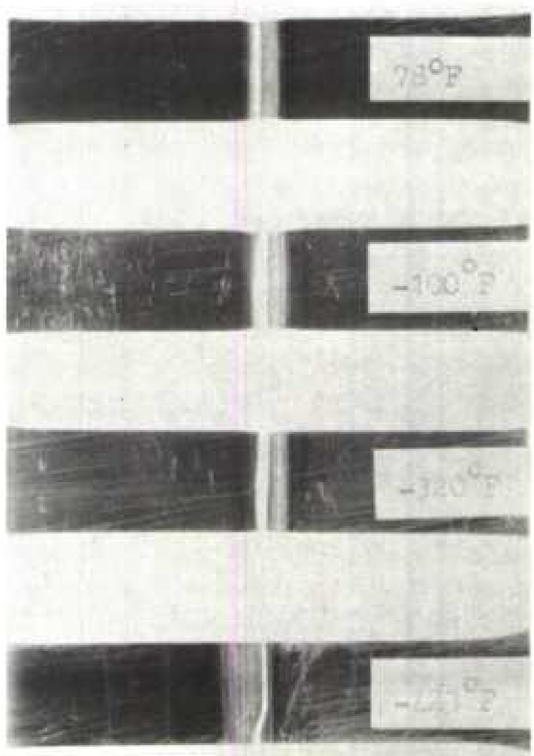
310 Stainless Steel



310 Stainless Steel Welds

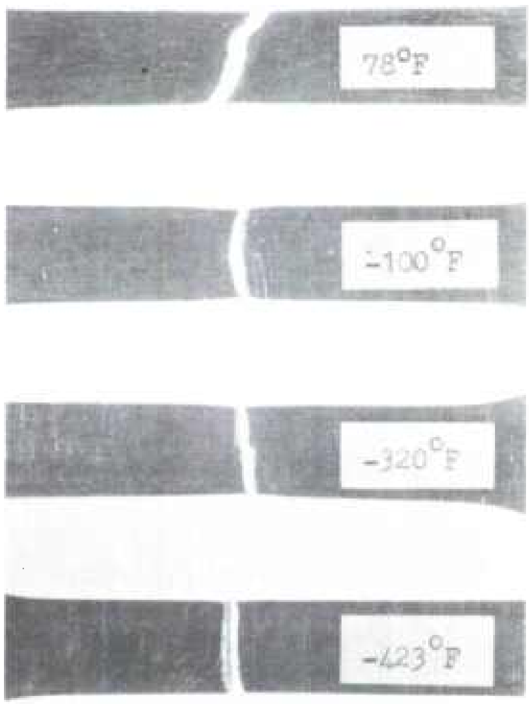


AM-355 Stainless Steel

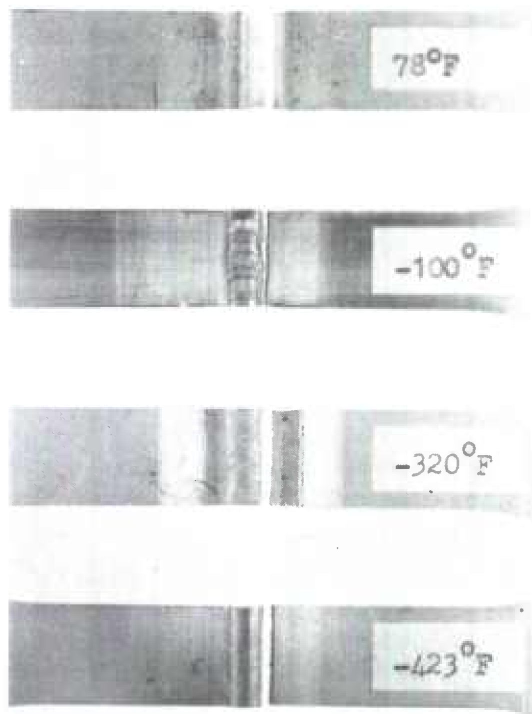


AM-355 Stainless Steel Welds

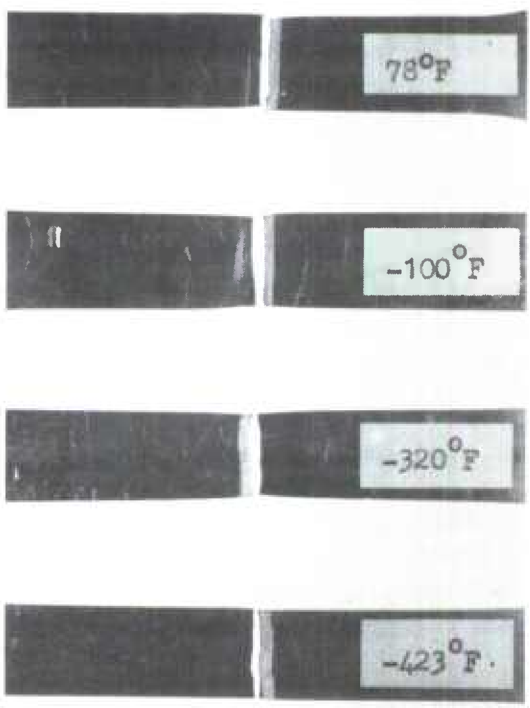
Figure 105. Photomacrographs of Fractured Tensile Specimens (310 and AM-355 Stainless Steels)



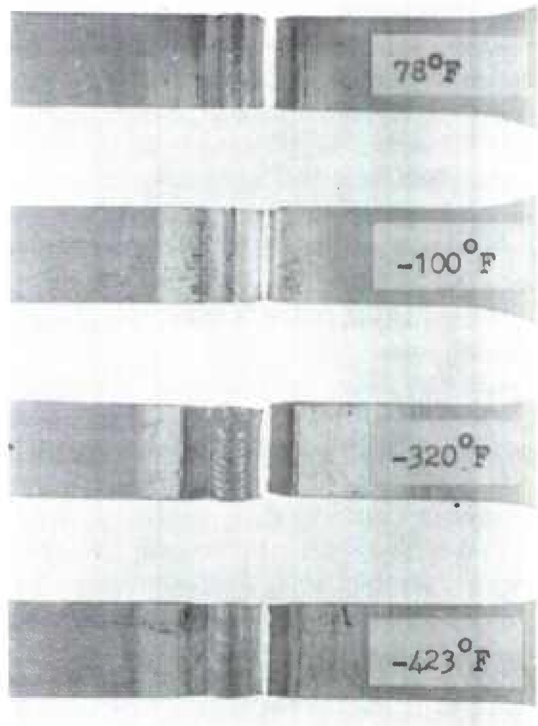
2014-T6 Aluminum Alloy



2014-T6 Aluminum Alloy Welds

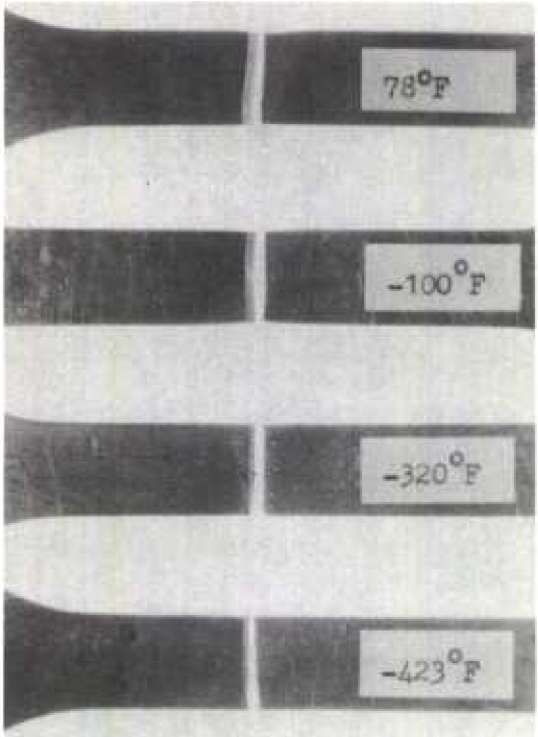


5052-H38 Aluminum Alloy

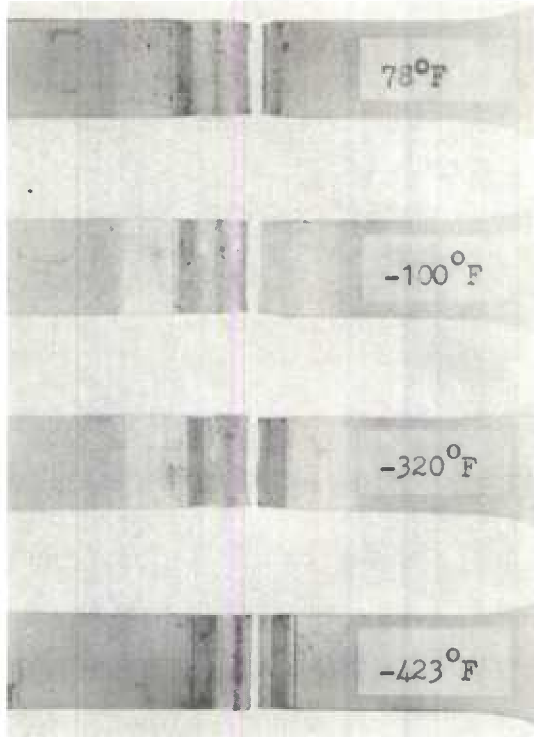


5052-H38 Aluminum Alloy Welds

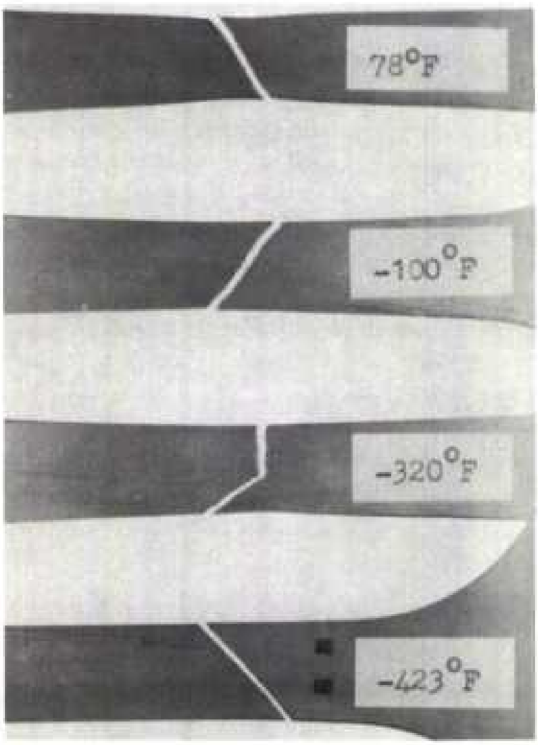
Figure 106. Photomacrographs of Fractured Tensile Specimens (2014-T6 and 5052-H38 Aluminum)



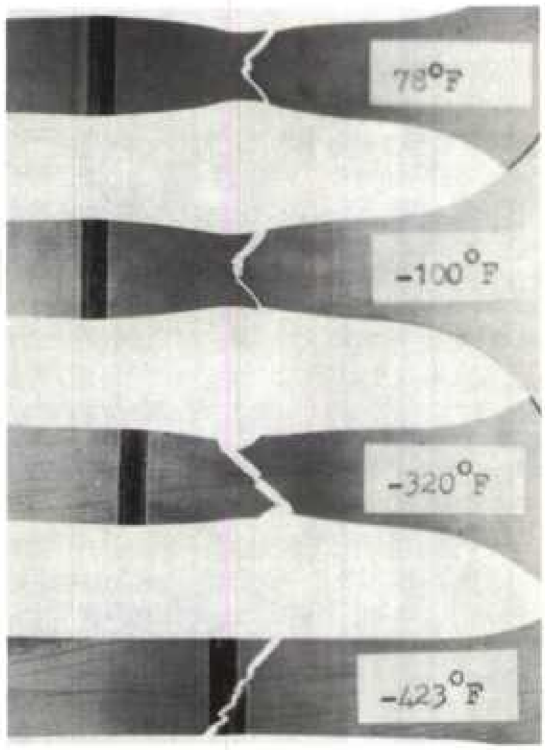
5456-H343 Aluminum Alloy



5456-H343 Aluminum Alloy Welds



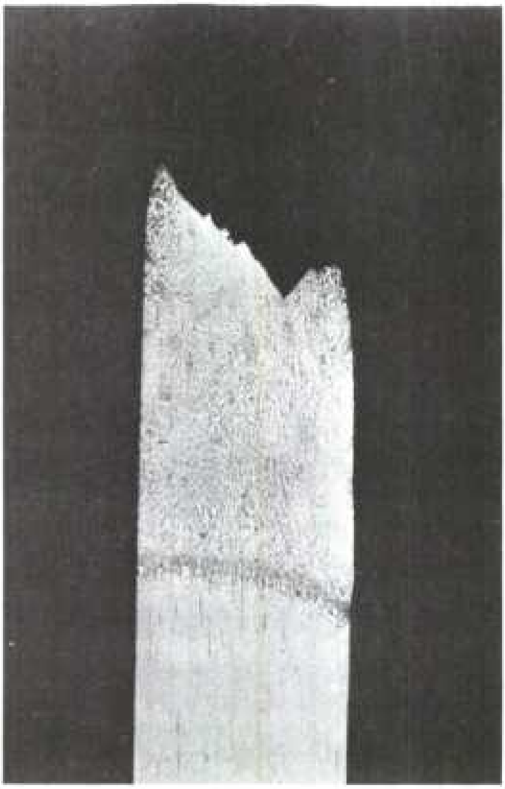
Ti-5Al-2.5Sn Alloy



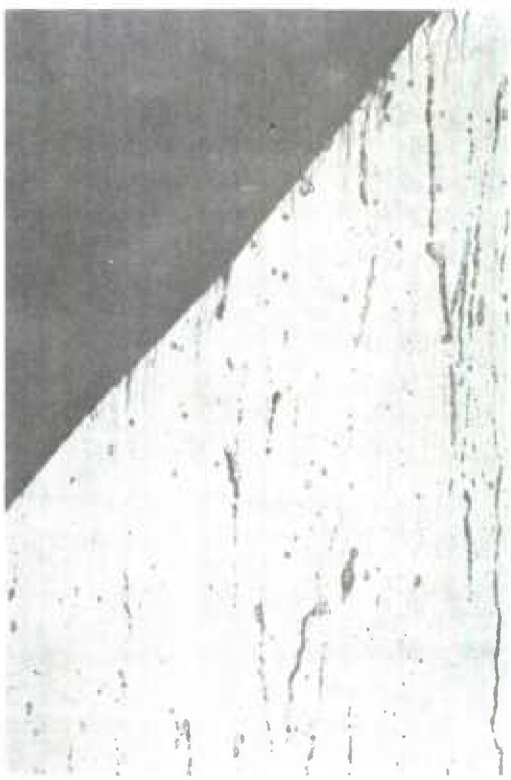
Ti-5Al-2.5Sn Alloy Welds

Figure 107. Photomacrographs of Fractured Tensile Specimens (5456-H343 Al and Ti-5Al-2.5Sn)

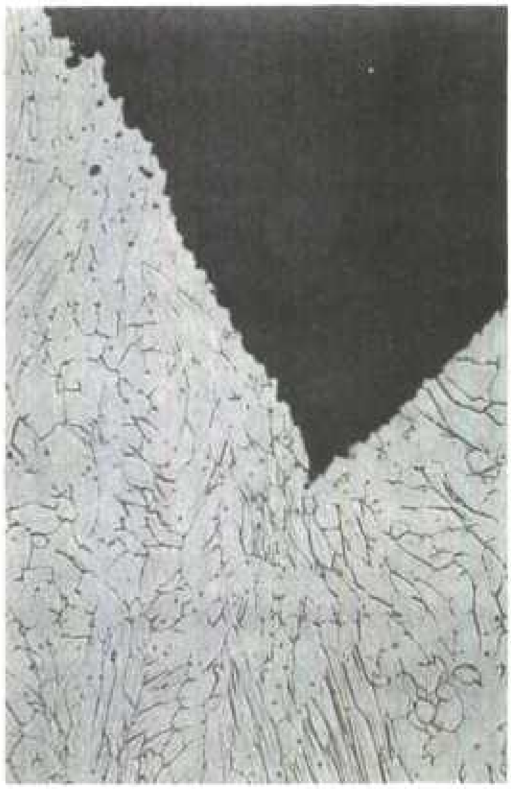
Weld 50X — 78° F — Oxalic Electrolytic Etchant



Weld 50X — -423° F — Oxalic Electrolytic Etchant

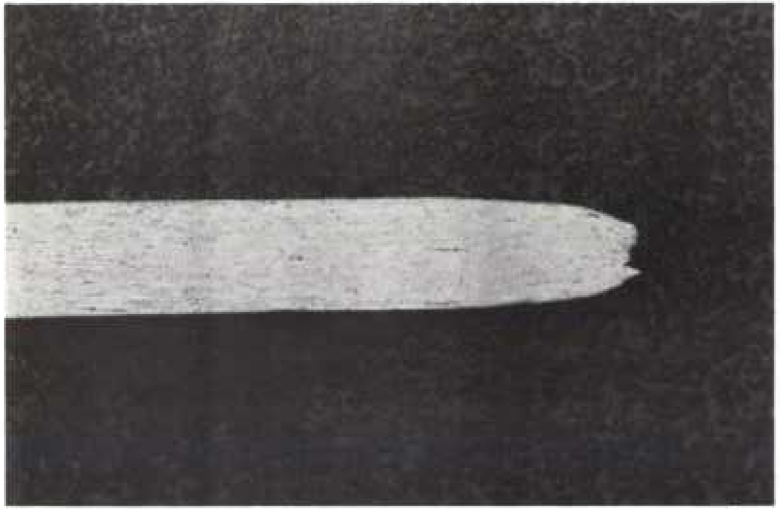


Base Metal 500X — -423° F — Oxalic Electrolytic Etchant

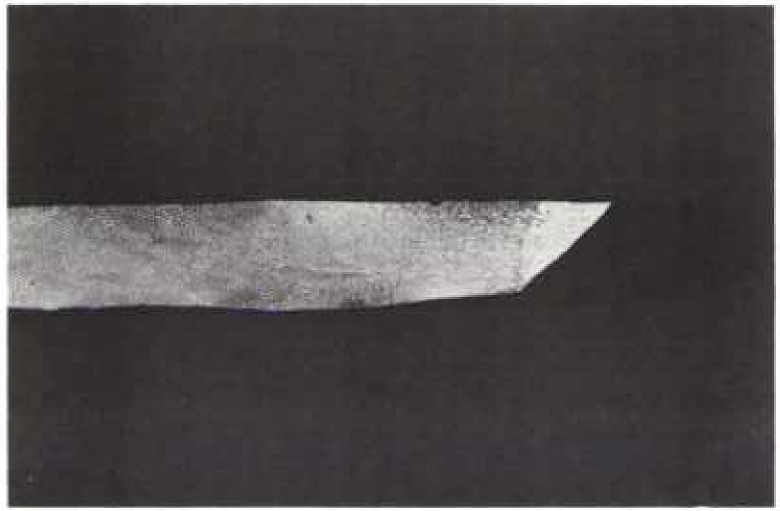


Weld 500X — -423° F — Oxalic Electrolytic Etchant

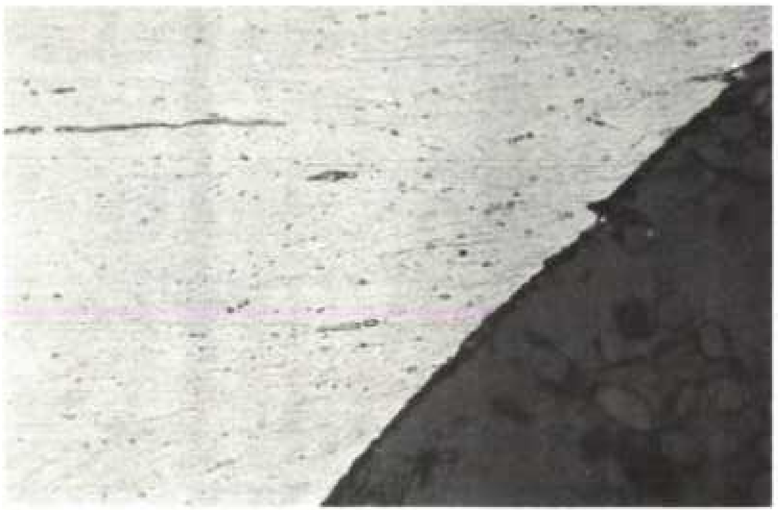
Figure 108. Photomicrographs of Fractured Tensile Specimens (301 SS)



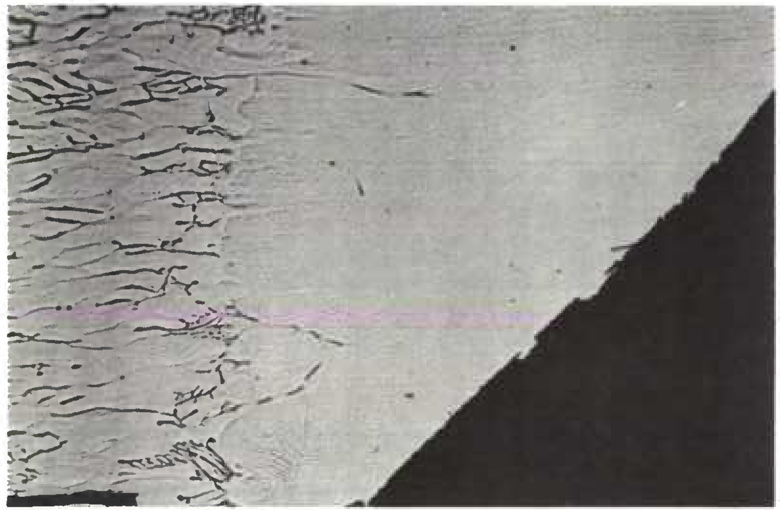
Base Metal -423° F
50X Oxalic Electrolytic Etchant



Weld -423° F
50X Oxalic Electrolytic Etchant

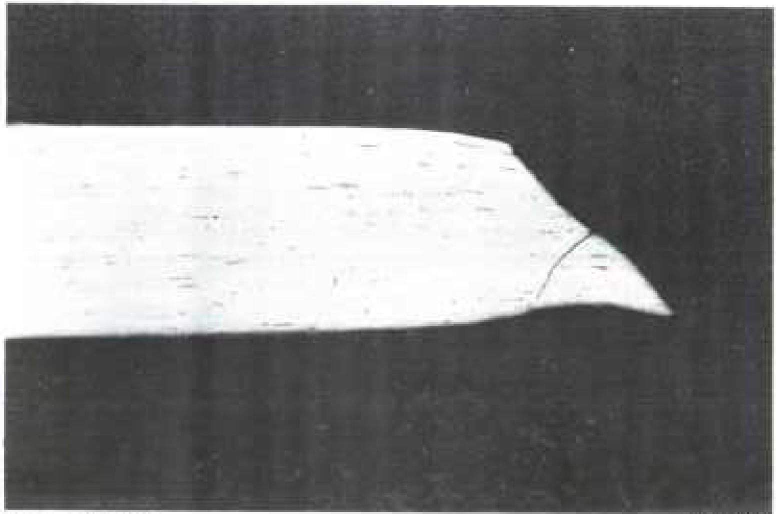


Base Metal -100° F
500X Oxalic Electrolytic Etchant

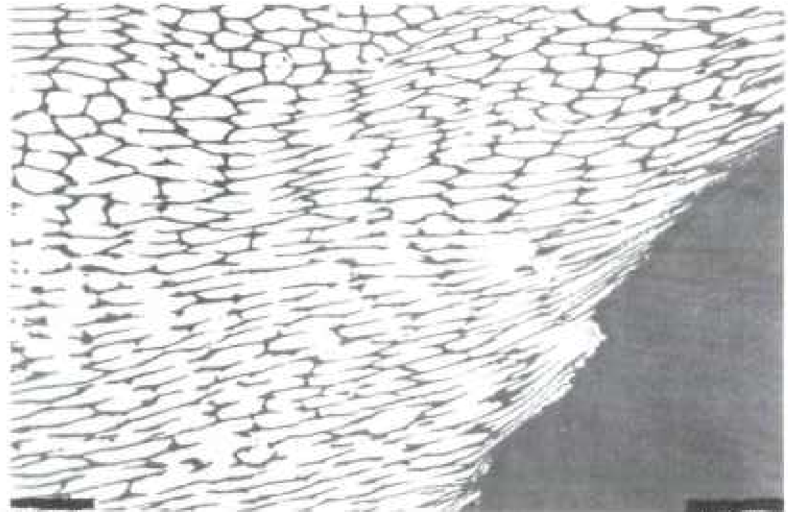


Weld -423° F
500X Oxalic Electrolytic Etchant

Figure 109. Photomicrographs of Fractured Tensile Specimens (304 SS)

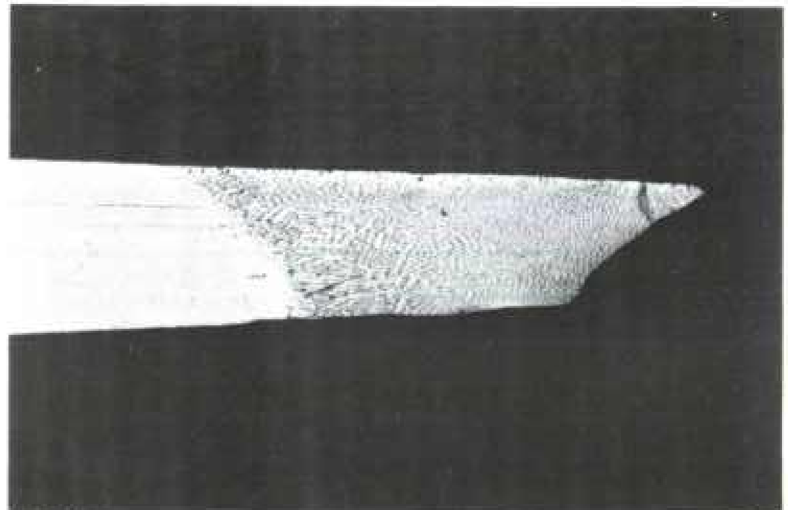


Base Metal -320° F
50X Oxalic Electrolytic Etchant



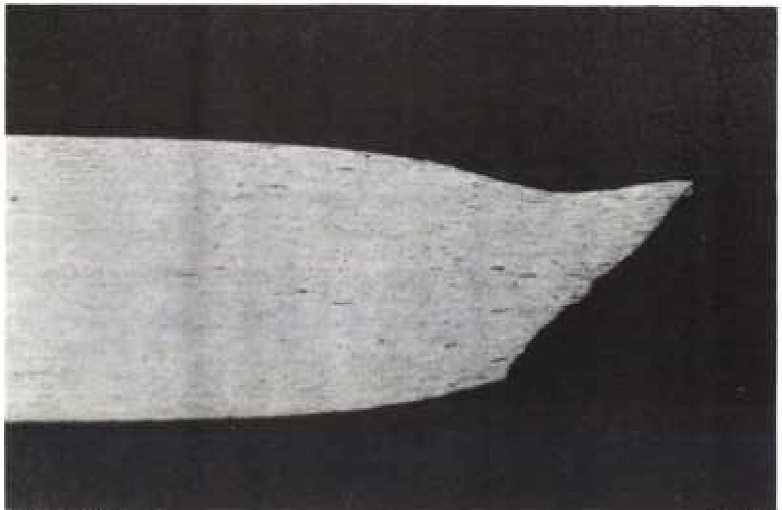
Weld -423° F
50X Oxalic Electrolytic Etchant

Base Metal -100° F
500X Oxalic Electrolytic Etchant

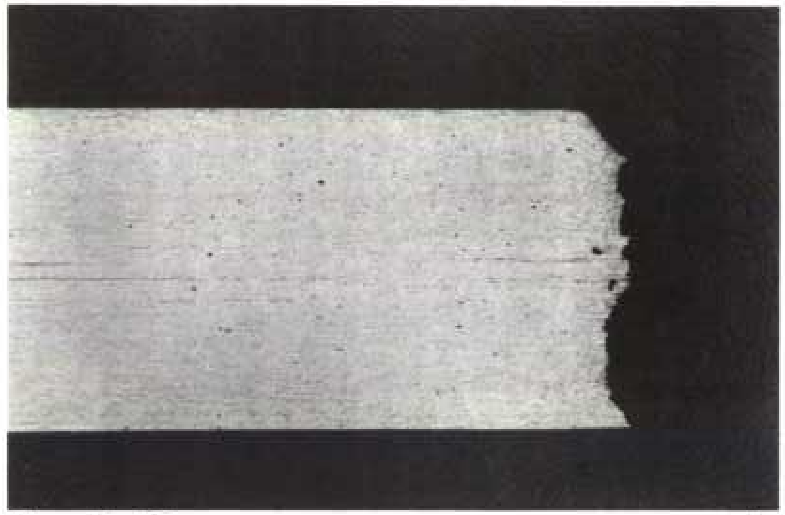


Weld 78° F
500X Oxalic Electrolytic Etchant

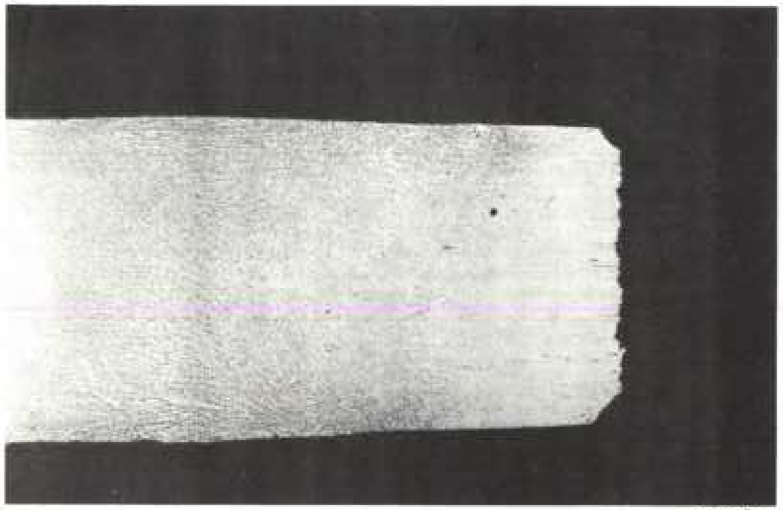
Figure 110. Photomicrographs of Fractured Tensile Specimens (310 SS)



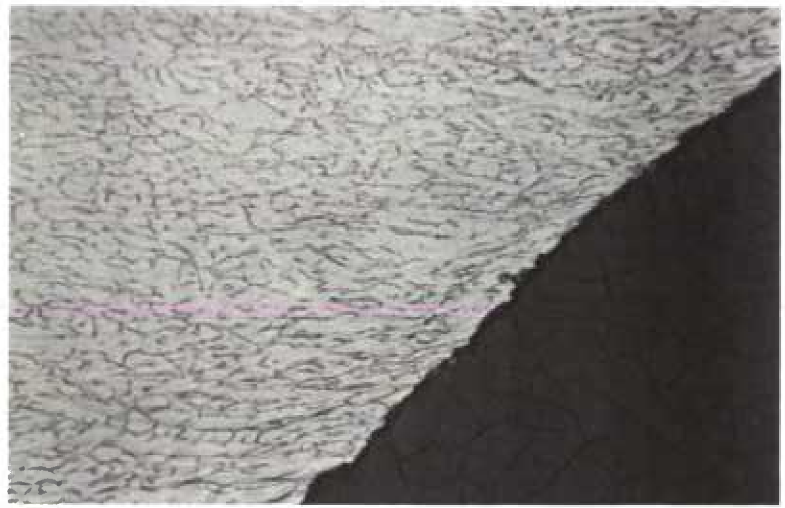
Base Metal 78° F
50X Oxalic Electrolytic Etchant



Base Metal -320° F
50X Oxalic Electrolytic Etchant

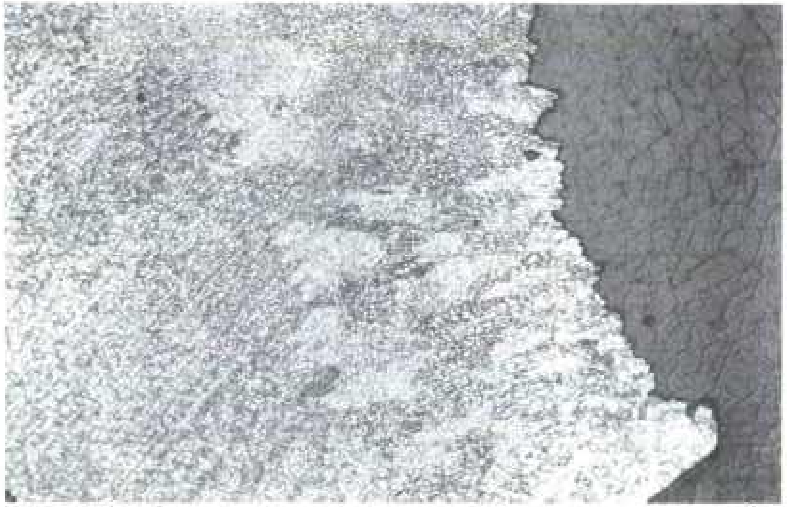


Weld -320° F
50X Oxalic Electrolytic Etchant

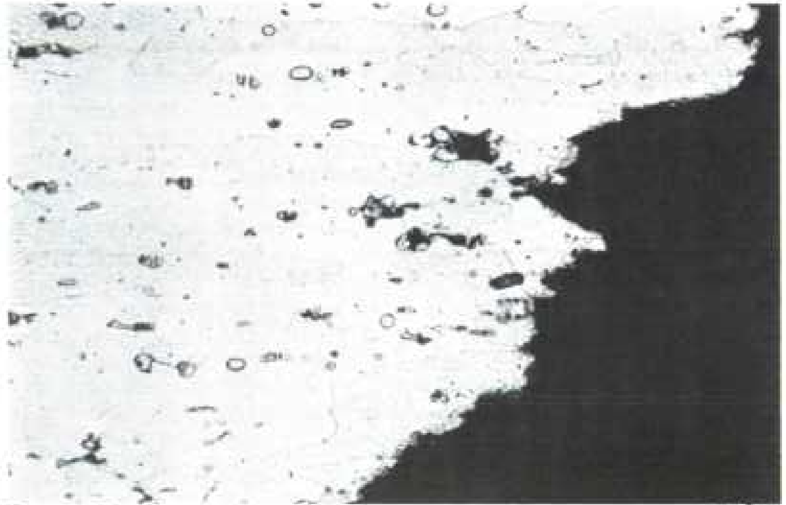


Weld -100° F
500X Oxalic Electrolytic Etchant

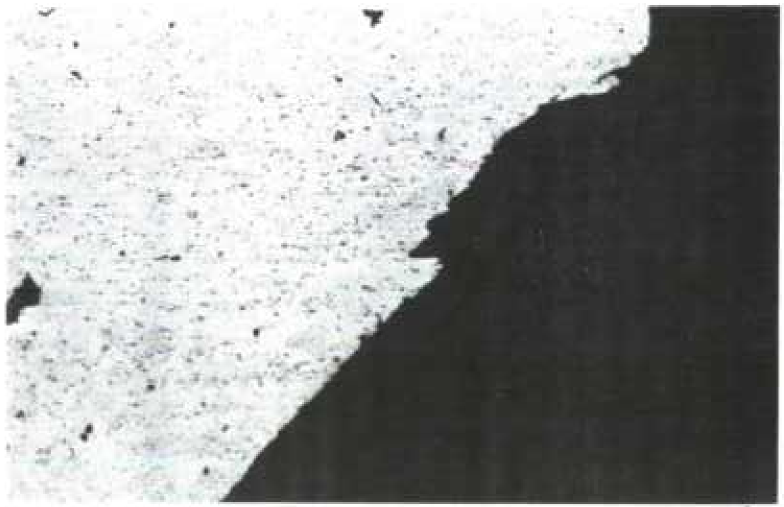
Figure 111. Photomicrographs of Fractured Tensile Specimens (AM-355 SS)



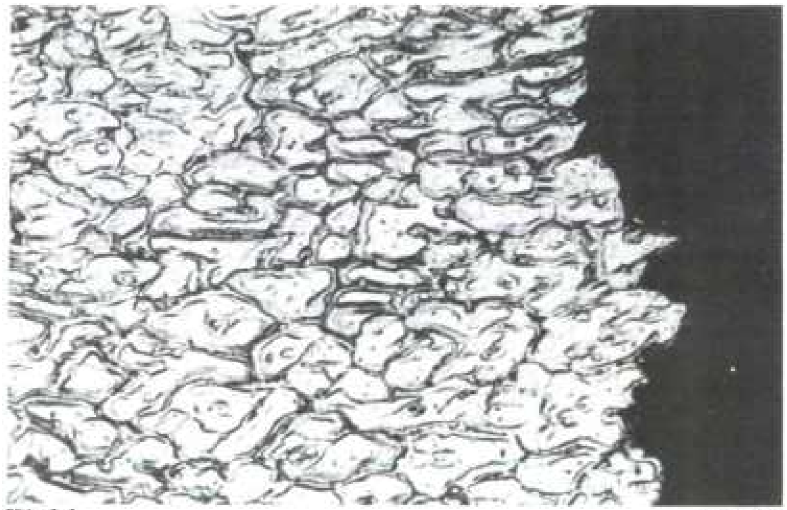
Base Metal -423° F
50X Keller's Etchant



Base Metal -100° F
500X Keller's Etchant

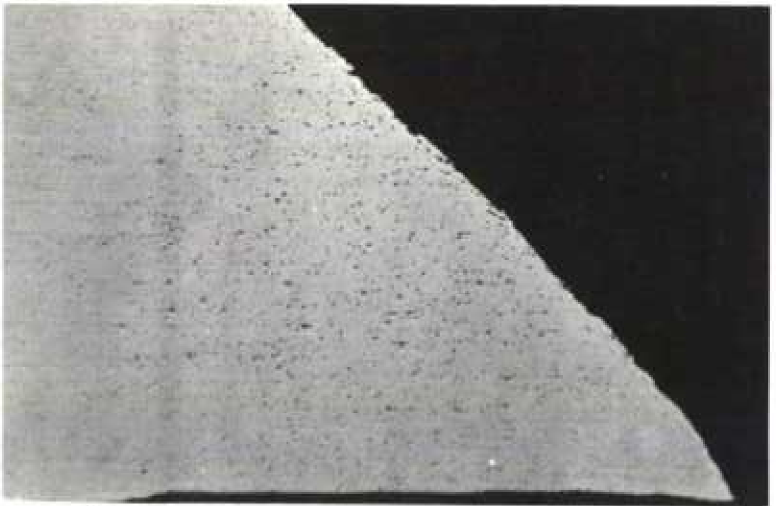


Weld -423° F
50X Keller's Etchant



Weld -423° F
500X Keller's Etchant

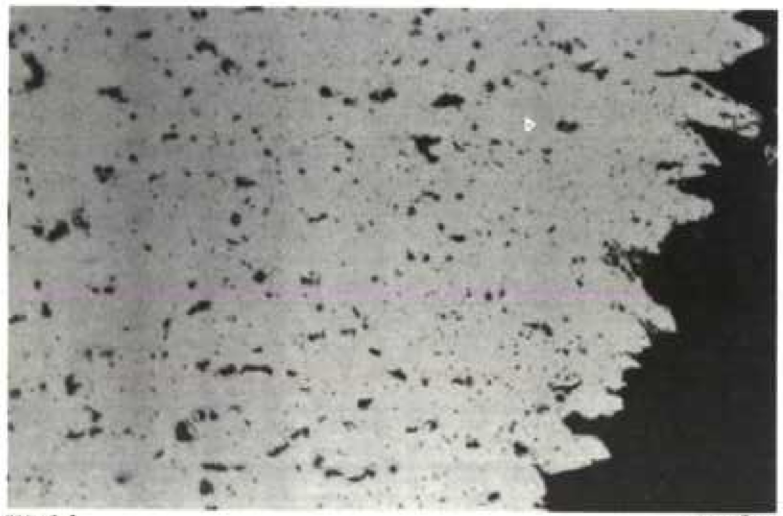
Figure 112. Photomicrographs of Fractured Tensile Specimens (2014-T6 Al Alloy)



Base Metal 78° F
50X Keller's Etchant

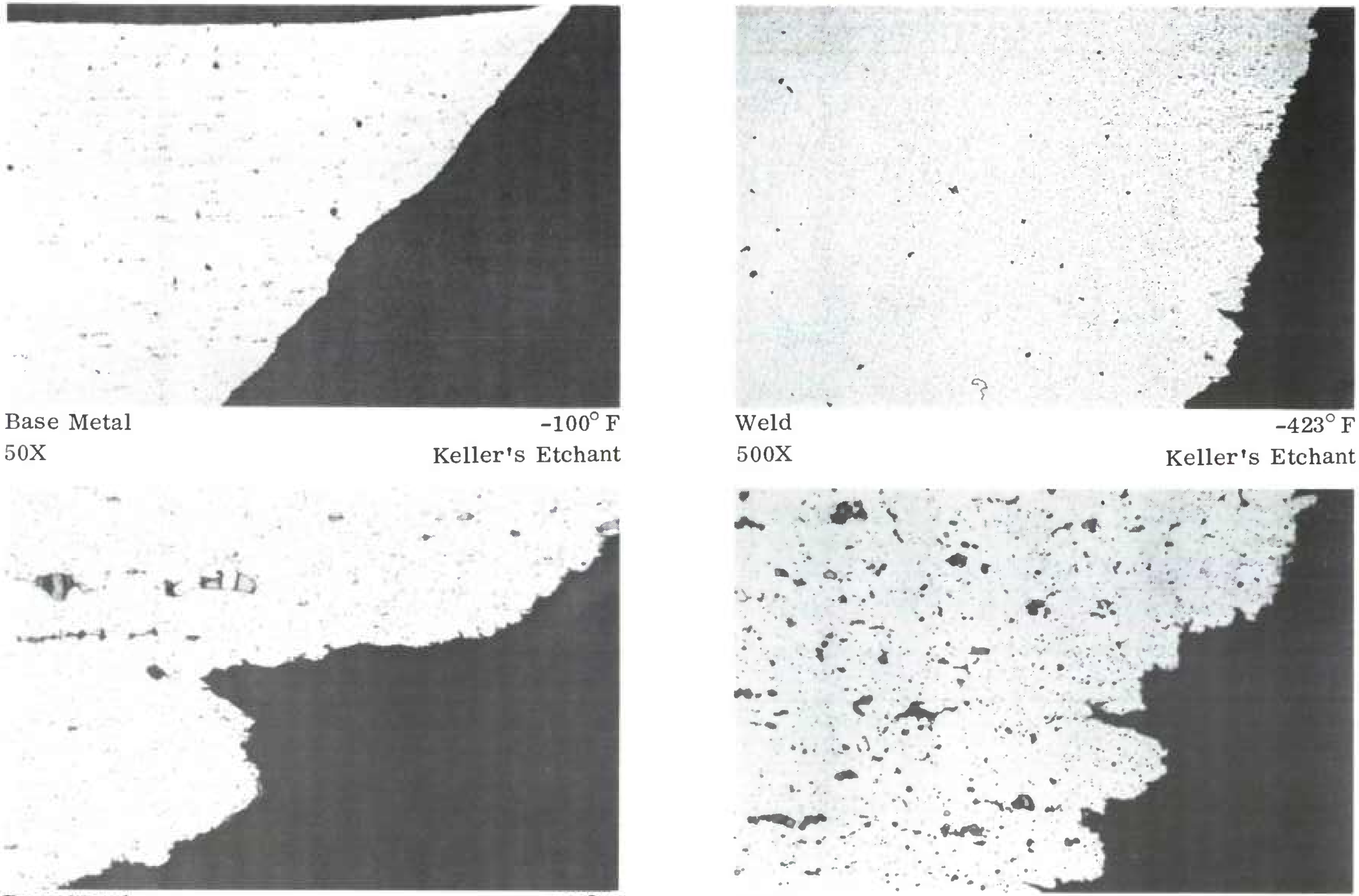
Weld -100° F
50X Keller's Etchant

Base Metal -423° F
500X Keller's Etchant



Weld -320° F
500X Keller's Etchant

Figure 113. Photomicrographs of Fractured Tensile Specimens (5052-H38 Al Alloy)



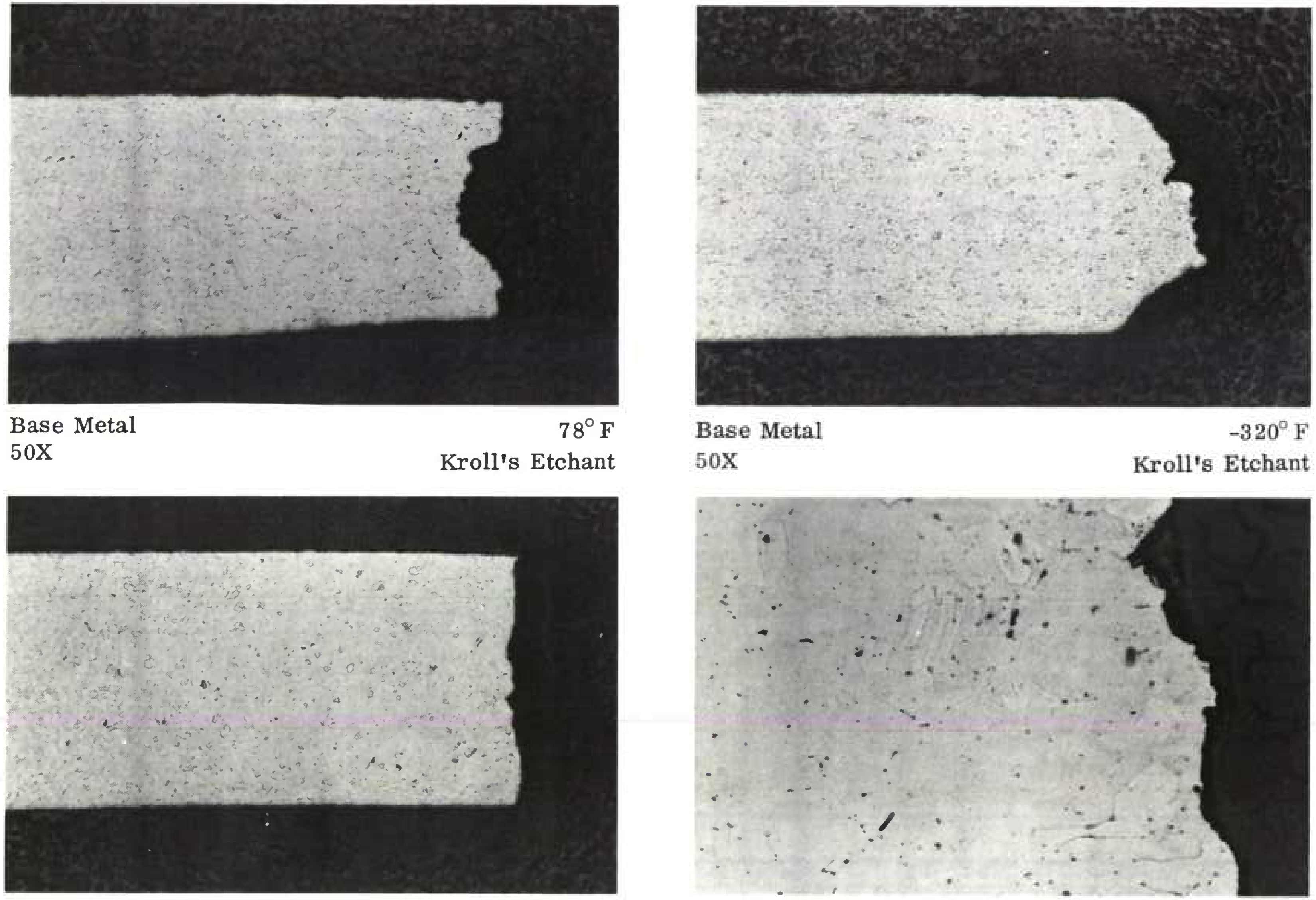
Base Metal 50X — -100° F, Keller's Etchant

Weld 500X — -423° F, Keller's Etchant

Base Metal 500X — -100° F, Keller's Etchant

Weld 500X — -423° F, Keller's Etchant

Figure 114. Photomicrographs of Fractured Tensile Specimens (5456-H343 Al Alloy)



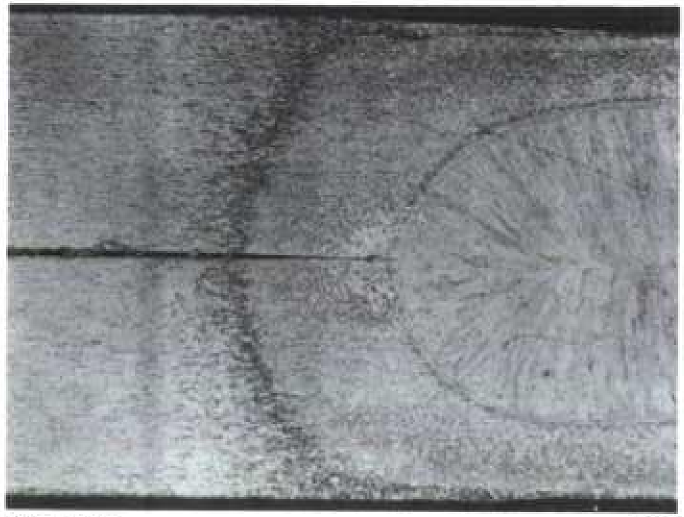
Base Metal 50X — 78° F Kroll's Etchant

Base Metal 50X — -320° F Kroll's Etchant

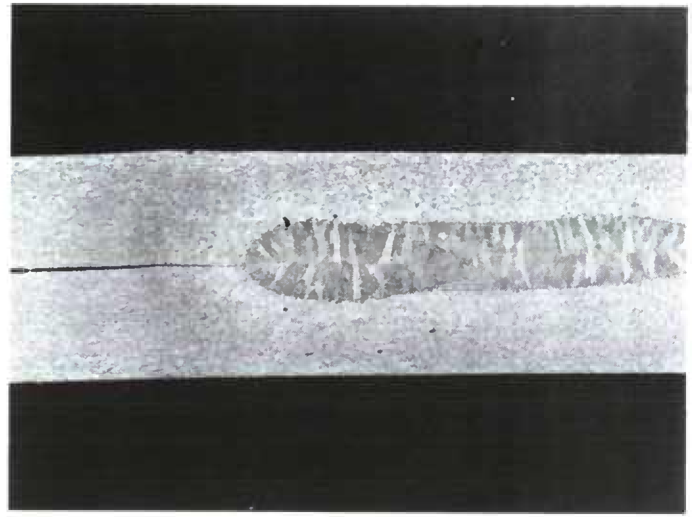
Base Metal 50X — -423° F Kroll's Etchant

Base Metal 500X — -423° F Kroll's Etchant

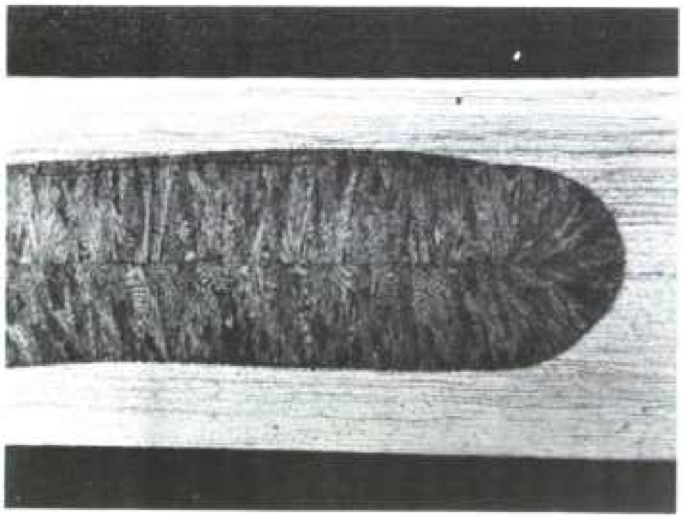
Figure 115. Photomicrographs of Fractured Tensile Specimens (Ti-5Al-2.4Sn Alloy)



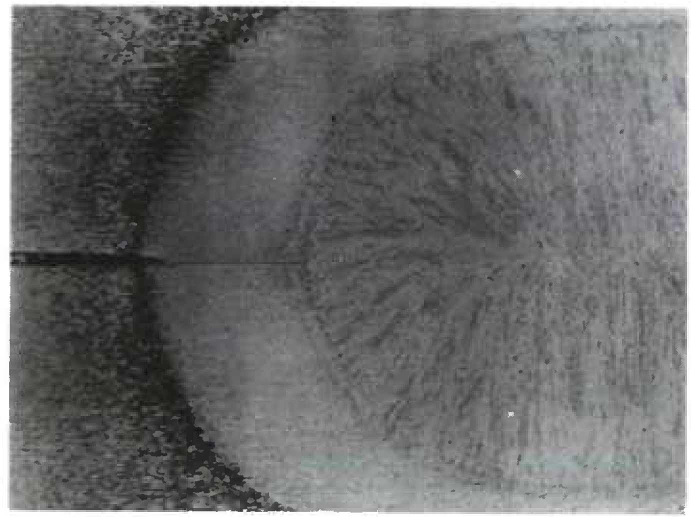
301 S.S. 50X
Oxalic Electrolytic Etchant



304 S.S. 50X
Oxalic Electrolytic Etchant

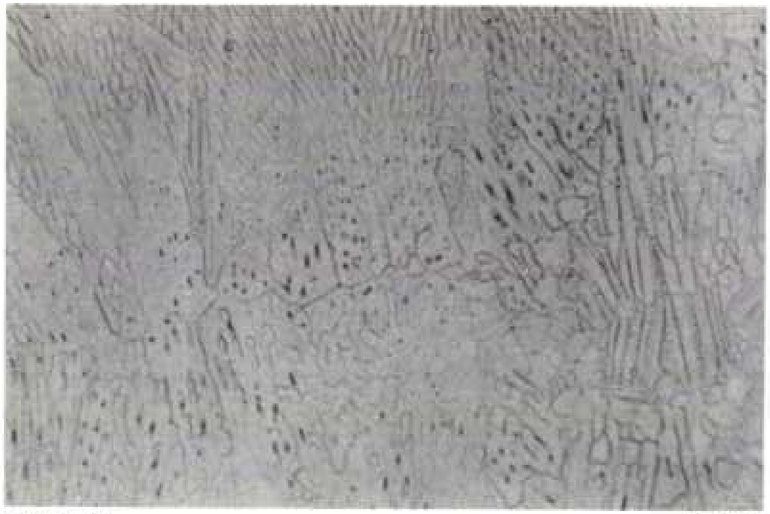


310 S.S. 50X
Oxalic Electrolytic Etchant

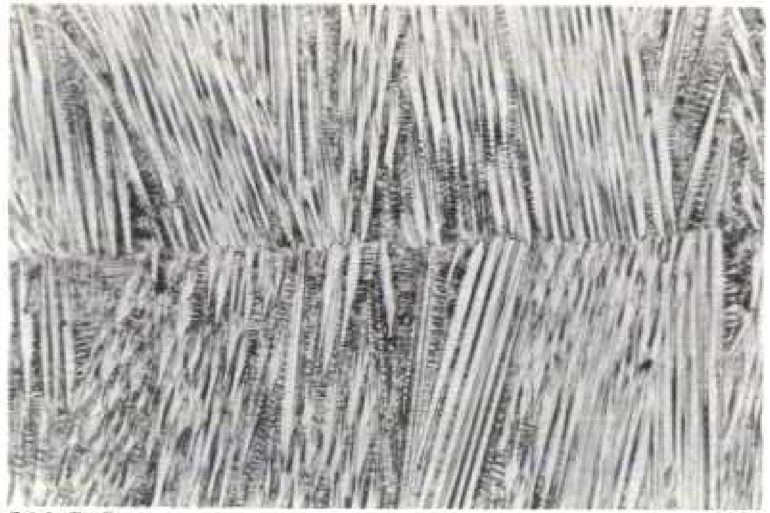


AM-355 S.S. 50X
Oxalic Electrolytic Etchant

Figure 116. Photomicrographs of Resistance Spot Welds (50X)



304 S.S. 500X
Oxalic Electrolytic Etchant



310 S.S. 500X
Oxalic Electrolytic Etchant

AM-355 S.S. 500X
Oxalic Electrolytic Etchant

Ti-5Al-2.5 Sn 500X
Kroll's Etchant

Figure 117. Photomicrographs of Resistance Spot Welds (500X)

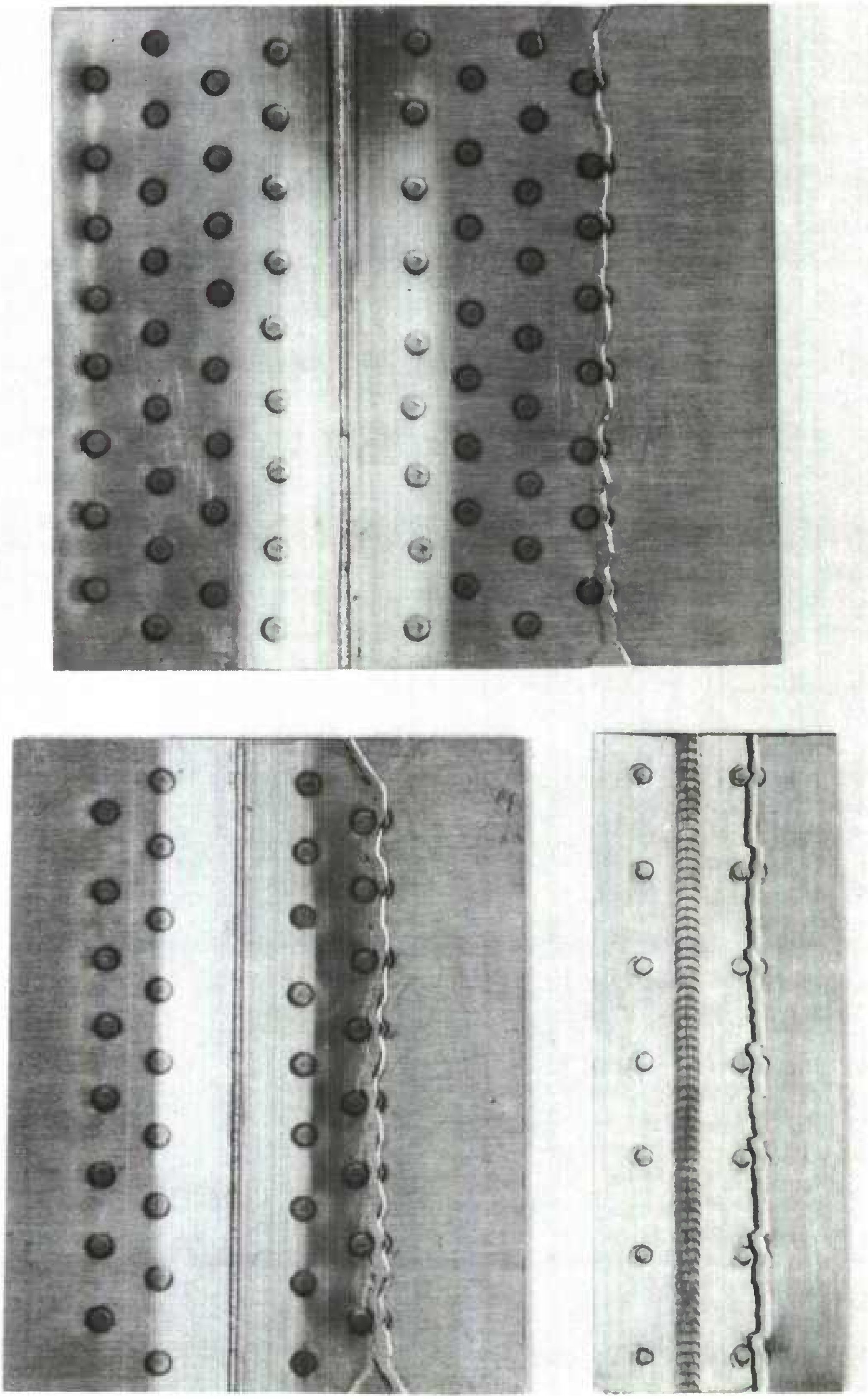


Figure 118. Fractured Fatigue Specimens - 301 SS (78° F)

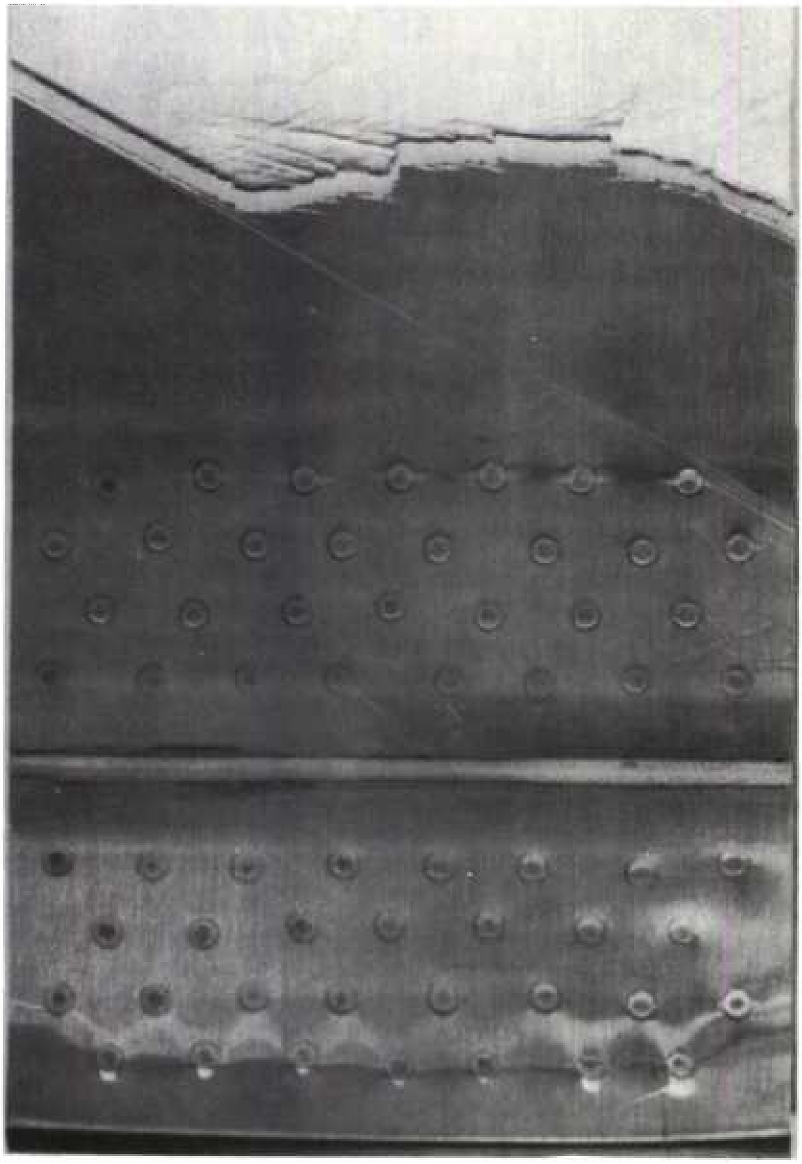


Figure 119. Fractured Fatigue Specimen - 301 SS

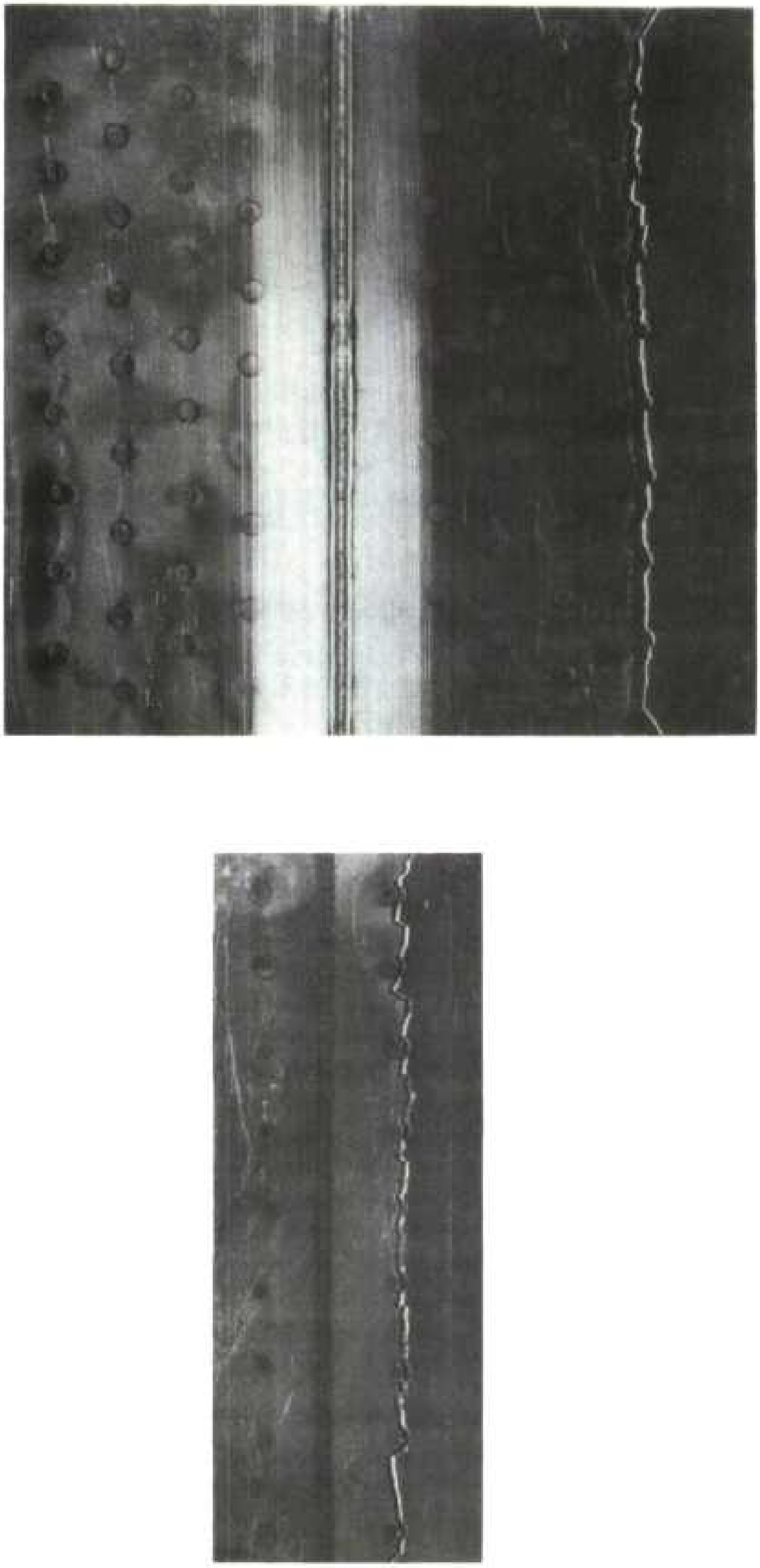


Figure 120. Fractured Fatigue Specimens - 304 SS (78° F)

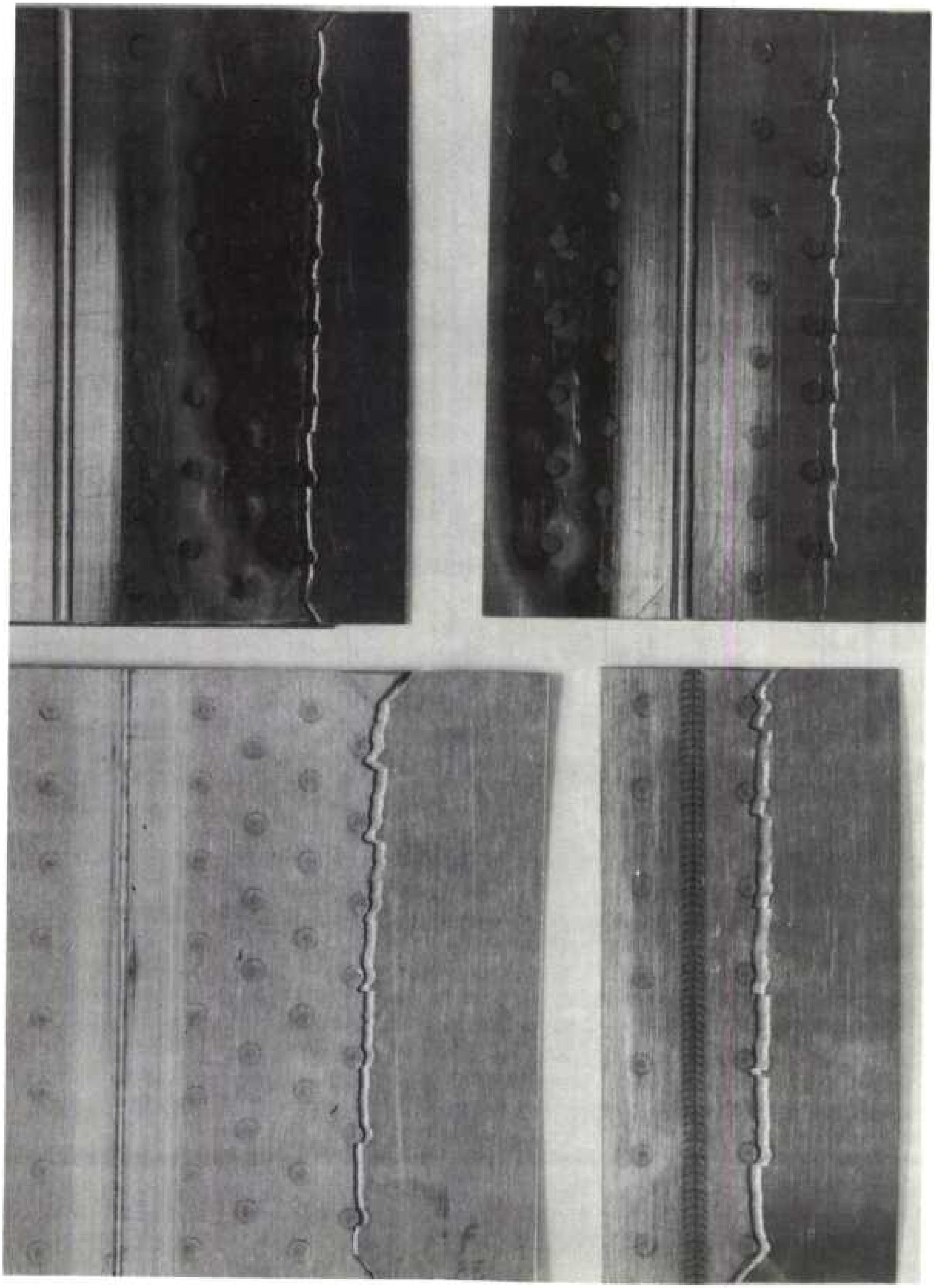


Figure 121. Fractured Fatigue Specimens - 310 SS (78° F)

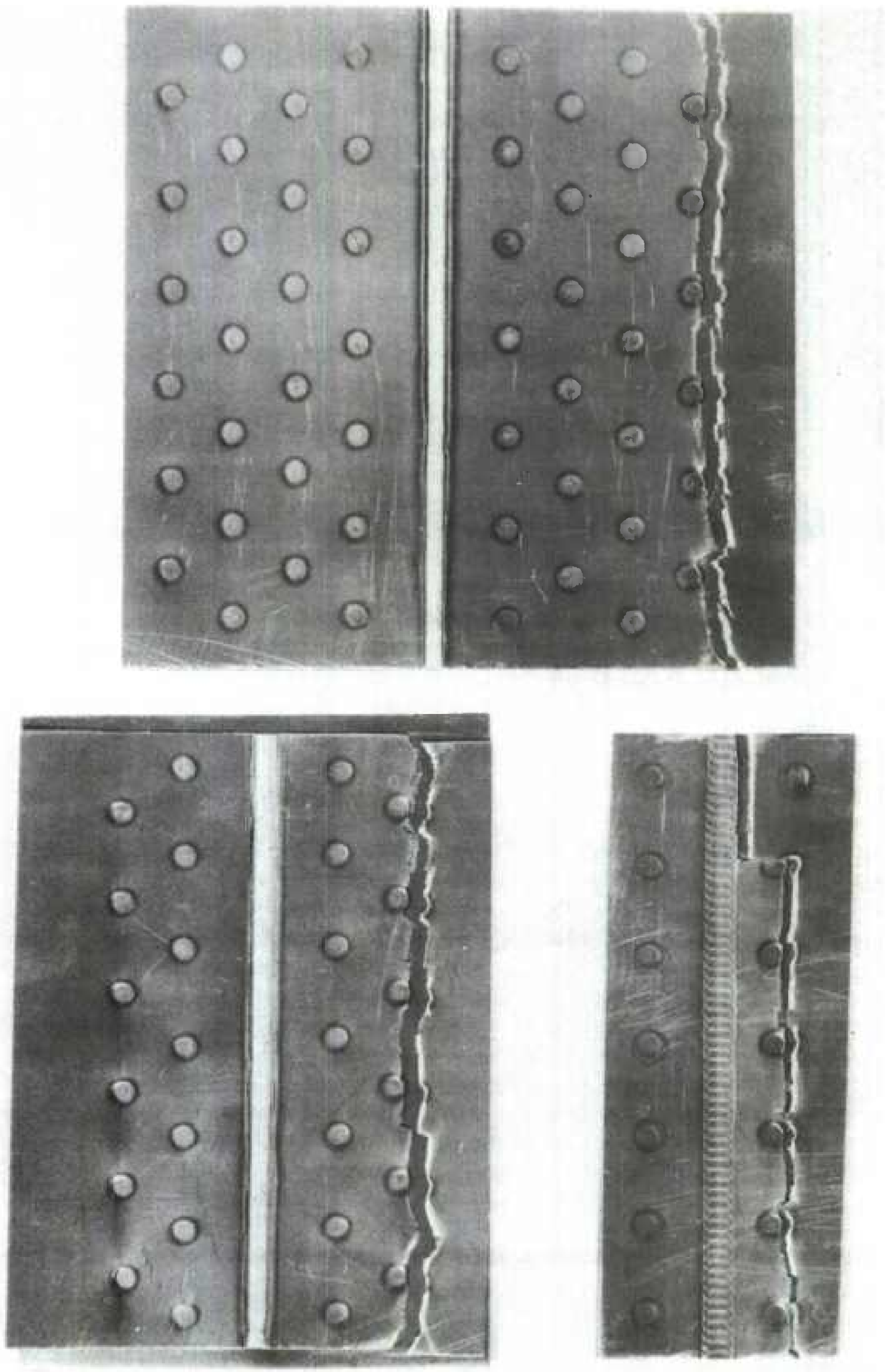


Figure 122. Fractured Fatigue Specimens - AM-355 SS (78° F)

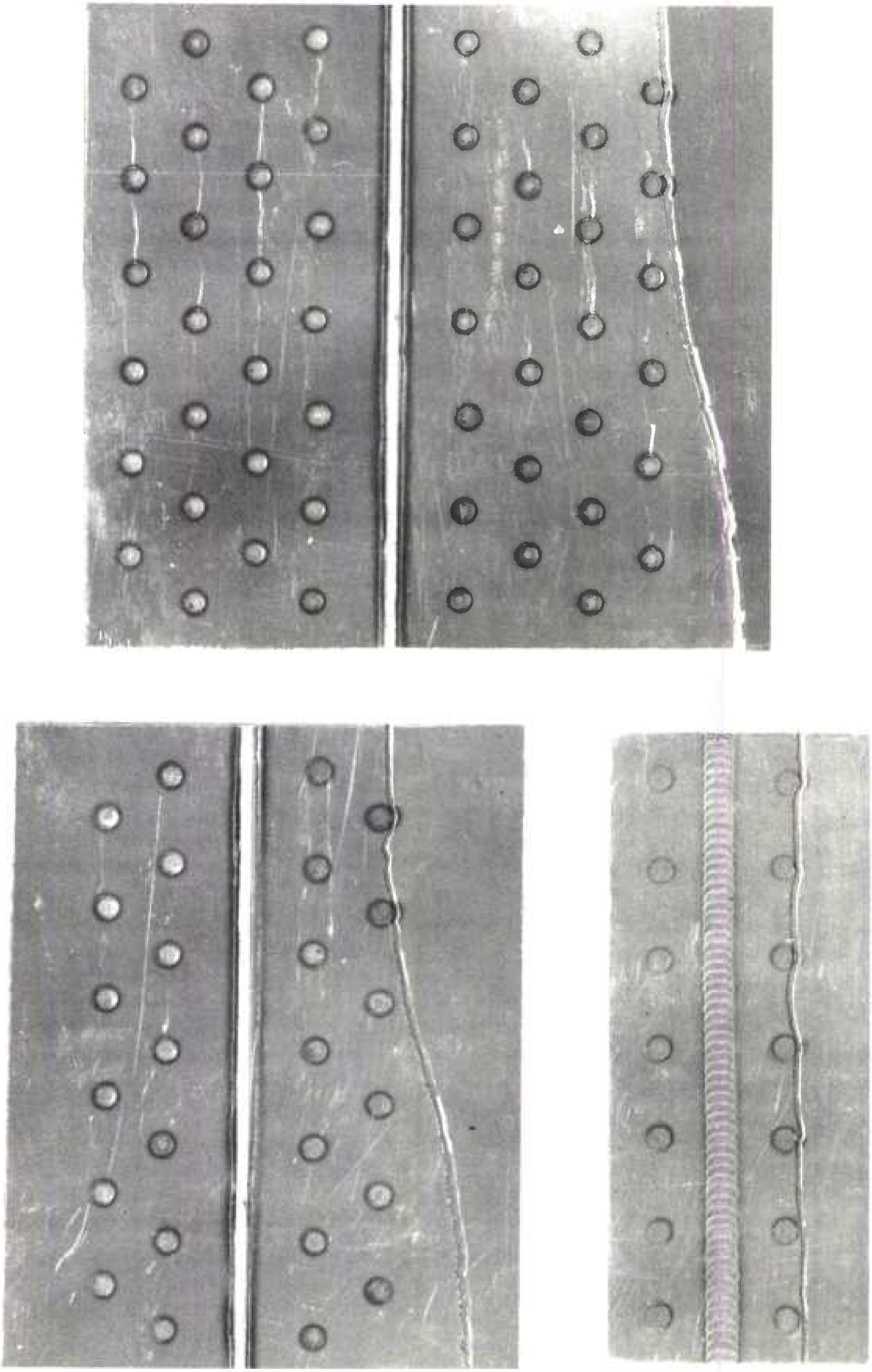


Figure 123. Fractured Fatigue Specimens - AM-355 SS (-423° F)

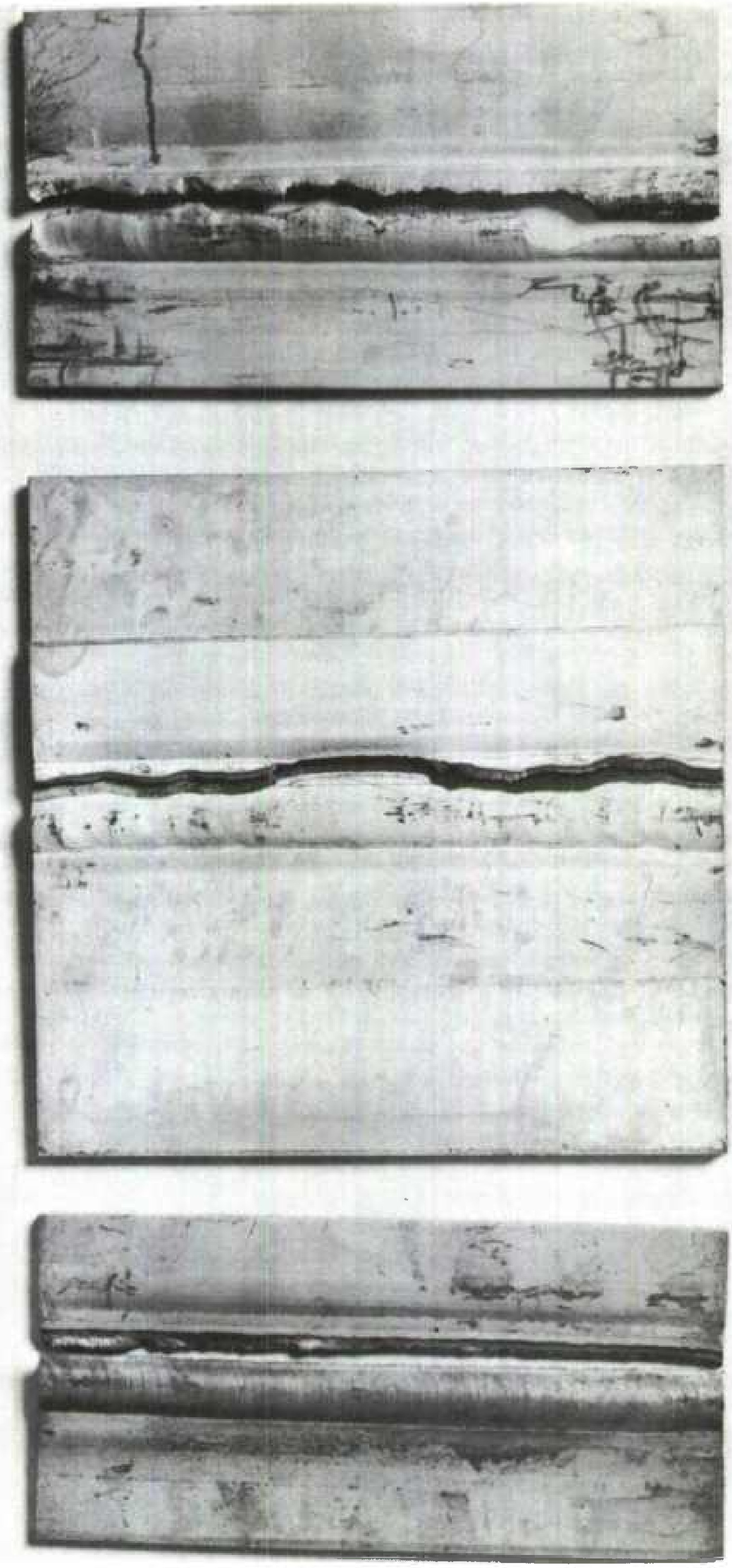


Figure 124. Fractured Fatigue Specimens - 2014-T6 Aluminum Alloy (78° F)

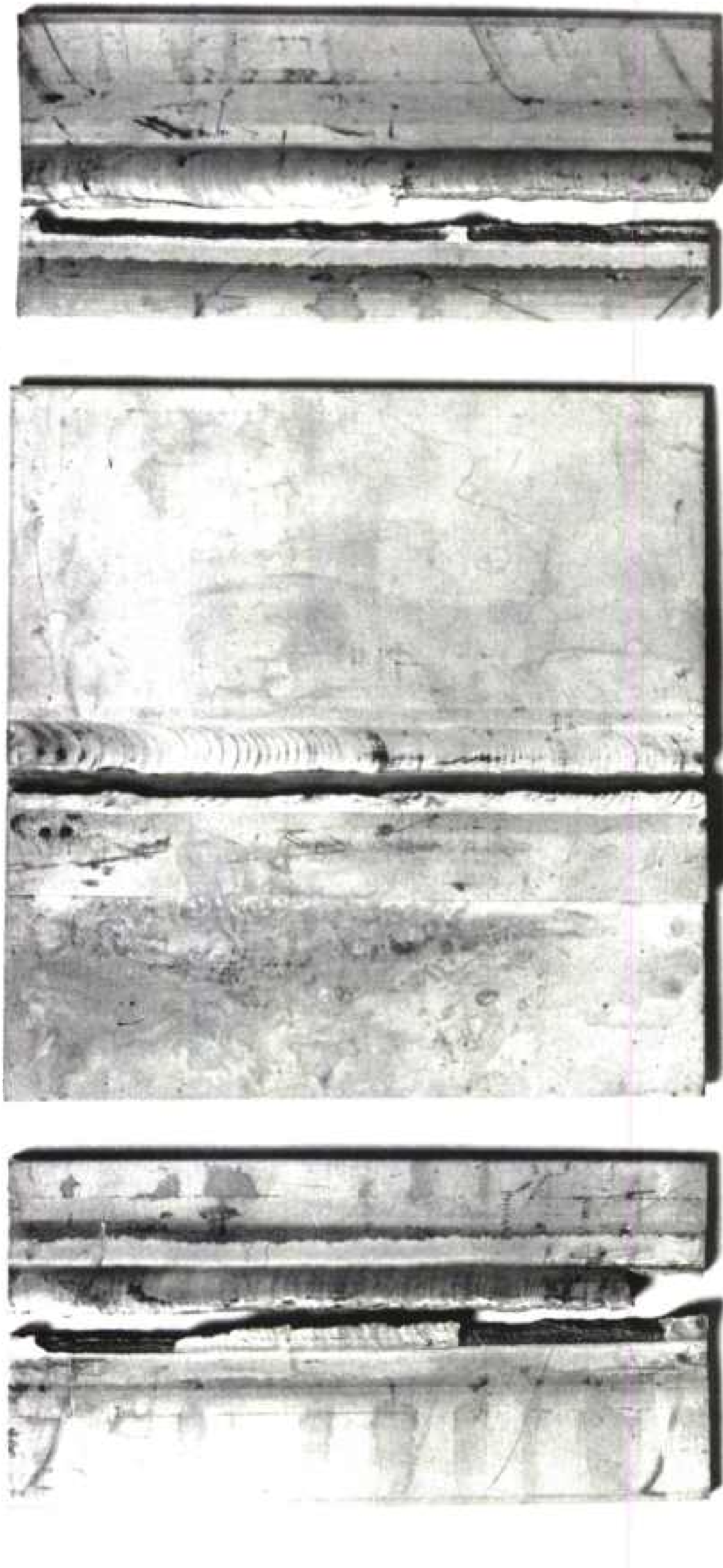


Figure 125. Fractured Fatigue Specimens - 2014-T6 Aluminum Alloy (-423° F)

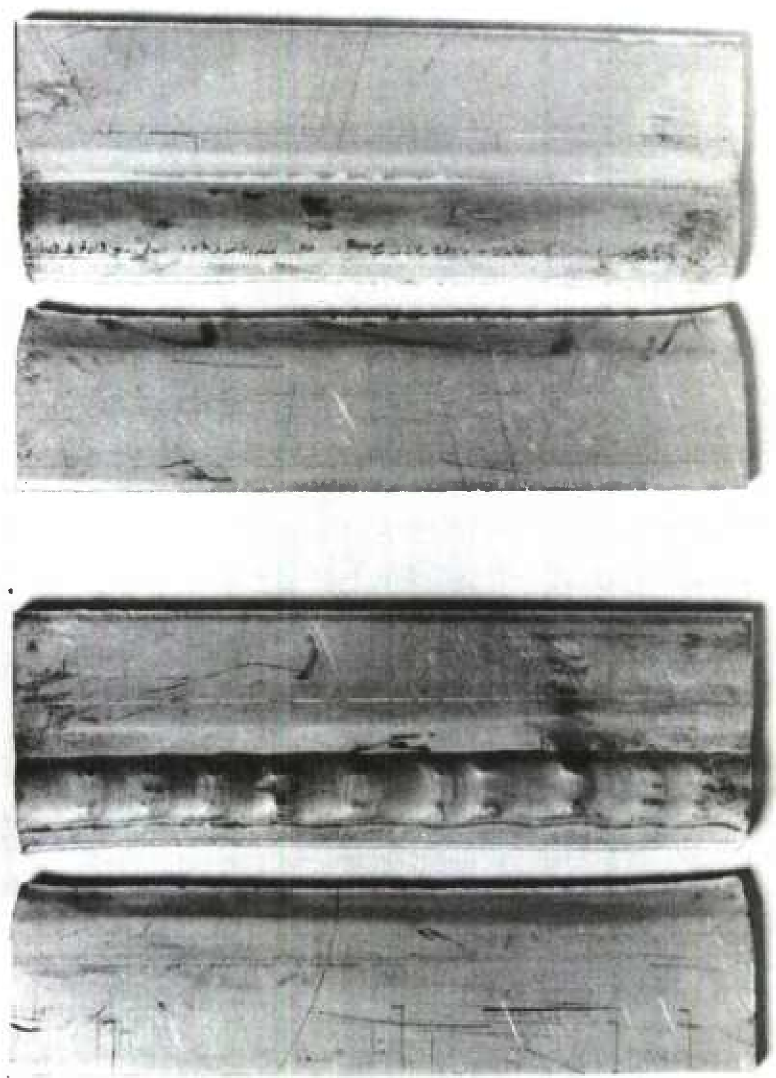


Figure 126. Fractured Fatigue Specimens 5052-H38 Aluminum Alloy (78° F)

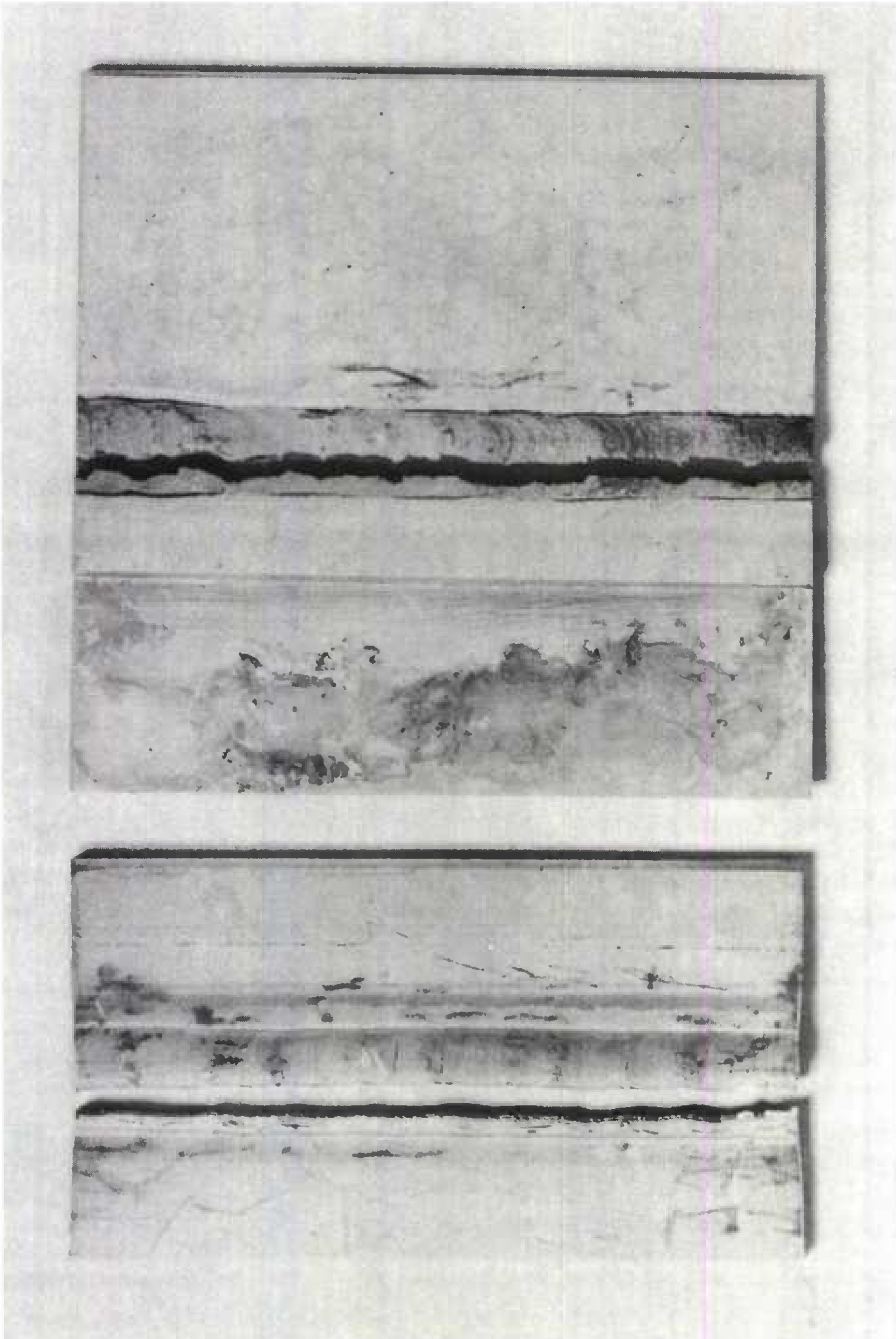


Figure 127. Fractured Fatigue Specimens - 5456-H343 Aluminum Alloy (-320° F)

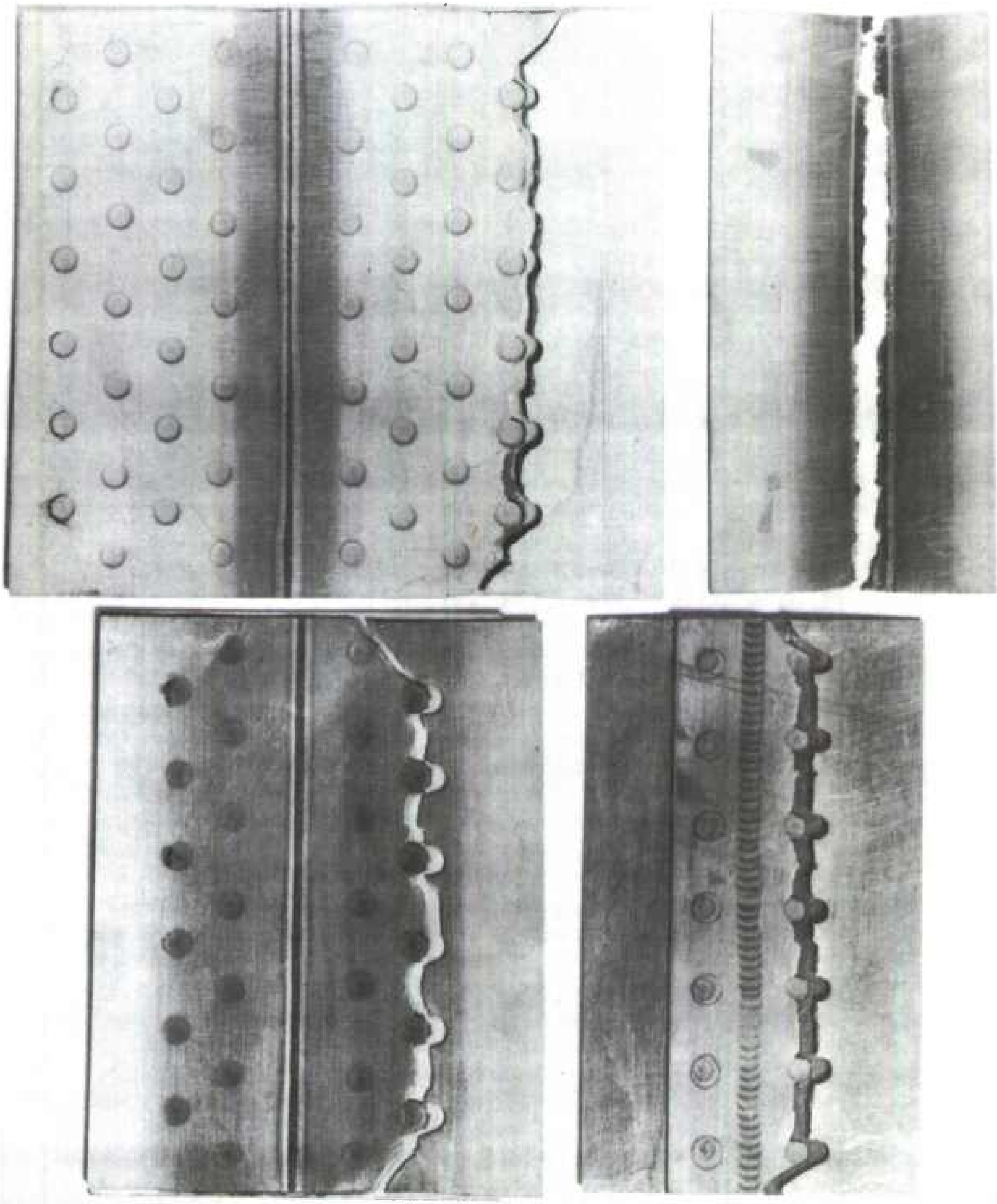


Figure 128. Fractured Fatigue Specimens - Ti-5Al-2.5Sn Alloy (78° F)

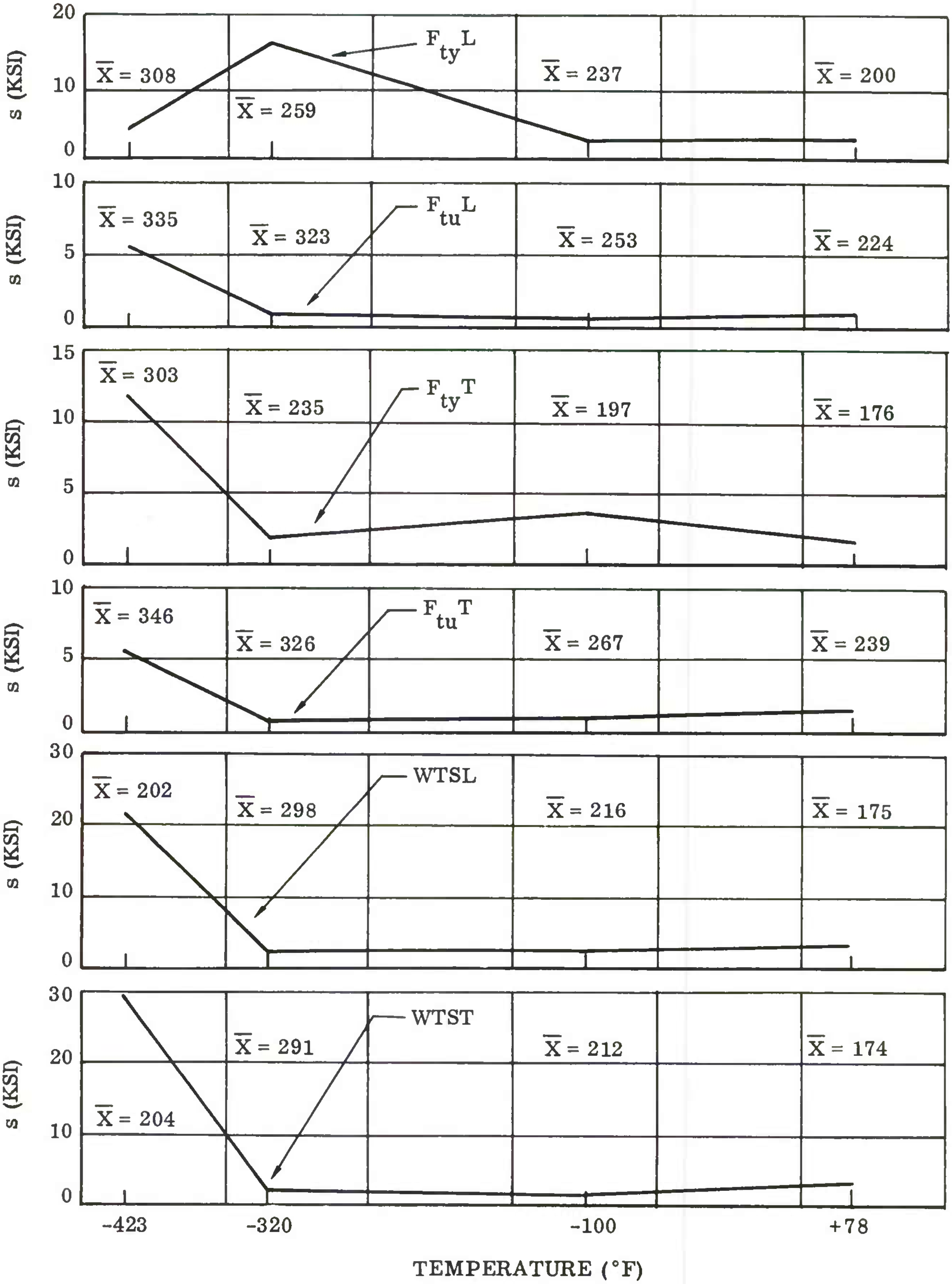


Figure 129. Standard Deviations Versus Temperature (301 SS)

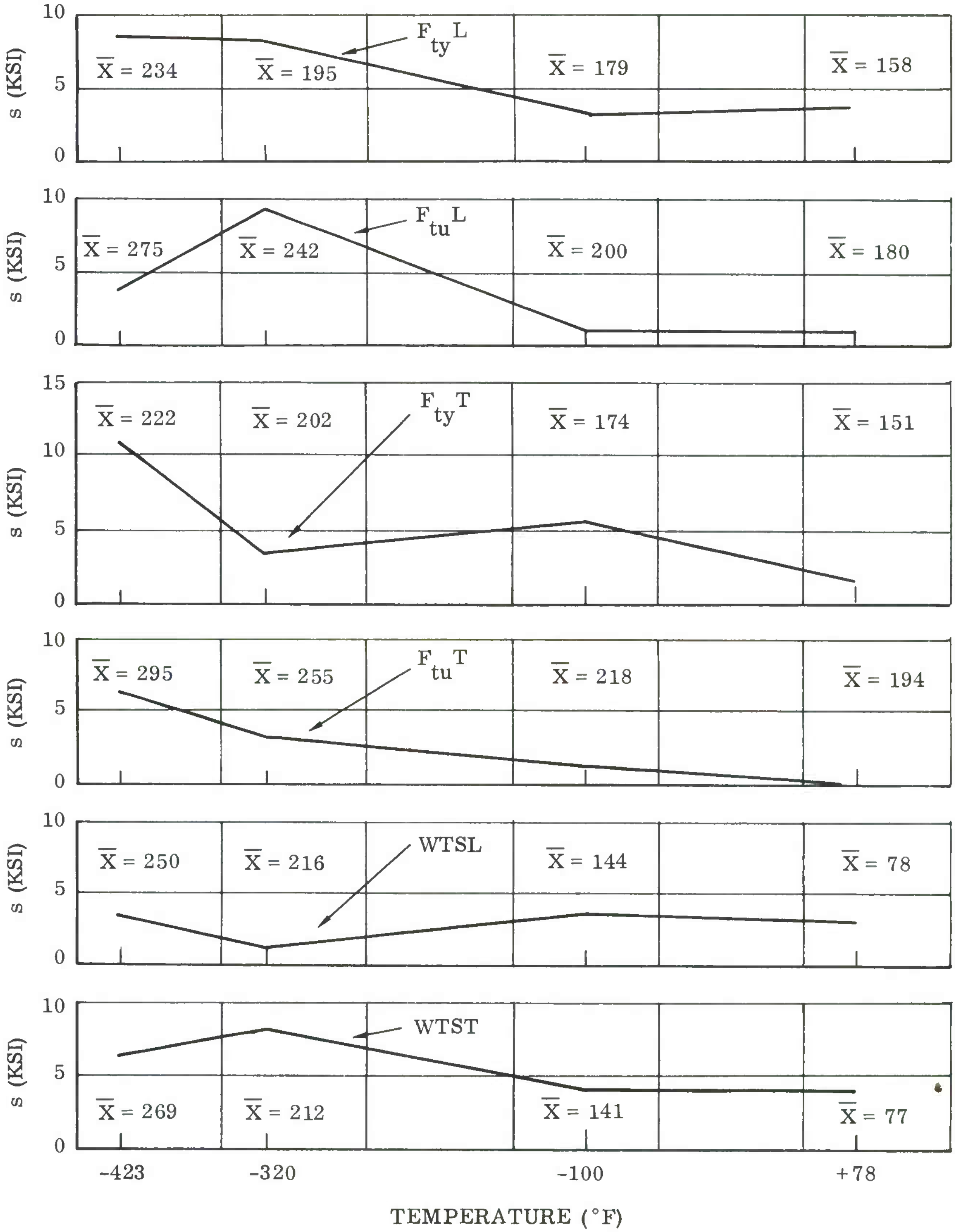


Figure 130. Standard Deviations Versus Temperature (304 SS)

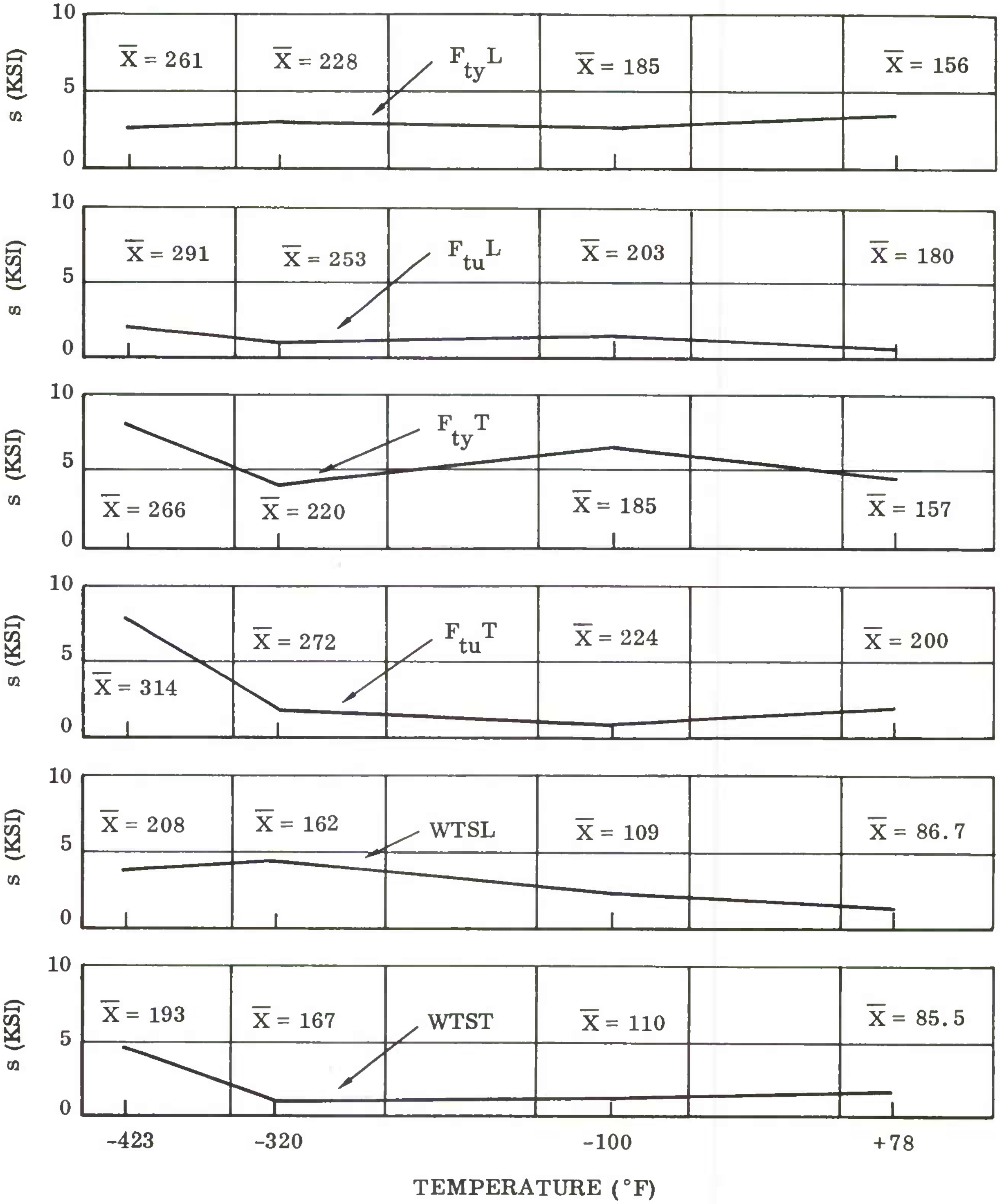


Figure 131. Standard Deviations Versus Temperature (310 SS)

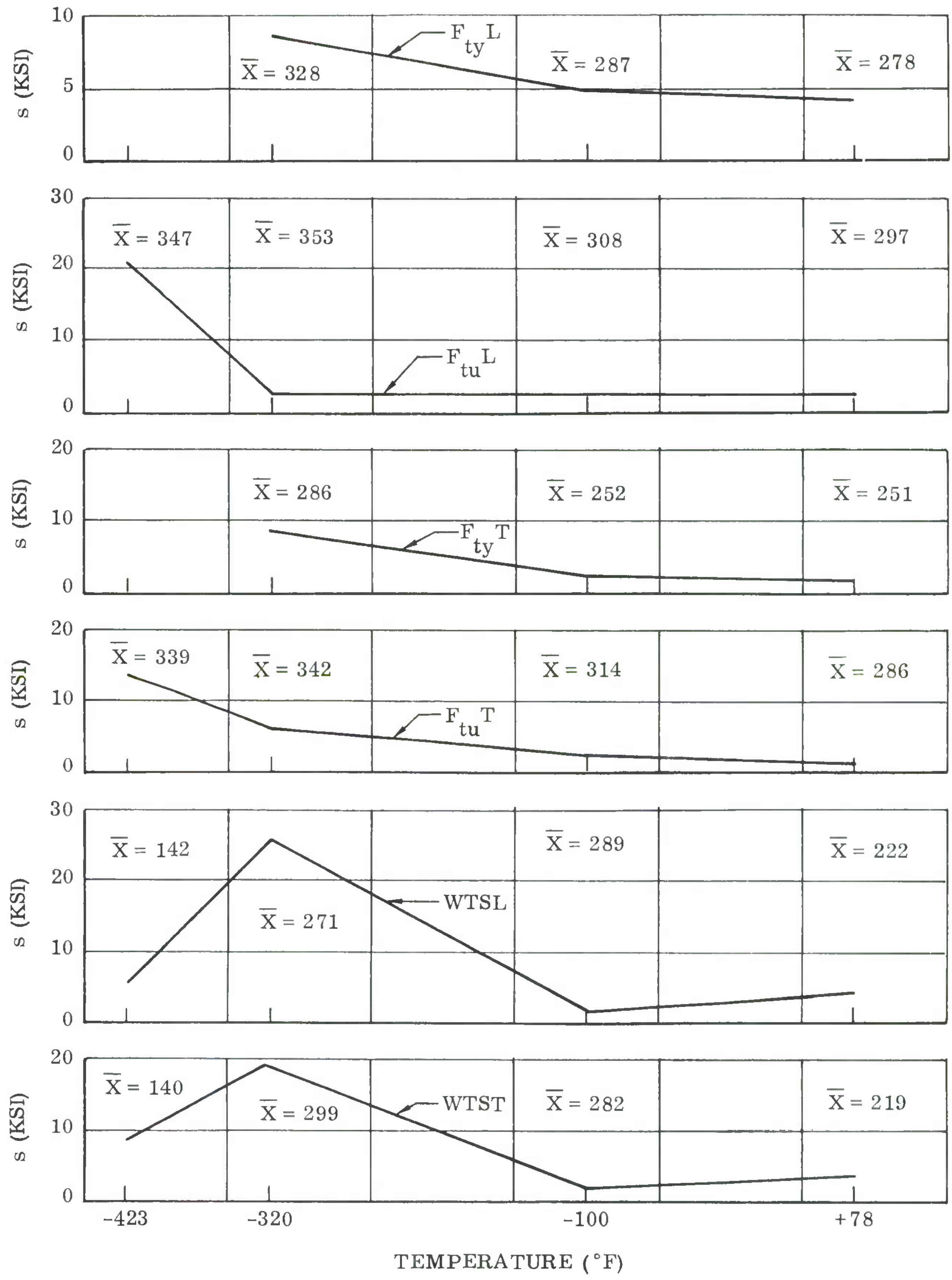


Figure 132. Standard Deviations Versus Temperature (AM-355 SS)

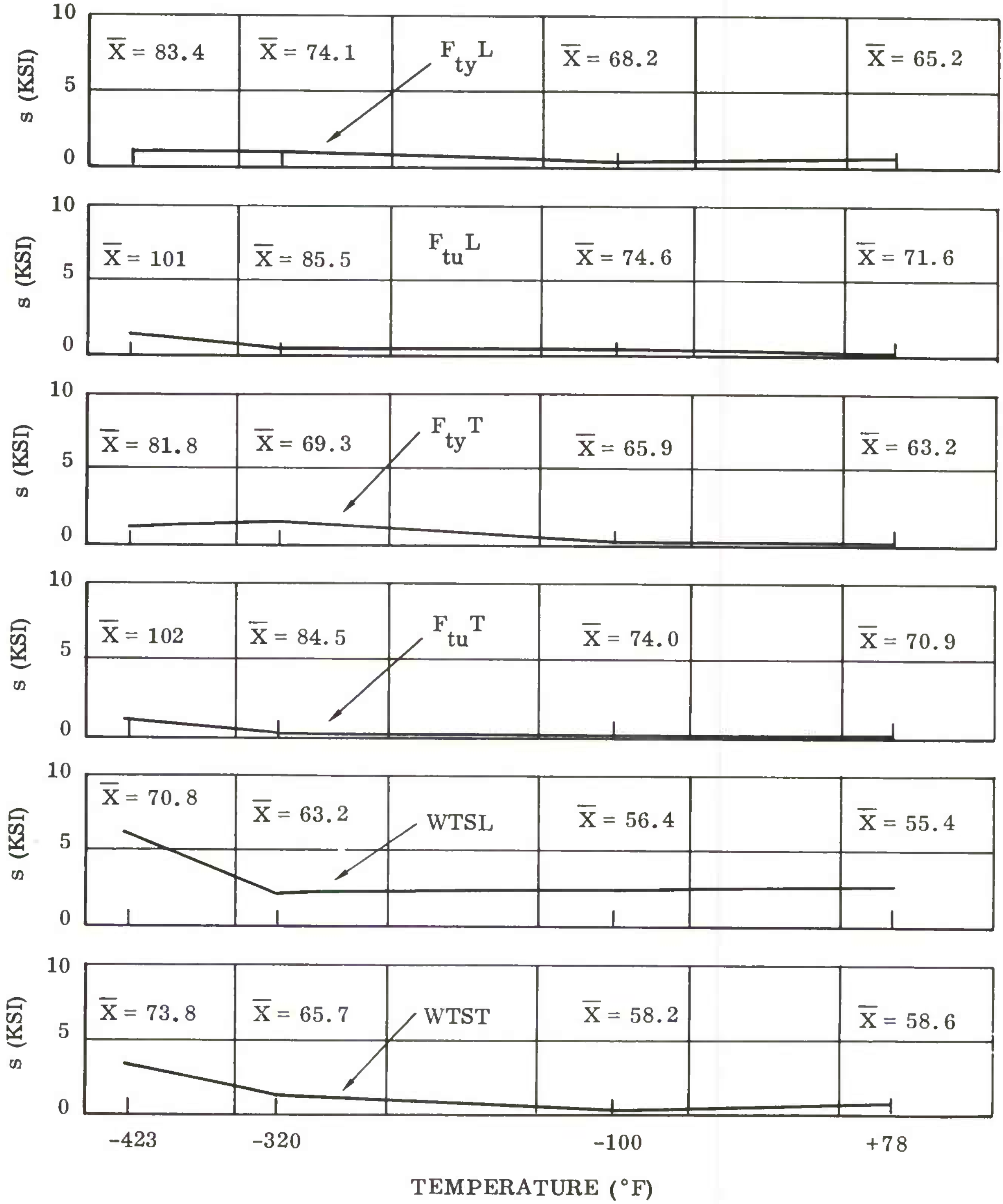


Figure 133. Standard Deviations Versus Temperature (2014-T6 Aluminum Alloy)

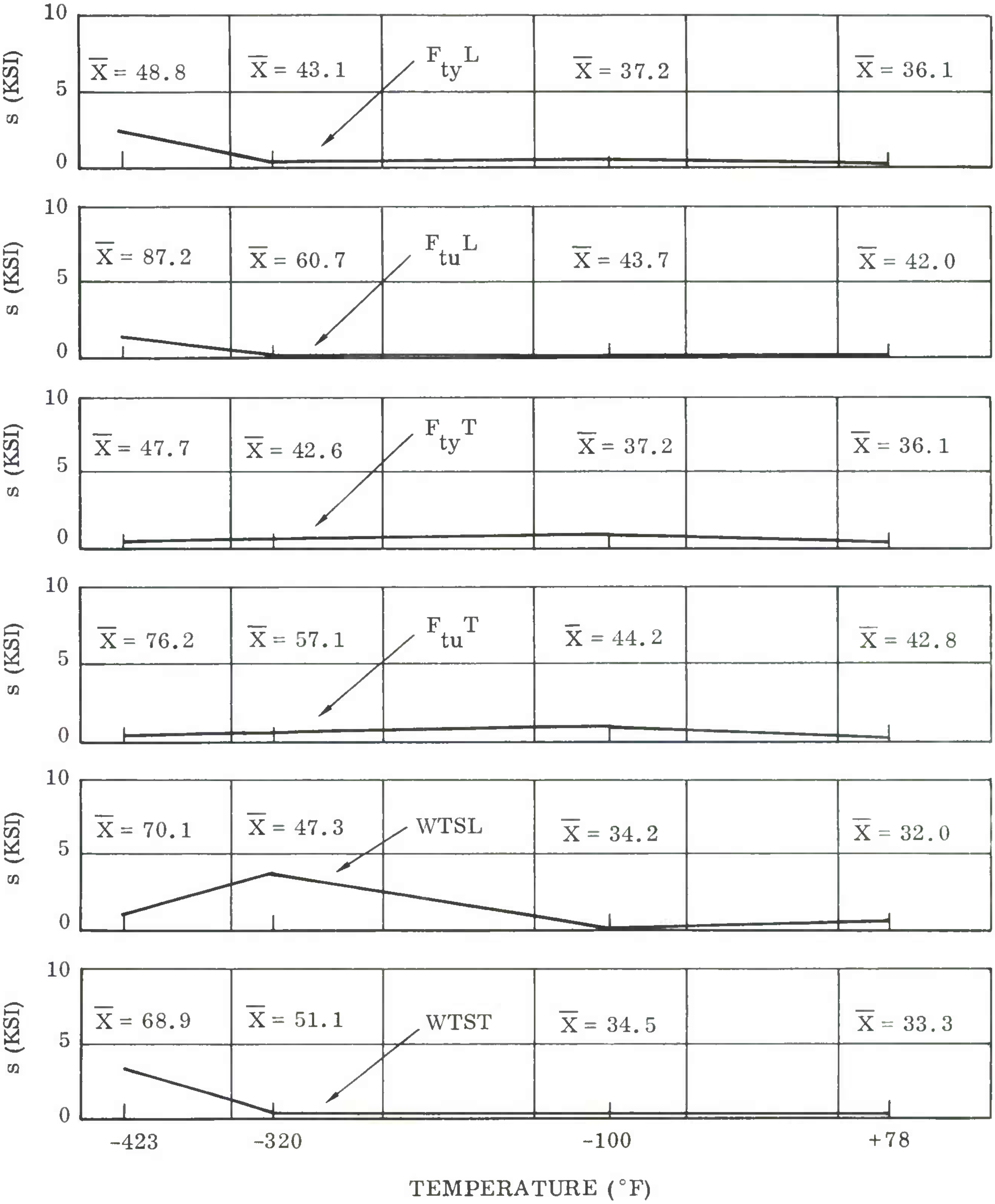


Figure 134. Standard Deviations Versus Temperature (5052-H38 Aluminum Alloy)

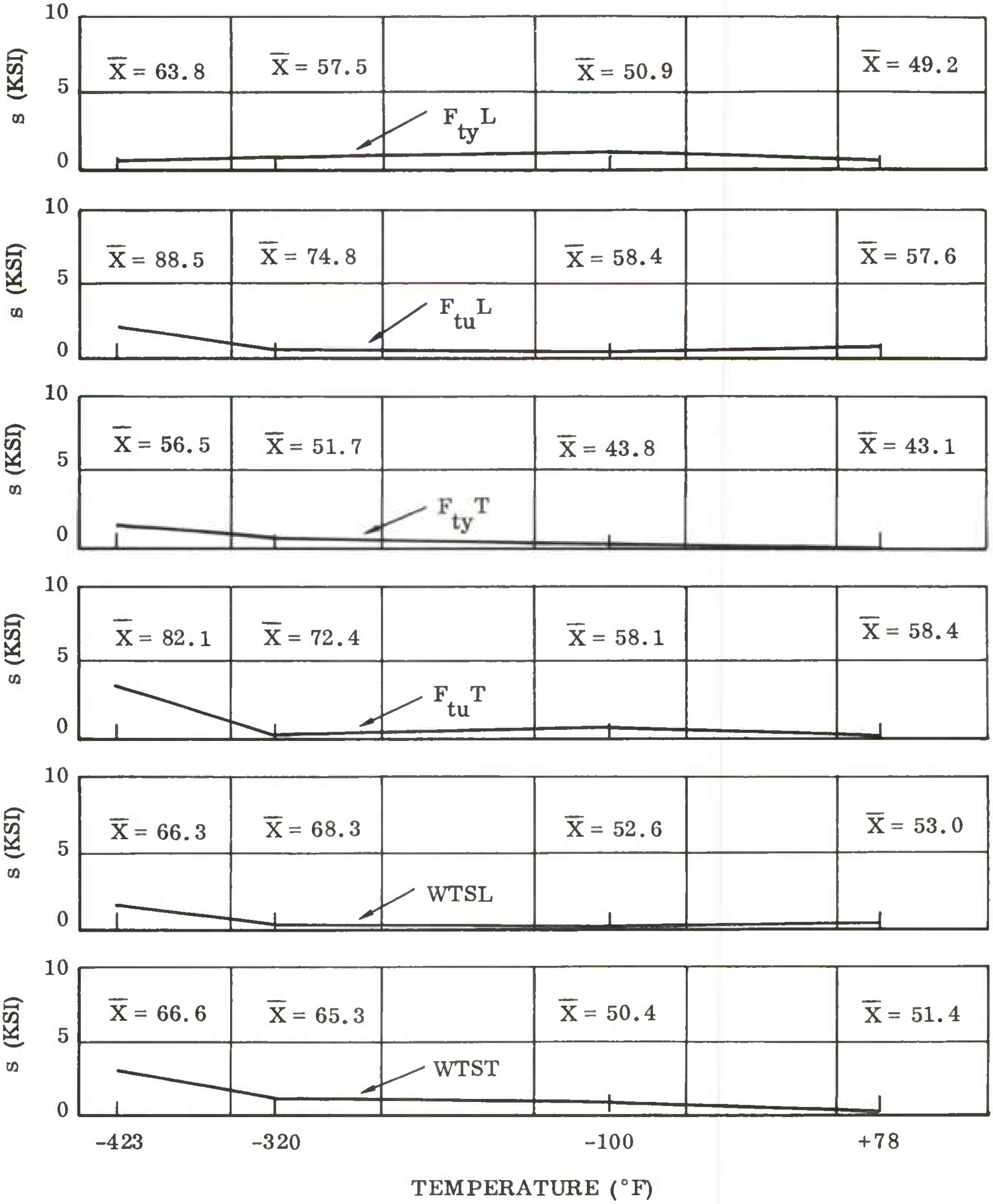


Figure 135. Standard Deviations Versus Temperature (5454-H343 Aluminum Alloy)

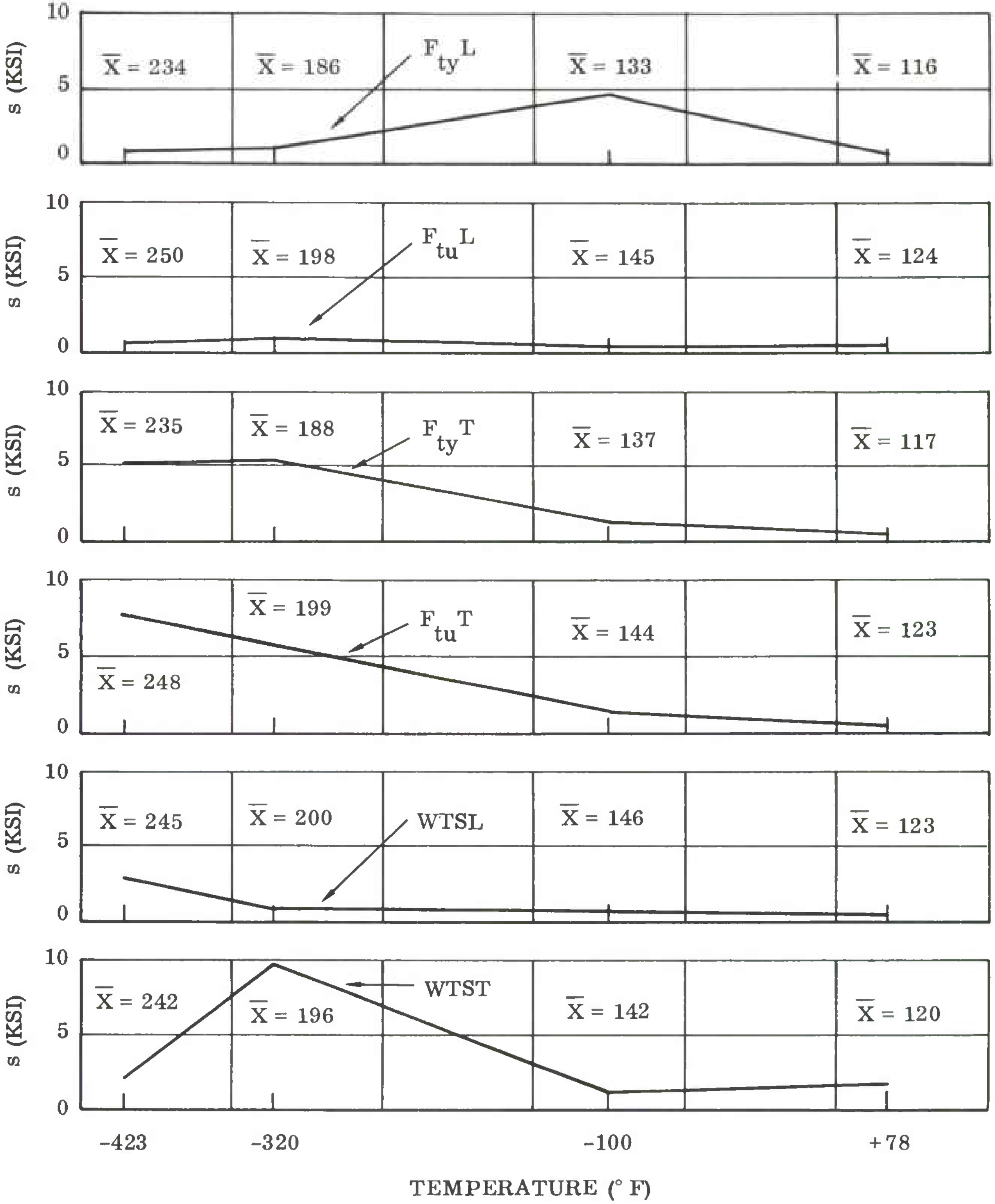


Figure 136. Standard Deviations Versus Temperature (Ti-5Al-2.5Sn Alloy)

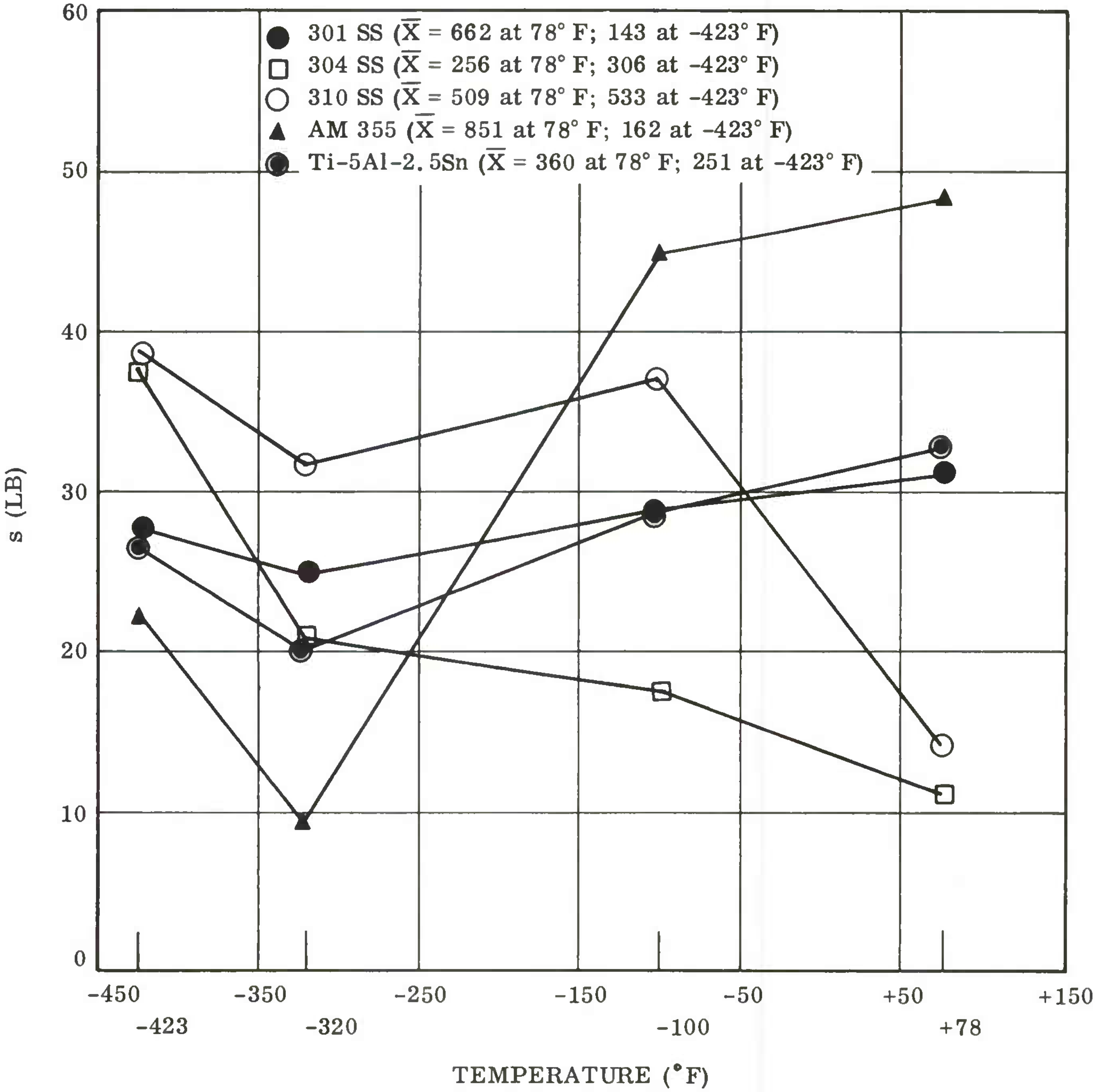


Figure 137. Standard Deviations Versus Temperature (Resistance Spot Welds - Tension)

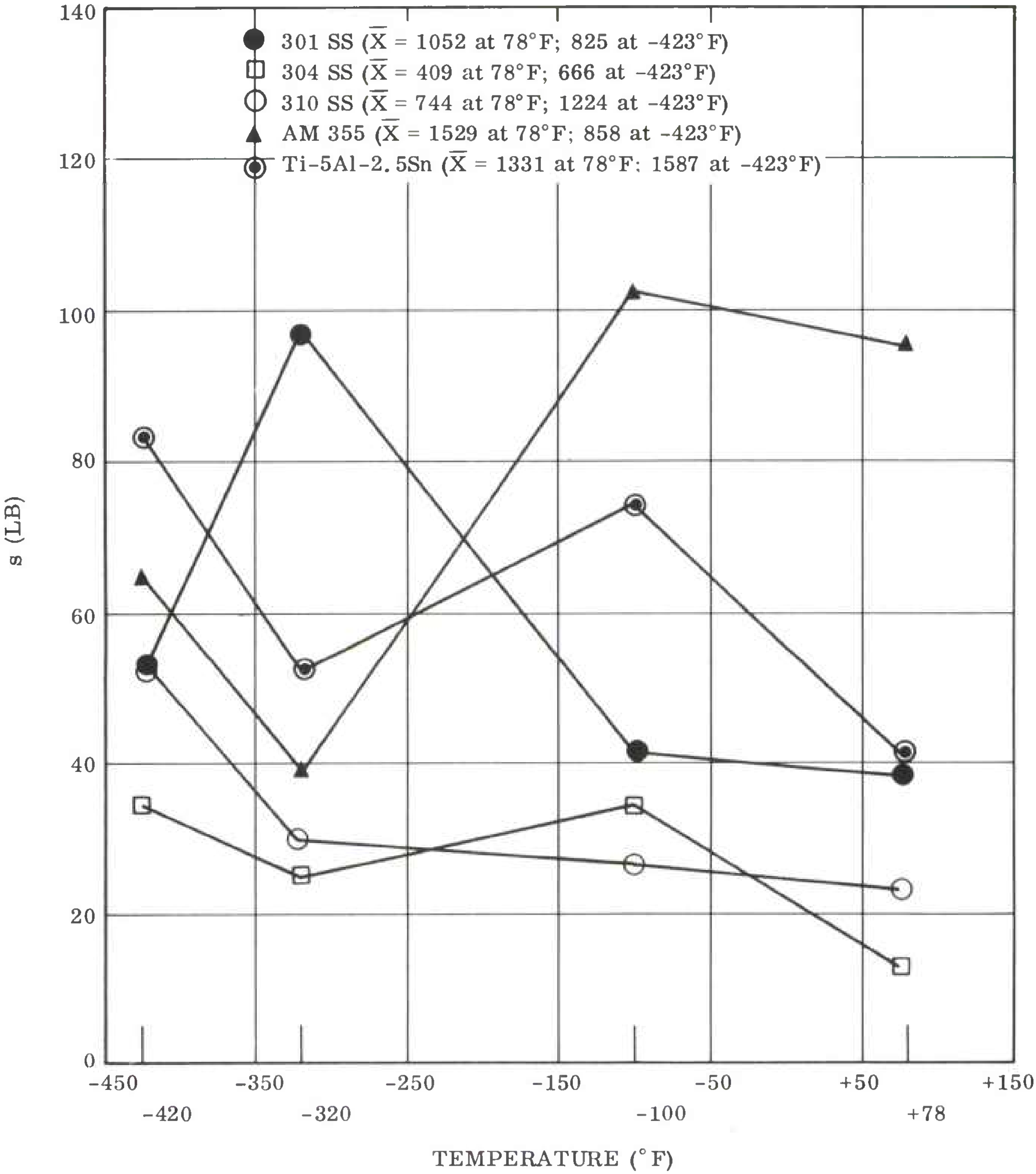


Figure 138. Standard Deviations Versus Temperature
(Resistance Spot Welds - Shear)

TABLES

Table 1. History and Chemical Analysis of Materials

ALLOY	301 SS	304 ELC SS	310 SS	AM-355 SS	2014 Al Alloy	5052 Al Alloy	5456 Al Alloy	Ti-5Al-2.5Sn
TEMPER	60%CR	50%CR	75%CR	CRT	-T6	-H38	-H343	Annealed
GAUGE (IN.)	0.025	0.012	0.020	0.032	0.063	0.063	0.063	0.032
SUPPLIER	Washington Steel	Rodney Metals	Washington Steel	Wallingford Steel	Alcoa	Alcoa	Alcoa	TMCA
HEAT NO.	49061	33251	43631	38174				M-8394
COIL NO.	7450		44942					
SPECIFICATION	GD/A-0-71004		GD/A-0-71004		AMS-4029	QQ-A-318	Mil-A-19842	Internal
HARDNESS (15-N)	83.9	76.8	79.3	86.6	58.7	40.9	49.2	77.5
MARTENSITE (%)	76	0	0	95	-	-	-	-
CHEMISTRY (WT.%)								
Al	-	-	-	-	Bal	Bal	Bal	5.6
C	0.07	0.023	0.060	0.14	-	-	-	0.015
Cr	17.28	18.04	24.62	15.60	0.01	0.189	0.13	-
Cu	-	-	0.23	-	4.51	0.019	0.052	-
Fe	Bal	Bal	Bal	Bal	0.48	0.222	0.20	0.04
H	-	-	-	-	-	-	-	0.013
Mg	-	-	-	-	0.472	2.34	4.85	-
Mn	0.66	1.54	1.60	0.72	0.70	0.01	0.67	-
Mo	-	-	0.32	2.71	-	-	-	-
N	0.031	-	-	0.11	-	-	-	0.009
Ni	6.70	10.39	19.66	4.38	-	-	-	-
O	-	-	-	-	-	-	-	0.17
P	0.022	0.026	0.030	0.018	-	-	-	-
S	0.015	0.011	0.011	0.018	-	-	-	-
Si	0.63	0.66	0.58	0.29	1.03	0.083	0.080	-
Sn	-	-	-	-	-	-	-	2.2
Ti	-	-	-	-	0.041	-	0.023	Bal
Zn	-	-	-	-	-	0.01	-	-

Table 2. Inert-Arc Straight Line Fusion Weld Schedules

MATERIAL	FILLER	AMPS	VOLTS	SPEED (IN/MIN)	BACKUP GAS (FT^3/HR)	TORCH GAS (FT^3/HR)	CLAMP PRES-SURE (psi)	BACKUP BAR (ROOM TEMP)	ELECTRODE (TUNGSTEN-2% THORIATED) (in)**
301 SS 0.025 in.	None	18	13*	15	A/15	A/10:He/35	40	Copper	0.060
304 ELC SS 0.012 in.	None	12	7*	12.5	A/15	A/50	40	Copper	0.040
310 SS 0.020 in.	None	15	14*	15	A/15	A/10:He/45	40	Copper	0.040
AM-355 SS 0.032 in.	None	18	11*	15	A/15	A/10:He/35	40	Copper	0.040
Ti-5Al-2.5Sn Alloy 0.032 in.	None	25	12*	10	He/15	A/5:He/30 Trailing Shield He/20	40	Copper	0.040
2014-T6 Al Alloy 0.063 in.	2319 Al Alloy	175***	-	4	None	A/12	40	Al with Copper insert	0.156
2014-T6 Al Alloy 0.125 in.	2319 Al Alloy	180***	-	6	None	A/10	40	Al with Copper insert	0.125
5052-H38 Al Alloy 0.125 in.	5356 Al Alloy	210***	-	10	None	A/12	40	Al with Copper insert	0.156
5456-H343 Al Alloy 0.063 in.	5356 Al Alloy	165-170***	-	4	None	A/12	40	Al with Copper Insert	0.156
5456-H343 Al Alloy 0.125 in.	5356 Al Alloy	165-175***	-	10	None	A/10	40	Al with Copper insert	0.125

* Direct current, straight polarity
** All electrodes tapered 30°
*** Alternating current, 60 cycle, single phase

Table 3. Resistance Spot Weld Schedules*

MATERIAL	ELECTRODE FORCE(LB)	IMPULSES	HEAT (CYCLES)	COOL (CYCLES)	SQUEEZE (CYCLES)	HOLD (CYCLES)	WELD (% HEAT)	ELECTRODES (TOP AND BOTTOM)		
								CLASS	FACE(IN.)	RADIUS(IN.)
301 SS 0.025 in.- 0.025 in.	1000	2	2	2	30	30	68	III	1/4	4
304 SS 0.012 in.- 0.012 in.	750	2	2	2	30	30	54	III	1/4	4
310 SS 0.020 in.- 0.020 in.	700	2	2	2	30	30	62	III	1/4	6
AM-355 SS 0.032 in.- 0.032 in.	1000	2	3	2	30	30	67	III	3/8	8
Ti-5Al-2.5Sn Alloy 0.032 in.- 0.032	1100	2	3	2	30	30	72	III	3/8	8

*Thomson Tri Mono Phase welder, General Electric panel, 90 KVA Transformer.

Table 4. Resistance Seam Weld Schedules*

MATERIAL	ELECTRODE FORCE (LB)	HEAT (CYCLES)	COOL (CYCLES)	WELD (%HEAT)	SPEED (IN/MIN)	ELECTRODES (TOP AND BOTTOM) CLASS	FACE (IN)	WHEEL DIAMETER (IN)	RADIUS (IN)	SPOTS PER INCH
301 SS 0.025 in. -0.025 in.	1000	2	6	80	20	III	3/8	10	4	15
304 SS 0.012 in. -0.012 in.	600	1	6	78	20	III	3/8	10	4	20
310 SS 0.020 in. -0.020 in.	900	2	6	56	20	III	3/8	10	4	18
AM-355 SS 0.032 in. -0.032 in.	1200	3	7	66	16	III	1/2	10	6	14
Ti-5Al-2.5Sn Alloy 0.032 in. -0.032 in.	1200	3	7	68	16	III	1/2	10	6	13

*Thomson Tri Mono Phase welder, General Electric panel, 125 KVA Transformer

Table 5. Properties of 60 Percent Cold Rolled 301 Stainless Steel (0.025 In. Sheet, Washington Steel, Heat No. 49061, Coil No. 7450)

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	PROPORTIONAL LIMIT (KSI)	ELASTIC MODULUS (PSI X 10^6)	HARDNESS (15-N) REDUCTION SECTION	HARDNESS (15-N) FRACTURED EDGE	% MARTENSITE REDUCED SECTION	% MARTENSITE FRACTURED EDGE
78	Long.	200	223	10.5	101	25.3	85.4	84.9	97	97
	Long.	205	225	10.5	72.3	24.4	85.9	85.3	96	97
	Long.	198	222	11.5	90.0	24.7	86.0	86.0	96	97
	Long.	200	224	10.5	80.3	25.3	85.4	85.0	96	97
	Long.	197	224	11.0	76.0	27.0	86.2	86.1	96	97
	Avg	200	224	10.8	83.9	25.3	85.8	85.5	96	97
78	Trans.	178	239	7.5	88.2	28.4	86.8	86.0	95	96
	Trans.	174	236	7.5	101	26.3	86.2	87.0	97	97
	Trans.	175	239	7.5	89.9	27.8	84.9	85.9	97	97
	Trans.	176	240	7.5	91.9	27.4	87.2	85.5	96	97
	Trans.	178	241	7.5	100	26.2	86.8	86.0	97	97
	Avg	176	239	7.5	94.2	27.2	86.4	86.1	96	97
-100	Long.	237	252	14.5	144	28.3	88.7	87.1	99	99
	Long.	240	252	14.0	101	26.4	85.9	85.9	99	99
	Long.	232	254	15.0	101	26.1	89.1	92.3	99	99
	Long.	238	253	15.0	138	29.7	88.8	91.8	99	99
	Long.	236	253	15.0	100	26.8	89.8	88.8	99	99
	Avg	237	253	14.7	117	27.5	88.5	89.2	99	99
-100	Trans.	200	267	11.5	122	30.0	86.4	84.8	99	99
	Trans.	199	265	11.5	113	30.2	88.0	88.0	99	99
	Trans.	191	268	11.0	100	30.4	86.5	86.5	99	98
	Trans.	199	268	12.0	103	28.0	89.5	86.6	99	99
	Trans.	195	266	11.5	126	29.0	86.6	85.8	99	98
	Avg	197	267	11.5	113	29.5	87.4	86.4	99	99

-320	Long.	262	323	20.0	140	31.9	89.9	87.1	99	98
	Long.	-	324	19.5	-	-	87.0	86.7	99	99
	Long.	249	321	19.0	142	27.3	90.2	88.8	99	99
	Long.	256	322	19.0	168	29.2	89.5	87.0	99	98
	Long.	285	322	19.5	161	25.8	91.1	90.0	100	99
	Long.	-	323	20.5	-	-	88.8	88.2	99	100
	Long.	244	324	19.0	141	27.8	89.0	87.1	99	99
	Avg	254	323	19.5	146	28.4	89.4	87.8	99	99
-320	Trans.	236	326	16.5	130	29.7	89.4	90.9	99	98
	Trans.	233	327	16.5	143	31.4	88.4	88.6	99	98
	Trans.	234	325	17.0	144	28.4	89.9	87.3	99	98
	Trans.	238	327	16.5	148	33.0	88.5	89.1	99	99
	Trans.	234	327	14.0	129	27.6	89.2	90.2	99	98
	Avg	235	326	16.1	139	30.0	89.1	89.2	99	98
-423	Long.	312	333	2.0	161	30.3	84.3	85.6	78	97
	Long.	305	335	1.5	171	31.9	84.8	83.5	78	97
	Long.	304	344	3.5	163	28.7	82.5	84.0	78	96
	Long.	313	336	8.0	182	29.1	82.9	86.0	82	98
	Long.	308	328	2.5	-	-	84.2	86.2	78	97
	Avg	308	335	3.5	169	30.0	83.6	85.1	79	97
-423	Trans.	313	342	7.0	171	28.4	87.0	87.0	94	97
	Trans.	312	349	5.0	164	29.4	85.6	86.8	96	98
	Trans.	308	354	3.0	149	33.9	87.3	88.1	94	95
	Trans.	293	342	2.5	174	33.6	86.8	85.5	94	95
	Trans.	287	341	5.5	177	29.3	88.2	87.8	96	97
	Avg	303	346	4.6	167	30.9	87.0	87.0	95	96

Table 5 (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t=3.2) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO	NOTCH T.S. (K_t=6.3) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO
78	Long.	241 (3.2)	67.4		241 (6.8)	67.4	
	Long.	246 (3.2)	69.0		238 (6.7)	66.8	
	Long.	247 (3.2)	69.1		241 (6.7)	67.6	
	Long.	248 (3.2)	69.3		241 (6.7)	67.4	
	Long.	247 (3.2)	69.2		238 (6.7)	66.8	
	Avg	246	68.8	1.10	240	67.2	1.07
78	Trans.	240 (3.2)	67.1		203 (6.5)	51.7	
	Trans.	242 (3.2)	67.8		200 (6.4)	53.6	
	Trans.	228 (3.1)	63.9		192 (6.4)	56.1	
	Trans.	228 (3.2)	63.8		210 (6.4)	59.9	
	Trans.	232 (3.2)	65.0		200 (6.4)	55.9	
	Avg	234	65.5	0.98	201	55.4	0.84
-100	Long.	248 (3.2)	69.3		248 (6.7)	69.4	
	Long.	270 (3.2)	75.6		248 (6.7)	69.3	
	Long.	270 (3.2)	75.7		249 (6.6)	69.7	
	Long.	269 (3.2)	75.3		248 (6.6)	69.5	
	Long.	268 (3.2)	75.1		249 (6.6)	69.8	
	Avg	265	74.2	1.05	248	69.5	0.98
-100	Trans.	256 (3.2)	71.6		213 (6.4)	59.5	
	Trans.	263 (3.2)	73.6		213 (6.4)	59.7	
	Trans.	258 (3.2)	72.2		206 (6.4)	57.8	
	Trans.	261 (3.2)	73.1		214 (6.7)	60.0	
	Trans.	260 (3.2)	72.7		217 (6.7)	60.9	
	Avg	260	72.6	0.97	213	59.6	0.80

-320	Long.	321 (3.2)	89.8		302 (6.6)	84.6	
	Long.	313 (3.2)	87.7		295 (6.6)	82.6	
	Long.	308 (3.2)	86.2		299 (6.6)	83.6	
	Long.	319 (3.2)	89.5		295 (6.6)	82.5	
	Long.	325 (3.2)	91.1		299 (6.6)	83.8	
	Avg	317	88.9	0.98	298	83.4	0.92
-320	Trans.	325 (3.2)	90.9		226 (6.7)	63.2	
	Trans.	311 (3.2)	86.9		223 (6.7)	62.4	
	Trans.	308 (3.2)	86.1		218 (6.7)	61.0	
	Trans.	314 (3.2)	88.0		222 (6.7)	62.1	
	Trans.	313 (3.2)	87.8		212 (6.7)	59.3	
	Avg	314	87.9	0.96	220	61.6	0.67
-423	Long.	375 (3.2)	105		306 (6.6)	85.7	
	Long.	353 (3.2)	99.0		310 (6.6)	86.8	
	Long.	376 (3.2)	105		292 (6.6)	81.8	
	Long.	386 (3.2)	108		299 (6.6)	83.8	
	Long.	378 (3.2)	106		303 (6.6)	84.9	
	Avg	374	103	1.11	302	84.6	0.90
-423	Trans.	296 (3.2)	82.9		228 (6.7)	63.9	
	Trans.	299 (3.2)	83.7		214 (6.7)	59.8	
	Trans.	324 (3.2)	90.9		205 (6.7)	57.3	
	Trans.	306 (3.2)	85.7		214 (6.7)	59.9	
	Trans.	311 (3.2)	87.2		236 (6.7)	66.2	
	Avg	307	86.1	0.89	219	61.4	0.63

Table 5 (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t=19) (KSI)	FRACTURE TOUGHNESS K (PSI$\sqrt{IN}$)	NOTCH/ UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)	HARDNESS (15-N) HEAT AFFECTED ZONE	HARDNESS (15-N) WELD	% MARTENSITE HEAT AFFECTED ZONE	% MARTENSITE WELD
78	Long.	210 (24.1)	102		170	2.5		83.1	80.9	75	98
	Long.	208 (24.1)	101		176	3.0		83.1	82.3	75	98
	Long.	214 (22.4)	103		179	3.0		82.8	81.8	77	97
	Long.	207 (24.1)	100		175	2.5		83.0	82.7	76	97
	Long.	211 (24.1)	102		176	3.0		82.0	83.2	78	96
	Avg	210	102	0.94	175	2.8	78	82.8	82.2	76	97
78	Trans.	138 (26.4)	66.5		171	2.0		84.2	84.6	78	98
	Trans.	148 (26.4)	71.5		172	2.5		84.2	83.1	81	99
	Trans.	157 (22.3)	76.0		172	2.0		83.6	80.2	75	100
	Trans.	153 (26.4)	73.9		179	2.5		83.8	83.9	78	99
	Trans.	165 (26.4)	79.8		175	2.0		83.5	84.2	78	99
	Avg	152	73.5	0.64	174	2.2	73	83.9	83.2	78	99
-100	Long.	219 (24.1)	106		219	6.0		85.7	81.2	96	99
	Long.	219 (22.4)	106		213	6.0		86.5	83.0	96	99
	Long.	217 (22.4)	105		218	5.0		86.0	84.1	97	99
	Long.	198 (22.4)	95.9		213	5.0		85.5	85.6	96	99
	Long.	184 (22.4)	88.9		218	6.0		87.0	84.0	97	98
	Avg	207	100	0.82	216	5.6	85	86.1	83.6	96	99
-100	Trans.	147 (26.4)	71.2		214	4.0		86.3	85.0	96	99
	Trans.	146 (26.4)	70.7		212	2.5		85.5	83.2	96	98
	Trans.	140 (26.4)	67.7		210	2.0		85.6	83.5	96	98
	Trans.	159 (22.3)	76.7		213	3.0		86.0	82.0	95	98
	Trans.	134 (22.3)	64.9		212	2.5		86.5	81.2	95	99
	Avg	145	70.2	0.54	212	2.8	79	86.0	83.0	96	98

-320	Long.	220 (22.4)	106		300	12.5		87.3	82.1	98	98
	Long.	203 (22.4)	97.9		301	10.0		87.0	86.2	98	98
	Long.	227 (22.4)	109		300	12.5		87.5	86.7	98	98
	Long.	192 (22.3)	92.9		296	12.5		86.8	87.0	98	98
	Long.	209 (22.4)	101		295	12.5		86.0	87.1	98	99
	Avg	206	101	0.64	298	12.0	92	86.9	85.8	98	98
-320	Trans.	132 (26.4)	63.5		293	7.5		88.9	84.5	97	99
	Trans.	170 (24.1)	82.0		287	4.0		87.6	89.1	96	99
	Trans.	154 (26.4)	74.5		292	5.0		88.8	90.0	97	99
	Trans.	120 (26.4)	57.9		291	5.0		86.0	85.5	97	98
	Trans.	110 (22.3)	53.2		290	5.0		87.2	82.2	97	98
	Avg	137	66.2	0.42	291	5.3	89	87.7	86.3	97	99
-423	Long.	207 (22.4)	99.8		216	1.0		84.1	85.4	77	97
	Long.	225 (22.3)	109		226	1.0		84.5	85.0	77	97
	Long.	218 (24.1)	105		208	1.0		84.5	86.0	78	97
	Long.	201 (22.4)	97.1		181	1.0		84.9	84.0	77	97
	Long.	217 (22.4)	100		177	1.0		83.5	84.5	77	97
	Avg	212	102	0.61	202	1.0	60	84.3	85.0	77	97
-423	Trans.	131 (22.3)	63.2		187	1.0		83.1	85.1	75	97
	Trans.	147 (26.4)	70.9		209	1.5		83.8	84.6	77	97
	Trans.	136 (26.4)	65.9		171	1.5		85.2	84.5	76	97
	Trans.	156 (22.3)	75.6		205	1.5		84.1	85.3	76	97
	Trans.	140 (26.4)	67.8		249	1.0		84.0	86.1	75	97
	Avg	142	68.7	0.41	204	1.3	59	84.0	85.1	76	97

Table 6. Properties of 50 Percent Cold Rolled 304 ELC Stainless Steel (0.012 In. Sheet, Rodney Metals, Heat No. 33251)

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	PROPORTIONAL LIMIT (KSI)	ELASTIC MODULUS (PSI x 10^6)	HARDNESS (15-N) REDUCED SECTION	HARDNESS (15-N) FRACTURED EDGE	% MARTENSITE REDUCED SECTION	% MARTENSITE FRACTURED EDGE
78	Long.	164	181	2.5	59.4	25.8	76.6	76.8	2	3
	Long.	153	179	2.5	37.9	25.0	76.4	77.6	1	1
	Long.	157	179	2.5	39.7	25.3	76.3	77.5	1	2
	Long.	159	180	2.5	42.4	25.6	76.8	76.8	1	1
	Long.	158	181	2.5	42.4	25.9	76.3	77.4	1	2
	Avg	158	180	2.5	44.4	25.5	76.5	77.2	1	2
78	Trans.	150	194	5.0	42.4	30.3	77.0	78.2	1	2
	Trans.	153	194	5.0	46.7	29.7	76.8	76.8	1	1
	Trans.	154	194	5.0	47.3	28.5	77.2	78.0	0	1
	Trans.	150	194	5.0	46.7	30.3	77.8	77.8	1	1
	Trans.	150	194	5.0	42.4	30.0	77.2	77.0	1	1
	Avg	151	194	5.0	45.1	29.8	77.2	77.6	1	1
-100	Long.	177	199	4.0	97.6	26.0	76.7	76.0	1	1
	Long.	179	201	3.5	83.1	26.2	76.9	76.4	2	4
	Long.	182	201	5.0	98.8	26.2	77.3	76.9	2	4
	Long.	183	200	5.0	91.6	27.7	77.0	78.0	1	2
	Long.	175	199	5.0	90.0	27.2	77.2	77.9	2	2
	Avg	179	200	4.5	92.2	26.7	77.0	77.0	2	3
-100	Trans.	177	219	5.5	83.3	29.5	76.8	78.4	1	1
	Trans.	175	219	5.5	87.4	29.1	76.5	78.0	2	2
	Trans.	178	219	7.0	89.1	30.8	76.7	79.0	1	2
	Trans.	164	217	6.0	75.5	29.8	76.5	78.3	1	1
	Trans.	175	217	2.0	81.8	30.7	77.0	77.2	2	3
	Avg	174	218	5.2	83.4	30.0	76.7	78.2	1	2

-320	Long.	190	235	25.0	91.3	25.7	76.8	79.9	1	97
	Long.	205	238	24.0	94.9	27.8	76.8	81.8	3	96
	Long.	189	253	30.0	94.9	27.4	82.2	82.1	1	97
	Long.	189	252	31.0	100	27.4	82.6	82.0	1	97
	Long.	204	234	22.5	100	27.1	83.0	80.0	2	97
	Avg	195	242	26.5	96.2	27.1	80.3	81.2	2	97
-320	Trans.	197	249	33.0	91.3	30.5	82.6	81.7	1	96
	Trans.	201	256	36.5	97.3	28.7	79.0	82.7	1	97
	Trans.	204	257	25.0	101	31.1	82.1	81.2	1	96
	Trans.	199	256	25.0	91.8	28.9	77.0	80.6	2	96
	Trans.	205	256	34.5	102	29.4	82.1	81.9	1	97
	Avg	201	255	30.8	96.7	29.9	80.6	81.6	1	96
-423	Long.	241	271	1.5	161	28.0	78.0	75.0	2	4
	Long.	231	271	2.0	152	27.6	75.9	76.3	1	2
	Long.	243	276	1.0	165	26.3	76.5	80.0	1	2
	Long.	222	276	1.5	152	27.7	76.5	76.0	2	2
	Long.	231	280	1.5	156	28.4	76.6	76.8	1	1
	Avg	234	275	1.5	157	27.6	76.7	76.8	1	2
-423	Trans.	210	293	1.5	---	31.9	76.5	75.4	1	1
	Trans.	211	301	2.0	156	28.4	76.5	77.8	1	2
	Trans.	228	289	2.5	152	28.3	76.5	76.8	2	2
	Trans.	227	292	1.5	143	28.9	77.0	76.7	1	2
	Trans.	---	289	1.5	---	----	76.6	76.9	2	3
	Trans.	233	304	2.0	157	30.6	76.8	77.1	1	1
	Avg	222	295	1.8	152	29.6	76.7	76.8	1	2

Table 6. (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t=3.2) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO	NOTCH T.S. (K_t=6.3) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO
78	Long.	192 (3.2)	53.8		199 (7.1)	55.8	
	Long.	191 (3.2)	53.5		201 (7.1)	56.2	
	Long.	191 (3.2)	53.5		198 (7.1)	55.6	
	Long.	190 (3.2)	53.2		201 (7.1)	56.2	
	Long.	189 (3.2)	52.9		197 (7.1)	55.2	
	Avg	191	53.4	106	199	55.8	1.11
78	Trans.	217 (3.2)	60.8		209 (7.1)	53.9	
	Trans.	218 (3.2)	61.0		218 (7.1)	61.1	
	Trans.	213 (3.2)	59.6		218 (7.1)	61.1	
	Trans.	217 (3.2)	60.8		216 (7.1)	60.5	
	Trans.	217 (3.2)	60.8		224 (7.1)	62.8	
	Avg	216	60.6	1.11	217	59.9	1.12
-100	Long.	214 (3.2)	59.9		216 (7.1)	60.5	
	Long.	214 (3.2)	59.9		220 (7.1)	61.6	
	Long.	216 (3.2)	60.5		221 (7.1)	61.9	
	Long.	214 (3.2)	59.9		219 (7.1)	61.3	
	Long.	214 (3.2)	59.9		217 (7.1)	60.8	
	Avg	214	60.0	1.07	219	61.3	1.10
-100	Trans.	254 (3.2)	71.1		243 (7.1)	68.0	
	Trans.	240 (3.2)	67.2		239 (7.1)	66.9	
	Trans.	249 (3.2)	69.7		236 (7.1)	66.1	
	Trans.	253 (3.2)	70.8		242 (7.1)	67.8	
	Trans.	253 (3.2)	70.8		246 (7.1)	68.9	
	Avg.	250	69.9	1.15	241	67.5	1.11

-320	Long.	226 (3.2)	74.5		277 (7.1)	77.6	
	Long.	262 (3.2)	73.4		266 (7.1)	74.5	
	Long.	259 (3.2)	72.5		264 (7.1)	73.9	
	Long.	268 (3.2)	75.0		263 (7.1)	73.6	
	Long.	262 (3.2)	73.4		263 (7.1)	73.6	
	Avg	263	73.8	1.08	267	74.8	1.10
-320	Trans.	310 (3.2)	86.8		301 (7.1)	84.3	
	Trans.	311 (3.2)	87.0		297 (7.1)	83.2	
	Trans.	310 (3.2)	86.8		294 (7.1)	82.3	
	Trans.	307 (3.2)	86.0		304 (7.1)	85.1	
	Trans.	308 (3.2)	86.2		304 (7.1)	85.1	
	Avg	309	86.6	1.21	300	84.0	1.18
-423	Long.	304 (3.2)	85.1		312 (7.1)	87.4	
	Long.	309 (3.2)	86.5		307 (7.1)	86.0	
	Long.	306 (3.2)	85.7		308 (7.1)	86.2	
	Long.	338 (3.2)	94.6		308 (7.1)	86.2	
	Long.	307 (3.2)	86.0		314 (7.1)	87.9	
	Avg	313	87.6	1.14	310	86.8	1.13
-423	Trans.	347 (3.2)	97.2		322 (7.1)	90.2	
	Trans.	355 (3.2)	99.4		333 (7.1)	93.2	
	Trans.	370 (3.2)	104		337 (7.1)	94.4	
	Trans.	371 (3.2)	104		348 (7.1)	97.4	
	Trans.	384 (3.2)	108		331 (7.1)	92.7	
	Avg	365	103	1.24	334	93.5	1.13

Table 6 (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t=19) (KSI)	FRACTURE TOUGHNESS K (PSI$\sqrt{IN}$)	NOTCH/ UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)	HARDNESS(15-N) HEAT AFFECTED ZONE	HARDNESS(15-N) WELD	% MARTENSITE HEAT AFFECTED ZONE	% MARTENSITE WELD
78	Long.	176 (18.8)	85.0		76.7	2.5		77.0	57.1	1	1
	Long.	158 (18.8)	76.3		76.1	1.5		76.5	52.2	1	1
	Long.	174 (18.8)	84.0		75.9	2.0		76.5	55.7	1	2
	Long.	173 (18.8)	83.6		79.9	2.0		77.1	52.5	1	2
	Long.	176 (18.8)	85.0		83.4	1.5		76.8	60.4	2	2
	Avg	171	82.8	0.95	78.4	1.9	44	76.8	55.6	1	2
78	Trans.	142 (18.3)	68.6		74.4	2.0		77.1	53.6	1	1
	Trans.	153 (18.3)	73.9		81.6	2.0		76.5	47.5	1	2
	Trans.	151 (18.3)	72.9		78.7	2.0		76.8	54.5	1	1
	Trans.	129 (18.3)	62.3		71.9	1.5		76.1	45.5	0	1
	Trans.	152 (18.3)	73.4		80.0	2.0		76.3	50.0	1	1
	Avg	145	70.2	0.75	77.3	1.9	40	76.6	50.2	1	1
-100	Long.	199 (18.8)	96.1		141	3.0		77.0	71.5	2	3
	Long.	202 (18.8)	97.6		149	2.5		76.6	64.5	1	2
	Long.	197 (18.8)	95.2		144	1.5		74.0	65.0	2	1
	Long.	190 (18.8)	91.8		145	2.5		76.8	65.0	1	1
	Long.	183 (18.8)	88.4		139	2.5		75.9	66.3	1	2
	Avg	194	93.8	0.97	144	2.4	72	76.1	66.5	1	2
-100	Trans.	181 (18.3)	87.4		144	2.5		76.7	59.8	2	1
	Trans.	196 (18.3)	94.7		144	3.0		77.0	60.0	2	2
	Trans.	147 (18.3)	71.0		142	2.0		76.0	59.3	2	2
	Trans.	189 (18.3)	91.3		134	2.5		77.0	72.0	1	1
	Trans.	172 (18.3)	83.1		143	2.5		76.4	63.1	2	2
	Avg	177	85.5	0.81	141	2.5	65	76.6	62.8	2	2

-320	Long.	232	(18.8)	112		215	3.0		76.7	70.4	1	1
	Long.	221	(18.8)	107		215	3.0		75.0	74.2	1	2
	Long.	246	(18.8)	119		217	4.0		77.7	68.9	2	2
	Long.	229	(18.8)	111		217	3.0		75.2	76.0	2	2
	Long.	241	(18.8)	116		215	2.0		75.5	71.4	1	1
	Avg	234		113	0.96	216	3.0	89	76.0	72.2	1	2
-320	Trans.	238	(18.3)	115		212	3.0		77.1	76.1	1	2
	Trans.	219	(18.3)	106		219	3.0		76.6	75.0	1	1
	Trans.	235	(18.3)	114		210	3.0		78.2	75.0	1	1
	Trans.	233	(18.3)	113		220	3.0		76.8	73.1	2	2
	Trans.	226	(18.3)	109		200	3.0		76.2	66.7	0	1
	Avg	230		111	0.90	212	3.0	83	77.0	73.2	1	1
-423	Long.	252	(18.8)	122		248	3.0		76.2	72.9	1	2
	Long.	229	(18.8)	111		248	3.0		76.2	77.8	1	4
	Long.	236	(18.8)	114		249	3.5		76.7	71.3	1	4
	Long.	238	(18.8)	115		249	3.0		76.0	74.4	1	2
	Long.	244	(18.8)	118		256	3.0		76.4	69.5	2	6
	Avg	240		116	0.87	250	3.1	91	76.3	73.2	1	4
-423	Trans.	220	(18.3)	106		261	2.0		76.2	73.1	1	4
	Trans.	193	(18.3)	93.2		264	4.0		77.1	72.4	1	4
	Trans.	204	(18.3)	98.5		275	3.5		76.2	74.1	2	8
	Trans.	199	(18.3)	96.1		269	3.0		76.0	70.7	1	2
	Trans.	211	(18.3)	102		275	4.0		77.0	69.9	2	2
	Avg	205		99.2	0.69	269	3.3	91	76.5	72.0	1	4

Table 7. Properties of 75-Percent Cold-Rolled 310 Stainless Steel (0.020 In. Sheet, Washington Steel, Heat No. 43631, Coil No. 44942)

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	PROPORTIONAL LIMIT (KSI)	ELASTIC MODULUS (PSI X10^6)	HARDNESS (15-N) REDUCED SECTION	HARDNESS (15-N) FRACTURED EDGE	% MARTENSITE REDUCED SECTION	% MARTENSITE FRACTURED EDGE
78	Long.	152	179	2.5	45.3	25.3	78.4	79.7	0	0
	Long.	155	180	2.5	41.1	26.8	78.1	79.8	0	0
	Long.	155	180	2.5	40.9	25.0	78.9	78.2	0	0
	Long.	160	180	2.5	66.5	23.5	78.7	78.7	0	0
	Long.	160	181	2.5	41.4	26.2	78.5	79.1	0	0
	Avg	156	180	2.5	47.0	25.4	78.5	79.1	0	0
78	Trans.	160	201	3.0	53.2	29.4	79.6	79.6	0	0
	Trans.	152	201	3.5	-	-	79.2	79.3	0	0
	Trans.	153	202	4.0	63.7	28.8	79.1	79.8	0	0
	Trans.	159	197	3.5	73.1	27.0	79.9	79.8	0	0
	Trans.	163	199	3.0	78.9	27.2	79.6	79.7	0	0
	Avg	157	200	3.4	67.2	28.1	79.5	79.6	0	0
-100	Long.	183	201	5.0	90.5	26.2	79.0	80.0	0	0
	Long.	182	202	5.0	102	26.6	80.0	80.5	0	0
	Long.	186	204	5.5	115	24.4	79.4	81.0	0	0
	Long.	189	205	5.0	114	26.3	79.1	81.1	0	0
	Long.	187	204	4.5	106	24.0	79.6	80.0	0	0
	Avg	185	203	5.0	105	25.5	79.4	80.5	0	0
-100	Trans.	187	224	7.5	102	26.0	79.9	81.7	0	0
	Trans.	176	224	7.0	-	28.4	79.8	81.0	0	0
	Trans.	182	223	6.5	95.3	30.3	80.0	80.8	0	0
	Trans.	189	223	7.5	97.8	26.9	80.3	82.0	0	0
	Trans.	193	225	7.5	101	26.3	79.5	80.5	0	0
	Avg	185	224	7.2	99.0	27.6	79.9	81.2	0	0

-320	Long.	223	254	9.5	129	26.0	80.0	82.0	0	0
	Long.	227	253	8.0	147	25.5	79.9	81.0	0	0
	Long.	231	254	8.0	165	27.8	80.1	82.0	0	0
	Long.	230	251	10.0	132	26.3	80.1	81.4	0	0
	Long.	227	252	8.0	110	26.2	80.0	81.0	0	0
	Avg	228	253	8.7	137	26.4	80.0	81.5	0	0
-320	Trans.	219	270	9.5	133	27.2	79.8	81.5	0	0
	Trans.	225	274	9.5	122	27.3	79.8	81.0	0	0
	Trans.	223	274	7.5	124	28.5	80.0	82.0	0	0
	Trans.	219	272	8.5	142	28.3	80.0	80.0	0	0
	Trans.	214	271	9.5	138	29.8	80.7	81.7	0	0
	Avg	220	272	8.9	132	28.2	80.1	81.2	0	0
-423	Long.	261	291	8.5	164	27.1	79.0	81.1	0	0
	Long.	257	290	7.5	164	28.9	79.4	80.0	0	0
	Long.	264	289	8.0	176	28.3	81.0	81.0	0	0
	Long.	262	293	9.0	199	28.4	80.5	82.0	0	0
	Long.	259	294	9.0	188	28.6	80.0	80.2	0	0
	Avg	261	291	8.4	178	28.3	80.0	80.9	0	0
-423	Trans.	261	314	9.5	164	30.8	79.8	81.0	0	0
	Trans.	261	322	8.0	161	30.0	79.9	80.8	0	0
	Trans.	266	301	8.5	183	28.8	79.5	79.7	0	0
	Trans.	262	318	9.0	183	27.1	79.2	79.6	0	0
	Trans.	280	315	11.0	164	28.9	79.4	81.1	0	0
	Avg	266	314	9.2	171	29.1	79.6	80.4	0	0

Table 7. (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t = 3.2) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/UNNOTCH TENSILE RATIO	NOTCH T.S. (K_t = 6.3) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/UNNOTCH TENSILE RATIO
78	Long.	196 (3.2)	54.8		198 (6.3)	55.6	
	Long.	198 (3.2)	55.5		199 (6.3)	55.6	
	Long.	198 (3.2)	55.4		198 (6.3)	55.4	
	Long.	198 (3.2)	55.4		197 (6.3)	55.3	
	Long.	198 (3.2)	55.4		199 (6.3)	55.8	
	Avg	198	55.3	1.10	198	55.5	1.10
78	Trans.	217 (3.2)	60.7		206 (6.3)	57.7	
	Trans.	219 (3.2)	61.4		196 (6.3)	54.9	
	Trans.	222 (3.2)	62.2		210 (6.3)	58.8	
	Trans.	221 (3.2)	61.8		196 (6.3)	52.8	
	Trans.	196 (3.2)	54.8		189 (6.3)	50.2	
	Avg	215	60.2	1.08	199	54.9	1.00
-100	Long.	223 (3.2)	62.4		224 (6.3)	62.7	
	Long.	221 (3.2)	61.9		226 (6.3)	63.3	
	Long.	221 (3.2)	61.9		223 (6.3)	62.5	
	Long.	224 (3.2)	62.6		223 (6.3)	62.4	
	Long.	222 (3.2)	62.0		222 (6.3)	62.0	
	Avg	222	62.2	1.09	224	62.6	1.10
-100	Trans.	261 (3.2)	73.2		244 (6.3)	68.4	
	Trans.	260 (3.2)	72.8		239 (6.3)	66.8	
	Trans.	260 (3.2)	72.9		226 (6.3)	63.2	
	Trans.	260 (3.2)	72.8		244 (6.3)	68.5	
	Trans.	263 (3.2)	73.5		240 (6.3)	67.2	
	Avg	261	73.0	1.18	239	66.8	1.08

-320	Long.	280 (3.2)	78.4		279 (6.3)	78.1	
	Long.	279 (3.2)	78.0		279 (6.3)	78.1	
	Long.	278 (3.2)	77.8		278 (6.3)	77.7	
	Long.	278 (3.2)	77.9		279 (6.3)	78.1	
	Long.	277 (3.2)	77.5		279 (6.3)	78.1	
	Avg	278	77.9	1.10	279	78.0	1.10
-320	Trans.	321 (3.2)	90.0		296 (6.3)	83.0	
	Trans.	321 (3.2)	90.0		305 (6.3)	85.4	
	Trans.	332 (3.2)	93.0		298 (6.3)	83.5	
	Trans.	336 (3.2)	94.2		304 (6.3)	85.0	
	Trans.	335 (3.2)	93.8		289 (6.3)	80.9	
	Avg	329	92.2	1.21	298	83.6	1.10
-423	Long.	329 (3.2)	92.2		330 (6.3)	92.3	
	Long.	334 (3.2)	93.5		323 (6.3)	90.6	
	Long.	331 (3.2)	92.8		335 (6.3)	93.7	
	Long.	335 (3.2)	93.8		327 (6.3)	91.6	
	Long.	339 (3.2)	94.9		327 (6.3)	91.6	
	Avg	334	93.4	1.15	328	92.0	1.13
-423	Trans.	393 (3.2)	110		340 (6.3)	95.1	
	Trans.	384 (3.2)	108		324 (6.3)	90.7	
	Trans.	381 (3.2)	107		327 (6.3)	91.6	
	Trans.	388 (3.2)	109		323 (6.3)	90.4	
	Trans.	386 (3.2)	108		330 (6.3)	92.3	
	Avg	386	108	1.23	329	92.0	1.05

Table 7. (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t = 19) (KSI)	FRACTURE TOUGHNESS K (PSI $\sqrt{IN.}$)	NOTCH/UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)	HARDNESS (15-N) HEAT AFFECTED ZONE	HARDNESS (15-N) WELD	% MARTENSITE HEAT AFFECTED ZONE	% MARTENSITE WELD
78	Long.	167(20.8)	80.6		86.6	2.5		79.5	67.1	0	0
	Long.	152(20.8)	73.3		85.8	1.5		79.9	63.0	0	0
	Long.	157(20.8)	75.7		88.3	1.5		79.0	66.8	0	0
	Long.	167(20.8)	80.7		85.8	2.5		80.5	63.4	0	0
	Long.	160(20.8)	77.3		87.1	2.0		79.0	64.0	0	0
	Avg	161	77.5	0.90	86.7	2.0	48	79.6	64.9	0	0
78	Trans.	118(19.8)	56.8		86.9	2.5		79.9	64.2	0	0
	Trans.	116(19.8)	56.2		82.8	2.0		80.0	69.1	0	0
	Trans.	121(19.8)	58.3		84.0	2.0		79.5	65.0	0	0
	Trans.	127(19.8)	61.4		86.3	2.0		79.5	65.8	0	0
	Trans.	123(19.8)	59.3		87.3	2.0		79.2	65.6	0	0
	Avg	121	58.4	0.61	85.5	2.1	43	79.6	65.9	0	0
-100	Long.	185(20.8)	89.2		111	2.5		80.7	66.2	0	0
	Long.	167(20.8)	80.9		108	2.0		79.7	65.6	0	0
	Long.	197(20.8)	95.2		109	2.5		79.7	67.8	0	0
	Long.	185(20.8)	89.3		106	2.5		79.8	65.2	0	0
	Long.	187(20.8)	90.5		112	2.0		79.8	65.0	0	0
	Avg	184	89.0	0.91	109	2.3	54	79.9	66.0	0	0
-100	Trans.	158(19.8)	76.3		110	2.0		79.8	65.2	0	0
	Trans.	170(19.8)	82.2		112	2.0		79.9	66.5	0	0
	Trans.	147(19.8)	71.1		109	2.5		79.9	66.5	0	0
	Trans.	160(19.8)	77.1		109	2.0		79.7	68.0	0	0
	Trans.	161(19.8)	78.0		110	2.5		80.5	65.2	0	0
	Avg	159	76.9	0.72	110	2.2	50	80.0	66.3	0	0

-320	Long.	208(20.8)	100		158	2.5		79.4	71.3	0	0
	Long.	191(20.8)	92.1		160	2.5		79.8	68.8	0	0
	Long.	230(20.8)	111		162	2.5		80.4	66.3	0	0
	Long.	221(20.8)	107		162	2.5		79.2	64.4	0	0
	Long.	218(20.8)	105		170	2.0		80.0	66.6	0	0
	Avg	214	103	0.85	162	2.4	64	79.8	67.5	0	0
-320	Trans.	163(19.8)	78.6		168	2.5		79.0	67.5	0	0
	Trans.	177(19.8)	85.5		169	2.0		80.7	68.3	0	0
	Trans.	181(19.8)	87.5		168	2.0		79.7	69.2	0	0
	Trans.	195(19.8)	94.0		166	2.5		79.5	67.0	0	0
	Trans.	161(19.8)	77.8		166	2.5		80.0	68.2	0	0
	Avg	175	84.7	0.64	167	2.3	61	79.8	68.0	0	0
-423	Long.	215(20.8)	104		203	1.5		79.8	69.1	0	0
	Long.	224(20.8)	108		209	2.0		79.4	68.9	0	0
	Long.	189(20.8)	91.5		209	2.0		79.4	71.1	0	0
	Long.	209(20.8)	101		213	2.0		79.9	70.6	0	0
	Long.	212(20.8)	103		206	2.0		79.9	69.3	0	0
	Avg	210	102	0.72	208	1.9	71	79.7	69.8	0	0
-423	Trans.	189(19.8)	91.1		192	2.5		79.0	69.0	0	0
	Trans.	206(19.8)	99.5		196	2.0		79.2	67.5	0	0
	Trans.	172(19.8)	82.9		187	2.0		79.4	67.7	0	0
	Trans.	183(19.8)	88.4		191	1.5		79.0	69.8	0	0
	Trans.	209(19.8)	101		199	2.0		79.0	69.9	0	0
	Avg	192	92.6	0.61	193	2.0	61	79.1	68.8	0	0

Table 8. Properties of AM-355 Stainless Steel (0.032 In. Sheet, Wallingford Steel, Heat No. 38174)

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} KSI	ELONG (%)	PROPORTIONAL LIMIT (KSI)	ELASTIC MODULUS (PSI x10^6)	HARDNESS (15-N) REDUCTION SECTION	HARDNESS (15-N) FRACTURED EDGE	% MARTENSITE REDUCED SECTION	% MARTENSITE FRACTURED EDGE
78	Long.	281	294	5.0	148	28.0	87.5	88.3	97	98
	Long.	272	298	5.5	138	28.9	86.5	87.7	96	99
	Long.	278	299	6.0	134	28.4	87.5	89.5	97	98
	Long.	278	294	5.0	142	27.2	86.0	88.9	97	97
	Long.	283	298	5.5	152	26.1	86.3	88.1	97	98
	Avg	278	297	5.4	143	27.7	86.8	88.5	97	98
78	Trans.	251	288	7.0	120	29.9	87.6	89.3	96	97
	Trans.	254	286	7.0	142	28.2	86.2	89.2	96	98
	Trans.	250	283	7.0	131	28.7	88.0	89.6	97	98
	Trans.	250	286	7.5	127	28.4	86.7	87.5	96	98
	Trans.	248	286	6.5	141	29.4	86.2	86.6	97	98
	Avg	251	286	7.0	132	28.9	86.9	88.4	96	98
-100	Long.	285	311	17.5	165	27.9	89.4	88.0	99	99
	Long.	294	311	16.5	163	28.5	87.1	88.7	98	98
	Long.	290	309	17.0	188	26.4	88.7	89.0	98	100
	Long.	286	306	17.0	162	26.6	88.4	88.6	100	100
	Long.	281	305	17.0	163	26.6	89.3	89.1	99	100
	Avg	287	308	17.0	168	27.2	88.6	88.7	99	99
-100	Trans.	253	310	12.0	153	30.8	89.0	89.2	98	99
	Trans.	249	314	12.0	175	27.3	87.2	87.9	98	98
	Trans.	249	316	10.5	154	27.7	88.2	87.5	99	100
	Trans.	254	313	12.5	141	28.9	88.4	89.9	98	99
	Trans.	253	315	10.5	156	30.1	89.5	89.8	100	99
	Avg	252	314	11.5	156	29.0	88.5	88.9	99	99

-320	Long.	329	349	9.0	171	28.4	85.9	87.4	96	97
	Long.	338	356	10.0	204	27.2	86.2	87.6	96	98
	Long.	324	353	10.0	183	27.8	86.0	87.2	97	99
	Long.	-	354	9.5	-	-	86.8	87.5	98	99
	Long.	-	350	9.5	-	-	88.8	88.5	96	97
	Long.	316	354	9.5	191	28.0	86.0	87.2	97	98
	Long.	333	352	9.0	208	28.3	88.5	86.7	96	97
	Avg	328	353	9.5	191	27.9	86.9	87.4	97	98
-320	Trans.	294	348	2.0	184	27.6	87.0	87.2	97	98
	Trans.	278	335	2.0	173	27.3	87.1	87.4	98	97
	Trans.	277	345	2.0	176	30.1	86.6	87.8	99	99
	Trans.	294	348	2.0	176	29.4	87.8	88.6	99	98
	Trans.	289	336	1.5	192	28.9	86.6	87.2	98	98
	Avg	286	342	1.9	180	28.7	87.0	87.6	98	98
-423	Long.	311	311	0	201	28.1	86.2	87.0	97	98
	Long.	346	346	0	228	28.7	87.0	87.3	99	99
	Long.	-	364	0	-	-	86.8	87.4	98	99
	Long.	-	355	0	-	-	87.8	87.8	99	99
	Long.	-	358	0	-	-	88.4	88.6	98	99
	Avg	329	347	0	215	28.4	87.2	87.6	98	99
-423	Trans.	319	319	0	198	29.0	86.8	87.1	97	98
	Trans.	-	344	0	-	-	86.8	87.6	97	97
	Trans.	-	349	0	-	-	87.0	87.2	98	99
	Trans.	-	353	0	-	-	88.2	88.2	99	99
	Trans.	-	331	0	-	-	87.7	88.4	98	99
	Avg	319	339	0	198	29.0	87.3	87.7	98	98

Table 8. (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (KSI) (K_t = 6.3)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)	HARDNESS (15-N) HEAT AFFECTED ZONE	HARDNESS (15-N) WELD	% MARTENSITE HEAT AFFECTED ZONE	% MARTENSITE WELD
78	Long.	257 (6.2)	71.9		226	2.0		85.8	84.5	95	98
	Long.	248 (6.2)	69.3		216	2.5		86.4	82.6	96	98
	Long.	239 (6.1)	66.9		226	2.0		86.4	85.2	96	98
	Long.	270 (6.2)	75.5		222	2.0		86.0	85.0	95	98
	Long.	252 (6.2)	70.7		218	2.0		85.7	80.0	95	98
	Avg	253	70.9	0.85	222	2.1	75	86.1	83.5	95	98
78	Trans.	228 (6.5)	63.9		223	2.0		87.2	84.5	96	98
	Trans.	227 (6.5)	63.5		223	2.5		85.9	85.2	95	98
	Trans.	228 (6.6)	63.8		218	2.5		87.0	85.4	96	97
	Trans.	240 (6.6)	67.2		217	2.5		90.0	85.4	96	98
	Trans.	233 (6.6)	65.3		215	2.0		86.3	84.7	96	98
	Avg	231	64.7	0.81	219	2.3	73	87.3	85.0	96	98
-100	Long.	287 (6.2)	80.3		288	2.5		87.8	86.0	96	100
	Long.	278 (6.2)	77.4		290	2.0		87.5	86.5	96	99
	Long.	288 (6.2)	80.6		291	2.5		87.6	83.7	97	98
	Long.	263 (6.2)	73.7		287	2.5		87.2	85.2	97	99
	Long.	260 (6.2)	72.9		290	2.5		86.5	88.4	96	99
	Avg	275	77.0	0.89	289	2.4	94	87.3	86.0	96	99
-100	Trans.	251 (6.6)	70.3		283	2.5		88.2	88.7	97	98
	Trans.	237 (6.6)	66.4		284	2.0		88.5	86.6	97	98
	Trans.	243 (6.6)	68.0		279	1.5		87.5	87.2	96	98
	Trans.	246 (6.6)	68.9		283	1.5		86.2	84.3	96	99
	Trans.	237 (6.6)	66.3		282	1.5		86.6	88.9	95	100
	Avg	243	68.0	0.77	282	1.8	90	87.4	87.2	96	99

-320	Long.	168 (6.2)	47.0		264	1.0		85.8	85.8	96	97
	Long.	164 (6.2)	45.9		265	1.0		86.1	85.1	96	98
	Long.	163 (6.2)	45.7		235	0.0		86.1	84.7	96	98
	Long.	147 (6.2)	41.1		294	1.0		87.1	85.9	96	99
	Long.	176 (6.2)	49.3		298	1.0		86.5	87.3	97	98
	Avg	164	45.8	0.46	271	0.8	77	86.3	84.8	96	98
-320	Trans.	169 (6.6)	47.2		283	1.0		87.9	87.0	97	98
	Trans.	166 (6.6)	46.5		326	1.0		88.6	85.8	97	98
	Trans.	192 (6.6)	53.8		291	1.0		86.8	86.1	97	100
	Trans.	170 (6.6)	47.6		283	1.0		86.5	88.2	96	99
	Trans.	164 (6.6)	45.9		312	1.0		87.1	88.1	96	99
	Avg	172	48.2	0.50	299	1.0	87	87.4	87.0	97	99
-423	Long.	113 (6.2)	31.7		140	0.5		86.3	82.7	95	92
	Long.	102 (6.2)	28.6		138	0.5		89.3	83.1	95	93
	Long.	117 (6.2)	32.8		142	0.5		86.8	85.2	95	91
	Long.	119 (6.2)	33.3		139	0.5		88.0	84.5	96	90
	Long.	144 (6.2)	40.3		151	0.5		87.6	85.0	95	95
	Avg	119	33.3	0.34	142	0.5	41	87.6	84.1	96	92
-423	Trans.	133 (6.6)	37.2		133	0.5		88.8	86.4	96	91
	Trans.	147 (6.6)	41.2		139	0.5		87.9	84.5	96	92
	Trans.	135 (6.6)	37.9		136	0.5		88.2	85.6	95	91
	Trans.	83 (6.6)	23.3		155	0.5		86.8	87.8	95	95
	Trans.	130 (6.6)	36.3		139	0.5		87.0	83.1	96	92
	Avg	126	35.2	0.37	140	0.5	41	87.7	85.5	96	92

Table 9. Properties of 2014-T6 Aluminum Alloy (0.063 In. Sheet, Aluminum Company of America, AMS-4029)

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	PROPORTIONAL LIMIT (KSI)	ELASTIC MODULUS (PSI X 10^6)	HARDNESS (15-N) REDUCED SECTION	HARDNESS (15-N) FRACTURED EDGE
78	Long.	66.3	72.0	10.0	54.8	10.0	60.0	60.5
	Long.	65.2	71.5	10.0	48.3	10.2	60.0	60.1
	Long.	65.3	71.7	10.0	53.0	9.6	60.0	59.7
	Long.	64.6	71.4	10.0	51.6	10.1	60.0	60.2
	Long.	64.7	71.6	10.0	52.2	10.3	60.8	61.0
	Avg	65.2	71.6	10.0	52.0	10.0	60.2	60.3
78	Trans.	63.4	70.7	11.0	43.3	9.7	59.0	59.2
	Trans.	62.7	70.8	10.5	43.6	9.9	58.8	59.0
	Trans.	63.3	70.9	10.0	43.6	10.1	60.0	62.0
	Trans.	63.1	71.0	10.0	45.7	10.3	59.0	61.0
	Trans.	63.3	71.1	10.0	45.7	10.1	60.0	61.7
	Avg	63.2	70.9	10.3	44.4	10.0	59.4	60.6
-100	Long.	67.7	74.0	10.0	60.3	10.1	62.1	61.1
	Long.	68.2	75.0	10.5	63.2	11.1	61.8	60.9
	Long.	68.6	74.9	10.0	51.1	11.0	60.5	60.3
	Long.	68.2	74.5	10.5	52.6	9.7	59.8	59.8
	Long.	68.1	74.5	11.5	51.0	11.0	60.3	60.0
	Avg	68.2	74.6	10.5	55.6	10.6	60.9	60.4
-100	Trans.	66.1	73.9	10.0	50.3	11.3	59.9	58.8
	Trans.	66.1	73.9	11.0	50.1	9.7	60.0	60.0
	Trans.	66.0	73.9	10.5	52.4	11.0	60.1	60.2
	Trans.	65.5	74.2	10.0	42.9	9.6	60.2	60.2
	Trans.	66.0	73.9	9.5	43.9	10.1	59.5	60.1
	Avg	65.9	74.0	10.2	47.9	10.4	59.9	59.9

-320	Long.	74.8	85.5	13.0	61.4	11.4	59.0	60.6
	Long.	72.8	85.5	11.0	61.7	10.8	59.6	60.6
	Long.	74.4	85.5	12.5	54.6	11.4	61.9	59.1
	Long.	74.2	85.2	13.0	54.4	11.2	59.1	59.7
	Long.	74.3	86.0	12.5	54.1	11.8	60.0	59.2
	Avg	74.1	85.5	12.4	57.2	11.3	59.9	59.8
-320	Trans.	70.7	84.5	12.5	54.7	10.7	59.5	60.2
	Trans.	66.7	84.5	12.5	47.7	10.3	59.6	60.1
	Trans.	70.0	84.5	12.0	54.0	11.6	60.1	60.7
	Trans.	70.1	84.4	12.5	47.9	11.8	59.7	60.6
	Trans.	69.0	84.4	12.5	51.7	11.4	59.4	59.9
	Avg	69.3	84.5	12.4	51.2	11.2	59.7	60.3
-423	Long.	84.6	102	11.0	74.3	11.4	61.3	61.2
	Long.	83.0	99.2	14.5	76.0	11.0	60.5	60.9
	Long.	83.5	103	15.5	62.3	11.9	61.9	61.1
	Long.	83.1	101	16.0	65.9	12.2	60.2	61.0
	Long.	83.0	100	16.5	72.7	12.3	60.7	61.3
	Avg	83.4	101	14.7	70.2	11.8	60.9	61.1
-423	Trans.	81.2	101	14.0	60.9	11.9	59.5	60.5
	Trans.	80.0	99.8	14.5	65.3	11.7	61.2	60.8
	Trans.	83.1	103	15.5	55.1	12.3	59.8	61.8
	Trans.	82.6	102	15.5	66.9	12.1	60.8	61.7
	Trans.	82.0	102	15.5	67.0	10.4	61.5	60.5
	Avg	81.8	102	15.0	63.0	11.7	60.6	61.3

Table 9 (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t=3.2) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO	NOTCH T.S. (K_t=6.3) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN}$)	NOTCH/ UNNOTCH TENSILE RATIO
78	Long.	76.6 (3.1)	21.4		75.6 (6.3)	21.2	
	Long.	77.6 (3.1)	21.7		75.2 (6.4)	21.1	
	Long.	78.4 (3.1)	22.0		75.7 (6.4)	21.2	
	Long.	78.0 (3.1)	21.8		74.9 (6.3)	21.0	
	Long.	77.6 (3.1)	21.7		75.4 (6.4)	21.1	
	Avg	77.6	21.7	1.08	75.4	21.1	1.05
78	Trans.	77.0 (3.2)	21.6		72.5 (6.3)	20.3	
	Trans.	77.2 (3.2)	21.6		70.7 (6.3)	19.8	
	Trans.	77.3 (3.2)	21.6		73.5 (6.3)	20.6	
	Trans.	78.6 (3.2)	22.0		72.6 (6.3)	20.3	
	Trans.	82.1 (3.2)	23.0		70.6 (6.3)	19.8	
	Avg	78.4	22.0	1.11	72.0	20.2	1.02
-100	Long.	80.1 (3.1)	22.4		77.4 (6.4)	21.7	
	Long.	80.6 (3.1)	22.6		77.4 (6.4)	21.7	
	Long.	80.6 (3.2)	22.6		77.6 (6.4)	21.7	
	Long.	79.8 (3.2)	22.3		76.6 (6.4)	21.7	
	Long.	79.5 (3.2)	22.3		77.9 (6.4)	21.8	
	Avg	80.1	22.4	1.07	77.4	21.7	1.04
-100	Trans.	79.1 (3.2)	22.1		74.6 (6.3)	21.2	
	Trans.	79.1 (3.2)	22.1		74.8 (6.3)	20.2	
	Trans.	79.4 (3.2)	22.2		71.4 (6.3)	20.0	
	Trans.	78.5 (3.2)	22.0		74.4 (6.3)	20.8	
	Trans.	78.3 (3.2)	22.0		74.4 (6.3)	20.8	
	Avg	78.9	22.1	1.07	73.9	20.7	1.00

-320	Long.	90.2 (3.2)	25.3		84.0 (6.4)	23.5	
	Long.	90.4 (3.2)	25.3		86.2 (6.4)	24.1	
	Long.	90.0 (3.2)	25.2		85.4 (6.4)	23.9	
	Long.	90.4 (3.2)	25.3		83.6 (6.5)	23.4	
	Long.	91.1 (3.2)	25.5		79.6 (6.4)	22.3	
	Avg	90.4	25.3	1.06	83.8	23.5	0.98
-320	Trans.	89.1 (3.2)	25.0		75.7 (6.3)	21.2	
	Trans.	89.3 (3.2)	25.0		82.1 (6.3)	23.0	
	Trans.	89.0 (3.2)	25.0		76.6 (6.4)	21.4	
	Trans.	88.2 (3.2)	24.7		80.4 (6.3)	22.5	
	Trans.	88.0 (3.2)	24.6		78.8 (6.3)	22.1	
	Avg	88.7	24.8	1.05	78.7	22.0	0.93
-423	Long.	101 (3.2)	28.3		101 (6.4)	28.3	
	Long.	104 (3.1)	29.1		84.2 (6.5)	23.6	
	Long.	105 (3.1)	29.4		94.1 (6.4)	26.3	
	Long.	102 (3.1)	28.6		91.7 (6.4)	25.7	
	Long.	102 (3.2)	28.6		95.3 (6.4)	26.7	
	Avg	103	28.8	1.02	93.3	26.1	0.92
-423	Trans.	104 (3.2)	29.1		91.6 (6.3)	25.6	
	Trans.	100 (3.2)	28.0		89.9 (6.3)	25.2	
	Trans.	101 (3.1)	28.3		88.1 (6.3)	24.7	
	Trans.	105 (3.2)	29.4		91.1 (6.3)	25.5	
	Trans.	104 (3.1)	29.1		91.8 (6.4)	25.7	
	Avg	103	28.8	1.01	90.5	25.3	0.89

Table 9 (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t=19) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)	HARDNESS (15-N) HEAT AFFECTED ZONE	HARDNESS (15-N) WELD
78	Long.	62.5 (22.5)	30.2		52.6	4.0		40	37
	Long.	64.6 (22.5)	31.2		57.8	3.0		54	43
	Long.	66.6 (22.5)	32.2		51.7	2.0		46	41
	Long.	64.1 (22.5)	31.0		57.1	2.0		46	40
	Long.	65.2 (22.5)	31.5		57.7	2.0		49	39
	Avg	64.6	31.2	0.90	55.4	2.6	77	47	40
78	Trans.	60.0 (21.9)	29.0		58.3	1.5		46	37
	Trans.	57.7 (21.9)	27.9		57.5	1.5		50	41
	Trans.	60.1 (21.9)	29.0		59.8	2.0		46	36
	Trans.	61.4 (21.9)	29.7		59.0	2.0		53	37
	Trans.	60.7 (21.9)	29.3		58.5	2.0		54	40
	Avg	60.0	29.0	0.85	58.6	1.8	83	50	38
-100	Long.	66.4 (22.5)	32.1		53.8	2.0		52	42
	Long.	52.6 (22.5)	25.4		53.4	2.0		49	47
	Long.	59.1 (22.5)	28.5		58.6	0.5		46	36
	Long.	56.8 (22.5)	27.4		56.3	1.0		47	39
	Long.	68.5 (22.5)	33.1		59.8	1.0		43	39
	Avg	60.7	29.3	0.81	56.4	1.3	76	47	41
-100	Trans.	51.0 (21.9)	24.6		58.0	2.0		42	36
	Trans.	52.1 (21.9)	25.2		58.3	1.0		49	44
	Trans.	55.2 (21.9)	26.7		57.7	1.5		42	37
	Trans.	54.0 (21.9)	26.8		58.7	1.5		49	39
	Trans.	57.3 (21.9)	27.7		58.2	1.5		43	37
	Avg	53.9	26.0	0.73	58.2	1.5	79	45	39

-320	Long.	53.9 (22.5)	26.0		65.9	1.5		43	38
	Long.	57.5 (22.5)	27.7		60.3	1.0		42	34
	Long.	58.0 (22.5)	28.0		63.7	1.0		47	37
	Long.	51.4 (22.5)	24.8		64.1	0.5		47	42
	Long.	57.9 (22.5)	28.0		61.9	0.5		40	36
	Avg	55.7	26.9	0.65	63.2	0.9	75	44	37
-320	Trans.	69.3 (21.9)	33.5		65.4	1.0		49	39
	Trans.	62.3 (21.9)	30.1		63.6	1.0		41	36
	Trans.	58.2 (21.9)	28.1		66.9	1.0		46	36
	Trans.	62.8 (21.9)	30.3		66.9	1.0		40	35
	Trans.	68.8 (21.9)	33.2		65.6	1.0		46	37
	Avg	64.3	31.1	0.76	65.7	1.0	78	44	37
-423	Long.	75.4 (22.5)	36.4		71.5	1.5		48	32
	Long.	76.4 (22.5)	36.9		71.6	1.5		45	43
	Long.	76.1 (22.5)	36.8		62.3	1.5		50	37
	Long.	77.2 (22.5)	37.3		69.4	1.0		41	36
	Long.	74.6 (22.5)	36.0		79.3	1.0		46	37
	Avg	75.9	36.7	0.75	70.8	1.3	70	46	37
-423	Trans.	81.6 (21.9)	39.4		73.1	1.5		41	34
	Trans.	69.3 (21.9)	33.5		79.1	1.0		52	35
	Trans.	65.5 (21.9)	31.6		71.8	1.0		49	35
	Trans.	71.7 (21.9)	34.6		70.1	1.5		41	35
	Trans.	69.8 (21.9)	33.7		75.0	1.5		40	36
	Avg	71.6	34.6	0.70	73.8	1.3	72	45	35

Table 10. Properties of 5052-H38 Aluminum Alloy (0.063 In. Sheet, Aluminum Company of America, QQ-A-318)

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	PROPORTIONAL LIMIT (KSI)	ELASTIC MODULUS (PSI x 10^6)	HARDNESS (15-N) REDUCED SECTION	HARDNESS (15-N) FRACTURED EDGE
78	Long.	36.3	42.0	8.0	32.9	9.6	42.5	45.1
	Long.	36.3	42.0	8.0	31.4	10.1	42.3	42.2
	Long.	36.2	42.0	8.0	32.2	10.3	43.9	44.1
	Long.	36.5	42.0	8.0	31.4	10.1	43.1	41.0
	Long.	35.4	42.0	8.0	32.2	10.4	40.9	42.9
	Avg	36.1	42.0	8.0	32.0	10.1	42.5	43.1
78	Trans.	36.3	42.9	11.0	30.1	10.3	42.3	43.2
	Trans.	36.4	42.9	12.5	27.8	10.1	43.0	43.1
	Trans.	36.1	42.7	11.0	26.2	10.0	42.2	42.9
	Trans.	35.8	42.7	11.0	32.0	9.9	42.0	42.9
	Trans.	35.7	42.6	11.0	28.5	10.2	43.0	42.0
	Avg	36.1	42.8	11.3	28.9	10.1	42.5	42.8
-100	Long.	36.8	43.6	13.0	--	11.5	44.8	45.4
	Long.	36.5	43.6	10.0	31.0	10.7	44.7	46.0
	Long.	37.4	43.8	10.5	29.8	10.4	44.5	44.0
	Long.	37.8	43.7	12.5	--	10.6	41.2	43.6
	Long.	37.4	43.8	13.0	36.2	10.7	45.2	42.8
	Avg	37.2	43.7	11.8	32.3	10.8	44.1	44.4
-100	Trans.	35.6	42.5	14.0	32.9	10.1	43.3	43.0
	Trans.	37.5	44.5	14.0	30.8	10.5	43.3	43.0
	Trans.	37.7	44.6	15.0	33.1	9.9	43.1	42.1
	Trans.	37.7	44.6	14.5	30.9	11.2	42.9	44.0
	Trans.	37.7	44.6	15.0	--	12.0	42.0	46.0
	Avg	37.2	44.2	14.5	31.9	10.7	42.9	43.6

-320	Long.	43.4	60.7	28.0	33.6	12.1	42.5	46.8
	Long.	43.1	60.7	30.0	36.1	12.3	46.6	46.9
	Long.	42.9	60.7	19.5	33.8	12.6	45.0	47.1
	Long.	43.1	60.8	39.5	37.0	12.4	44.2	45.5
	Long.	43.2	60.8	19.5	37.7	12.7	48.8	47.5
	Avg	43.1	60.7	27.3	35.6	12.4	45.4	46.8
-320	Trans.	42.4	56.9	28.5	36.3	11.6	42.9	44.7
	Trans.	42.6	57.0	29.5	37.7	11.2	45.9	47.8
	Trans.	42.9	57.4	29.0	37.1	12.8	44.8	43.4
	Trans.	41.9	57.2	30.0	--	13.0	43.9	46.9
	Trans.	43.0	57.2	29.5	37.1	12.3	44.2	47.5
	Avg	42.6	57.1	29.3	37.1	12.2	44.3	46.1
-423	Long.	52.9	89.5	21.0	47.2	12.1	45.9	48.5
	Long.	48.3	86.0	28.5	45.4	12.4	46.0	47.5
	Long.	47.5	86.0	29.0	47.0	12.3	46.2	48.1
	Long.	47.5	86.5	37.0	41.7	12.2	45.8	48.0
	Long.	47.7	87.8	37.5	42.7	13.2	45.4	47.8
	Avg	48.8	87.2	30.6	44.8	12.4	45.9	48.0
-423	Trans.	47.7	76.4	42.0	39.5	12.4	46.1	47.4
	Trans.	47.4	76.1	41.0	41.1	12.3	47.0	48.1
	Trans.	47.7	76.1	41.5	38.5	12.2	45.8	48.0
	Trans.	47.7	76.1	42.5	46.0	12.8	46.1	48.4
	Trans.	47.8	76.2	41.0	45.9	11.9	46.5	47.1
	Avg	47.7	76.2	41.6	42.2	12.3	46.3	47.8

Table 10. (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t = 6.3) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCHED TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)	HARDNESS (15-N) HEAT AFFECTED ZONE	WELD
78	Long.	45.1 (6.3)	12.6		31.0	4.0		37.0	20.4
	Long.	44.7 (6.3)	12.5		32.5	3.0		41.2	21.5
	Long.	46.2 (6.3)	12.9		32.8	3.5		41.0	24.0
	Long.	45.2 (6.3)	12.7		31.6	2.0		38.5	22.3
	Long.	44.9 (6.4)	12.6		32.3	3.0		39.4	24.0
	Avg	45.2	12.7	1.08	32.0	3.1	76	39.4	22.0
78	Trans.	43.6 (6.3)	12.2		33.4	3.5		40.2	26.2
	Trans.	47.4 (6.3)	13.3		33.3	4.0		37.0	26.2
	Trans.	47.1 (6.4)	13.2		33.4	3.0		40.1	24.1
	Trans.	49.5 (6.4)	13.9		33.0	3.0		41.6	19.8
	Trans.	50.1 (6.4)	14.0		33.4	3.0		38.9	26.3
	Avg	47.5	13.3	1.11	33.3	3.3	78	39.6	24.5
-100	Long.	46.1 (6.4)	12.9		34.2	4.0		40.0	23.0
	Long.	46.6 (6.4)	13.0		34.3	4.0		41.1	21.8
	Long.	46.4 (6.4)	13.0		34.1	4.0		40.0	21.5
	Long.	46.6 (6.4)	13.0		34.2	4.0		41.0	21.5
	Long.	46.7 (6.4)	13.1		34.4	4.0		41.5	21.0
	Avg	46.5	13.0	1.06	34.2	4.0	78	40.7	21.8
-100	Trans.	51.0 (6.4)	14.3		34.4	3.0		42.0	25.0
	Trans.	51.2 (6.4)	14.3		34.6	3.0		40.5	27.0
	Trans.	51.3 (6.4)	14.4		34.2	2.5		40.5	24.4
	Trans.	51.2 (6.4)	14.3		34.6	4.0		39.5	24.4
	Trans.	51.2 (6.4)	14.3		34.7	4.0		40.0	26.5
	Avg	51.2	14.3	1.16	34.5	3.3	78	40.5	25.5

-320	Long.	61.4	(6.4)	17.2		49.0	7.5		41.0	27.6
	Long.	61.4	(6.4)	17.2		46.1	5.0		41.5	26.5
	Long.	61.4	(6.4)	17.2		41.5	4.0		39.8	22.0
	Long.	62.7	(6.4)	17.6		49.5	7.5		43.5	27.5
	Long.	61.1	(6.4)	17.1		50.3	7.5		40.0	23.5
	Avg	61.6		17.3	1.01	47.3	6.3	78	41.2	25.4
-320	Trans.	63.1	(6.3)	17.7		51.6	9.0		42.5	29.0
	Trans.	63.7	(6.3)	17.8		50.7	9.5		41.5	29.5
	Trans.	63.7	(6.3)	17.8		51.6	10.0		41.0	28.0
	Trans.	63.7	(6.3)	17.8		50.6	9.0		43.5	28.0
	Trans.	63.3	(6.3)	17.7		51.1	9.5		38.0	27.5
	Avg	63.5		17.8	1.11	51.1	9.4	89	41.3	28.4
-423	Long.	76.6	(6.4)	21.4		71.4	12.5		44.5	26.5
	Long.	76.0	(6.4)	21.2		68.4	11.0		42.5	24.8
	Long.	77.0	(6.4)	21.6		71.1	12.0		45.5	27.0
	Long.	78.8	(6.4)	22.1		69.6	11.5		46.0	28.0
	Long.	76.0	(6.4)	21.3		70.1	11.0		46.5	27.5
	Avg	76.9		21.5	0.88	70.1	11.6	80	44.0	26.8
-423	Trans.	77.5	(6.3)	21.7		68.4	14.0		45.0	31.0
	Trans.	76.0	(6.3)	21.3		69.8	15.5		45.5	28.0
	Trans.	76.3	(6.3)	21.4		68.8	14.0		46.0	29.0
	Trans.	79.3	(6.3)	22.2		73.1	19.5		45.0	27.0
	Trans.	82.2	(6.3)	23.0		64.2	12.0		42.5	22.5
	Avg	78.3		21.9	1.03	68.9	15.0	90	44.8	27.5

Table 11. Properties of 5456-H343 Aluminum Alloy (0.063 In. Sheet, Aluminum Company of America, Mil-A-19842)

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	PROPORTIONAL LIMIT (KSI)	ELASTIC MODULUS (PSI x 10^6)	HARDNESS (15-N) REDUCED SECTION	HARDNESS (15-N) FRACTURED EDGE
78	Long.	48.2	56.4	7.0	36.0	10.2	51.0	52.0
	Long.	49.9	58.6	8.0	45.9	10.5	51.0	53.0
	Long.	49.2	57.5	7.5	42.0	10.6	51.3	52.0
	Long.	49.3	57.7	8.0	40.6	10.5	50.0	52.0
	Long.	49.4	57.9	7.5	34.7	10.5	52.0	53.0
	Avg	49.2	57.6	7.6	39.8	10.5	51.1	52.4
78	Trans.	43.0	58.4	9.5	28.7	10.1	49.5	50.1
	Trans.	43.2	58.7	9.5	29.2	10.2	52.0	50.1
	Trans.	43.0	58.4	10.0	31.0	10.0	51.5	52.0
	Trans.	43.3	58.5	10.0	29.9	10.1	51.0	52.0
	Trans.	43.2	58.1	9.5	30.0	10.4	50.0	51.0
	Avg	43.1	58.4	9.7	29.8	10.2	50.8	51.0
-100	Long.	52.5	58.9	10.0	37.9	11.0	52.5	54.5
	Long.	50.4	58.9	10.0	43.5	10.8	53.0	52.8
	Long.	49.7	58.0	10.0	35.2	11.0	51.2	52.0
	Long.	50.5	58.2	10.0	40.2	10.8	52.0	53.2
	Long.	51.3	58.2	10.0	36.1	10.1	52.0	52.0
	Avg	50.9	58.4	10.0	38.6	10.7	52.2	52.9
-100	Trans.	43.9	58.9	11.0	30.0	11.1	52.0	52.5
	Trans.	43.7	57.2	10.5	31.4	10.8	52.0	52.0
	Trans.	44.1	57.6	13.0	30.7	10.1	52.0	52.5
	Trans.	43.3	58.2	11.0	28.1	10.5	52.0	53.2
	Trans.	43.8	58.6	10.5	32.6	10.4	51.0	52.0
	Avg	43.8	58.1	11.2	30.6	10.6	51.8	52.4

-320	Long.	58.5	74.7	12.0	38.3	10.6	52.0	52.8
	Long.	56.8	74.5	13.5	37.8	11.0	51.5	53.2
	Long.	57.6	76.0	13.0	41.6	10.3	53.0	53.1
	Long.	57.4	74.3	12.0	38.6	10.2	53.0	53.6
	Long.	57.4	74.4	12.5	35.7	10.4	52.0	52.5
	Avg	57.5	74.8	12.6	38.4	10.5	52.3	53.0
-320	Trans.	52.0	72.5	12.0	45.1	10.9	51.2	51.5
	Trans.	52.1	72.7	13.0	30.0	10.7	52.1	54.3
	Trans.	51.3	72.2	11.5	44.9	10.0	52.5	53.5
	Trans.	50.5	72.0	12.0	35.8	10.7	52.0	52.8
	Trans.	52.6	72.4	11.5	43.6	10.8	52.5	52.8
	Avg	51.7	72.4	12.0	39.9	10.6	52.1	53.0
-423	Long.	64.1	90.6	9.5	50.2	10.9	51.3	50.5
	Long.	63.5	85.3	8.0	49.0	11.6	51.0	52.0
	Long.	63.8	89.5	10.0	49.0	11.6	52.0	53.0
	Long.	63.8	87.4	9.0	42.9	11.1	53.5	52.6
	Long.	63.9	89.5	10.0	42.6	11.0	53.3	52.5
	Avg	63.8	88.5	9.3	46.7	11.2	52.2	52.1
-423	Trans.	58.4	81.1	7.0	45.9	11.5	51.0	52.9
	Trans.	56.3	84.2	9.5	47.4	11.4	52.9	53.0
	Trans.	57.5	76.4	5.0	48.3	11.8	52.0	51.5
	Trans.	54.5	85.0	8.0	41.3	11.8	51.9	52.0
	Trans.	55.9	83.9	9.0	47.8	11.9	51.0	53.6
	Avg	56.5	82.1	7.7	46.2	11.7	51.8	52.6

Table 11. (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t = 6.3) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)	HARDNESS (15-N) HEAT AFFECTED ZONE	HARDNESS (15-N) WELD
78	Long.	57.6 (6.2)	16.1		52.8	4.5		51.6	37.4
	Long.	56.9 (6.2)	15.9		52.8	5.0		51.2	35.3
	Long.	56.6 (6.2)	15.8		53.7	5.0		52.0	36.0
	Long.	56.7 (6.2)	15.9		53.3	5.0		51.5	35.2
	Long.	57.0 (6.2)	16.0		52.6	5.0		50.4	36.2
	Avg	57.0	15.9	0.99	53.0	4.9	92	51.3	36.0
78	Trans.	56.7 (6.6)	15.9		51.1	4.0		48.1	27.9
	Trans.	56.8 (6.7)	15.9		51.5	4.5		51.0	28.9
	Trans.	58.0 (6.6)	16.2		51.8	4.0		50.0	31.6
	Trans.	58.0 (6.6)	16.2		51.3	3.5		50.0	32.8
	Trans.	57.2 (6.6)	16.0		51.2	5.0		49.4	35.7
	Avg	57.3	16.0	0.98	51.4	4.2	88	49.7	31.4
-100	Long.	57.5 (6.2)	16.1		52.2	4.5		51.6	39.0
	Long.	57.3 (6.2)	16.0		52.2	5.0		52.2	35.0
	Long.	57.7 (6.2)	16.2		52.9	6.0		52.2	34.0
	Long.	56.8 (6.3)	15.9		52.8	4.5		52.0	33.1
	Long.	56.9 (6.3)	15.9		52.9	4.5		51.4	34.4
	Avg	57.2	16.0	0.98	52.6	4.9	90	51.9	35.1
-100	Trans.	56.7 (6.6)	15.9		48.8	4.5		52.0	27.6
	Trans.	58.2 (6.6)	16.3		40.8	4.5		51.8	32.8
	Trans.	57.9 (6.6)	16.2		50.4	4.5		51.7	29.7
	Trans.	55.6 (6.9)	15.6		51.1	5.0		50.2	35.4
	Trans.	56.1 (6.9)	15.7		50.8	4.5		50.2	38.5
	Avg	56.9	15.9	0.98	50.4	4.6	86	51.2	32.8

-320	Long.	64.6 (6.3)	18.3		68.6	9.0		50.0	38.5
	Long.	64.4 (6.3)	18.0		68.4	9.0		51.0	32.5
	Long.	64.1 (6.3)	18.0		68.2	9.0		52.5	36.4
	Long.	64.5 (6.3)	18.1		68.2	9.0		51.5	36.2
	Long.	64.6 (6.3)	18.1		68.0	9.0		51.0	34.4
	Avg	64.4	18.1	0.86	68.3	9.0	91	51.2	35.6
-320	Trans.	60.8 (6.9)	17.9		67.1	9.0		50.2	36.2
	Trans.	60.2 (6.9)	16.9		64.8	7.5		51.2	36.2
	Trans.	57.2 (6.9)	16.0		65.9	6.5		52.0	33.6
	Trans.	59.1 (6.9)	16.5		64.0	8.0		51.4	35.8
	Trans.	59.5 (6.9)	16.7		64.7	6.0		51.4	33.0
	Avg	59.4	16.6	0.82	65.3	7.4	90	51.2	35.0
-423	Long.	69.5 (6.3)	19.5		66.3	3.5		51.0	33.8
	Long.	67.1 (6.3)	18.8		67.5	2.0		50.0	35.6
	Long.	67.4 (6.3)	18.9		66.9	3.0		51.8	33.9
	Long.	69.3 (6.3)	19.4		63.7	1.5		49.8	34.7
	Long.	69.4 (6.3)	19.4		67.3	2.5		49.9	34.0
	Avg	68.5	19.2	0.77	66.3	2.5	75	50.5	34.4
-423	Trans.	61.7 (6.9)	17.3		65.5	2.5		46.6	36.0
	Trans.	61.1 (6.9)	17.1		63.8	3.5		50.8	31.6
	Trans.	61.8 (6.9)	17.3		67.1	3.0		47.9	33.4
	Trans.	59.9 (6.8)	16.8		65.1	3.0		51.9	36.5
	Trans.	61.4 (6.8)	17.2		71.5	4.0		48.0	36.5
	Avg	61.2	17.1	0.75	66.6	3.2	81	49.0	34.8

Table 12. Properties of Ti-5Al-2.5Sn Annealed (0.032 In. Sheet, TMCA, Heat No. M-8394)

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	PROPORTIONAL LIMIT (KSI)	ELASTIC MODULUS (PSI x 10^6)	HARDNESS (15-N) REDUCED SECTION	HARDNESS (15-N) FRACTURED EDGE
78	Long.	115	125	15.0	92.7	14.7	80.0	79.0
	Long.	116	123	16.5	93.7	13.9	80.0	80.0
	Long.	116	124	16.5	103	13.5	79.5	81.0
	Long.	117	124	16.5	96.3	13.9	79.0	78.0
	Long.	117	124	17.0	102	14.8	79.5	78.5
	Avg	116	124	16.3	97.5	14.2	79.6	79.3
78	Trans.	118	124	14.0	89.8	14.8	79.5	79.5
	Trans.	118	124	15.0	98.0	14.7	79.0	79.5
	Trans.	117	123	11.0	90.6	15.7	79.5	79.5
	Trans.	117	123	13.5	90.8	14.7	79.0	79.5
	Trans.	117	123	13.0	92.7	15.7	79.0	78.0
	Avg	117	123	13.3	92.4	15.1	79.2	79.2
-100	Long.	142	145	12.5	118	15.8	79.0	78.5
	Long.	135	144	12.5	126	16.9	79.5	79.0
	Long.	134	145	12.5	125	15.9	79.5	80.0
	Long.	133	145	12.5	121	17.5	79.5	79.0
	Long.	129	144	14.0	126	16.8	79.5	79.5
	Avg	135	145	12.8	123	16.6	79.4	79.6
-100	Trans.	136	143	7.5	127	18.8	79.0	79.5
	Trans.	139	145	12.5	127	18.6	79.5	79.5
	Trans.	136	142	12.0	129	16.2	80.0	79.0
	Trans.	138	144	12.0	125	16.8	79.0	79.0
	Trans.	138	145	10.0	127	18.2	79.0	79.5
	Avg	137	144	10.8	127	17.7	79.3	79.3

-320	Long.	185	198	12.0	173	16.8	78.0	79.0
	Long.	186	197	12.0	177	18.0	80.0	78.0
	Long.	185	197	12.0	170	17.6	80.0	79.5
	Long.	187	199	11.0	168	17.0	79.5	80.0
	Long.	187	199	12.0	161	18.7	79.0	79.0
	Avg	186	198	11.8	170	17.6	79.3	79.1
-320	Trans.	188	197	9.0	176	18.0	77.5	78.0
	Trans.	187	197	7.5	167	18.0	79.0	79.0
	Trans.	187	198	5.5	165	19.0	78.5	80.5
	Trans.	197	210	11.0	189	19.4	78.0	79.0
	Trans.	183	195	9.0	162	17.2	78.5	79.5
	Avg	188	199	8.4	172	18.3	78.3	79.2
-423	Long.	235	249	5.5	198	17.1	79.0	79.0
	Long.	233	249	5.5	198	16.9	79.0	79.5
	Long.	235	251	5.0	176	17.3	79.0	78.5
	Long.	234	250	5.0	185	19.0	78.5	78.0
	Long.	235	250	5.0	192	20.6	78.0	78.5
	Avg	234	250	5.2	190	18.2	78.7	78.7
-423	Trans.	230	244	5.0	189	19.9	78.0	78.0
	Trans.	242	261	4.5	205	19.1	78.0	78.5
	Trans.	235	250	2.5	188	18.5	78.0	78.0
	Trans.	238	247	6.0	191	19.7	78.0	78.0
	Trans.	232	240	2.0	178	19.8	78.0	78.0
	Avg	235	248	4.0	190	19.4	78.0	78.1

Table 12. (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t = 3.2) (KSI)	FRACTURE TOUGHNESS K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO	NOTCH T.S. (K_t = 6.3) (KSI)	FRACTURE TOUGHNESS K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO
78	Long.	166 (3.2)	46.5		164 (6.4)	45.9	
	Long.	164 (3.2)	45.9		160 (6.5)	44.8	
	Long.	166 (3.2)	46.5		159 (6.4)	44.5	
	Long.	166 (3.2)	46.5		164 (6.5)	45.9	
	Long.	165 (3.2)	46.2		161 (6.5)	45.1	
	Avg	165	46.3	1.33	162	45.2	1.31
78	Trans.	161 (3.2)	45.1		161 (6.4)	45.1	
	Trans.	162 (3.2)	45.4		161 (6.4)	45.1	
	Trans.	164 (3.2)	45.9		162 (6.4)	45.4	
	Trans.	165 (3.2)	46.2		162 (6.4)	45.4	
	Trans.	161 (3.2)	45.1		165 (6.4)	46.2	
	Avg	163	45.5	1.33	162	49.4	1.32
-100	Long.	181 (3.2)	50.7		179 (6.5)	50.1	
	Long.	179 (3.2)	50.1		164 (6.5)	45.9	
	Long.	180 (3.2)	50.4		178 (6.5)	49.8	
	Long.	180 (3.2)	50.4		176 (6.5)	49.3	
	Long.	180 (3.2)	50.4		181 (6.5)	50.7	
	Avg	180	50.4	1.24	176	49.2	1.21
-100	Trans.	179 (3.2)	50.1		174 (6.4)	48.7	
	Trans.	181 (3.2)	50.7		176 (6.4)	49.3	
	Trans.	181 (3.2)	50.7		178 (6.4)	49.8	
	Trans.	181 (3.2)	50.7		178 (6.4)	49.8	
	Trans.	180 (3.2)	50.4		182 (6.4)	51.0	
	Avg	180	50.5	1.25	178	49.7	1.24

-320	Long.	252 (3.2)	70.6		236 (6.5)	66.1	
	Long.	249 (3.2)	69.7		237 (6.5)	66.4	
	Long.	249 (3.2)	69.7		236 (6.5)	66.1	
	Long.	250 (3.2)	70.0		243 (6.5)	68.0	
	Long.	249 (3.2)	69.7		232 (6.5)	65.0	
	Avg	250	69.9	1.26	237	66.3	1.20
-320	Trans.	246 (3.2)	68.9		233 (6.4)	65.2	
	Trans.	244 (3.2)	68.3		236 (6.4)	66.1	
	Trans.	244 (3.2)	68.3		233 (6.4)	65.2	
	Trans.	244 (3.2)	68.3		235 (6.4)	65.8	
	Trans.	245 (3.2)	68.6		236 (6.4)	66.1	
	Avg	245	68.5	1.23	235	65.7	1.18
-423	Long.	261 (3.2)	73.1		218 (6.5)	61.0	
	Long.	281 (3.2)	78.7		208 (6.5)	58.2	
	Long.	266 (3.2)	74.5		233 (6.5)	65.2	
	Long.	275 (3.2)	77.0		211 (6.5)	59.1	
	Long.	265 (3.2)	74.2		220 (6.5)	61.6	
	Avg	270	75.5	1.10	218	61.0	0.87
-423	Trans.	271 (3.2)	75.9		221 (6.4)	61.9	
	Trans.	273 (3.2)	76.4		210 (6.4)	58.8	
	Trans.	276 (3.2)	77.3		220 (6.4)	61.6	
	Trans.	263 (3.2)	73.6		220 (6.4)	61.6	
	Trans.	272 (3.2)	76.2		208 (6.4)	58.2	
	Avg	271	75.9	1.10	216	60.4	0.87

Table 12. (Cont)

TEST TEMP (°F)	DIR	NOTCH T.S. (K_t = 19) (KSI)	FRACTURE TOUGHNESS, K (PSI $\sqrt{IN.}$)	NOTCH/ UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)	HARDNESS (15-N) HEAT AFFECTED ZONE	HARDNESS (15-N) WELD
78	Long.	141 (21.0)	68.1		123	16.5		79.0	78.5
	Long.	142 (21.0)	68.6		124	15.5		79.5	78.5
	Long.	142 (21.0)	68.6		123	11.5		79.5	77.5
	Long.	142 (21.0)	68.6		123	15.0		78.5	77.5
	Long.	147 (21.0)	71.0		123	15.5		79.5	77.5
	Avg	143	68.9	1.15	123	14.8	99	79.2	77.9
78	Trans.	145 (20.9)	70.0		121	13.0		79.5	80.0
	Trans.	139 (20.9)	67.1		121	13.5		79.0	77.0
	Trans.	141 (20.9)	68.1		117	13.0		80.0	77.0
	Trans.	146 (20.9)	70.5		121	14.0		79.0	78.0
	Trans.	140 (20.9)	67.6		121	13.5		79.5	78.0
	Avg	142	69.7	1.15	120	13.4	98	79.4	78.0
-100	Long.	151 (21.0)	72.9		145	15.0		78.0	79.0
	Long.	126 (21.0)	60.9		145	12.5		79.0	78.0
	Long.	131 (21.0)	63.3		146	12.5		79.5	80.0
	Long.	153 (21.0)	73.9		147	16.0		79.0	78.0
	Long.	147 (21.0)	71.0		145	16.0		79.0	78.0
	Avg	142	68.4	0.98	146	14.0	100	78.9	78.6
-100	Trans.	143 (20.9)	69.1		140	12.5		78.0	77.0
	Trans.	137 (20.9)	66.2		143	12.5		78.5	78.0
	Trans.	194 (20.9)	93.7		142	11.0		79.5	77.0
	Trans.	143 (20.9)	69.1		143	12.5		78.5	79.0
	Trans.	208 (20.9)	101.0		141	12.0		79.0	78.0
	Avg	165	79.8	1.15	142	12.1	99	78.7	77.8

-320	Long.	151	(21.0)	72.9		200	12.0		79.0	78.0
	Long.	156	(21.0)	75.3		200	12.5		78.0	77.0
	Long.	125	(21.0)	60.4		201	8.5		80.0	78.0
	Long.	131	(21.0)	63.3		201	13.5		78.0	78.5
	Long.	130	(21.0)	62.8		199	10.0		79.5	78.5
	Avg	139		66.9	0.70	200	11.3	100	78.9	78.0
-320	Trans.	120	(20.9)	58.0		213	5.5		77.0	77.5
	Trans.	130	(20.9)	62.8		192	12.0		77.5	78.5
	Trans.	128	(20.9)	61.8		194	12.0		78.0	78.0
	Trans.	124	(20.9)	59.9		194	13.0		79.0	77.0
	Trans.	130	(20.9)	62.8		187	11.5		77.5	78.0
	Avg	126		61.1	0.63	196	10.8	98	77.8	77.8
-423	Long.	122	(21.0)	58.9		245	5.5		79.0	78.0
	Long.	128	(21.0)	61.8		248	8.5		80.0	78.0
	Long.	127	(21.0)	61.3		241	3.5		77.5	77.5
	Long.	121	(21.0)	58.4		247	3.5		78.5	77.5
	Long.	122	(21.0)	58.9		244	2.5		77.0	78.0
	Avg	124		59.9	0.50	245	4.7	98	78.4	77.8
-423	Trans.	103	(20.9)	49.7		245	3.0		78.5	78.0
	Trans.	113	(20.9)	54.6		244	4.5		78.0	77.0
	Trans.	114	(20.9)	55.1		241	8.0		77.5	80.5
	Trans.	113	(20.9)	54.6		241	3.0		78.0	77.0
	Trans.	109	(20.9)	52.6		241	6.5		78.0	77.5
	Avg	110		53.3	0.44	242	5.0	98	78.0	78.0

Table 13. Properties of Resistance Spot Welds of 60 Percent Cold Rolled 301 Stainless Steel, (0.025 In. Sheet, Washington Steel, Heat No. 49061, Coil No. 7450)

TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO	TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO
78	688	1060		-100	600	1310	
	686	1080			625	1305	
	694	1065			590	1285	
	630	1035			595	1365	
	610	1090			625	1240	
	667	1000			610	1330	
	620	1060			555	1280	
	614	1060			545	1240	
	635	1065			585	1330	
	709	1045			535	1305	
	655	1000			605	1255	
	692	1015			550	1300	
	638	1110			590	1270	
	641	1085			580	1285	
	642	1085			610	1260	
	700	945			635	1240	
	678	1045			590	1185	
	692	1080			600	1230	
	680	1060			605	1300	
	667	1045			636	1295	
Average	662	1052	0.63		593	1281	0.46

-320	170	965		-423	90	830	
	176	1180			166	815	
	198	1000			165	818	
	140	1000			180	900	
	196	1160			140	792	
	130	965			140	720	
	140	1000			155	888	
	138	1000			150	807	
	130	940			115	863	
	184	1125			125	798	
	178	970			210	810	
	155	1265			125	705	
	186	1005			145	845	
	184	990			130	815	
	132	1225			127	895	
	142	930			93	820	
	130	1010			150	825	
	138	985			144	895	
	182	1070			160	870	
	176	1035			150	790	
Average	160	1041	0.15		143	821	0.17

Table 14. Properties of Resistance Spot Welds of 50 Percent Cold Rolled 304 ELC Stainless Steel (0.012 In. Sheet, Rodney Metals, Heat No. 33251)

TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO	TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO
78	260	400		-100	243	535	
	248	400			222	520	
	261	415			236	545	
	260	398			240	555	
	235	410			238	535	
	260	410			244	550	
	255	408			280	510	
	264	414			246	525	
	256	442			212	475	
	272	425			250	485	
	270	400			252	450	
	265	385			224	495	
	245	412			244	480	
	269	404			250	485	
	243	420			280	440	
	260	390			254	470	
	246	419			246	520	
	263	413			222	545	
	233	405			222	535	
	258	413			236	535	
Average	256	409	0.63		242	510	0.47

-320	280	640		-423	271	636	
	276	665			295	685	
	232	638			370	640	
	262	664			235	662	
	226	610			330	582	
	274	642			255	686	
	258	634			305	732	
	274	636			295	663	
	276	586			320	656	
	284	588			250	648	
	276	635			345	648	
	272	672			300	666	
	250	658			325	711	
	272	648			350	675	
	242	648			340	695	
	280	614			325	661	
	268	644			260	626	
	246	636			285	720	
	272	620			330	680	
	284	593			340	652	
Average	265	634	0.42		306	666	0.46

Table 15. Properties of Resistance Spot Welds of 75 Percent Cold Rolled 310 Stainless Steel (0.020 In. Sheet, Washington Steel, Heat No. 43631, Coil No. 44942)

TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO	TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO
78	485	725		-100	570	870	
	521	720			476	880	
	514	725			586	860	
	516	770			546	850	
	519	775			582	875	
	497	725			570	885	
	505	725			610	835	
	508	735			560	875	
	511	745			486	865	
	507	740			566	885	
	507	755			578	875	
	509	770			582	940	
	490	800			570	885	
	531	730			570	835	
	534	735			570	835	
	521	740			576	925	
	502	735			584	840	
	484	745			482	840	
	496	710			588	870	
	521	775			586	870	
Average	509	744	0.68		562	871	0.65

-320	614	1090		-423	535	1161	
	568	1050			540	1193	
	592	1115			540	1260	
	548	1050			580	1365	
	584	1070			440	1230	
	642	1125			520	1165	
	542	1090			575	1185	
	584	1085			454	1270	
	562	1130			554	1215	
	578	1100			600	1250	
	580	1070			549	1225	
	596	1110			500	1175	
	580	1150			550	1145	
	630	1075			507	1270	
	540	1050			509	1180	
	530	1075			545	1270	
	578	1130			525	1220	
	564	1120			545	1215	
	640	1115			530	1200	
	596	1120			565	1290	
Average	582	1096	0.53		533	1224	0.44

Table 16. Properties of Resistance Spot Welds of AM-355 CRT Stainless Steel (0.032 In. Sheet, Wallingford Steel, Heat No. 38174)

TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO	TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO
78	788	1595		-100	292	1685	
	849	1485			224	1855	
	905	1640			276	1545	
	880	1290			326	1765	
	830	1465			286	1615	
	814	1590			328	1815	
	860	1465			316	1785	
	845	1515			222	1770	
	715	1500			206	1970	
	930	1640			326	1705	
	846	1600			322	1840	
	876	1660			400	1755	
	887	1620			295	1660	
	865	1635			282	1770	
	933	1380			308	1820	
	848	1540			286	1705	
	840	1515			294	1720	
	822	1495			300	1635	
	849	1475			356	1890	
	835	1470			312	1860	
Average	851	1529	0.56		298	1758	0.17

-320	166	920		-423	175	852	
	172	922			155	873	
	186	874			170	925	
	186	960			192	845	
	178	858			170	862	
	198	890			182	838	
	192	906			175	792	
	186	912			175	912	
	178	900			115	689	
	180	776			180	815	
	190	940			182	840	
	184	922			175	935	
	200	886			122	800	
	198	948			160	900	
	184	910			144	810	
	188	926			175	915	
	172	890			138	900	
	198	912			140	955	
	192	880			176	920	
	188	920			131	790	
Average	186	903	0.21		162	858	0.19

Table 17. Properties of Resistance Spot Welds of Ti-5Al-2.5Sn Alloy, Annealed (0.032 In. Sheet, TMCA, Heat No. M8394)

TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO	TEST TEMPERATURE (°F)	TENSION (ULTIMATE LB)	SHEAR (ULTIMATE LB)	TENSION/ SHEAR RATIO
78	305	1395		-100	256	1395	
	398	1435			208	1440	
	308	1375			280	1450	
	391	1420			256	1480	
	350	1365			272	1335	
	320	1425			278	1450	
	375	1375			234	1370	
	339	1395			248	1360	
	367	1320			276	1270	
	381	1365			222	1460	
	380	1460			306	1255	
	400	1350			242	1435	
	384	1390			210	1435	
	349	1350			286	1315	
	299	1325			238	1395	
	392	1365			292	1335	
	335	1340			286	1345	
	367	1320			216	1225	
	396	1440			254	1395	
	372	1400			260	1465	
Average	360	1381	0.26		256	1381	0.19

-320	286	1735		-423	250	1710	
	286	1660			260	1515	
	250	1655			260	1500	
	260	1735			240	1525	
	258	1675			260	1640	
	290	1750			290	1635	
	276	1725			240	1540	
	254	1725			240	1655	
	304	1590			225	1600	
	274	1620			225	1550	
	262	1735			240	1475	
	270	1695			232	1685	
	282	1660			240	1630	
	244	1585			320	1525	
	310	1655			250	1535	
	234	1655			245	1470	
	252	1595			239	1700	
	260	1615			300	1730	
	252	1655			209	1625	
	256	1685			248	1500	
Average	268	1670	0.16		251	1587	0.16

Table 18. Fatigue Properties of Complex Welded Joints of 60 Percent Cold Rolled 301 Stainless Steel (0.025 In. Sheet, Washington Steel, Heat No. 49061, Coil No. 7450)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	78	46L	-----	---	---	222	
1	Long.	78	1L	0-150	600	987		
1	Long.	78	2L	0-150	465	898		
1	Long.	78	3L	0-150	500	968		
1	Long.	78	4L	0-150	300	643		
1	Long	78	5L	0-150	500	814		
Average					473	862		
1	Long.	78	6L	0-170	400	581		
1	Long.	78	7L	0-170	429	498		
1	Long.	78	8L	0-170	350	599		
1	Long.	78	9L	0-170	350	516		
1	Long.	78	10L	0-170	350	528		
Average					376	544		
1	Long.	78	11L	0-190	300	423		
1	Long.	78	12L	0-190	250	393		
1	Long.	78	13L	0-190	300	402		
1	Long.	78	14L	0-190	300	406		
1	Long.	78	15L	0-190	350	474		
Average					300	420		
2	Long.	78	66L	----	---	---	203	
2	Long.	78	51L	0-170	400	560		
2	Long.	78	52L	0-170	400	651		
2	Long.	78	53L	0-170	450	649		
2	Long.	78	54L	0-170	300	604		
2	Long.	78	55L	0-170	300	487		
Average					370	590		

1	Trans.	78	46T	-----	---	---	203	
1	Trans.	78	1T	0-132	377	460		
1	Trans.	78	2T	0-132	350	365		
1	Trans.	78	3T	0-132	---	398		No leak detected.
1	Trans.	78	4T	0-132	350	393		
1	Trans.	78	5T	0-132	350	411		
Average					357	405		
1	Trans.	78	6T	0-150	150	212		
1	Trans.	78	7T	0-150	223	273		
1	Trans.	78	8T	0-150	---	323		No leak detected.
1	Trans.	78	9T	0-150	490	601		
1	Trans.	78	10T	0-150	400	422		
Average					316	366		
1	Trans.	78	11T	0-170	---	443		No leak detected.
1	Trans.	78	12T	0-170	---	296		No leak detected.
1	Trans.	78	13T	0-170	---	439		No leak detected.
1	Trans.	78	14T	0-170	---	254		No leak detected.
1	Trans.	78	15T	0-170	---	302		No leak detected.
Average					---	347		
1	Long.	-320	47L	-----	---	---	259	
1	Long.	-320	16L	0-189	---	1155		
1	Long.	-320	17L	0-189	---	1154		
1	Long.	-320	18L	0-189	---	---		Failed in pin hole.
1	Long.	-320	19L	0-189	---	997		
1	Long.	-320	20L	0-189	700	855		
1	Long.	-320	49L	0-189	---	982		
Average					700	1029		

Table 18 (Cont)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	-320	21L	0-214	---	530		
1	Long.	-320	22L	0-214	---	418		
1	Long.	-320	23L	0-214	---	376		
1	Long.	-320	24L	0-214	---	357		
1	Long.	-320	25L	0-214	300	350		
Average					300	406		
1	Long.	-320	26L	0-239	---	84		
1	Long.	-320	27L	0-239	---	68		
1	Long.	-320	28L	0-239	---	58		
1	Long.	-320	29L	0-239	---	129		
1	Long.	-320	30L	0-239	---	32		No leak detected.
Average					---	74		
2	Long.	-320	67L	-----	---	---	244	
2	Long.	-320	56L	0-214	---	281		
2	Long.	-320	57L	0-214	---	156		
2	Long.	-320	58L	0-214	---	103		
2	Long.	-320	59L	0-214	---	54		
2	Long.	-320	60L	0-214	---	140		No leak detected.
Average					---	147		

1	Trans.	-320	47T	-----	---	---	220	
1	Trans.	-320	16T	0-189	---	246		
1	Trans.	-320	17T	0-189	---	388		
1	Trans.	-320	18T	0-189	---	298		
1	Trans.	-320	19T	0-189	---	307		
1	Trans.	-320	20T	0-189	---	80		No leak detected.
Average					---	266		
1	Trans.	-320	21T	0-214	---	41		
1	Trans.	-320	22T	0-214	---	2		
1	Trans.	-320	23T	0-214	---	21		
1	Trans.	-320	24T	0-214	---	5		
1	Trans.	-320	25T	0-214	---	3		No leak detected.
Average					---	14		
1	Trans.	-320	26T	0-165	---	917		
1	Trans.	-320	27T	0-165	---	669		
1	Trans.	-320	28T	0-165	---	766		
1	Trans.	-320	29T	0-165	---	984		
1	Trans.	-320	30T	0-165	---	555		No leak detected.
Average					---	778		
1	Long.	-423	48L	-----	---	---	208	
			LX2	-----	---	---	210	
1	Long.	-423	31L	0-157	---	50		
1	Long.	-423	32L	0-157	---	40		
1	Long.	-423	33L	0-157	---	140		
1	Long.	-423	34L	0-157	---	105		
1	Long.	-423	35L	0-157	---	28		No leak detected.
Average					---	73		

Table 18 (Cont)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	-423	36L	0-178	---	39		
1	Long.	-423	37L	0-178	---	38		
1	Long.	-423	38L	0-178	---	117		
1	Long.	-423	39L	0-178	---	21		
1	Long.	-423	40L	0-178	48	51		
Average					48	53		
1	Long.	-423	41L	0-194	---	6		
1	Long.	-423	42L	0-199	---	5		
1	Long.	-423	43L	0-199	---	3		
1	Long.	-423	44L	0-199	---	4		
1	Long	-423	45L	0-199	---	3		No leak detected.
Average					---	4		
2	Long.	-423	68L	-----	---	---	214	
			69L	-----	---	---	207	
2	Long.	-423	61L	0-178	---	19		
2	Long.	-423	62L	0-178	---	16		
2	Long.	-423	63L	0-178	---	13		
2	Long.	-423	64L	0-178	---	16		
2	Long.	-423	65L	0-178	---	19		No leak detected.
Average					---	17		

1	Trans.	-423	48T	-----	---	---	168	
1	Trans.	-423	49T	-----	---	---	159	
1	Trans.	-423	31T	0-123	---	72		
1	Trans.	-423	32T	0-123	---	28		
1	Trans.	-423	33T	0-123	---	115		
1	Trans.	-423	34T	0-123	---	106		
1	Trans.	-423	35T	0-123	---	72		No leak detected.
Average						79		
1	Trans.	-423	36T	0-139	---	25		
1	Trans.	-423	37T	0-139	---	7		
1	Trans.	-423	38T	0-139	---	10		
1	Trans.	-423	40T	0-139	---	12		No leak detected.
1	Trans.	-423	50T	0-139	---	57		
Average					---	22		
1	Trans.	-423	41T	0-156	---	4		
1	Trans.	-423	42T	0-156	---	2		
1	Trans.	-423	43T	0-156	---	3		
1	Trans.	-423	44T	0-156	---	3		
1	Trans.	-423	45T	0-156	---	5		No leak detected.
Average					---	3		

Table 19. Fatigue Properties of Complex Welded Joints of 50 Percent Cold Rolled 304 ELC Stainless Steel (0.012 In. Sheet, Rodney Metals, Heat No. 33251)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	78	16L	-----	---	---	182	
1	Long.		1L	0-134	150	423		
1	Long.		2L	0-134	160	542		
1	Long.		3L	0-134	177	480		
1	Long.		4L	0-134	200	610		
1	Long.		5L	0-134	150	348		
	Average				167	481		
1	Trans.	78	16T	-----	---	---	179	Partial seam-weld failure.
1	Trans.		1T	0-134	250	523		
1	Trans.		2T	0-134	250	637		
1	Trans.		3T	0-134	300	562		
1	Trans.		4T	0-134	250	701		
1	Trans.		5T	0-134	282	688		
	Average				266	622		
1	Long.	-320	17L	-----	---	---	235	
1	Long.		6L	0-166	---	1241		
1	Long.		7L	0-166	---	1609		
1	Long.		8L	0-166	---	1237		
1	Long.		9L	0-166	---	1453		
1	Long.		10L	0-166	800	1204		
	Average				800	1349		

1	Trans. -320	17T	-----	---	---	252	
1	Trans.	6T	0-166	---	---		Error in load.
1	Trans.	7T	0-166	---	1430		
1	Trans.	8T	0-166	---	1332		
1	Trans.	9T	0-166	---	1339		
1	Trans.	10T	0-166	850	1243		
1	Trans.	19T	0-166	---	1894		
	Average			850	1448		
1	Long. -423	18L	-----	---	---	251	
1	Long.	11L	0-196	---	545		
1	Long.	12L	0-196	---	453		
1	Long.	13L	0-196	---	457		
1	Long.	14L	0-196	---	519		
1	Long	15L	0-196	300	585		
	Average			300	512		
1	Trans. -423	18T	-----	---	---	269	
1	Trans.	11T	0-196	---	449		
1	Trans.	12T	0-196	---	747		
1	Trans.	13T	0-196	---	617		
1	Trans.	14T	0-196	---	695		
1	Trans.	15T	0-196	500	970		
	Average			500	696		

Table 20. Fatigue Properties of Complex Welded Joints of 75 Percent Cold Rolled 310 Stainless Steel (0.020 In. Sheet, Washington Steel, Heat No. 43631, Coil No. 44942)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	78	46L	---	---	---	187	
1	Long.		1L	0-117	550	1130		
1	Long.		2L	0-117	649	1220		
1	Long.		3L	0-117	560	1308		
1	Long.		4L	0-117	520	1331		
1	Long.		5L	0-117	445	1266		
	Average				545	1251		
1	Long.	78	6L	0-133	234	539		
1	Long.		7L	0-133	260	694		
1	Long.		8L	0-133	252	536		
1	Long.		9L	0-133	200	493		
1	Long.		10L	0-133	263	606		
	Average				242	574		
1	Long.	78	11L	0-148	150	320		
1	Long.		12L	0-148	250	466		
1	Long.		13L	0-148	197	390		
1	Long.		14L	0-148	200	402		
1	Long.		15L	0-148	200	411		
	Average				199	398		
2	Long.	78	66L	---	---	---	184	
2	Long.		51L	0-133	250	524		
2	Long.		52L	0-133	350	547		
2	Long.		53L	0-133	250	618		
2	Long.		54L	0-133	200	409		
2	Long.		55L	0-133	200	498		
	Average				250	519		

1	Trans.	78	46T	---	---	---	194
1	Trans.		1T	0-117	415	764	
1	Trans.		2T	0-117	400	855	
1	Trans.		3T	0-117	450	802	
1	Trans.		4T	0-117	400	833	
1	Trans.		5T	0-117	500	840	
	Average				433	819	
1	Trans.	78	6T	0-133	240	413	
1	Trans.		7T	0-133	300	456	
1	Trans.		8T	0-133	300	505	
1	Trans.		9T	0-133	250	549	
1	Trans.		10T	0-133	250	493	
	Average				268	483	
1	Trans.	78	11T	0-148	150	319	
1	Trans.		12T	0-148	150	255	
1	Trans.		13T	0-148	150	261	
1	Trans.		14T	0-148	150	340	
1	Trans.		15T	0-148	200	301	
	Average				160	295	
2	Trans.	78	46LT	---	---	---	195
2	Trans.		1LT	0-117	333	704	
2	Trans.		2LT	0-117	435	804	
2	Trans.		3LT	0-117	305	574	
2	Trans.		4LT	0-117	432	767	
2	Trans.		5LT	0-117	260	480	
	Average				353	666	
2	Trans.	78	6LT	0-133	310	517	
2	Trans.		7LT	0-133	180	311	
2	Trans.		8LT	0-133	203	301	
2	Trans.		9LT	0-133	199	411	
2	Trans.		10LT	0-133	192	388	
	Average				217	386	

Table 20. (Cont)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
2	Trans.	78	11LT	0-148	166	220		
2	Trans.		12LT	0-148	45	290		
2	Trans.		13LT	0-148	179	224		
2	Trans.		14LT	0-148	168	266		
2	Trans.		15LT	0-148	192	279		
	Average				150	256		
1	Long.	-320	47L	---	---	---	259	
1	Long.		16L	0-170	---	1971		
1	Long.		17L	0-170	---	1646		
1	Long.		18L	0-170	---	2012		
1	Long.		19L	0-170	---	1146		
1	Long.		20L	0-170	851	1950		
	Average				851	1745		
1	Long.	-320	21L	0-193	---	636		
1	Long.		22L	0-193	---	650		
1	Long.		23L	0-193	---	703		
1	Long.		24L	0-193	---	798		
1	Long.		25L	0-193	401	664		
	Average				401	690		
1	Long.	-320	26L	0-216	---	307		
1	Long.		27L	0-216	---	292		
1	Long.		28L	0-216	---	292		
1	Long.		29L	0-216	---	296		
1	Long.		30L	0-216	---	321		No leaks detected
	Average				---	302		at 300 cycles.

2	Long.	-320	67L	---	---	---	256	
2	Long.		56L	0-193	---	573		
2	Long.		57L	0-193	---	722		
2	Long.		58L	0-193	---	485		
2	Long.		59L	0-193	---	583		
2	Long.		60L	0-193	302	476		
	Average				302	568		
1	Trans.	-320	47T	---	---	---	269	Failed in seam weld
1	Trans.		16T	0-170	---	1096		
1	Trans.		17T	0-170	---	1040		
1	Trans.		18T	0-170	---	959		
1	Trans.		19T	0-170	---	1217		
1	Trans.		20T	0-170	---	554		No leak detected at 550 cycles.
	Average				---	973		
1	Trans.	-320	21T	0-193	---	550		
1	Trans.		22T	0-193	---	642		
1	Trans.		23T	0-193	---	613		
1	Trans.		24T	0-193	---	643		
1	Trans.		25T	0-193	250	659		
	Average				250	619		
1	Trans.	-320	26T	0-216	---	344		
1	Trans.		27T	0-216	---	344		
1	Trans.		28T	0-216	---	---		Hydraulic cyl-. inder froze due to night humidity.
1	Trans.		29T	0-216	---	381		
1	Trans.		30T	0-216	253	315		
1	Trans.		49T	0-216	---	198		
	Average				253	316		
2	Trans.	-320	47LT	---	---	---	270	
2	Trans.		16LT	0-170	---	750		
2	Trans.		17LT	0-170	---	875		
2	Trans.		18LT	0-170	---	987		
2	Trans.		19LT	0-170	---	962		
2	Trans.		20LT	0-170	672	1051		
	Average				672	925		

Table 20. (Cont)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
2	Trans.	-320	21LT	0-193	---	493		
2	Trans.		22LT	0-193	---	652		
2	Trans.		23LT	0-193	---	522		
2	Trans.		24LT	0-193	---	463		
2	Trans.		25LT	0-193	250	404		
	Average				250	507		
2	Trans.	-320	26LT	0-216	---	224		
2	Trans.		27LT	0-216	---	211		
2	Trans.		28LT	0-216	---	282		
2	Trans.		29LT	0-216	---	209		
2	Trans.		30LT	0-216	208	211		
	Average				208	227		
1	Long.	-423	48L	---	---	---	286	Failed in base metal
1	Long.		31L	0-199	---	772		
1	Long.		32L	0-199	---	1068		
1	Long.		33L	0-199	---	616		
1	Long.		34L	0-199	---	811		
1	Long.		35L	0-199	348	703		
	Average				348	794		
1	Long.	-423	36L	0-225	---	649		
1	Long.		37L	0-225	---	218		
1	Long.		38L	0-225	---	317		
1	Long.		39L	0-225	---	187		
1	Long.		40L	0-225	---	254		No leak detected at 250 cycles.
	Average				---	325		

1	Long.	-423	41L	0-252	---	100	
1	Long.		42L	0-252	---	109	
1	Long.		43L	0-252	---	121	
1	Long.		44L	0-252	---	186	
1	Long.		45L	0-252	---	150	
	Average				---	133	
2	Long.	-423	68L	---	---	---	282
2	Long.		61L	0-225	---	201	
2	Long.		62L	0-225	---	295	
2	Long.		63L	0-225	---	220	
2	Long.		64L	0-225	---	154	
2	Long.		65L	0-225	---	248	
	Average				---	224	
1	Trans.	-423	48T	---	---	---	288
1	Trans.		31T	0-199	---	855	
1	Trans.		32T	0-199	---	620	
1	Trans.		33T	0-199	---	1002	
1	Trans.		34T	0-199	---	678	
1	Trans.		35T	0-199	550	662	
	Average				550	763	
1	Trans.	-423	36T	0-225	---	240	
1	Trans.		37T	0-225	---	350	
1	Trans.		38T	0-225	---	330	
1	Trans.		39T	0-225	---	312	
1	Trans.		40T	0-225	350	375	
	Average				350	321	

Table 20. (Cont)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Trans.	-423	41T	0-252	---	75		Failed in base metal.
1	Trans.		42T	0-252	---	113		
1	Trans.		43T	0-252	---	86		
1	Trans.		44T	0-252	---	165		
1	Trans.		45T	0-252	---	88		No leaks detected.
	Average				---	105		
2	Trans.	-423	48LT	---	---	---	298	
2	Trans.		31LT	0-199	---	415		
2	Trans.		32LT	0-199	---	467		
2	Trans.		33LT	0-199	---	412		
2	Trans.		34LT	0-199	---	457		
2	Trans.		35LT	0-199	450	511		
	Average				450	452		
2	Trans.	-423	36LT	0-225	---	96		
2	Trans.		37LT	0-225	---	182		
2	Trans.		38LT	0-225	---	221		
2	Trans.		39LT	0-225	---	271		
2	Trans.		40LT	0-225	---	124		No leaks detected.
	Average				---	179		
2	Trans.	-423	41LT	0-252	---	67		
2	Trans.		42LT	0-252	---	119		
2	Trans.		43LT	0-252	---	76		
2	Trans.		44LT	0-252	---	76		
2	Trans.		45LT	0-252	100	101		
	Average				100	88		

Table 21. Fatigue Properties of Complex Welded Joints of AM-355 CRT Stainless Steel (0.032 In. Sheet, Wallingford Steel, Heat No. 38174)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	78	16L	-----	---	---	290	
1	Long.	78	1L	0-236	100	109		
1	Long.	78	2L	0-236	100	164		
1	Long.	78	3L	0-236	100	134		
1	Long.	78	4L	0-236	100	144		
1	Long.	78	5L	0-236	100	144		
Average					100	139		
2	Long.	78	36L	-----	---	---	282	
2	Long.	78	21L	0-236	77	133		
2	Long.	78	22L	0-236	50	107		
2	Long.	78	23L	0-236	50	134		
2	Long.	78	24L	0-236	50	144		
2	Long.	78	25L	0-236	72	132		
Average					60	130		
1	Trans.	78	16T	-----	---	---	241	
1	Trans.	78	1T	0-213	---	10		No leak detected.
1	Trans.	78	2T	0-213	---	38		No leak detected.
1	Trans.	78	3T	0-213	---	24		No leak detected.
1	Trans.	78	4T	0-213	---	5		No leak detected.
1	Trans.	78	5T	0-213	---	33		No leak detected.
Average					---	22		

Table 21 (Con't)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	-320	17L	-----	---	---	148	
1	Long.	-320	6L	0-126	---	---		Failed at 124 ksi.
1	Long.	-320	7L	0-126	---	3		
1	Long.	-320	8L	0-126	---	4		
1	Long.	-320	9L	0-126	---	7		
1	Long.	-320	10L	0-126	---	4		No leak detected.
Average					---	5		
2	Long.	-320	37L	-----	---	---	132	
2	Long.	-320	26L	0-112	---	19		
2	Long.	-320	27L	0-112	---	31		
2	Long.	-320	28L	0-112	---	71		
2	Long.	-320	29L	0-112	---	11		No leak detected.
2	Long.	-320	30L	0-112	---	---		No test - failed after 7 cycles at 124 ksi.
Average					---	33		
1	Trans.	-320	17T	-----	---	---	110	
1	Trans.	-320	6T	0-94	---	15		
1	Trans.	-320	7T	0-94	---	72		
1	Trans.	-320	8T	0-94	---	55		
1	Trans.	-320	9T	0-94	---	29		
1	Trans.	-320	10T	0-94	50	51		
Average					50	44		

1	Long.	-423	18L	----	---	---	98.9	
1	Long.	-423	11L	0-85	---	20		
1	Long.	-423	12L	0-85	---	7		
1	Long.	-423	13L	0-85	---	30		
1	Long.	-423	14L	0-85	---	30		
1	Long.	-423	15L	0-85	---	7		No leak detected.
Average					---	19		
2	Long.	-423	38L	----	---	---	90.2	
2	Long.	-423	31L	0-77	---	84		
2	Long.	-423	32L	0-77	---	208		
2	Long.	-423	33L	0-77	---	184		
2	Long.	-423	34L	0-77	---	227		
2	Long.	-423	35L	0-77	---	70		No leak detected.
Average						155		
1	Trans.	-423	18T	----	---	---		
1	Trans.	-423	11T	0-55	---	393		
1	Trans.	-423	12T	0-55	---	309		
1	Trans.	-423	13T	0-55	---	562		
1	Trans.	-423	14T	0-55	---	7		
1	Trans.	-423	15T	0-55	---	17		No leak detected.
Average					---	258		

Table 22. Fatigue Properties of Complex Welded Joints of 2014-T6 Aluminum Alloy (0.063 In. and 0.125 In. Sheet, Aluminum Company of America, AMS-4029)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	78	46L	------	----	43.7	
1	Long.	78	1L	0-34.2	3065+		No failure.
1	Long.	78	2L	0-34.2	2505		End plate failure.
1	Long.	78	3L	0-34.2	2365		End plate failure.
1	Long.	78	4L	0-34.2	2373+		No failure.
1	Long.	78	5L	0-34.2	2000+		No failure.
Average					2462+		
1	Long.	78	6L	0-38.8	2000+		No failure.
1	Long.	78	7L	0-38.8	1714		End plate failure.
1	Long.	78	8L	0-38.8	1337		End plate failure.
1	Long.	78	9L	0-38.8	1871		End plate failure.
1	Long.	78	10L	0-38.8	2020+		No failure.
Average					1788+		
1	Long.	78	11L	0-43.4	1937		End plate failure.
1	Long.	78	12L	0-43.4	2000+		No failure.
1	Long.	78	13L	0-43.4	2076+		No failure.
1	Long.	78	14L	0-43.4	2003+		No failure.
1	Long.	78	15L	0-43.4	2000+		No failure.
Average					2003+		
2	Long.	78	66L	------	----		
2	Long.	78	51L	0-38.8	----	30.9	Failed statically.
2	Long.	78	52L	0-38.8	325		Failed in weld.
2	Long.	78	53L	0-38.8	14		Failed in weld.
2	Long.	78	54L	0-38.8	40		Failed in weld.
2	Long.	78	55L	0-38.8	----	30.9	Failed statically.
Average					126		

1	Trans.	78	46T	------	----	47.7	
1	Trans.	78	3T	0-34.2	2000+		No failure.
1	Trans.	78	4T	0-34.2	2000+		No failure.
1	Trans.	78	5T	0-34.2	2019+		No failure.
Average					2016+		
1	Trans.	78	8T	0-38.8	2019+		No failure.
1	Trans.	78	9T	0-38.8	2055+		No failure.
1	Trans.	78	10T	0-38.8	2055+		No failure.
Average					2043+		
1	Trans.	78	12T	0-43.4	1134		Failed at weld.
1	Trans.	78	13T	0-43.4	2000+		No failure.
1	Trans.	78	14T	0-43.4	1683		Failed at weld.
1	Trans.	78	15T	0-43.4	2000+		No failure.
Average					1704+		
1	Long.	-320	47L	------	----	54.8	
1	Long.	-320	16L	0-41.2	2000+		No failure.
1	Long.	-320	17L	0-41.2	2000+		No failure.
1	Long.	-320	18L	0-41.2	2000+		No failure.
1	Long.	-320	19L	0-41.2	2000+		No failure.
1	Long.	-320	20L	0-41.2	2000+		No failure.
Average					2000+		
1	Long.	-320	21L	0-46.7	2000+		No failure.
1	Long.	-320	22L	0-46.7	1789		Failed at weld.
1	Long.	-320	23L	0-46.7	2000+		No failure.
1	Long.	-320	24L	0-46.7	2000+		No failure.
1	Long.	-320	25L	0-46.7	2000+		No failure.
Average					1958+		

Table 22. (Cont)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	-320	28L	0-52.2	13		Failed at weld.
1	Long.	-320	29L	0-52.2	2000+		No failure.
1	Long.	-320	30L	0-52.2	2000+		No failure.
Average					1338+		
2	Long.	-320	67L	------	----		
2	Long.	-320	56L	0-46.7	----	45.2	Failed statically.
2	Long.	-320	57L	0-46.7	----	23.8	Failed statically.
2	Long.	-320	58L	0-46.7	----	36.8	Failed statically.
2	Long.	-320	59L	0-46.7	----	44.0	Failed statically.
2	Long.	-320	60L	0-46.7	----	39.8	Failed statically.
Average					----	37.8	
1	Trans.	-320	47T			55.3	
1	Trans.	-320	16T	0-41.2	2012+		No failure.
1	Trans.	-320	17T	0-41.2	2152+		No failure.
1	Trans.	-320	18T	0-41.2	2000+		No failure.
1	Trans.	-320	19T	0-41.2	2000+		No failure.
1	Trans.	-320	20T	0-41.2	2086+		No failure.
Average					2050+		
1	Trans.	-320	21T	0-46.7	2000+		No failure.
1	Trans.	-320	22T	0-46.7	2000+		No failure.
1	Trans.	-320	23T	0-46.7	2000+		No failure.
1	Trans.	-320	24T	0-46.7	2000+		No failure.
1	Trans.	-320	25T	0-46.7	2074+		No failure.
Average					2015+		

1	Trans.	-320	26T	0-52.2	2074+		No failure.
1	Trans.	-320	27T	0-52.2	3		Failed in weld.
1	Trans.	-320	28T	0-52.2	2000+		No failure.
1	Trans.	-320	29T	0-52.2	58		Failed in weld.
1	Trans.	-320	30T	0-52.2	4		Failed in weld.
Average					828+		
1	Long.	-423	48L	------	----	71.0	
1	Long.	-423	31L	0-49.9	2001+		No failure.
1	Long.	-423	32L	0-49.9	2001+		No failure.
1	Long.	-423	33L	0-49.9	2000+		No failure.
1	Long.	-423	34L	0-49.9	2000+		No failure.
1	Long.	-423	35L	0-49.9	2000+		No failure.
Average					2000+		
1	Long.	-423	37L	0-56.5	2000+		No failure.
1	Long.	-423	38L	0-56.5	659		Failed in weld.
1	Long.	-423	39L	0-56.5	2000+		No failure.
1	Long.	-423	40L	0-56.5	2000+		No failure.
Average					1665+		
2	Long.	-423	68L	------	----		
2	Long.	-423	61L	0-56.5	----	27.1	Failed statically.
2	Long.	-423	62L	0-56.5	----	36.7	Failed statically.
2	Long.	-423	63L	0-56.5	----	43.2	Failed statically.
2	Long.	-423	64L	0-56.5	----	38.1	Failed statically.
2	Long.	-423	65L	0-56.5	----	43.4	Failed statically.
Average					----	37.7	
1	Trans.	-423	48T	------	----	61.9	
1	Trans.	-423	31T	0-49.9	2000+		No failure.
1	Trans.	-423	32T	0-49.9	2000+		No failure.
Average					2000+		

Table 23. Fatigue Properties of Complex Welded Joints of 5052-H38 Aluminum Alloy (0.125 In. Sheet, Aluminum Company of America, QQ-A-318)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	78	16L	------	----	30.5	
1	Long.	78	1L	0-26.3	2000+		No failure.
1	Long.	78	2L	0-26.3	2000+		No failure.
1	Long.	78	3L	0-26.3	2000+		No failure.
1	Long.	78	4L	0-26.3	2000+		No failure.
1	Long.	78	5L	0-26.3	2000+		No failure.
Average					2000+		
1	Trans.	78	16T	------	----	31.2	
1	Trans.	78	1T	0-26.3	2041+		No failure.
1	Trans.	78	2T	0-26.3	2000+		No failure.
1	Trans.	78	3T	0-26.3	2000+		No failure.
1	Trans.	78	4T	0-26.3	2000+		No failure.
1	Trans.	78	5T	0-26.3	2000+		No failure.
Average					2008+		
1	Long.	-320	17L	-----	----	49.5	
1	Long.	-320	6L	0-42.1	2000+		No failure.
1	Long.	-320	7L	0-42.1	2000+		No failure.
1	Long.	-320	8L	0-42.1	2000+		No failure.
1	Long.	-320	9L	0-42.1	2000+		No failure.
1	Long.	-320	10L	0-42.1	2000+		No failure.
Average					2000+		

1	Trans.	-320	17T	------	----	48.9	
1	Trans.	-320	6T	0-42.1	2096+		No failure.
1	Trans.	-320	7T	0-42.1	2096+		No failure.
1	Trans.	-320	8T	0-42.1	2134+		No failure.
1	Trans.	-320	9T	0-42.1	2011+		No failure.
1	Trans.	-320	10T	0-42.1	2062+		No failure.
Average					2080+		
1	Long.	-423	18L	------	----	58.2	
1	Long.	-423	11L	0-49.7	2000+		No failure.
1	Long.	-423	12L	0-49.7	2000+		No failure.
1	Long.	-423	13L	0-49.7	2000+		No failure.
1	Long.	-423	14L	0-49.7	2000+		No failure.
1	Long.	-423	15L	0-49.7	2000+		No failure.
Average					2000+		
1	Trans.	-423	18T	------	----	58.8	
1	Trans.	-423	11T	0-49.7	1167		Failed at weld.
1	Trans.	-423	12T	0-49.7	1926		Failed at weld.
1	Trans.	-423	13T	0-49.7	2000+		No failure.
1	Trans.	-423	14T	0-49.7	2000+		No failure.
1	Trans.	-423	15T	0-49.7	1867		Failed at weld.
Average					1792		

Table 24. Fatigue Properties of Complex Welded Joints of 5456-H343 Aluminum Alloy (0.063 In. and 0.125 In. Sheet, Aluminum Company of America, Mil-A-19842)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	78	16L	-----	----	-	
1	Long.	78	2L	0-42.5	2000+		No. failure.
1	Long.	78	3L	0-42.5	2000+		No. failure.
1	Long.	78	4L	0-42.5	2000+		No. failure.
1	Long.	78	5L	0-42.5	2000+		No. failure.
Average					2000+		
2	Long.	78					
2	Long.	78	21L	-----	--	32.9	Failed in weld.
2	Long.	78	22L	0-30.0	1		Failed in weld.
2	Long.	78	23L	0-30 0	58		Failed in weld.
2	Long.	78	24L	0-30.0	5		Failed in weld.
2	Long.	78	25L	0-30.0	96		Failed in weld.
Average					40		
1	Trans.	78	16T			48.0	
1	Trans.	78	1T	0-42.5	1109		Failed in end plate.
1	Trans.	78	2T	0-42.5	1177		Failed in end plate.
1	Trans.	78	3T	0-42.5	2000+		No failure.
1	Trans.	78	4T	0-42.5	2000+		No failure.
1	Trans.	78	5T	0-42.5	2000+		No failure.
Average					1657+		
1	Long.	-320	17L	-----	----	63.2	
1	Long.	-320	6L	0-53.7	2000+		No failure.
1	Long.	-320	7L	0-53.7	1594		Failed in weld.
1	Long.	-320	8L	0-53.7	1826		Failed in weld.
1	Long.	-320	9L	0-53.7	1800		Failed in weld.
1	Long.	-320	10L	0-53.7	1105		Failed in weld.
Average					1665+		

2	Long.	-320	26L	0-53.7	-	45.2	Failed statically.
2	Long.	-320	27L	0-53.7	-	36.6	Failed statically.
2	Long.	-320	28L	0-53.7	-	35.6	Failed statically.
2	Long.	-320	29L	0-53.7	-	39.6	Failed statically.
2	Long.	-320	30L	0-53.7	-	36.5	Failed statically.
Average					-	38.8	
1	Trans.	-320	17T	------	----	59.9+	Failed in end plate.
1	Trans.	-320	6T	0-53.7	2255		Failed in weld.
1	Trans.	-320	7T	0-53.7	1567		Failed in weld.
1	Trans.	-320	8T	0-53.7	2000+		No failure.
1	Trans.	-320	9T	0-53.7	766		Failed in weld.
1	Trans.	-320	10T	0-53.7	2000+		No failure.
Average					1718+		
1	Long.	-423	18L	------	-	55.8	
1	Long.	-423	11L	0-47.9	2000+		No failure.
1	Long.	-423	12L	0-47.9	2000+		No failure.
1	Long.	-423	13L	0-47.9	2073+		No failure
1	Long.	-423	14L	0-47.9	2173+		No failure.
1	Long.	-423	15L	0-47.9	1652		Failed in weld.
Average					1980+		
2	Long.	-423	31L	------	---	36.6	
2	Long.	-423	32L	0-31.2	938		Failed in weld.
2	Long.	-423	33L	0-31.2	1639		Failed in weld.
2	Long.	-423	34L	0-31.2	2000+		No failure.
Average					1526+		
1	Trans.	-423	18T	------	-	56.6	
1	Trans.	-423	11T	0-47.9	2000+		No failure.
1	Trans.	-423	12T	0-47.9	2000+		No failure.
1	Trans.	-423	13T	0-47.9	2000+		No failure.
1	Trans.	-423	14T	0-47.9	2000+		No failure.
1	Trans.	-423	15T	0-47.9	2000+		No failure.
Average					2000+		

Table 25. Fatigue Properties of Complex Welded Joints of Ti-5AL-2.5Sn Alloy (0.032 In. Sheet, TMCA, Heat No. M-8394, Mill annealed)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	78	46L	----	----	---	120	
1	Long.	78	1L	0-87	1100	1827		
1	Long.	78	2L	0-87	1093	1773		
1	Long.	78	3L	0-87	700	1164		
1	Long.	78	4L	0-87	704	1483		
1	Long.	78	5L	0-87	950	1772		
Average					909	1604		
1	Long.	78	6L	0-99	600	902		
1	Long.	78	7L	0-99	1250	1531		
1	Long.	78	8L	0-99	650	847		
1	Long.	78	9L	0-99	400	520		
1	Long.	78	10L	0-99	500	---		Failed in radius at 508 cycles.
1	Long.	78	49L	0-99	600	949		
Average					800	950		
1	Long.	78	11L	0-110	300	455		
1	Long.	78	12L	0-110	300	388		
1	Long.	78	13L	0-110	272	323		
1	Long.	78	14L	0-110	500	564		
1	Long.	78	15L	0-110	350	468		
Average					344	440		
2	Long.	78	51L	0-99	---	584		
2	Long.	78	52L	0-99	---	556		
2	Long.	78	53L	0-99	200	456		
2	Long.	78	54L	0-99	184	639		
Average					192	549		

3	Long.	78	75L	0-99	2000+	2000+		No leaks or failure.
3	Long.	78	76L	0-99	2000+	2000+		No leaks or failure.
Average					2000+	2000+		
3	Long.	78	77L	0-110	----	566		Failed in weld.
3	Long.	78	78L	0-110	----	507+		No failure, specimen yielded.
Average					----	537+		
1	Trans.	78	1T	0-87	708	883		
1	Trans.	78	2T	0-87	700	937		
1	Trans.	78	3T	0-87	850	1294		
1	Trans.	78	4T	0-87	850	1205		
1	Trans.	78	5T	0-87	850	1645		
Average					792	1187		
1	Trans.	78	46T		---	---	112	
1	Trans.	78	6T	0-99	500	729		
1	Trans.	78	7T	0-99	350	672		
1	Trans.	78	8T	0-99	300	560		
1	Trans.	78	9T	0-99	300	461		
1	Trans.	78	10T	0-99	400	430		
Average					370	570		
1	Trans.	78	11T	0-110	400	633		
1	Trans.	78	12T	0-110	450	570		
1	Trans.	78	13T	0-110	350	489		
1	Trans.	78	14T	0-110	350	605		
Average					370	574		
1	Long.	-320	47L		---	---	188	
1	Long.	-320	16L	0-140	---	516		
1	Long.	-320	17L	0-140	---	425		
1	Long.	-320	18L	0-140	---	299		
1	Long.	-320	19L	0-140	---	168		
1	Long.	-320	20L	0-140	150	167		
Average					150	315		

Table 25 (Cont)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	-320	21L	0-159	---	39		
1	Long.	-320	22L	0-159	---	45		
1	Long.	-320	23L	0-159	---	51		
1	Long.	-320	24L	0-159	---	79		
1	Long.	-320	25L	0-159	---	73		No leak detected.
Average					---	57		
1	Long.	-320	26L	0-178	---	6		
1	Long.	-320	27L	0-178	---	6		
1	Long.	-320	28L	0-178	---	8		
1	Long.	-320	29L	0-178	---	8		
1	Long.	-320	30L	0-178	---	19		No leak detected.
Average					---	9		
2	Long.	-320	67L		---	---		
2	Long.	-320	56L	0-159	---	107		
2	Long.	-320	57L	0-159	---	108		
2	Long.	-320	58L	0-159	---	169		
2	Long.	-320	59L	0-159	---	134		
2	Long.	-320	60L	0-159	---	122		
Average					---	128		
3	Long.	-320	79L	0-159	---	2000+		No failure.
3	Long.	-320	80L	0-159	---	2000+		No failure.
3	Long.	-320	81L	0-159	---	1878		Failed in end plate.
Average					---	1959+		
3	Long.	-320	82L	0-178	---	956		Failed in end plate.
3	Long.	-320	83L	0-178	---	704		Failed in end plate.
3	Long.	-320	84L	0-178	---	468		Failed in end plate.
Average					---	709		

1	Trans.	-320	47T	----	----	--	164	
1	Trans.	-320	21T	0-159	----	9		
1	Trans.	-320	22T	0-159	----	38		
1	Trans.	-320	23T	0-159	----	--	154	Failed on loading.
1	Trans.	-320	24T	0-159	----	--	157	Failed on loading.
1	Trans.	-320	25T	0-159	----	--	157	Failed on loading.
Average					----	24	158	
1	Long.	-423	48L	----	----	----	172	
1	Long.	-423	31L	0-129	----	596		
1	Long.	-423	32L	0-129	----	600		
1	Long.	-423	33L	0-129	----	245		
1	Long.	-423	34L	0-129	----	158		
1	Long.	-423	35L	0-129	----	----	172	Error in test-failed statically.
1	Long.	-423	50L	0-129	----	1714		
Average					----	663	172	
1	Long.	-423	36L	0-146	----	91		
1	Long.	-423	37L	0-146	----	58		
1	Long.	-423	38L	0-146	----	83		
1	Long.	-423	39L	0-146	----	8		
1	Long.	-423	40L	0-146	----	34		No leak detected.
Average					----	55		
1	Long.	-423	41L	0-163	----	8		
1	Long.	-423	42L	0-163	----	3		
1	Long.	-423	43L	0-163	----	--	160	Failed on loading.
1	Long.	-423	44L	0-163	----	--	162	Failed on loading.
1	Long.	-423	45L	0-163	----	8		No leak detected.
1	Long.	-423	LX1	0-163	----	26		
Average					----	11	161	
2	Long.	-423	61L	G-156	----	---		Error in load.
2	Long.	-423	62L	0-146	----	240		
Average					----	240		

Table 25 (Cont)

JOINT CONFIG.	DIR	TEST TEMP (°F)	SPECIMEN NO.	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
3	Long.	-423	85L	0-184	----	----		Failed in base metal. (35)
3	Long.	-423	86L	0-184	----	1054		Failed in end plate.
3	Long.	-423	87L	0-184	----	220		Failed in weld.
Average					----	637		
3	Long.	-423	88L	0-208	----	446		Failed in end plate.
3	Long.	-423	89L	0-208	----	846		Failed in weld.
3	Long.	-423	90L	0-208	----	409		Failed in end plate.
Average					----	567		
1	Trans.	-423	48T	----	----	-	159	
1	Trans.	-423	36T	0-146	----	6		
1	Trans.	-423	37T	0-146	----	7		
1	Trans.	-423	38T	0-146	----	2		
1	Trans.	-423	39T	0-146	----	2		
1	Trans.	-423	40T	0-146	----	4		No leaks detected.
Average					----	4		

Table 26. Properties of 60 Percent Cold Rolled 301 Stainless Steel (0.010 In. Sheet, Heat No. 57644, Coil No. 11976) *

TEST TEMP (°F)	DIR	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	NOTCH T.S. (K_t=6.3) (KSI)	NOTCH/UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	JOINT EFF (%)	FATIGUE (JOINT CONFIG. NO. 1) STRESS (KSI)	CYCLES TO LEAK	CYCLES TO FAILURE
78	Long.	192	204	5.0	220		208		0-140	124	347
	Long.	190	203	5.0	221		208		0-140	127	489
	Long.	191	207	6.5	222		-		-----	---	---
	Long.	190	207	6.5	220		-		-----	---	---
	Long.	193	209	9.5	219		-		-----	---	---
	Long.	192	202	4.0	217		-		-----	---	---
	Long.	196	208	9.0	-		-		-----	---	---
	Long.	192	204	4.0	-		-		-----	---	---
	Avg.	192	206	6.2	220	1.07	208	100	0-140	126	418
78	Trans.	171	219	7.0	221		189				
	Trans.	169	218	7.0	213		194				
	Trans.	169	217	7.0	211		199				
	Avg.	170	218	7.0	215	0.99	194	89			
-423	Long.	240	281	----	273		258		0-140	300	555
	Long.	271	302	12.0	290		248		0-140	250	423
	Long.	282	305	14.0	294		264		0-140	300	462
	Long.	294	304	3.0	298		---		0-140	200	498
	Long.	---	301	3.0	278		---		0-140	300	827
	Long.	245	298	1.0	294		---		-----	---	---
	Long.	248	288	2.0	---		---		-----	---	---
	Long.	271	292	4.0	---		---		-----	---	---
	Avg.	264	296	5.3	288	0.97	257	87	0-140	270	553
-423	Trans.	237	297	6.5	276		239				
	Trans.	232	308	6.0	245		261				
	Trans.	270	320	8.5	238		228				
	Avg.	246	308	7.0	253	0.82	243	79			

* Chemistry: Cr-17.38, Ni-7.32, Mn-1.04, C-0.09.

Table 27. Properties of Annealed Ti-5Al-2.5Sn Alloy (0.014 In. Sheet, Republic Steel Co.. Heat No. 3930131, Specification GD/A-0-71010)

TEST TEMP (°F)	DIR.	F_{ty} (KSI)	F_{tu} (KSI)	ELONG (%)	NOTCH T.S. (K_t = 6.3) (KSI)	NOTCH/UNNOTCH TENSILE RATIO	WELD T.S. (KSI)	WELD ELONG (%)	JOINT EFF (%)
78	Long.	114	125	16.0	165		116	2.0	
	Long.	116	128	17.0	166		111	1.0	
	Long.	118	127	14.5	167		116	2.0	
	Long.	118	128	14.5	170		114	1.5	
	Long.	120	128	14.5	170		114	2.0	
	Avg.	117	127	15.3	168	1.32	114	1.7	90
78	Trans.	118	126	13.5	168		118	2.0	
	Trans.	118	125	12.5	168		116	1.5	
	Trans.	119	126	14.5	166		120	2.0	
	Trans.	118	126	14.0	167		118	1.5	
	Trans.	118	125	14.0	169		113	1.0	
	Avg.	118	126	13.7	168	1.33	117	1.6	93
-320	Long.	175	188	18.5	233		181	2.0	
	Long.	173	187	18.5	---		184	2.0	
	Long.	176	189	17.5	---		188	3.0	
	Long.	176	189	18.5	---		180	1.5	
	Long	175	190	18.5	---		180	1.5	
	Avg.	175	189	18.3	233	1.23	183	2.0	97

-320	Trans.	181	189	16.0	242		184	2.5	
	Trans.	180	189	16.0	243		180	1.0	
	Trans.	182	191	17.0	---		172	0.5	
	Trans.	183	190	17.5	---		172	1.0	
	Trans.	184	192	16.5	---		186	3.0	
	Avg.	182	190	16.6	243	1.28	179	1.6	94
-423	Long.	221	238	15.0	287		226	2.5	
	Long.	219	235	15.0	273		215	1.0	
	Long.	228	243	10.0	266		227	1.5	
	Long.	228	237	----	246		222	1.5	
	Long.	230	242	12.0	230		218	1.0	
	Avg.	225	239	13.0	260	1.09	222	1.5	93
-423	Trans.	224	232	----	270		193	1.0	
	Trans.	225	232	----	253		205	1.0	
	Trans.	229	238	10.5	230		199	1.0	
	Trans.	227	237	11.0	246		230	1.0	
	Trans.	227	236	12.5	236		243	1.0	
	Avg.	226	235	11.3	247	1.05	214	1.0	91

* Chemistry: C-0.035; N_2-0.011; O_2-0.12; H_2-0.0099; Fe-0.11; Al-5.45; Sn-2.50; Ti-Rem.

Table 27 (Cont'd.)

TEST TEMP (°F)	RESISTANCE SPOT WELD		
	TENSION (LB)	SHEAR (LB)	TENSILE/SHEAR RATIO
78	100	530	
	123	530	
	119	555	
	130	530	
	131	500	
	124	550	
	126	---	
	128	455	
	148	495	
	146	465	
	128	512	0.25
-320	102	524	
	86	488	
	95	542	
	91	483	
	90	564	
	80	433	
	91	476	
	80	476	
	95	534	
	88	522	
	90	504	0.18
-423	75	485	
	80	540	
	90	564	
	75	630	
	100	515	
	85	520	
	85	540	
	75	485	
	100	540	
	75	535	
	84	535	0.16

Table 28. Fatigue Properties of Complex Welded Joints of Ti-5AL-2.5Sn Alloy (0.014 In. Sheet, Republic Steel Co., Heat No. 3930131, Spec GD/A-0-71010)

JOINT CONFIG.	DIR	TEST TEMP (°F)	STRESS RANGE (KSI)	NO. CYCLES TO FIRST LEAK	NO. CYCLES TO FAILURE	STATIC STRENGTH (KSI)	REMARKS
1	Long.	-423	-----	---	---	193	
1	Long.	-423	0-140	50	405		
1	Long.	-423	0-140	100	709		
Average				75	557		
1	Trans.	78	0-88	400	751		
1	Trans.	78	0-88	550	1191		
Average				475	971		
1	Trans.	-320	0-140	150	320		
1	Trans.	-320	0-140	150	420		
Average				150	370		
1	Trans.	-423	-----	---	---	199	
1	Trans.	-423	0-140	50	358		
1	Trans.	-423	0-140	50	273		
Average				50	316		
3	Long.	78	0-102	---	106		
3	Long.	78	0-102	---	176		
Average				---	141		
3	Long.	-320	0-140	---	2100+		No failure.
3	Long.	-320	0-140	---	2100+		No failure.
Average				---	2100+		
3	Long.	-423	0-140	---	2000+		No failure.
3	Long.	-423	0-140	---	2000+		No failure.
Average				---	2000+		
3	Long.	-423	0-192	---	159		
3	Long.	-423	0-192	---	975		
Average				---	567		

Table 29A. Results of Statistical Analysis, F_{ty} (ksi)

MATERIAL, CONDITION	GRAIN DIR	78°F				-100°F			
		MEAN	s	A	B	MEAN	s	A	B
301 SS, 60% CR	Long.	200	3.08	182	189	237	2.97	219	226
	Trans.	176	1.79	166	170	197	3.77	175	184
304 SS, 50% CR	Long	158	3.96	135	145	179	3.35	160	168
	Trans.	151	1.95	140	145	174	5.63	141	154
310 SS, 75% CR	Long.	156	3.51	136	144	185	2.88	169	175
	Trans.	157	4.72	130	141	185	6.58	147	163
AM-355 SS, CRT	Long.	278	4.16	254	264	287	4.97	259	270
	Trans.	251	2.19	238	243	252	2.41	238	243
2014-T6	Long.	65.2	0.68	61.3	62.9	68.2	0.32	66.3	67.1
	Trans.	63.1	0.28	61.5	62.2	65.9	0.25	64.5	65.1
5052-H38	Long.	36.1	0.43	33.7	34.7	37.2	0.52	34.2	35.4
	Trans.	36.0	0.30	34.3	35.0	37.2	0.92	31.9	34.1
5456-H343	Long.	49.2	0.62	45.6	47.1	50.9	1.07	44.7	47.2
	Trans.	43.1	0.13	42.4	42.7	43.8	0.30	42.0	42.7
Ti-5Al-2.5Sn, Annealed	Long.	116	0.84	111	113	135	4.72	107*	118*
	Trans.	117	0.55	114	116	137	1.34	130	133

* Value of s large so that $\bar{X} - k_A s < 0.80\ \bar{X}$ and $\bar{X} - k_B s < 0.88\ \bar{X}$

Table 29 A. (Cont)

MATERIAL, CONDITION	GRAIN DIR	-320°F				-423°F			
		MEAN	s	A	B	MEAN	s	A	B
301 SS, 60% CR	Long.	259	16.0	167*	204*	308	4.04	285	294
	Trans.	235	2.0	223	228	303	11.8	234*	262*
304 SS, 50% CR	Long.	195	8.32	147	167	234	8.53	184*	204*
	Trans.	201	3.35	182	190	222	10.6	161*	185*
310 SS, 75% CR	Long.	228	3.13	210	217	261	2.70	245	251
	Trans.	220	4.24	196	205	266	8.09	219	238
AM-355 SS, CRT	Long.	328	8.46	279	299	**			
	Trans.	286	8.38	238	258	**			
2014-T6	Long.	74.1	0.76	69.7	71.5	83.4	0.68	79.5	81.1
	Trans.	69.3	1.58	60.2	63.9	81.7	1.22	74.7	77.5
5052-H38	Long.	43.1	0.18	42.1	42.5	48.8	2.33	35.3*	40.8*
	Trans.	42.6	0.44	40.0	41.0	47.7	0.15	46.8	47.1
5456-H343	Long.	57.5	0.61	54.0	55.4	63.8	0.22	62.6	63.1
	Trans.	51.7	0.81	47.0	48.9	56.5	1.50	47.9	51.4
Ti-5Al-2.5Sn, Annealed	Long.	186	1.00	180	183	234	0.89	229	231
	Trans.	188	5.18	159	171	235	4.77	208	219

* Value of s large so that $\bar{X} - k_A s < 0.80\ \bar{X}$ and $\bar{X} - k_B s < 0.88\ \bar{X}$

** Insufficient test data to permit analysis

Table 29B. Results of Statistical Analysis, F_{tu} (ksi)

MATERIAL, CONDITION	GRAIN DIR	78°F				-100°F			
		MEAN	s	A	B	MEAN	s	A	B
301 SS, 60% CR	Long.	224	1.14	217	220	253	0.84	248	250
	Trans.	239	1.87	228	233	267	1.30	259	262
304 SS, 50% CR	Long.	180	1.00	174	177	200	1.00	194	197
	Trans.	194	0	---	---	218	1.10	212	214
310 SS, 75% CR	Long.	180	0.71	176	178	203	1.64	194	198
	Trans.	200	2.00	188	193	224	0.84	219	221
AM-355 SS, CRT	Long.	297	2.41	283	288	308	2.79	292	299
	Trans.	286	1.79	275	280	314	2.30	300	306
2014-T6	Long.	71.6	0.23	70.3	70.8	74.6	0.40	72.3	73.2
	Trans.	70.9	0.16	70.0	70.4	74.0	0.13	73.2	73.5
5052-H38	Long.	42.0	0	----	----	43.7	0.10	43.1	43.4
	Trans.	42.8	0.13	42.0	42.3	44.2	0.93	38.8	41.0
5456-H343	Long.	47.6	0.80	53.0	54.9	58.4	0.43	56.0	57.0
	Trans.	58.4	0.22	57.2	57.7	58.1	0.70	54.1	55.7
Ti-5Al-2.5Sn, Annealed	Long.	124	0.71	120	122	145	0.55	141	143
	Trans.	123	0.55	121	122	144	1.30	136	139

Table 29B. (Cont)

MATERIAL, CONDITION	GRAIN DIR	-320°F				-423°F			
		MEAN	s	A	B	MEAN	s	A	B
301 SS, 60% CR	Long.	323	1.11	318	320	335	5.81	302*	315*
	Trans.	326	0.89	321	323	346	5.68	313	326
304 SS, 50% CR	Long.	242	9.34	188*	210*	275	3.83	253	262
	Trans.	255	3.27	236	244	295	6.35	262	275
310 SS, 75% CR	Long.	253	1.30	245	248	291	2.07	279	284
	Trans.	272	1.79	262	266	314	7.91	268	287
AM-355 SS, CRT	Long.	353	2.44	341	346	347	21.0	225*	274*
	Trans.	342	6.43	305	320	339	14.0	258*	291*
2014-T6	Long.	85.5	0.29	83.9	84.5	101	1.52	92.3	95.8
	Trans.	84.5	0.05	84.1	84.3	102	1.21	94.6	97.4
5052-H38	Long.	60.7	0.05	60.4	60.6	87.2	1.50	78.5	82.0
	Trans.	57.1	0.19	56.0	56.5	76.2	0.13	75.4	75.7
5456-H343	Long.	74.8	0.70	70.8	72.4	88.5	2.11	76.3	81.2
	Trans.	72.4	0.27	70.8	71.4	82.1	3.52	61.8*	70.0*
Ti-5Al-2.5Sn, Annealed	Long.	198	1.00	192	195	250	0.84	245	247
	Trans.	199	6.02	165	179	248	7.96	202	221

* Value of s large so that $\overline{X} - k_A s < 0.80\ \overline{X}$ and $\overline{X} - k_B s < 0.88\ \overline{X}$

Table 29C. Results of Statistical Analysis, Weld T.S. (ksi)

MATERIAL, CONDITION	GRAIN DIR	78°F MEAN	78°F s	78°F A	78°F B	-100°F MEAN	-100°F s	-100°F A	-100°F B
301 SS, 60% CR	Long.	175	3.27	156	164	216	2.95	199	206
	Trans.	174	3.27	155	163	212	1.48	204	207
304 SS, 50% CR	Long.	78.4	3.23	59.8	67.3	144	3.85	121	130
	Trans.	77.3	4.04	54.0	63.4	141	4.22	117	127
310 SS, 75% CR	Long.	86.7	1.04	80.6	83.1	109	2.39	95.4	101
	Trans.	85.5	1.96	74.1	78.7	110	1.22	103	106
AM-355 SS, CRT	Long.	222	4.56	195	206	289	1.64	280	284
	Trans.	219	3.63	198	207	282	1.92	271	276
2014-T6	Long.	55.4	2.98	38.1*	45.1*	56.4	2.84	40.0*	46.6*
	Trans.	58.6	0.85	53.7	55.7	58.2	0.37	56.0	56.9
5052-H38	Long.	32.0	0.73	27.8	29.5	34.2	0.11	33.6	33.8
	Trans.	33.3	0.17	32.3	32.7	34.5	0.20	33.3	33.8
5456-H343	Long.	53.0	0.45	50.4	51.5	52.6	0.37	50.5	51.3
	Trans.	51.4	0.28	49.8	50.4	50.4	0.92	45.1	47.2
Ti-5Al-2.5Sn, Annealed	Long.	123	0.45	121	122	146	0.89	140	143
	Trans.	120	1.79	110	114	142	1.30	134	137

* Value of s large so that $\overline{X} - k_A s < 0.80\ \overline{X}$ and $\overline{X} - k_B s < 0.88\ \overline{X}$

Table 29C. (Cont)

MATERIAL, CONDITION	GRAIN DIR	-320°F				-423°F			
		MEAN	s	A	B	MEAN	s	A	B
301 SS, 60% CR	Long.	298	2.70	283	289	202***	21.6	76.6*	127*
	Trans.	291	2.30	277	283	204***	29.3	35.1*	103*
304 SS, 50% CR	Long.	216	1.10	209	212	250	3.39	230	238
	Trans.	212	8.07	166*	184*	269	6.34	232	247
310 SS, 75% CR	Long.	162	4.56	136	147	208	3.74	186	195
	Trans.	167	1.34	160	163	193	4.64	166	177
AM-355 SS, CRT	Long.	271	25.7	123*	183*	142	5.24	112*	124*
	Trans.	299	19.2	188*	233*	140	8.53	91.1*	111*
2014-T6	Long.	63.2	2.15	50.8	55.8	70.8	6.07	35.7*	49.9*
	Trans.	65.7	1.36	57.8	61.0	73.8	3.45	53.9*	61.9*
5052-H38	Long.	47.3	3.60	26.5*	34.9*	70.1	1.21	63.1	66.0
	Trans.	51.1	0.48	48.4	49.5	68.9	3.19	50.4*	57.9*
5456-H343	Long.	68.3	0.23	67.0	67.5	66.3	1.55	57.4	61.0
	Trans.	65.3	1.21	58.3	61.1	66.6	2.98	49.4*	56.3*
Ti-5Al-2.5Sn, Annealed	Long.	200	0.84	195	197	245	2.74	229	236
	Trans.	196	9.92	139*	162*	242	1.95	231	236

* Value of s large so that $\overline{X} - k_A s < 0.80\ \overline{X}$ and $\overline{X} - k_B s < 0.88\ \overline{X}$

***Low values with large standard deviation probably indicates severe embrittlement, not necessarily typical of 301 SS

Table 29D. Results of Statistical Analysis, Spot Weld Tension and Shear, Ultimate (lb)

		78°F				-100°F			
MATERIAL, CONDITION	TEST	MEAN	s	A	B	MEAN	s	A	B
301 SS, 60% CR	Tensile	662	31.0	559	602	593	28.9	498	538
	Shear	1052	38.3	925	978	1281	41.6	1143	1200
304 SS, 50% CR	Tensile	256	11.1	220	235	242	17.5	184*	208*
	Shear	409	12.6	368	385	510	34.6	396*	443*
310 SS, 75% CR	Tensile	509	13.9	463	482	562	37.0	440*	491*
	Shear	744	23.1	668	699	871	26.7	783	820
AM-355 SS, CRT	Tensile	851	38.4	691	758	298	44.9	150	211*
	Shear	1529	95.4	1214	1345	1758	103	1420	1561
Ti-5Al-2.5Sn, Annealed	Tensile	360	32.9	252	297	256	28.6	162*	201*
	Shear	1381	41.0	1245	1302	1381	74.5	1135	1237

* Value of s large so that $\overline{X} - k_A s < 0.80\ \overline{X}$ and $\overline{X} - k_B s < 0.88\ \overline{X}$

Table 29D. (Cont)

MATERIAL, CONDITION	TEST	-320°F MEAN	s	A	B	-423°F MEAN	s	A	B
301 SS, 60% CR	Tensile	160	24.7	78.8	113	143	27.7	51.5*	89.5*
	Shear	1041	97.1	721	854	825	52.6	652*	724*
304 SS, 50% CR	Tensile	265	17.2	208*	232*	306	37.5	183*	234*
	Shear	634	24.9	552	586	666	34.3	553	600
310 SS, 75% CR	Tensile	582	31.6	478	522	533	38.6	406*	459*
	Shear	1096	29.9	998	1039	1224	53.2	1049	1122
AM-355 SS, CRT	Tensile	186	9.42	155	168	162	22.2	88.3*	119*
	Shear	903	39.0	774	828	858	64.7	645*	734*
Ti-5Al-2.5Sn, Annealed	Tensile	268	20.1	202*	229*	251	26.3	164*	200*
	Shear	1670	52.3	1498	1570	1587	83.2	1313	1427

* Value of s large so that $\bar{X} - k_A s < 0.80 \bar{X}$ and $\bar{X} - k_B s < 0.88 \bar{X}$

Table 30. Materials Recommended for Future Study

MATERIAL, TEMPER	GAUGE (IN.)	STRENGTH/DENSITY RATIO (IN. X 10^6)	RECOMMENDED TEST CONDITIONS (FROM 78°F to -423°F)
301 SS, 60% CR	0.020-0.030	0.76	Crack Propagation.
304 SS, 50-60% CR	0.020-0.030	0.61	Crack Propagation.
310 SS, 75% CR	0.020-0.030	0.62	Crack Propagation.
AM-355 SS, CRT	0.020-0.030	0.89	Crack Propagation.
Rene 41, Aged	0.020-0.030	0.46	Tensile, Fatigue, and Crack Propagation.
Hastelloy B, 40% CR	0.020-0.030	0.63	Tensile, Fatigue, and Crack Propagation.
20 or 25% Ni Steel, 50% CR	0.020-0.030	0.54	Tensile, Fatigue, and Crack Propagation.
2014 Al Alloy, T6	0.063	0.68	Crack Propagation.
2219 Al-Alloy, T87	0.063-0.125	0.59	Tensile, Fatigue, and Crack Propagation.
5052 Al-Alloy, H38	0.063	0.47	Crack Propagation.
5456 Al-Alloy, H343	0.063	0.45	Crack Propagation.
Ti-5Al-2.5Sn, Annealed	0.025-0.040	0.75	Crack Propagation.
Ti-5Al-2.5Sn,20-30% CR	0.025-0.040	0.80-0.90	Tensile, Fatigue, and Crack Propagation.
Ti-6Al-4V, Annealed	0.025-0.040	0.83	Tensile, Fatigue, and Crack Propagation.
Ti-8Al-2Cb-1Ta, Annealed	0.025-0.040	0.86	Tensile, Fatigue, and Crack Propagation.

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