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TENSILE PROPERTIES AND CREEP STRENGTH OF THREE ALUMINUM ALLOYS EXPOSED UP TO 25 000 HOURS AT 200° TO 400° F (370° TO 480° K)

by Dick M. Royster

Langley Research Center
Langley Station, Hampton, Va.

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SUMMARY

The tensile properties and creep strength of three aluminum-alloy sheet materials exposed up to 25 000 hours at 200° to 400° F (370° to 480° K) were investigated. The materials investigated were clad 2024-T81, X2020-T6, and clad RR-58 aluminum alloys. These alloys are representative of the types considered for a supersonic transport operating in the Mach 2 speed range.

The effect of longtime, elevated-temperature exposures was determined from changes in tensile and notch properties at room temperature. The short-time, elevated-temperature tensile properties as well as the tensile stress required to produce 0.1-percent creep were determined. Metallurgical studies were made to determine microstructural changes in the alloys due to exposure. With the exception of the X2020-T6 alloy, the material tensile properties were not severely affected by longtime unstressed exposure. The X2020-T6 alloy also exhibited poor notch toughness. Low creep strength in the aluminum alloys at temperatures above 300° F (420° K) may limit their use for longtime exposures.

INTRODUCTION

Materials research in support of a commercial supersonic transport in the U.S.A. began about 1960 when the speed and other operating characteristics of such a transport were tentatively defined. Since then, materials investigations have been initiated in many diverse problem areas. One aspect of the materials research program at the Langley Research Center has been concerned primarily with the effects of longtime environmental exposure on the mechanical properties of various sheet materials: titanium alloys, stainless steels, glass-reinforced composites, and aluminum alloys. (For example, see ref. 1.)

The present investigation on aluminum alloys was begun in 1963 to provide materials information for the Mach 2 speed range. This report summarizes the results obtained on the stability, strength, and creep of three aluminum-alloy sheet materials exposed up to

25 000 hours to temperatures from 200° to 400° F (370° to 480° K). The aluminum alloys investigated were clad 2024-T81, X2020-T6, and clad RR-58. Data were obtained on the tensile properties of the alloys at room temperature and -110° F (190° K) and on the effects of longtime, elevated-temperature exposure on unstressed tensile and notched specimens. The short-time, elevated-temperature tensile properties as well as the tensile stress to produce 0.1-percent creep were determined. The creep data were correlated by a time-temperature parameter. Metallurgical studies were included to determine changes in the microstructure of the alloys due to exposure.

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating the two systems are given in reference 2, and those used in the present investigation are presented in the appendix.

MATERIALS AND SPECIMENS

Materials

The three aluminum-alloy sheet materials utilized in this investigation were selected from considerations involving strength, notch toughness, prospective creep resistance, and stability at room and elevated temperatures. Stability is defined as the ability of the alloys to retain their preexposure tensile properties. Two of the alloys are American (clad 2024-T81 and X2020-T6), and the third is British (clad RR-58). A description of the sheet materials and heat treatments is found in table I. The alloy RR-58 or AU2GN (French designation) is being used in the construction of the British-French supersonic transport, the Concorde (ref. 3). However, the material has been modified somewhat in its manufacturing processes to improve its creep resistance. The modified material is designated as CM.001 (CM indicates Concorde material).

The clad 2024-T81 and X2020-T6 alloys contain copper and small percentages of other elements as hardeners. The clad RR-58 alloy contains less copper and more magnesium, nickel, and iron than the two American alloys. The nominal chemical composition of the sheet materials is given in table II.

Specimens

The specimen configurations are shown in figure 1. The tensile and notched specimens were machined from both the longitudinal and transverse rolling directions of the sheets, but the creep specimens were machined from only the longitudinal direction. All specimens from each alloy were made from the same heat but not necessarily the same sheet. The tensile specimen conforms to the specifications prescribed in reference 4. The notched specimen is 1 inch (2.54 cm) wide as recommended in reference 5. The radius at the base of the notch varied from about 500 to 700 microinches (approximately 13 to 18 μm), which corresponds to an elastic stress concentration factor of approximately 20. The last step in finishing the radius was performed by hand drawing a shaping tool through the notch. This operation was done repeatedly until the desired radius was obtained. The creep specimen is a modification of the tensile specimen. The increased shoulder length permitted the specimen to be gripped outside the furnace during exposure to elevated temperature.

PROCEDURES

The specimens were thoroughly cleaned before exposure. The cleaning procedure consisted of removing markings, such as crayon or manufacturer's stamp, with acetone and a cloth. The specimens were then vapor degreased with trichlorethylene, after which they were rinsed in water at 125° F (320° K). A room-temperature water rinse followed. The specimens were then dried with absorbent paper towels and packaged in clean containers.

Tensile Tests

Room temperature and -110° F (190° K).- After being cleaned, tensile and notched specimens were tested at room temperature and at -110° F (190° K). Tensile and notched specimens for elevated-temperature exposure were placed in air-circulating electric ovens operating at 250° and 300° F (390° and 420° K). None of the specimens were stressed during exposure. In order to study the stability of the alloys, specimens were removed at predetermined times for testing at room temperature. The nominal exposure schedule was 500, 1000, 2000, 4000, 7000, 10 000, 14 000, 18 000, and 22 000 hours; however, there were variations in the schedule due to furnace malfunctions. The tensile specimens were tested in a hydraulic testing machine at a strain rate of 0.005 per minute through the 0.2-percent offset strain, and the rate was then increased to 0.05 per minute until fracture occurred. The notched specimens were tested at a constant net-section stress rate corresponding to a strain rate of about 0.00125 per minute in the same hydraulic testing machine as was used in the tensile tests. Additional details of test apparatus and procedures are described in reference 6.

Elevated temperature.- The elevated-temperature tensile stress-strain tests were made at 200°, 250°, 300°, 350°, and 400° F (370°, 390°, 420°, 450°, and 480° K). The specimens were exposed to the test temperature for 1/2 hour and then loaded to failure. The tests were run at a strain rate of 0.005 per minute through the 0.2-percent offset strain, and this rate was then increased to 0.05 per minute until fracture occurred. Specimen temperatures during the test were constant within 3° F (2° K) of the test temperature, and the variation in temperature over the gage length of the specimen did not exceed 3° F (2° K). Additional details of test apparatus and procedures are described in reference 7.

Tensile Creep Tests

The tensile creep tests were made at 250°, 300°, and 350° F (390°, 420°, and 450° K) over a range of stresses from 5 to 60 ksi (34 to 410 MN/m^2). The creep tests were performed in deadweight loading machines (creep machines) equipped with vertical tube furnaces which heated the test section of the specimen uniformly to within 3° F (2° K) of the prescribed test temperatures. The load was applied after 1/2 hour exposure to the test temperature. The tensile creep specimens were marked on one face with a microhardness tester at every 0.5 inch (1.3 cm) along the center line over a 2-inch (5-cm) gage section. Precise measurements to the nearest 100 microinches (2.5 μm) were made between the marks with an optical microscope having an attached micrometer. Creep strain was determined by removing the specimens from the creep machines approximately once a week and measuring the permanent extension between the hardness marks. These measurements were made at room temperature with the same optical microscope used previously. The increase in the distance between the marks indicated the amount of permanent strain experienced by the specimens. Tests were terminated when the permanent strain reached 0.1 percent. Curves were faired through the creep strain data obtained for various exposure times to determine when 0.1-percent creep strain occurred.

Metallurgical Investigation

The metallurgical investigation was based on microstructure examination in the longitudinal direction of cross sections removed from the as-received and from the exposed test specimens and mounted on edge in plastic. The sections were wet ground, mechanically polished, and etched. The alloys were etched at room temperature for 30 seconds with a solution consisting of 1 gram sodium hydroxide (NaOH) and 99 milliliters (99 cm^3) distilled water. Photomicrographs were taken at ×1000.

TENSILE PROPERTIES BEFORE EXPOSURE

The tensile properties of the sheet materials obtained in static tests before exposure are reviewed. The data are given in tables III and IV, and typical or average results are shown in figures 2, 3, and 4.

Yield Strength Stress-Strain Characteristics

Typical tensile stress-strain curves for the aluminum-alloy sheet materials at room temperature (80° F (300° K)) and at -110° F (190° K) are shown in figure 2 for both the longitudinal and transverse directions. The stress-strain characteristics are approximately the same in both the longitudinal and transverse directions for each alloy at each temperature. The X2020-T6 alloy has a 0.2-percent yield strength that is 31 percent higher than that of the clad 2024-T81 alloy. The clad RR-58 alloy has a slightly lower yield strength than the clad 2024-T81 alloy.

Ultimate Strength and Elongation

The average ultimate tensile strength and the elongation in 2 inches (5 cm) at room temperature and at -110° F (190° K) are summarized in figure 3. The tensile strengths at room temperature varied from about 59 to 84 ksi (410 to 580 MN/m^2), and the strengths were about 8 percent higher at -110° F (190° K) for the three alloys. In general, the tensile strength was approximately the same in both directions for each alloy.

At -110° F (190° K), the elongation decreased slightly for the clad 2024-T81 and X2020-T6 alloys but increased slightly for the clad RR-58 alloy.

Notch Strength

The average notch strength and notch strength ratios, an indication of notch sensitivity, were obtained at room temperature and at -110° F (190° K) and are summarized in figure 4. The ratio of the notch strength to the tensile strength (i.e., notch strength ratio) was lower at -110° F (190° K) than at room temperature for the clad 2024-T81 and X2020-T6 alloys, mainly because of the increase in tensile strength at the low temperature. The notch strength is based upon the average net-section stress. The notch strength ratio for the clad RR-58 alloy is above 0.9 at room temperature and at -110° F (190° K). For clad 2024-T81, the notch strength ratio is about 0.9 at room temperature and is slightly less at -110° F (190° K). The notch strength ratio for X2020-T6 is about 0.6 at room temperature and at -110° F (190° K).

Another indication of the notch sensitivity of the material is given by the amount of shear lip occurring at fracture. (See table III.) Shear lip is defined as the percentage of the fracture that failed in shear. Ductile, shear type of fractures with shear-lip values of 100 percent were characteristic of clad 2024-T81 and clad RR-58 at both room and low temperatures. However, the X2020-T6 alloy exhibited brittle and irregular fracture characteristics at low temperatures with the shear-lip value ranging from 0 to 85 percent.

Young's Modulus

Values of Young's modulus in tension at room temperature, obtained from Tuckerman optical strain-gage measurements, are listed in table IV. The values presented are the average of two specimens for each alloy.

EFFECT OF PROLONGED EXPOSURE AT 250° AND 300° F (390° AND 420° K) ON TENSILE PROPERTIES

The effects of longtime exposure at 250° and 300° F (390° and 420° K) on the tensile properties at room temperature are illustrated in figure 5 for the three alloys. These effects are depicted by changes in the ratio of the property after exposure to the corresponding property before exposure (i.e., base property). The ratios are based upon averages of the results at each exposure for both the longitudinal and transverse directions. The test data are given in table III.

Clad 2024-T81

The ratios for the tensile, yield, and notch strengths and for elongation in 2 inches (5 cm) remain above 0.9 in the room-temperature tests of clad 2024-T81 for exposures at 250° F (390° K) and for times up to 22 000 hours (18 000 hours for the notch strength). (See fig. 5(a).) It should be noted that there is little difference between the data for the longitudinal and transverse directions. At 300° F (420° K) for exposures up to 22 000 hours, the ratios remain above 0.8 with a reduction of 17 percent occurring in the yield strength. (See fig. 5(b).)

X2020-T6

The tensile and yield strength ratios for the X2020-T6 alloy at 250° F (390° K) decrease slightly for exposures up to 25 000 hours (fig. 5(c)). The notch strength decreases up to 4000 hours and then increases slightly for longer exposures. At 300° F (420° K) (fig. 5(d)), a substantial decrease occurs in tensile and yield strengths for exposures up to 20 000 hours. This decrease is indicative of overaging (ref. 8). The increase in elongation is also indicative of overaging. There is little change in the ratio for the notch strength.

Clad RR-58

The strength and elongation ratios of the clad RR-58 alloy at 250° F (390° K) for exposures up to 22 000 hours remain relatively unchanged. (See fig. 5(e).) However, at 300° F (420° K) (fig. 5(f)) because of overaging, the tensile and yield strengths are reduced and elongation is increased after exposures for 10 000 hours. Furnace malfunction forced the termination of the exposure beyond 10 000 hours. The notch strength also shows a slight reduction at 300° F (420° K).

Alloy Comparison

A comparison of the residual tensile and notch strengths of the three alloys at 250° and 300° F (390° and 420° K) for exposures up to 25 000 hours is shown in figure 6. At 250° F (390° K) the tensile strength of the X2020-T6 alloy (fig. 6(a)) is higher than that of the other two alloys. The clad 2024-T81 alloy has slightly higher tensile strength than the clad RR-58 alloy. At 300° F (420° K) the tensile strength of X2020-T6 is higher than that of clad 2024-T81 for exposures up to approximately 10 000 hours, after which the two alloys have nearly the same strength. Clad RR-58 has the lowest tensile strength.

The symbols in figure 6(a) represent data taken from reference 3 for the 2024-T81 and CM.001 alloys and show the ultimate tensile strength at room temperature after 20 000 hours exposure at 250° and 300° F (390° and 420° K). At 250° F (390° K) the clad 2024-T81 and clad RR-58 data agree very well with the data from reference 3. At 300° F (420° K) the clad 2024-T81 alloy of this investigation had slightly higher strength than that reported in reference 3. The CM.001 alloy after 20 000 hours exposure had higher strength than the clad RR-58 alloy after 10 000 hours exposure.

A comparison of the notch strength (fig. 6(b)) shows that at both 250° and 300° F (390° and 420° K) all three alloys appear stable, with clad 2024-T81 having the highest strength. The X2020-T6 alloy exhibits the lowest notch strength of the three alloys at the temperatures tested for exposures beyond 5000 hours.

SHORT-TIME, ELEVATED-TEMPERATURE TENSILE PROPERTIES

The short-time, elevated-temperature tensile properties at 200°, 250°, 300°, 350°, and 400° F (370°, 390°, 420°, 450°, and 480° K) of the three alloys are tabulated in table V, and the tensile and yield strengths are summarized in figure 7. The tensile and yield strengths of the X2020-T6 alloy are higher than those of the other alloys at any given test temperature. Up to 400° F (480° K), the clad RR-58 alloy exhibits lower strength than the other two alloys.

EFFECT OF STRESS AND TEMPERATURE ON CREEP RESISTANCE

Stress Required to Produce 0.1-Percent Creep Strain

The stresses to produce creep strain of 0.1 percent for the three alloys at 250°, 300°, and 350° F (390°, 420°, and 450° K) are presented in figure 8 for times up to

18 000 hours. The curves of figure 8 are faired through the open-symbol data points. In order to determine differences between intermittent exposure and continuous exposure, one specimen of each alloy was tested at 350° F (450° K) for 2000 hours at a stress which was estimated to produce 0.1-percent strain. Clad RR-58 required an additional 1000 hours to produce 0.1-percent strain. The results for continuous and intermittent exposure were in good agreement as shown by the solid symbols in figure 8. Therefore, removal of the specimens from the furnaces to determine creep strains did not appear to influence the magnitude of the creep strain reported in this investigation.

The triangular symbol in figures 8(a) and (c) is obtained from data in reference 3 for 2024-T81 and CM.001. The 2024-T81 alloy from the reference has less creep strength than the clad 2024-T81 alloy of this investigation, whereas the CM.001 alloy from the reference has improved creep resistance over the clad RR-58 alloy. It was for improved creep resistance that the RR-58 material was modified in its manufacturing processes.

Alloy Comparison

The creep strength at a 0.1-percent creep strain for a 10 000-hour exposure is shown in figure 9 for the three alloys. The creep curves of figure 8 were extrapolated to 10 000 hours to provide the information necessary to produce figure 9. The alloy X2020-T6 has the highest creep strength at 250° F (390° K), but its strength is reduced rapidly at the higher temperatures, and at 350° F (450° K) it has a creep strength of approximately 4 ksi (28 MN/m^2). Clad 2024-T81 has the highest creep strength at and above 300° F (420° K), and at 350° F (450° K) its strength is about 10 ksi (69 MN/m^2). Clad RR-58 exhibits poor creep strength at the lower temperatures, and at 350° F (450° K) its strength is 6 ksi (41 MN/m^2). These low values of creep strength for all three alloys might limit their use for longtime exposures at temperatures above 300° F (420° K).

Correlation of Creep Results

A number of time-temperature parameters have been developed to correlate creep data. An analysis of the creep data, by means of the procedures presented in reference 9, showed that the Dorn time-temperature parameter provided a convenient method to correlate the 0.1-percent creep strain for the three alloys. In the Dorn parameter,

$$\theta = F(\sigma) = t \exp \frac{-\Delta H}{RT_K}$$

or as used herein in the common logarithmic form

$$\log \theta = \log t - \frac{\Delta H}{2.3RT_K}$$

where σ is stress, t is time in hours, ΔH is the activation energy, R is the gas constant (2.0 cal/mole-°K or 8.4 J/mole-°K), 2.3 is logarithmic conversion from natural to common, and T_K is temperature in degrees Kelvin.

The correlation of the test results with the master stress-time-temperature curve for each material is shown in figure 10. The close grouping of the data points with the master curve indicates good agreement for all three alloys over the temperatures and stresses investigated. Thus the Dorn time-temperature parameter appears to be appropriate for predicting 0.1-percent creep strain for these alloys at 250° to 350° F (390° to 450° K).

METALLURGICAL INVESTIGATION

The metallurgical investigation consisted of microstructural examination of sections taken from the as-received and exposed test specimens. Representative photomicrographs taken of these sections are shown in figure 11. The changes observed in the microstructure of exposed specimens were consistent with the trends found in the mechanical properties.

After 22 000 hours at 300° F (420° K) (fig. 11(a)) there is little change in the microstructure of the clad 2024-T81 alloy when compared with the as-received condition. This observation is consistent with the stability of the alloy as shown in figure 5(b). At 350° F (450° K) after 14 521 hours there appears to be a slight increase in visible precipitates.

The microstructure of the X2020-T6 alloy (fig. 11(b)) after 22 000 hours at 300° F (420° K) when compared with the as-received shows a slight increase in grain size and a more complete precipitation, which is indicative of overaging (ref. 8). The general result of overaging is a decrease in strength and an increase in elongation due to softening which is evidenced in figure 5(d). This trend of overaging is also apparent at 350° F (450° K) after 12 751 hours as evidenced by the poor creep strength of the X2020-T6 alloy.

The microstructures of the clad RR-58 alloy (fig. 11(c)) after exposures of 300° and 350° F (420° and 450° K) for 10 000 and 4484 hours, respectively, appear to differ very little from the as-received material except for a possible increase in the number of visible precipitates with increased exposure. The decrease in strength and increase in elongation of the clad RR-58 alloy at 300° F (420° K) (fig. 5(f)) may again be indicative of overaging.

CONCLUSIONS

The tensile properties and creep strength of three aluminum alloys exposed up to 25 000 hours at 200° to 400° F (370° to 480° K) have been investigated. The alloys include clad 2024-T81, X2020-T6, and clad RR-58. The following conclusions are based upon the results of this investigation:

1. The X2020-T6 alloy has the highest tensile and yield strengths at room temperature and -110° F (190° K). The tensile properties for each alloy in the longitudinal and transverse directions are approximately the same. At room temperature, the notch strength ratio is about 0.9 for the clad 2024-T81 and clad RR-58 alloys and is about 0.6 for the X2020-T6 alloy.

2. At 250° F (390° K) all three alloys were stable, with the X2020-T6 alloy having the highest tensile strength. At 300° F (420° K) the tensile strength of X2020-T6 is higher than that of clad 2024-T81 for exposures up to approximately 10 000 hours, after which the two alloys have nearly the same strength. The notch strengths of the three alloys appeared stable for exposures at 250° and 300° F (390° and 420° K) with clad 2024-T81 having the highest strength. The X2020-T6 alloy exhibited the highest strength for short-time exposures up to 400° F (480° K).

3. Low creep strength in all three alloys might limit their use for longtime exposures at temperatures above 300° F (420° K). The X2020-T6 alloy showed the highest creep strength at 250° F (390° K). Above 300° F (420° K), the clad 2024-T81 alloy showed the highest creep strength. The Dorn stress-rupture parameter can be used for predicting 0.1-percent creep strain for these alloys at 250° to 350° F (390° to 450° K). The changes observed in the microstructure of exposed specimens were consistent with the trends found in the mechanical properties.

Langley Research Center,
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720-02-00-06-23.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures in 1960. (See ref. 2.) Factors required for converting the U.S. Customary Units used herein to the International System of Units (SI) are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI unit (**)
Force	lbf	4.44822	newtons (N)
Length	in.	0.0254	meters (m)
Stress	ksi	6.895×10^6	newtons/meter^2 (N/m^2)
Temperature	$^{\circ}$F	$\frac{5}{9}(F + 459.67)$	degrees Kelvin ($^{\circ}$K)
Energy	cal	4.184	joules (J)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI unit.

**Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
giga (G)	10^9
mega (M)	10^6
kilo (k)	10^3
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}

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TABLE I.- DESCRIPTION OF ALUMINUM-ALLOY SHEET MATERIALS AND HEAT TREATMENTS

Material[a]	Thickness		Heat treatment (a)	Cladding thickness	
	in.	mm		in.	mm
Clad 2024-T81	0.064	1.6	Solution treatment: 910° to 930° F (760° to 770° K) water quenched, cold worked, and precipitation heat treated at 375° F (460° K) between 11 and 13 hours	0.0022	0.056
X2020-T6	.048	1.2	Solution treatment: 950° to 970° F (780° to 790° K) water quenched, aged 16 to 20 hours at 315° to 325° F (430° to 440° K)		
Clad RR-58[b]	.064	1.6	Solution treatment: 977° to 995° F (800° to 810° K) water quenched, aged 20 hours at 392° F (470° K)	.0030	.076

[a] Vendor supplied information.

[b] Clad RR-58 was purchased in the United Kingdom and is designated as AU2GN in France and as 2618 in the United States.

TABLE II.- NOMINAL CHEMICAL COMPOSITION OF ALUMINUM-ALLOY SHEET MATERIALS[a]

[Percent given on weight basis]

Material	Lithium	Copper	Manganese	Cadmium	Magnesium	Iron	Silicon	Zinc	Titanium	Lead	Tin	Chromiun	Nickel	Aluminum
Clad 2024-T81	--------	3.8 to 4.9	0.30 to 0.90	-----------	1.2 to 1.8	0.050	0.050	0.25	---	---	---	0.10	--------	Balance
Cladding	--------	.10	.05	-----------	--------	(← .7 →)			---	---	---	.10	--------	Balance
X2020-T6	0.9 to 1.7	4.0 to 5.0	0.30 to 0.80	0.10 to 0.035	0.03	0.40	0.40	0.25	0.10	---	---	---	--------	Balance
Clad RR-58	--------	1.8 to 2.7	0.2	-----------	1.2 to 1.8	0.9 to 1.4	0.15 to 0.25	0.1	0.2	0.05	0.25	---	0.8 to 1.4	Balance
Cladding	--------	--------	----------	-----------	--------	--------	----------	0.8 to 1.2	---	---	---	---	--------	Balance

[a] Vendor supplied information.

TABLE III.- TENSILE PROPERTIES FOR ALUMINUM-ALLOY SHEET

(a) Clad 2024-T81

Exposure, hr	Test temperature		Tensile strength				Yield strength				Elongation, percent				Notch strength				Shear lip, percent	
			Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal	Transverse
	°F	°K	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	Uniform	In 2 in. (5 cm)	Uniform	In 2 in. (5 cm)	ksi	MN/m^2	ksi	MN/m^2		
As received																				
0	80	300	66.4	460	65.4	450	58.8	390	59.5	410	7	7.5	5	7	61.8	430	59.7	410	100	100
0	80	300	65.7	450	64.8	450	61.6	420	59.0	410	5	6	4	6.5	61.1	420	58.4	400	100	100
0	-110	190	70.5	490	69.0	480	64.5	450	62.5	430	3	3.5	3	3.5	64.0	440	56.3	390	100	100
0	-110	190	70.8	490	69.5	490	64.0	440	62.8	430	5	7	3.5	4	60.0	410	59.3	410	100	100
Exposure at 250° F (390° K)																				
600	80	300	66.4	460	65.3	450	61.6	420	62.0	430	5	7	5	7	62.0	430	55.0	380	100	100
600			66.3	460	65.8	450	62.7	430	60.8	420	6	8	5	7.5	58.4	400	60.0	410	100	100
1 000			65.2	450	65.0	450	59.8	410	60.0	410	5	7	5	7	60.9	420	59.0	410	100	100
1 000			66.0	460	65.5	450	60.7	420	60.8	420	4.5	7	5	6.5	61.3	420	55.5	380	100	100
2 000			64.3	440	65.2	450	58.0	400	60.7	420	4.5	7.5	4	5.5	60.1	410	53.6	370	100	100
2 000			65.8	450	64.8	450	60.5	420	60.1	410	6.5	8	4	6.5	61.3	420	57.8	400	100	100
4 000			62.8	430	64.5	450	55.8	390	58.8	400	6	8	5	7	60.3	420	58.7	410	100	100
4 000			64.7	450	64.7	450	59.1	410	59.5	410	5	6.5	5	7	62.3	430	56.6	390	100	100
10 777			65.0	450	63.8	440	59.8	410	58.7	410	6	7.5	4	7	55.8	390	55.7	380	100	100
10 777			64.5	450	65.0	450	59.2	410	59.7	410	5	7.5	5	6.5	59.5	410	57.4	400	100	100
18 000			64.2	440	64.3	440	57.6	400	58.3	400	6	8	5	7	57.7	400	56.4	390	75	75
18 000			64.7	450	64.4	440	58.2	400	58.2	400	6	8	5	7	61.2	420	56.9	390	100	100
22 000			64.7	450	63.9	440	58.3	400	57.7	400	4	7	5	7						100
22 000	↓	↓	65.1	450	65.5	450	59.2	410	60.0	410	6	7.5	5	7						100
Exposure at 300° F (420° K)																				
1 030	80	300	62.0	430	63.8	440	54.2	370	57.5	400	4	7.5	3	6	60.6	420	58.8	410	100	100
1 030			63.4	440	63.8	440	56.3	390	57.6	400	3	6.5	2	5	57.3	400	55.5	380	80	100
2 000			61.6	430	64.2	440	53.7	370	57.5	400	7	8	4	7	59.5	410	57.6	400	100	100
2 000			62.7	430	64.5	440	55.4	380	58.4	400	6.5	8	5	7	60.1	410	57.9	400	100	100
4 000			61.1	420	62.3	430	53.4	370	55.0	380	6	7.5	6	7.5	57.5	400	56.0	390	100	100
4 000			61.0	420	62.9	430	53.9	370	55.9	390	6.5	8	6	8	58.4	400	56.4	390	80	100
7 000			61.3	420	62.4	430	53.1	370	54.8	380	5.5	7	5	6.5	57.9	400	55.5	380	100	100
7 000			61.9	430	62.4	430	54.0	370	55.3	380	6	8	4	5.5	57.5	400	57.2	390	100	100
12 243			60.7	420	61.7	430	52.2	360	53.4	370	5	7.5	5	7.5	54.9	380	53.7	370	100	100
12 243			60.7	420	61.7	430	52.4	360	53.2	370	5.5	7.5	6	7	53.7	370	42.5	360	100	100
15 000			58.1	400	60.5	420	49.0	340	51.7	360	7	8.5	5	6.5	54.1	370	53.3	370	100	100
15 000			59.6	410	61.4	420	50.8	350	51.6	360	6	8.5	5	7	55.4	380	51.7	360	100	100
18 000			59.6	410	61.8	430	50.1	350	52.7	360	8	10.0	8	10.0	56.7	390	53.6	370	100	100
18 000			61.3	420	62.1	430	52.7	360	53.2	370	9	9.5	8	10.0	56.4	390	55.9	390	100	100
22 000			60.9	420	61.5	420	51.6	360	52.9	360	8	10.0	7.5	9	54.9	380	54.3	370	100	100
22 000	↓	↓	60.5	420	61.4	420	50.7	350	52.2	360	8	9	7.5	9	55.1	380	53.4	370	100	100

TABLE III.- TENSILE PROPERTIES FOR ALUMINUM-ALLOY SHEET – Continued

(b) X2020-T6

Exposure, hr	Test temperature		Tensile strength				Yield strength				Elongation, percent				Notch strength				Shear lip, percent	
			Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal	Transverse
	°F	°K	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	Uniform	In 2 in. (5 cm)	Uniform	In 2 in. (5 cm)	ksi	MN/m^2	ksi	MN/m^2		
As received																				
0	80	300	82.3	570	83.0	570	78.2	540	76.0	520	5	9	2.5	6	58.8	410	51.8	360	90	95
0	80	300	83.5	580	83.6	580	79.2	550	77.8	540	6	7.5	6.5	7.5	49.8	340	52.2	360	95	90
0	-110	190	87.5	600	86.3	600	81.0	560	78.5	540	5	7	5	8	46.9	320	53.8	370	0	0
0	-110	190	89.9	620	89.4	620	84.5	580	83.3	570	5.5	5.5	6	6	54.5	380	54.0	370	85	50
Exposure at 250° F (390° K)																				
4 000	80	300	82.0	570	80.7	560	78.2	540	74.7	520	5.5	7.5	5	7	47.4	330	45.1	310	100	95
4 000	↓	↓	81.2	560	82.4	570	77.0	530	76.3	530	4.5	7	5	7	42.8	300	45.2	310	95	95
14 000			80.2	550	80.6	560	75.4	520	71.0	490	5	6.5	6	7.5	40.9	280	49.2	340	90	100
14 000			79.8	550	78.4	540	74.9	520	72.1	500	5	7	7	7.5	46.9	320	46.6	320	85	100
25 000			77.0	530	76.6	530	71.5	490	70.2	480	6	(a)	5	6	44.3	300	47.8	330	95	100
25 000			76.9	530	76.5	530	71.5	490	70.1	480	5.5	(a)	4	7	47.2	320	48.5	330	100	100
Exposure at 300° F (420° K)																				
4 000	80	300	71.2	490	69.8	480	63.6	440	61.0	420	6	7.5	6	7	54.4	370	53.3	370	100	100
4 000	↓	↓	70.9	490	69.6	480	63.0	440	60.5	420	8	8	5	6.5	53.8	370	53.5	370	95	96
8 000			66.4	460	64.5	450	55.6	380	53.5	370	5	8	6	7.5	52.6	360	53.1	370	100	100
8 000			65.9	460	65.7	450	55.0	380	54.7	380	5.5	8	5.5	7.5	50.3	350	53.2	370	100	100
14 000			62.3	430	61.7	430	50.4	350	49.6	340	6	8	6	8.5	53.1	370	51.2	350	100	100
14 000			62.2	430	61.2	420	50.0	350	49.0	340	6	8	6	7.5	49.5	340	50.6	350	100	100
20 000			59.4	410	58.5	400	47.1	320	46.3	320	5	8.5	5	7.5	49.7	340	50.1	350	80	80
20 000			59.3	410	59.5	410	47.2	320	45.7	320	6	9	5	8	49.7	340	48.6	340	75	80

[a] Broke outside gage area.

TABLE III.- TENSILE PROPERTIES FOR ALUMINUM-ALLOY SHEET – Concluded

(c) Clad RR-58

Exposure, hr	Test temperature		Tensile strength				Yield strength				Elongation, percent				Notch strength				Shear lip, percent	
			Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal		Transverse		Longitudinal	Transverse
	°F	°K	ksi	MN/m²	ksi	MN/m²	ksi	MN/m²	ksi	MN/m²	Uniform	In 2 in. (5 cm)	Uniform	In 2 in. (5 cm)	ksi	MN/m²	ksi	MN/m²		
As received																				
0	80	300	59.4	410	59.5	410	55.0	380	53.8	370	4.5	7	4	7	57.6	400	56.2	390	100	100
0	80	300	59.5	410	59.3	410	55.2	380	53.8	370	4	7	5	7	57.9	400	54.5	380	100	100
0	-110	190	63.7	440	63.5	440	59.3	410	59.0	410	6	7.5	6	8.5	60.0	410	59.1	410	100	100
0	-110	190	63.5	440	63.6	440	59.8	410	57.4	400	5	8	5	8	63.2	440	60.2	410	100	100
Exposure at 250° F (390° K)																				
500	80	300	59.4	410	59.5	410	54.7	380	54.2	370	5	7	4.5	7.5	57.8	400	56.3	390	100	100
500			59.6	410	59.4	410	55.2	380	54.8	380	5	7	4.0	7	56.6	390	55.7	380	100	100
1 000			60.2	410	59.7	410	55.6	380	54.4	380	5	7	5	7.5	57.2	390	55.3	380	100	100
1 000			60.5	420	59.3	410	56.2	390	53.7	370	5	7	5	7	55.9	390	55.5	380	100	100
2 000			59.6	410	59.2	410	54.7	380	53.5	370	6	7.5	4.5	7	52.1	360	55.6	380	100	100
2 000			59.8	410	59.5	410	55.2	380	53.8	370	5	7.5	6	7.5	54.5	380	54.2	370	100	100
4 000			59.6	410	58.9	410	55.6	380	54.0	370	5	7	5	7	56.3	390	52.5	360	100	100
4 000			59.7	410	59.0	410	55.9	390	54.0	370	5	7	4	6.5	53.3	370	56.7	390	100	100
7 000			60.9	420	60.2	410	56.2	390	53.6	370	4	7	6	7	54.5	380	55.4	380	100	100
7 000			61.3	420	60.0	410	55.5	380	53.8	370	5	8	4	7	56.8	390	53.5	370	100	100
10 000			60.1	410	59.3	410	55.8	390	53.9	370	7	9	7	10	57.8	400	56.6	390	100	100
10 000			60.1	410	59.6	410	55.8	390	54.5	380	7	10	7	9	56.6	390	55.8	390	100	100
14 000			58.8	410	58.8	410	53.4	370	52.2	360	6	7	6	7.5	58.0	400	55.6	380	100	100
14 000			59.2	410	58.6	400	54.4	380	52.3	360	6	7.5	5	7	54.3	370	56.6	390	100	100
18 000			59.2	410	58.7	410	55.5	380	54.1	370	4	6.5	4	6.5	55.9	390	55.5	380	100	100
18 000			59.6	410	58.8	410	54.9	380	54.1	370	5	7.5	5	7	54.9	380	55.5	380	100	100
22 000			58.4	400	57.7	400	53.5	370	51.8	360	5	7	5	6.5	55.3	380	55.7	380	100	100
22 000	↓	↓	58.2	400	57.8	400	53.5	370	51.9	360	5	7	4	7	56.6	390	55.7	380	100	100
Exposure at 300° F (420° K)																				
500	80	300	59.3	410	59.3	410	54.5	380	53.8	370	5	7.5	5	7.5	56.2	390	55.8	380	100	100
500			59.3	410	59.4	410	54.7	380	53.8	370	5	7.5	4	7	56.4	390	56.8	390	100	100
1 000			59.1	410	58.9	410	54.1	370	53.4	370	5	7.5	5	7.5	57.3	390	56.6	390	80	85
1 000			59.1	410	58.4	400	54.3	370	52.6	360	6	7	4.5	7	56.6	390	55.4	380	80	100
2 000			58.3	400	58.3	400	53.0	370	52.2	360	4	7	4.5	7.5	55.0	380	55.0	380	100	100
2 000			58.4	400	58.3	400	53.4	370	52.3	360	5	7.5	5	7	54.3	370	54.2	370	100	100
4 000			57.4	400	57.5	400	52.0	360	51.5	350	6	7.5	4	6.5	51.8	360	51.8	360	100	100
4 000			57.8	400	57.7	400	52.1	360	51.4	350	6	7.5	5	7.5	53.3	370	51.8	360	100	100
7 000			57.6	400	57.7	400	50.7	350	50.2	350	6	7.5	5	7	53.8	370	54.1	370	70	100
7 000			57.7	400	57.2	390	50.6	350	50.4	350	6	7.5	5	7	55.0	380	53.5	370	100	100
10 000			50.7	350	51.4	350	44.5	310	44.6	310	7.5	10	7.5	10	52.3	360	51.5	360	100	100
10 000	↓	↓	52.0	360	51.4	350	46.5	310	44.9	310	7.5	10	7.5	10	54.3	370	51.3	350	100	100

TABLE IV.- YOUNG'S MODULUS IN TENSION AT 80° F (300° K) FOR THE ALUMINUM-ALLOY SHEET MATERIALS

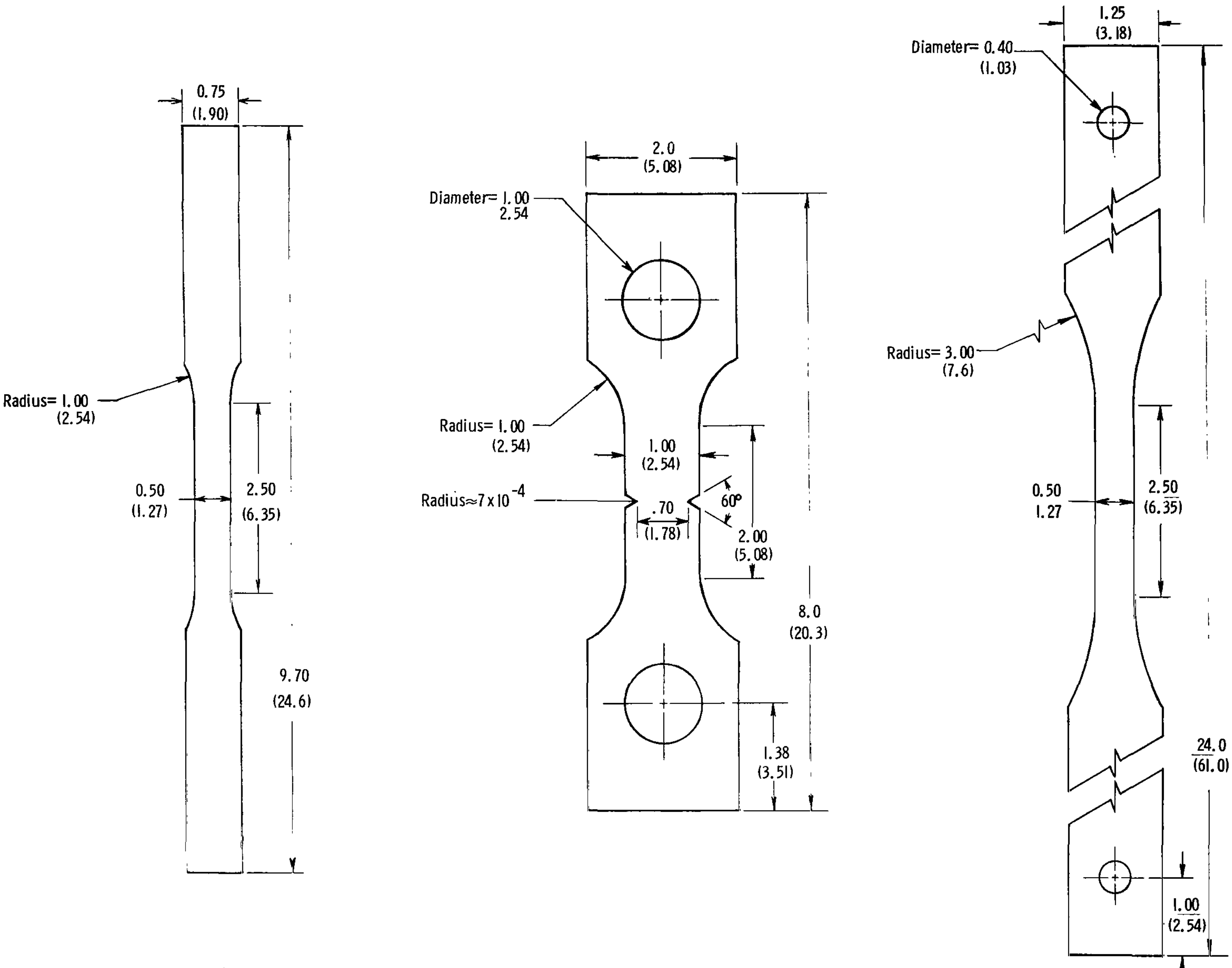
Material[a]	Young's modulus (b)	
	ksi	GN/m^2
Clad 2024-T81	10 300	71.0
X2020-T6	11 000	76.0
Clad RR-58	10 500	72.0

[a] Longitudinal grain direction.

[b] Tuckerman optical strain-gage measurements; data average of two test specimens.

TABLE V.- SHORT-TIME, ELEVATED-TEMPERATURE TENSILE PROPERTIES OF ALUMINUM-ALLOY SHEET

Temperature		Tensile strength		Yield strength		Elongation, percent	
°F	°K	ksi	MN/m^2	ksi	MN/m^2	Uniform	In 2 in. (5 cm)
Clad 2024-T81							
200	370	60.7	420	57.4	400	4.5	7.5
200	370	60.8	420	57.4	400	4	7
250	390	58.2	400	55.2	380	4	8.5
250	390	57.9	400	55.8	390	4.5	9
300	420	54.5	380	51.6	360	7	10.5
300	420	53.5	380	52.3	360	9	10.5
350	450	49.6	390	47.1	330	7	10.5
350	450	48.5	390	46.4	320	8	11
400	480	43.2	300	40.9	280	5	10
400	480	43.4	300	41.5	290	5	10
X2020-T6							
200	370	73.1	500	72.9	500	8	8
200	370	73.4	510	73.2	510	7	8.5
250	390	69.9	480	69.7	480	6	9.5
250	390	70.0	480	70.0	480	6	8.5
300	420	64.9	450	64.6	450	8	10
300	420	65.1	450	65.0	450	5	8
350	450	59.1	410	58.6	400	5	7.5
350	450	59.2	410	58.9	410	5	6
400	480	50.3	350	49.5	340	2	4
400	480	50.3	350	49.9	340	2	4
Clad RR-58							
200	370	56.4	390	53.3	370	6	8.5
200	370	56.2	390	53.6	370	5	7.5
250	390	53.6	370	50.8	350	6	9
250	390	53.2	370	50.4	350	6	9
300	420	49.5	340	48.3	330	5	11.5
300	420	48.7	340	48.4	330	6	12
350	450	44.5	310	43.9	300	6	12
350	450	44.8	310	43.8	300	7	14
400	480	38.9	270	36.7	250	5	12
400	480	39.1	270	37.8	260	7	12.5



Tensile

Notch

Creep

Figure 1.- Specimens used in tensile and creep tests. Dimensions in inches (centimeters).

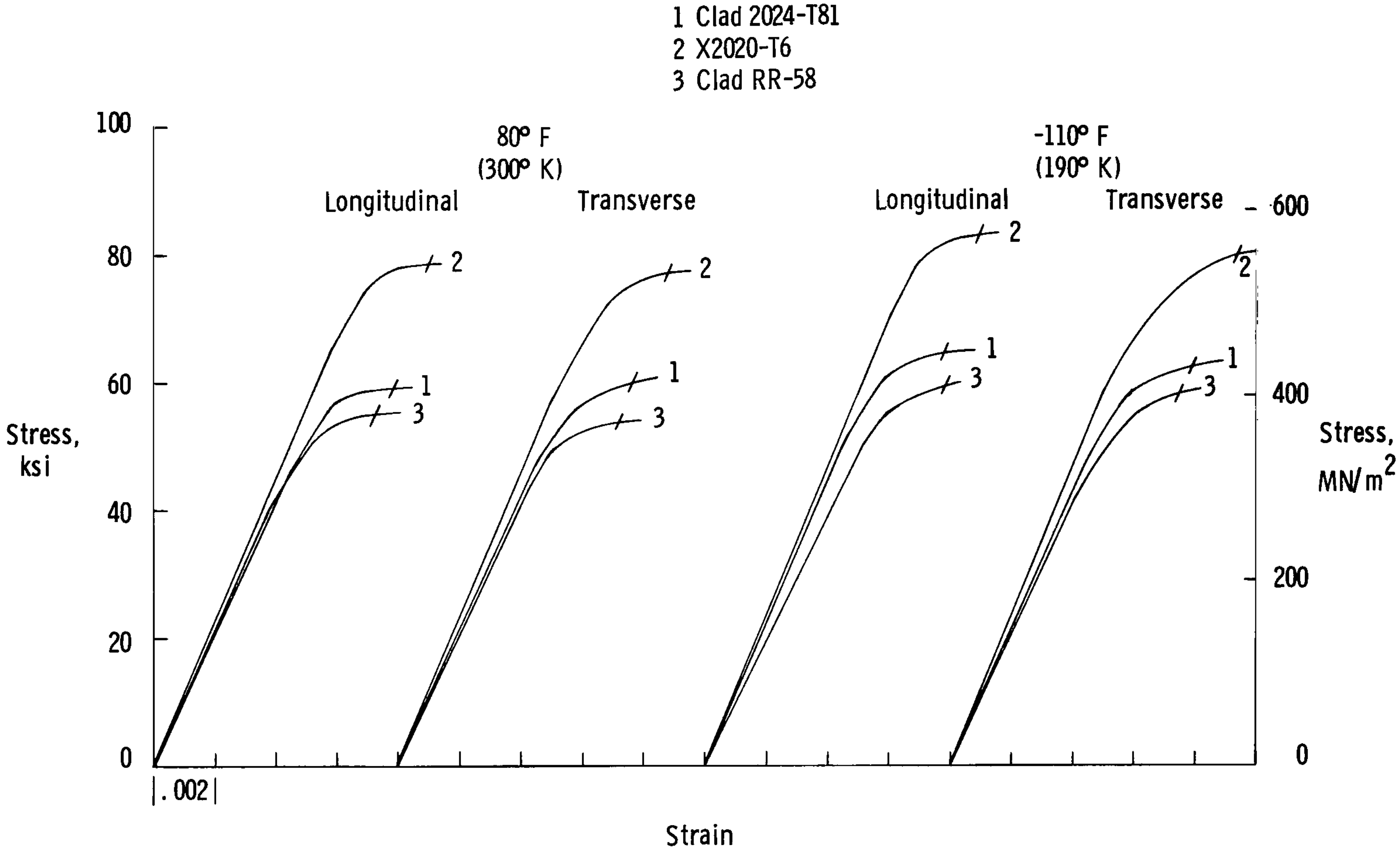
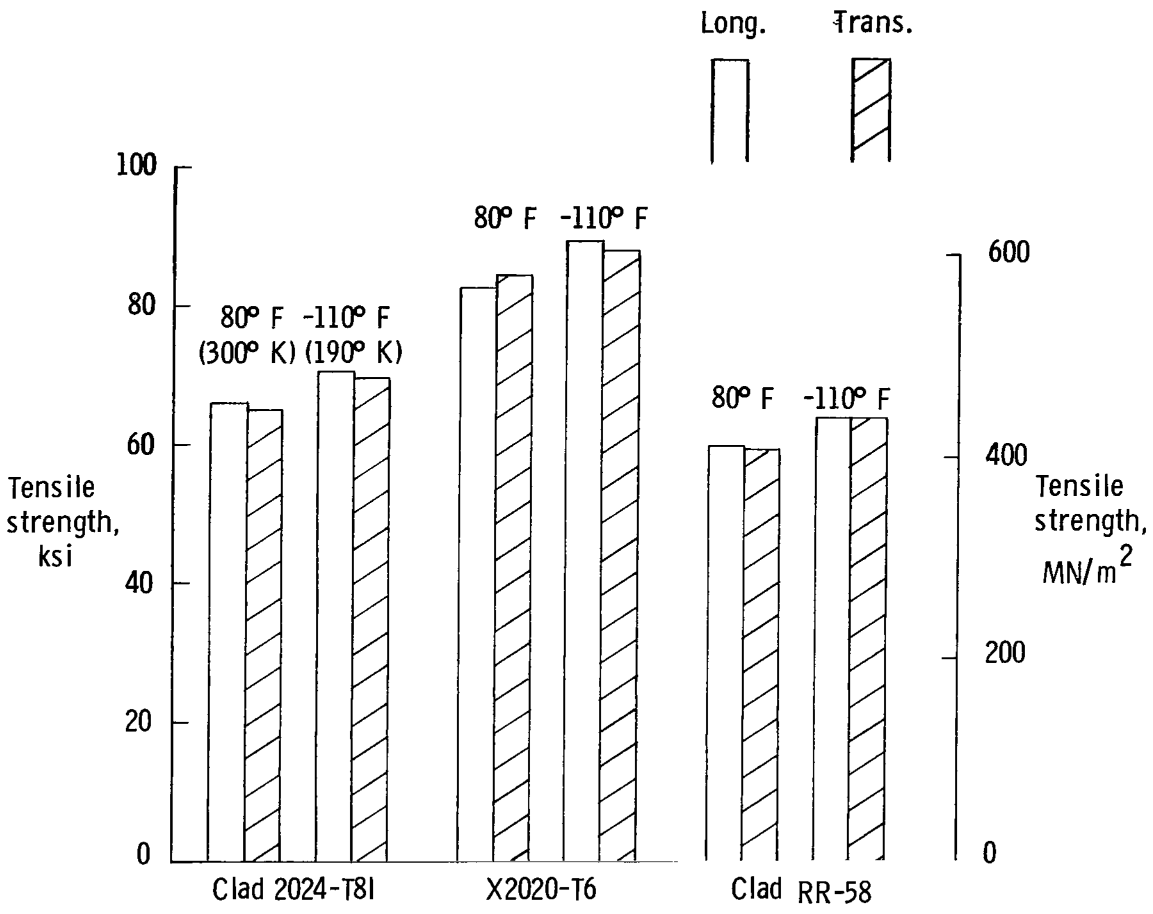
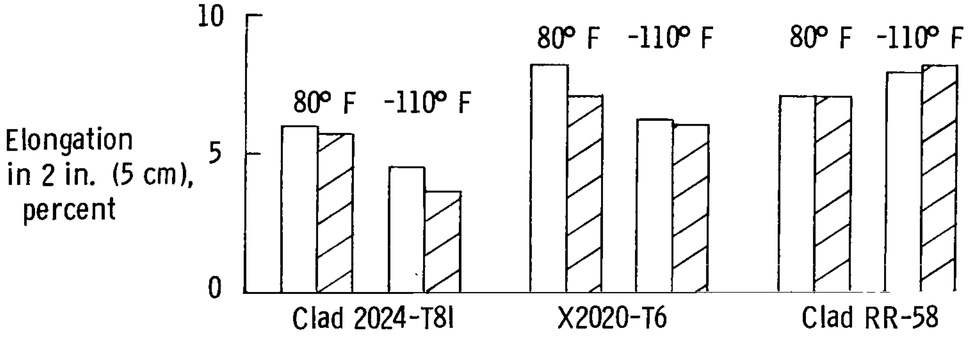


Figure 2.- Typical tensile stress-strain curves for as-received aluminum-alloy sheet at 80° and -110° F (300° and 190° K). Ticks indicate yield stress.

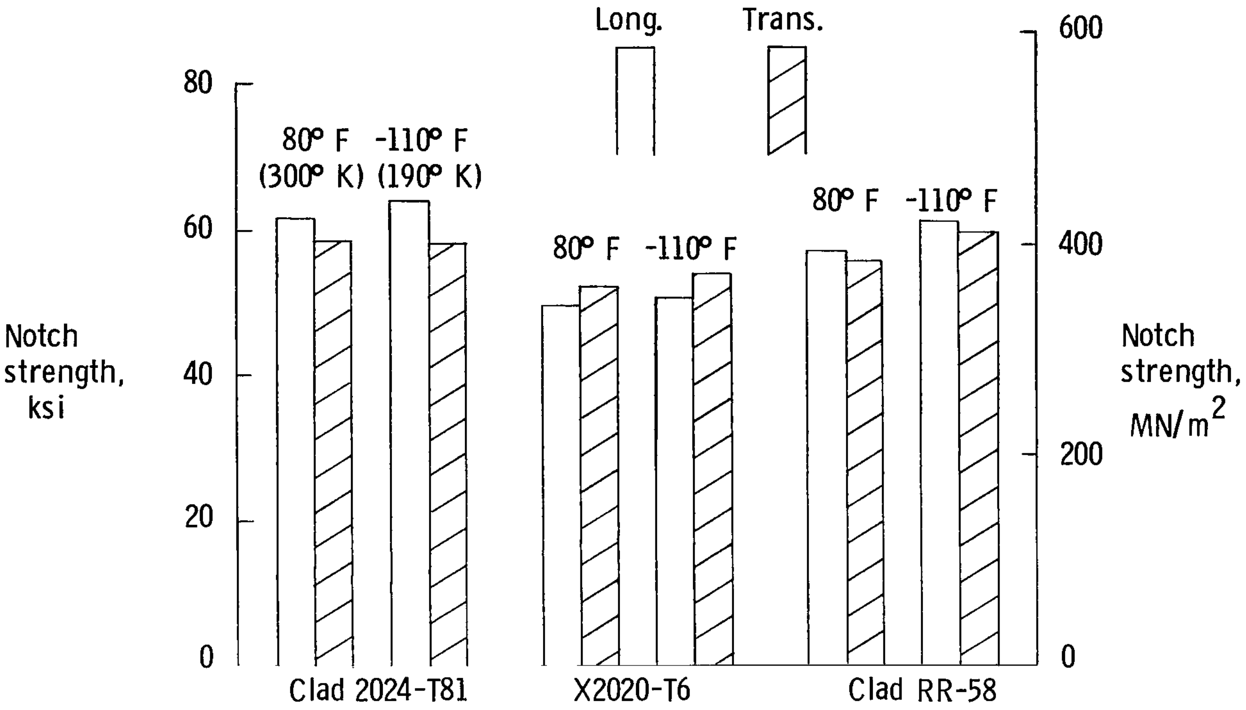


(a) Ultimate tensile strength.

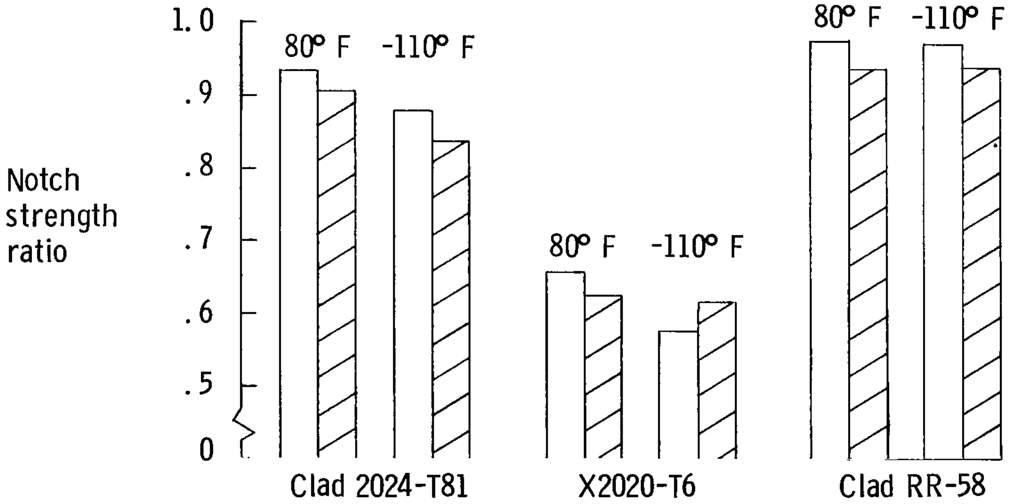


(b) Elongation.

Figure 3.- Average tensile properties of as-received aluminum-alloy sheet at 80° and -110° F (300° and 190° K).

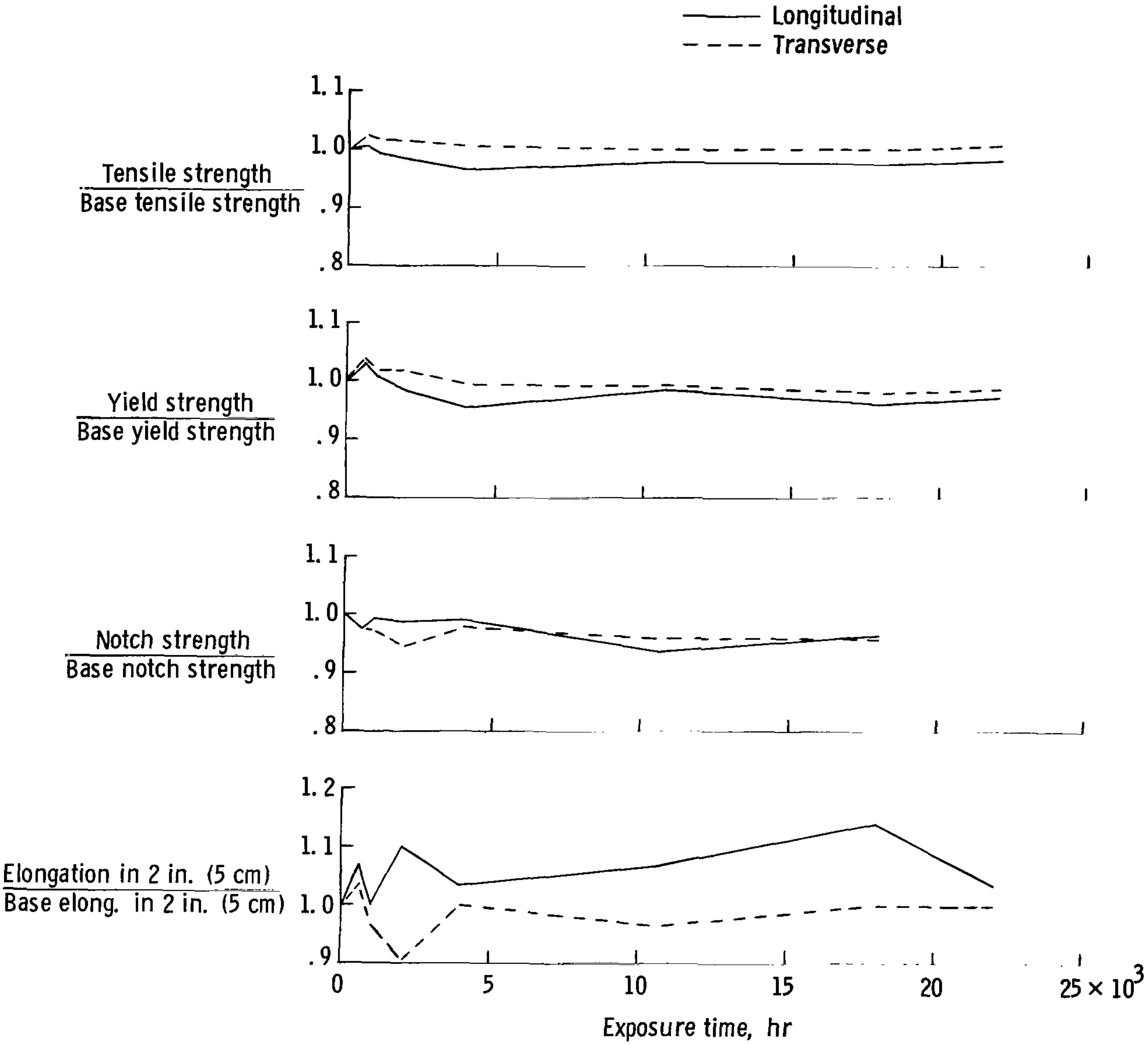


(a) Notch strength.



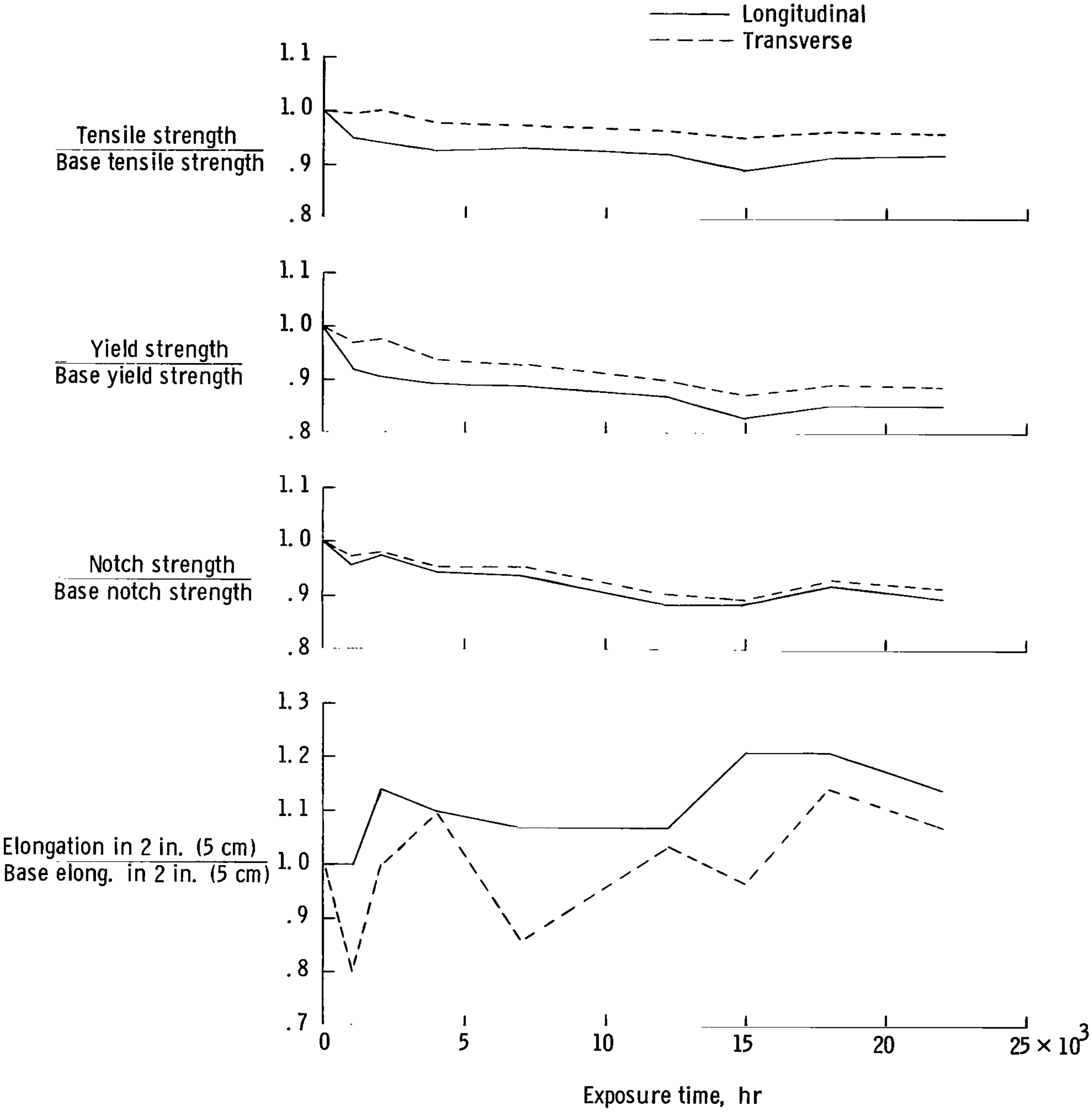
(b) Notch strength ratio.

Figure 4.- Average notch strengths and notch strength ratios of as-received aluminum-alloy sheet at 80° and -110° F (300° and 190° K).



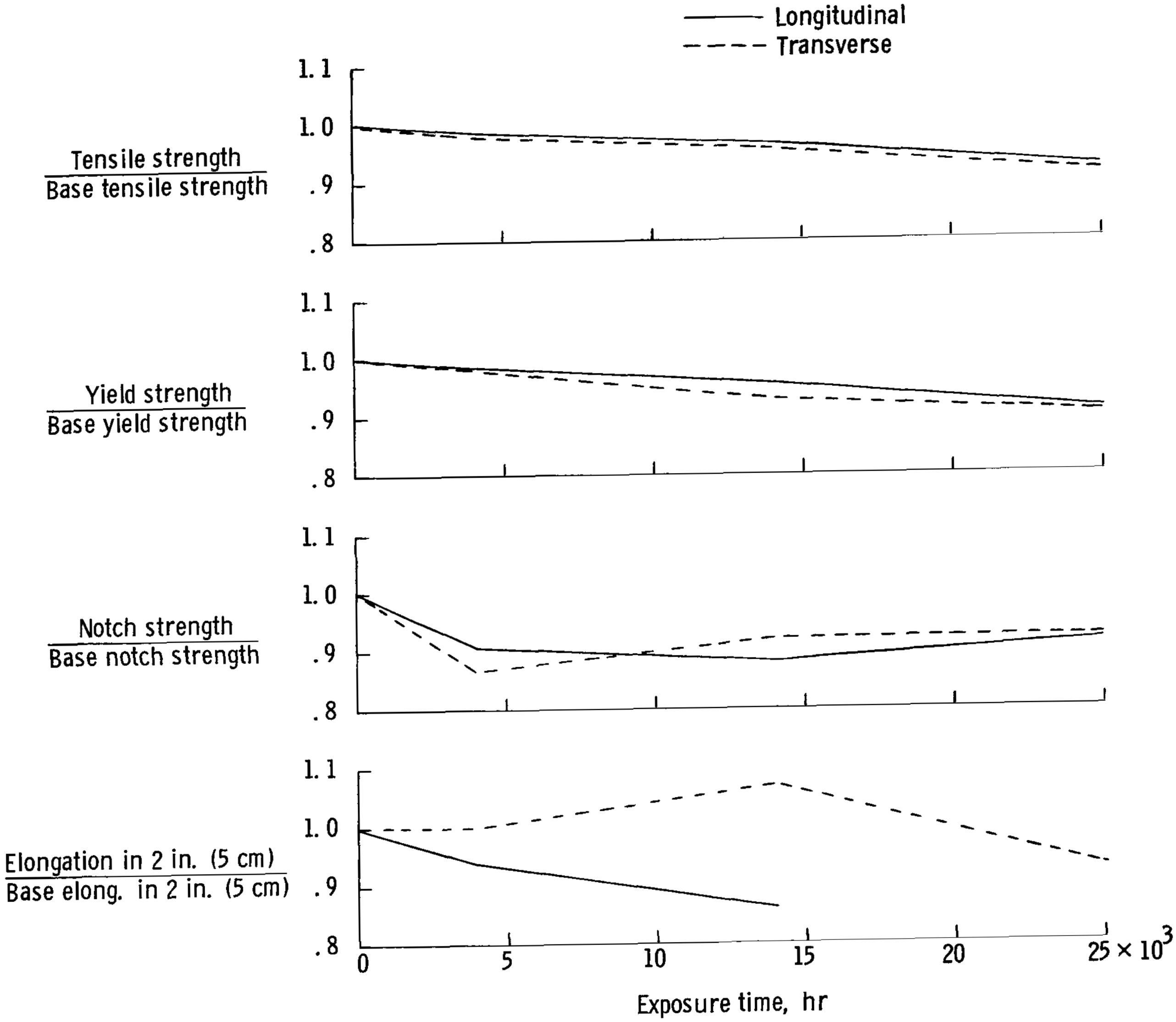
(a) Clad 2024-T81 at 250° F (390° K).

Figure 5.- Effect of exposure at 250° and 300° F (390° and 420° K) on ratios of tensile strength, yield strength, notch strength, and elongation in 2 inches (5 cm) for aluminum-alloy sheet materials at room temperature.



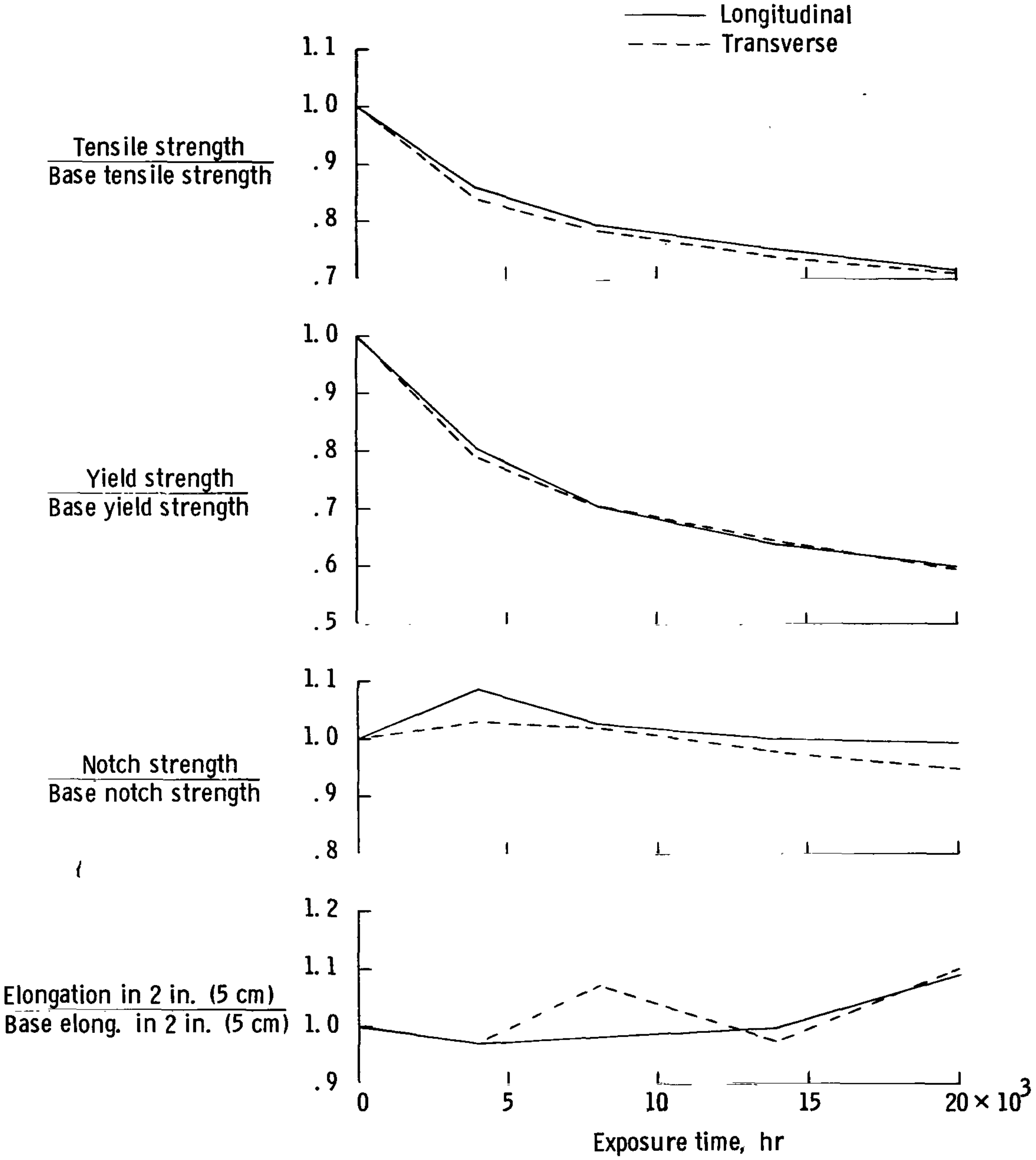
(b) Clad 2024-T81 at 300° F (420° K).

Figure 5.- Continued.



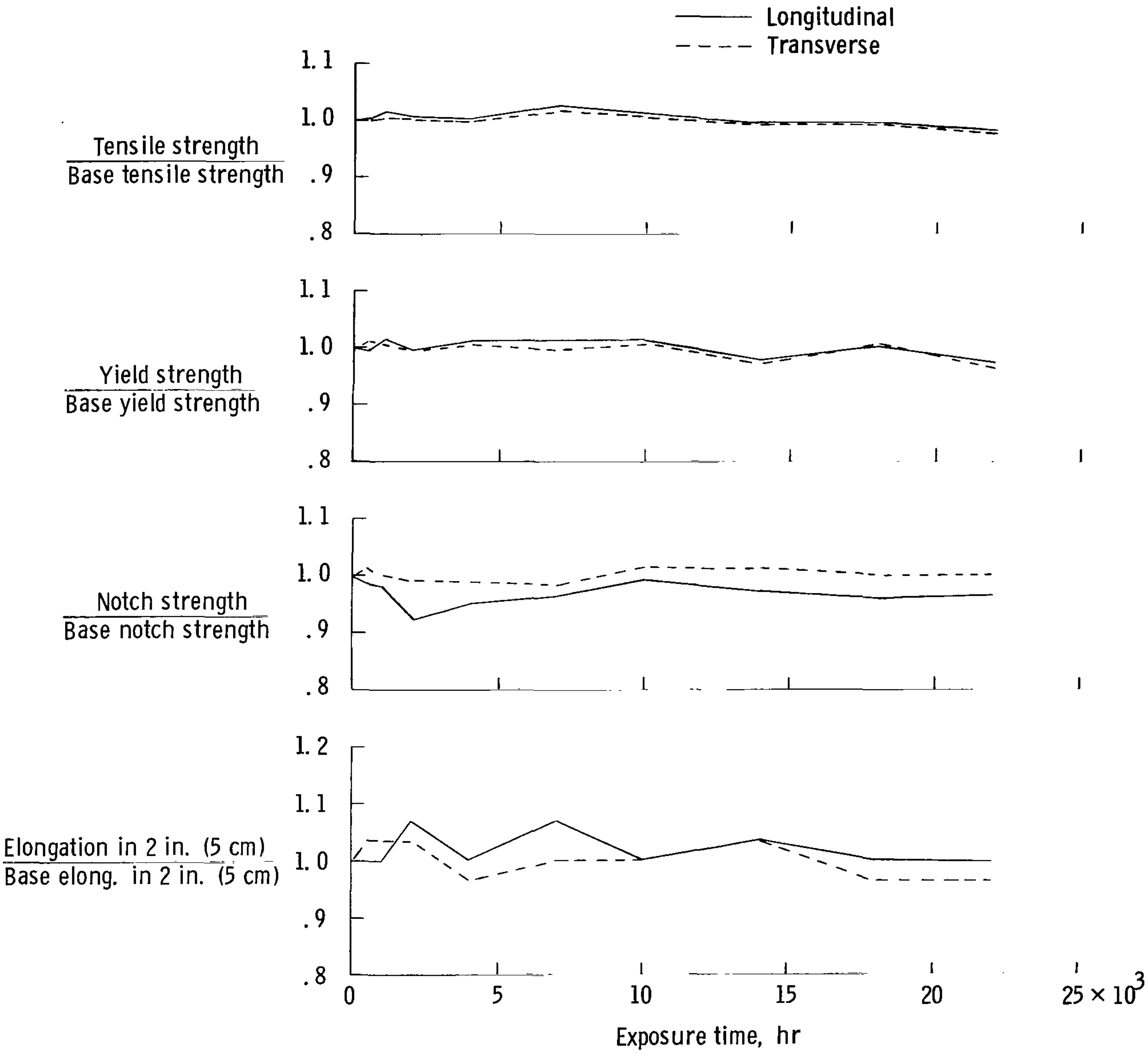
(c) X2020-T6 at 250° F (390° K).

Figure 5.- Continued.



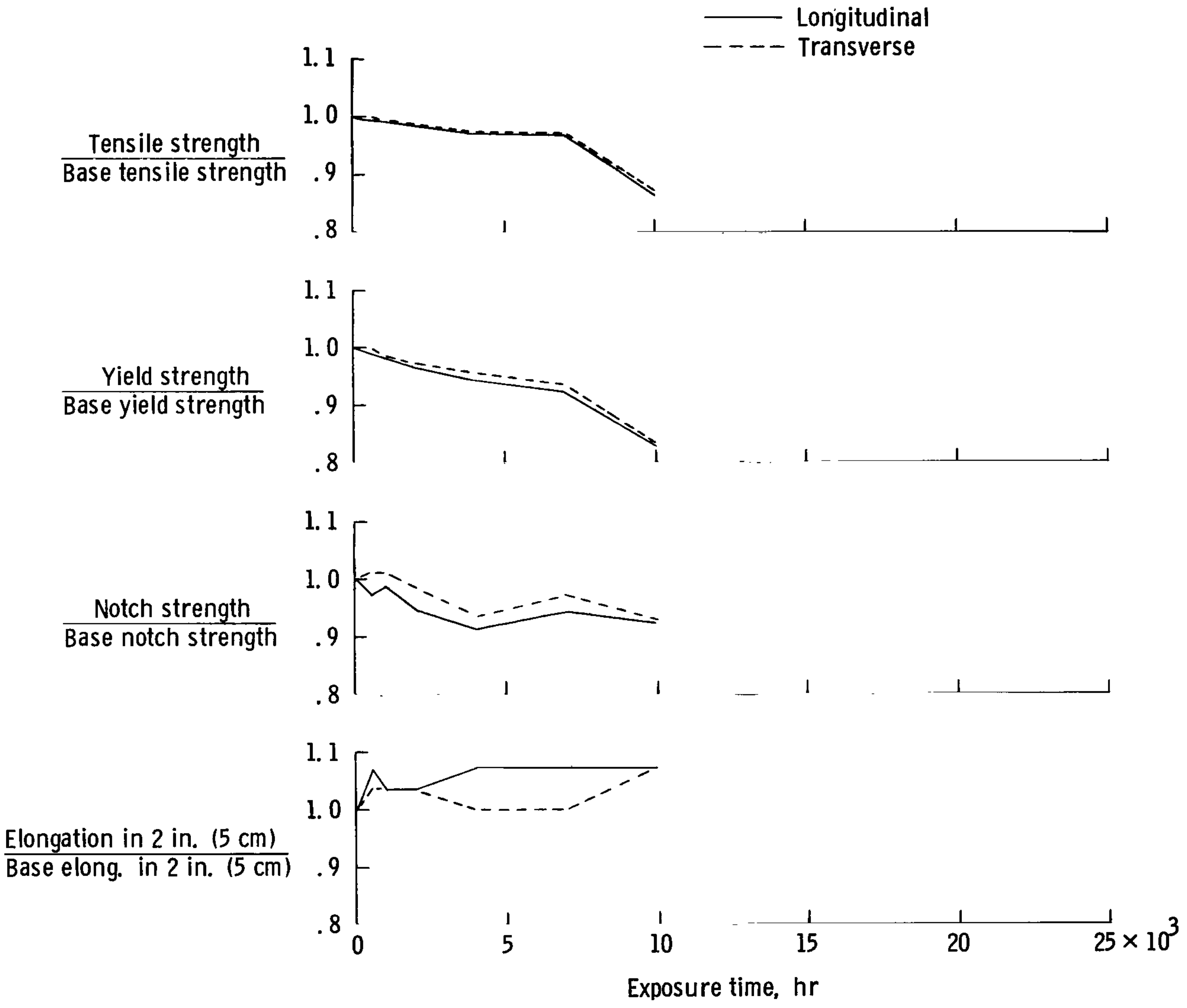
(d) X2020-T6 at 300° F (420° K).

Figure 5.- Continued.



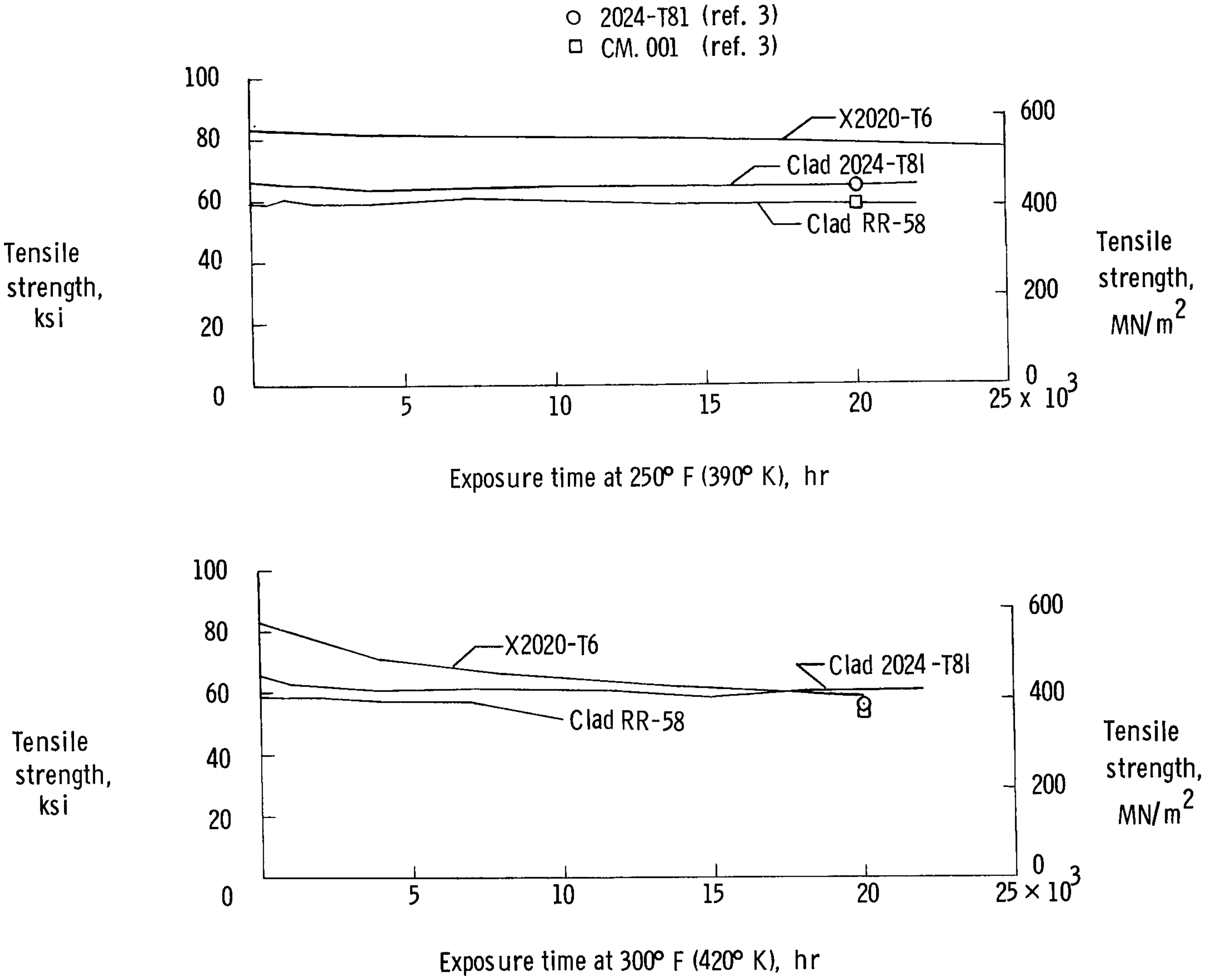
(e) Clad RR-58 at 250° F (390° K).

Figure 5.- Continued.



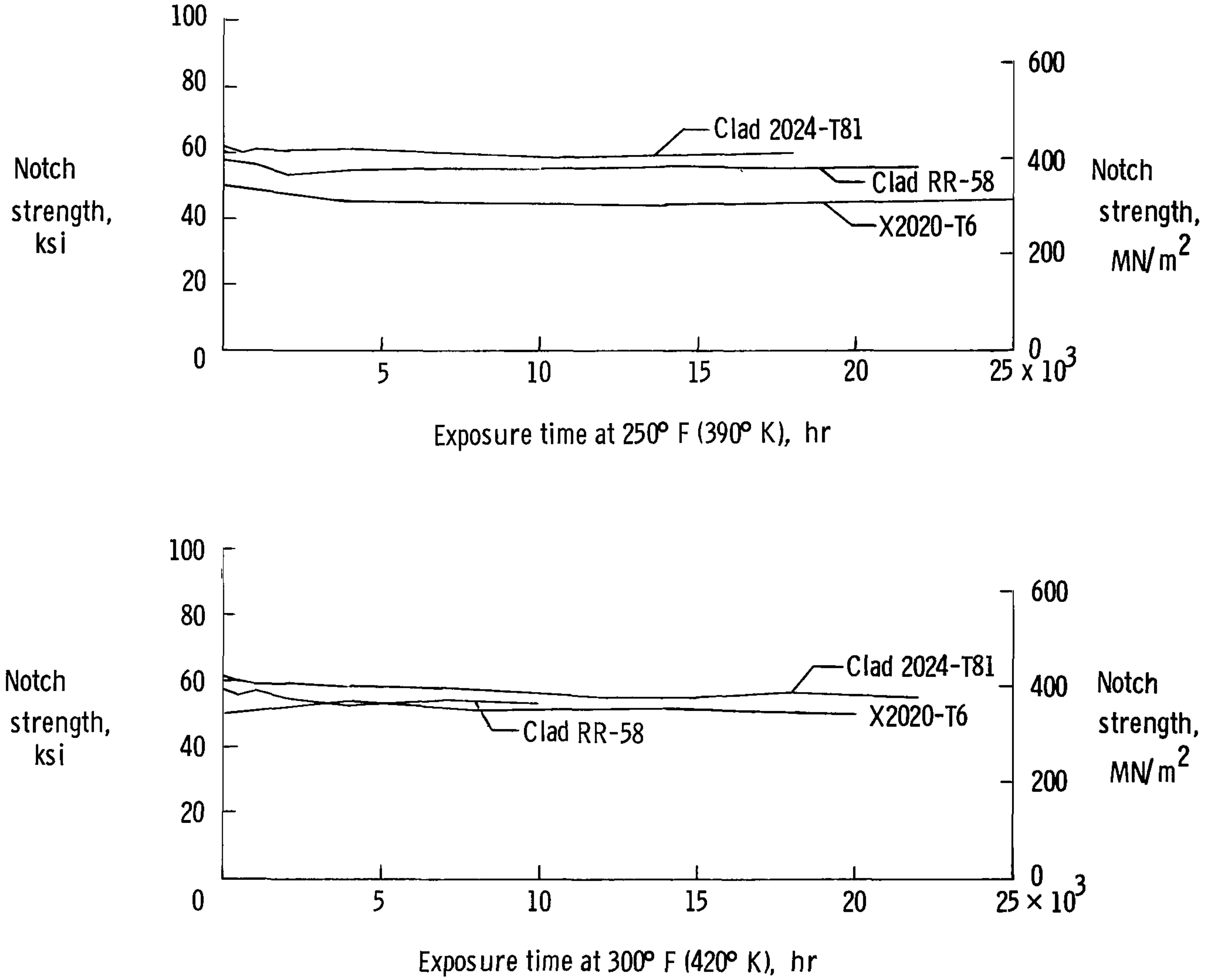
(f) Clad RR-58 at 300° F (420° K).

Figure 5.- Concluded.



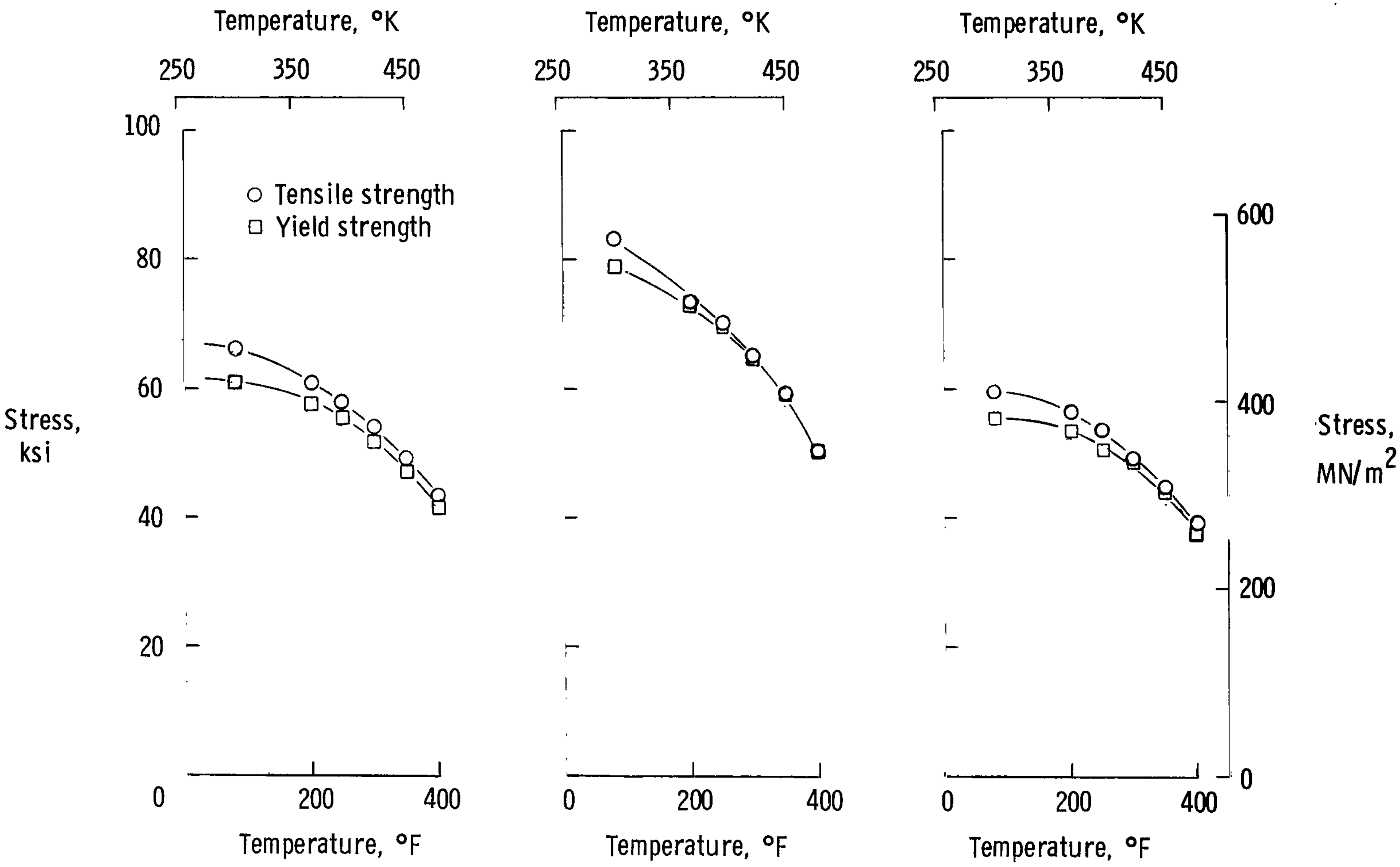
(a) Tensile strength.

Figure 6.- Strength comparison of the aluminum-alloy sheet materials after exposure.



(b) Notch strength.

Figure 6.- Concluded.

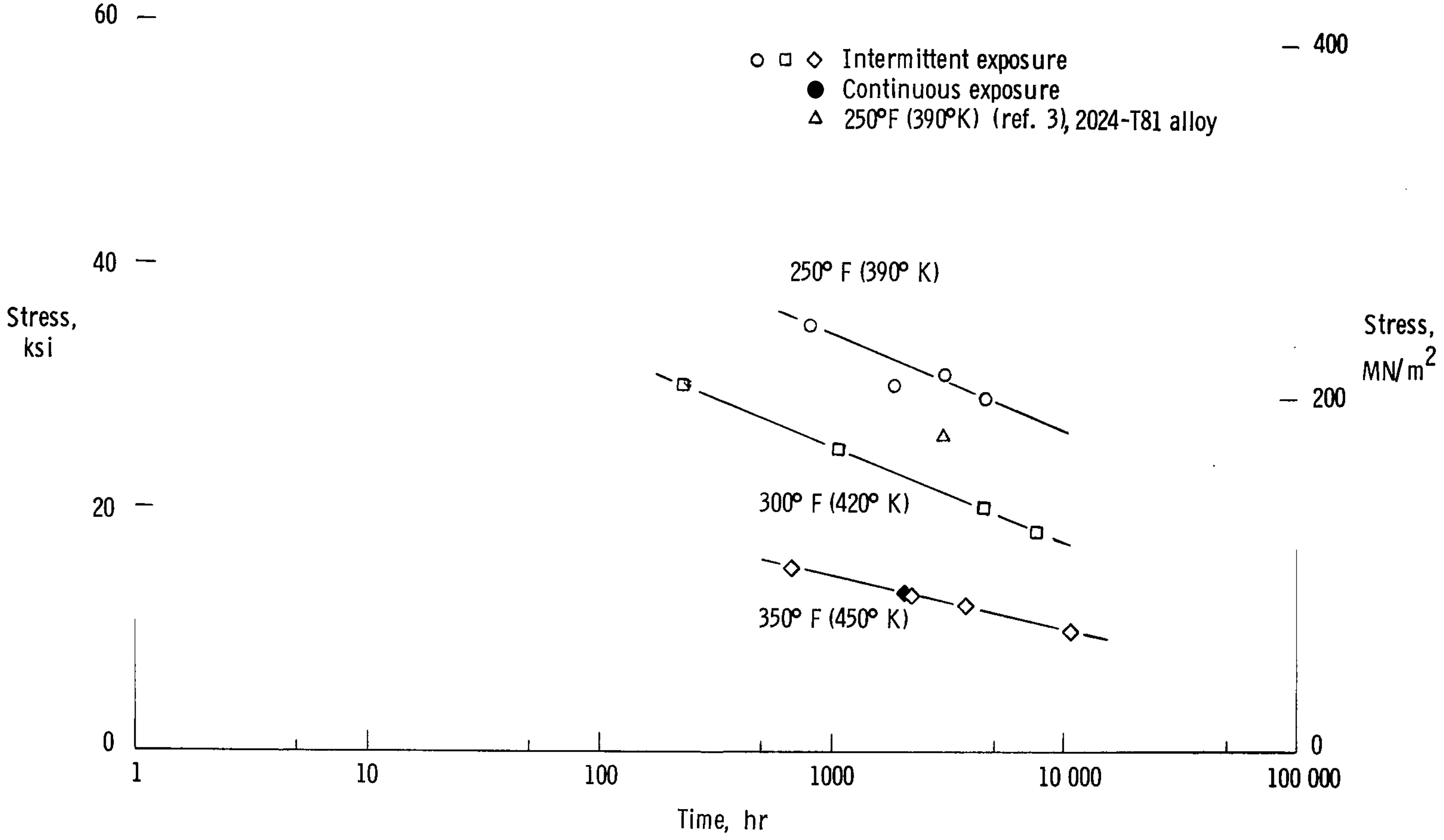


(a) Clad 2024-T81

(b) X2020-T6

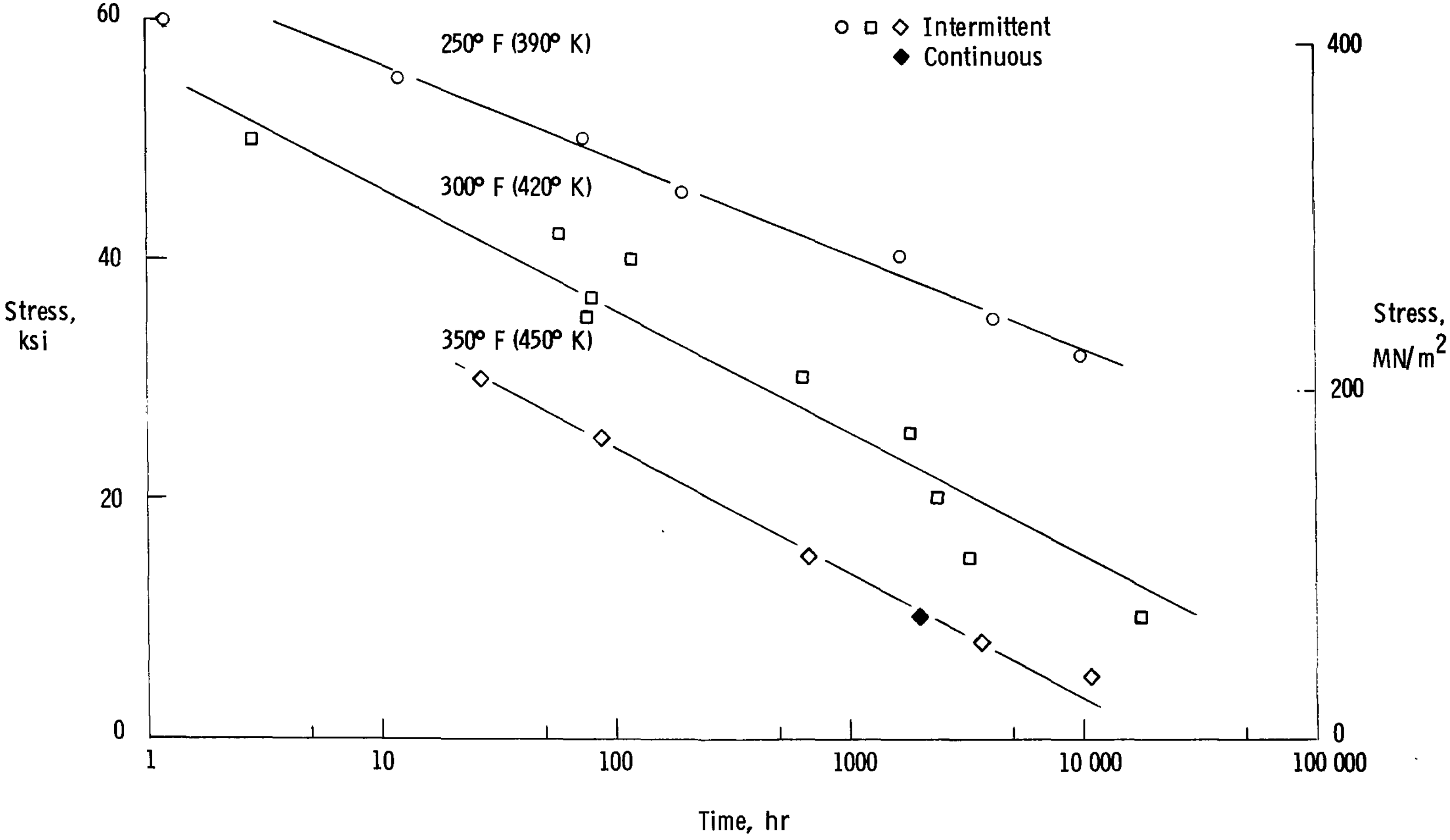
(c) Clad RR-58

Figure 7.- Average short-time, elevated-temperature tensile and yield strengths of the aluminum-alloy sheet materials in longitudinal grain direction. (Symbols are average of two tests.)



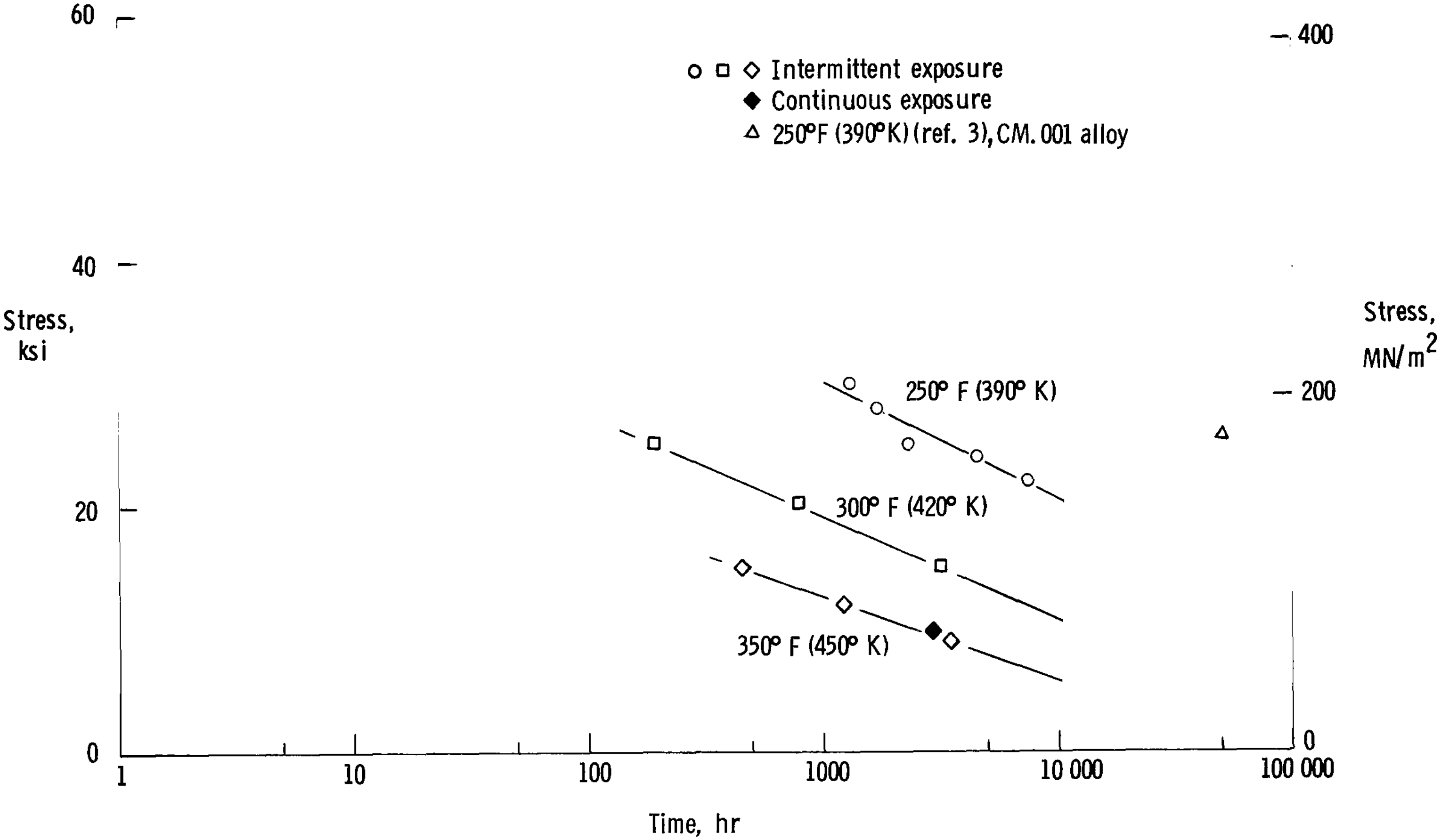
(a) Clad 2024-T81.

Figure 8.- Stress to produce 0.1-percent creep strain in aluminum-alloy sheet materials.



(b) X2020-T6.

Figure 8.- Continued.



(c) Clad RR-58.

Figure 8.- Concluded.

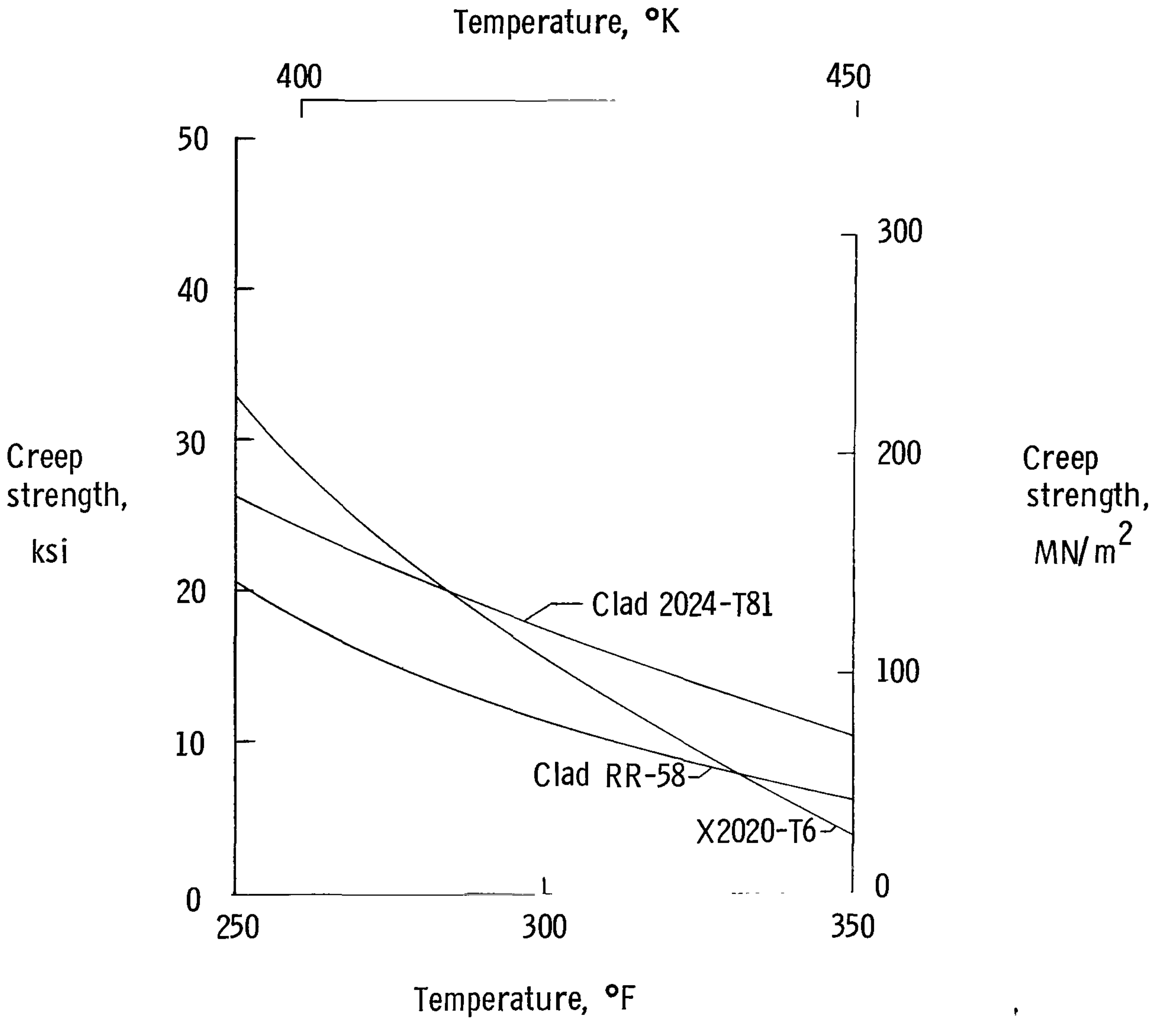
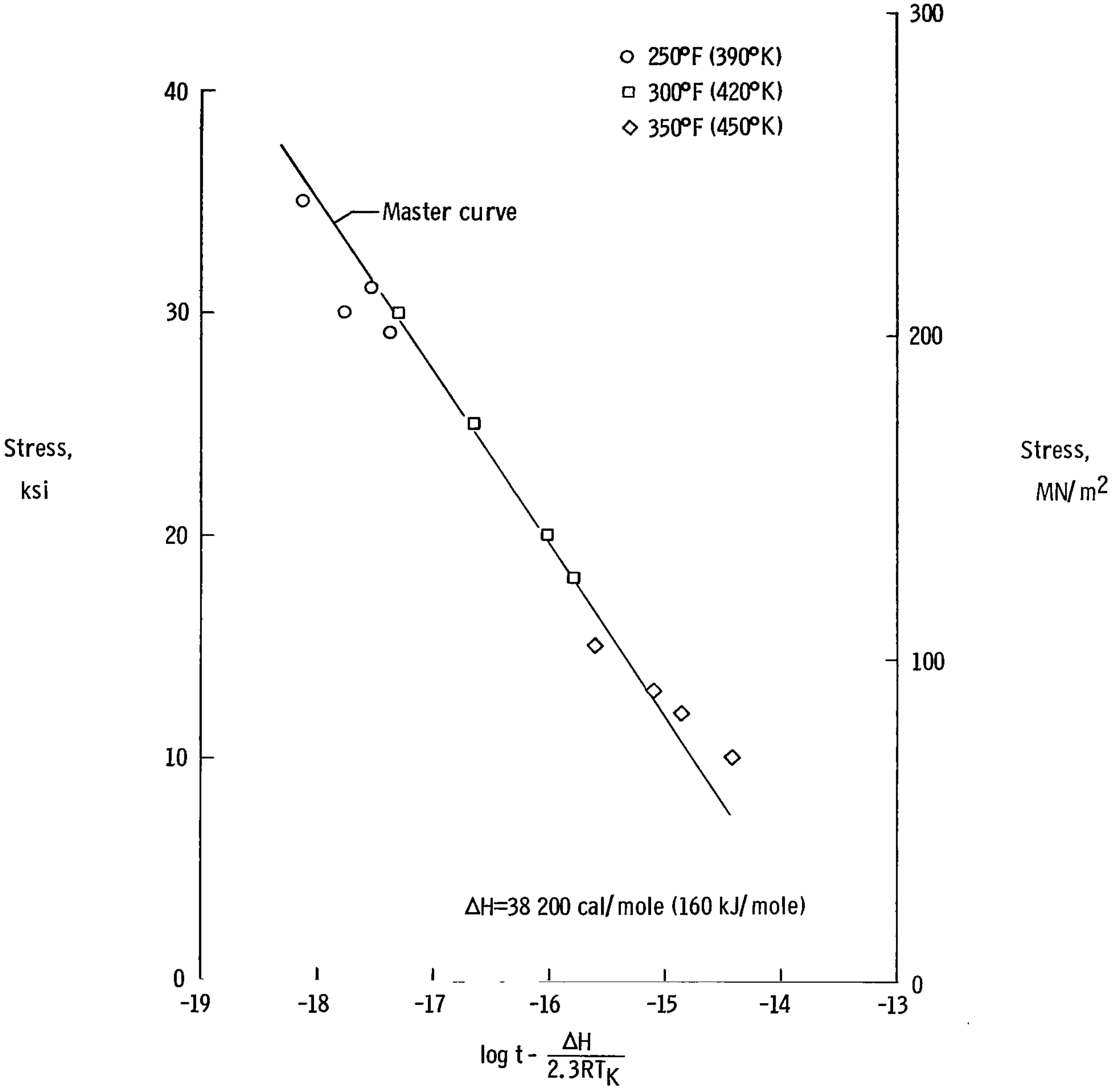
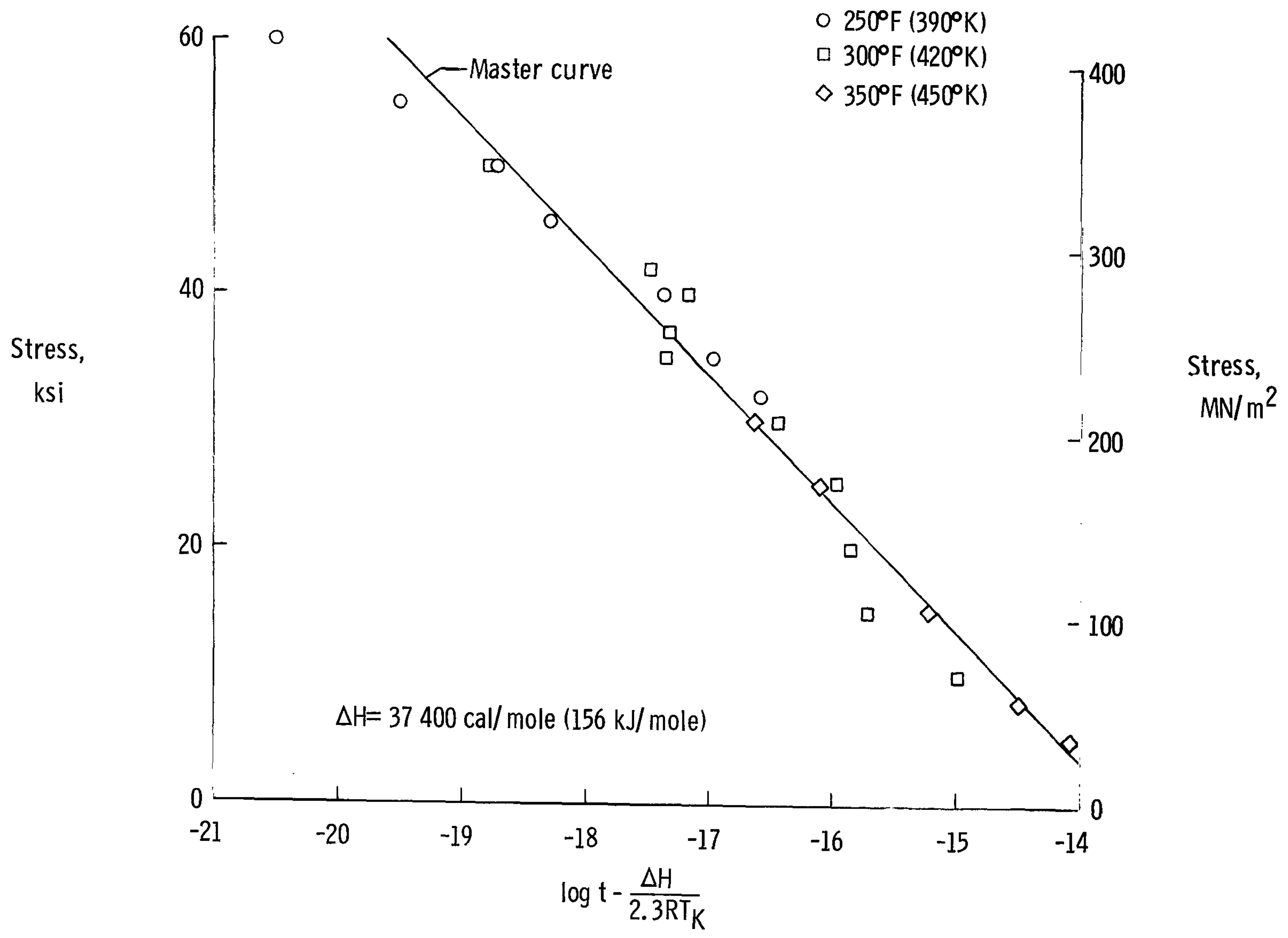


Figure 9.- Comparison of creep strength for the aluminum-alloy sheet materials after 10 000 hours.



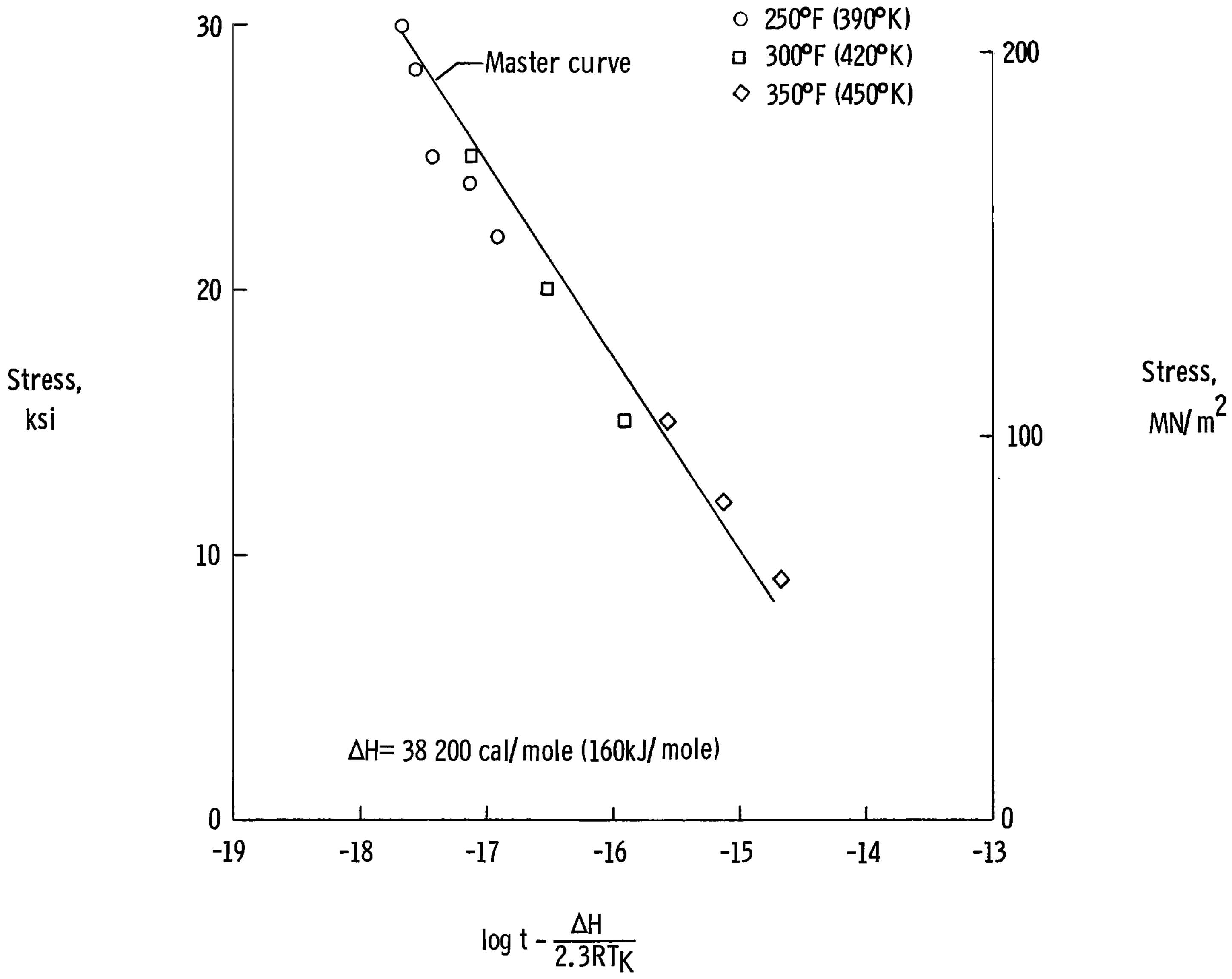
(a) Clad 2024-T81.

Figure 10.- Application of Dorn parameter for predicting 0.1-percent creep strain in aluminum-alloy sheet materials.



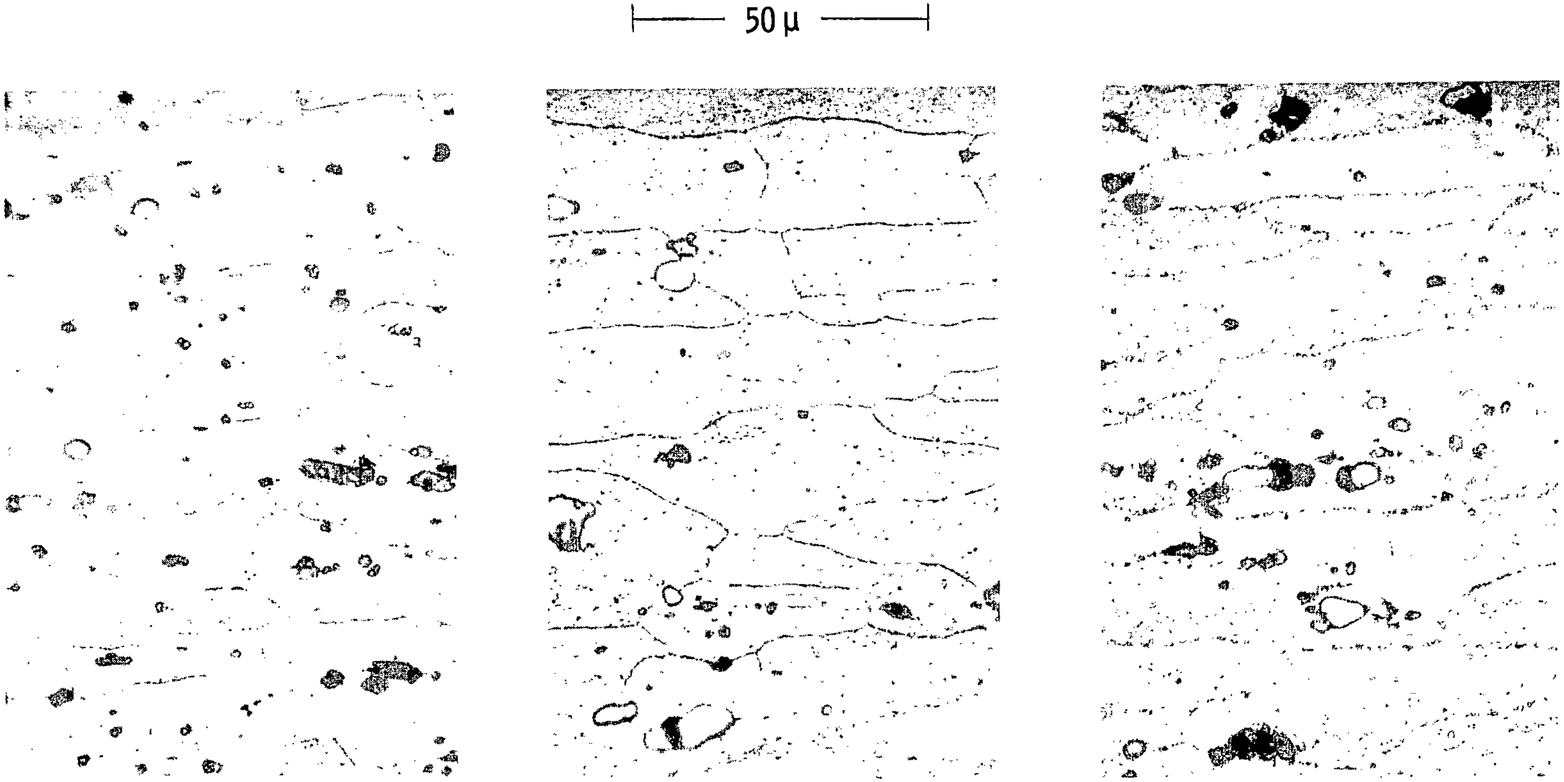
(b) X2020-T6.

Figure 10.- Continued.



(c) Clad RR-58.

Figure 10.- Concluded.



As received

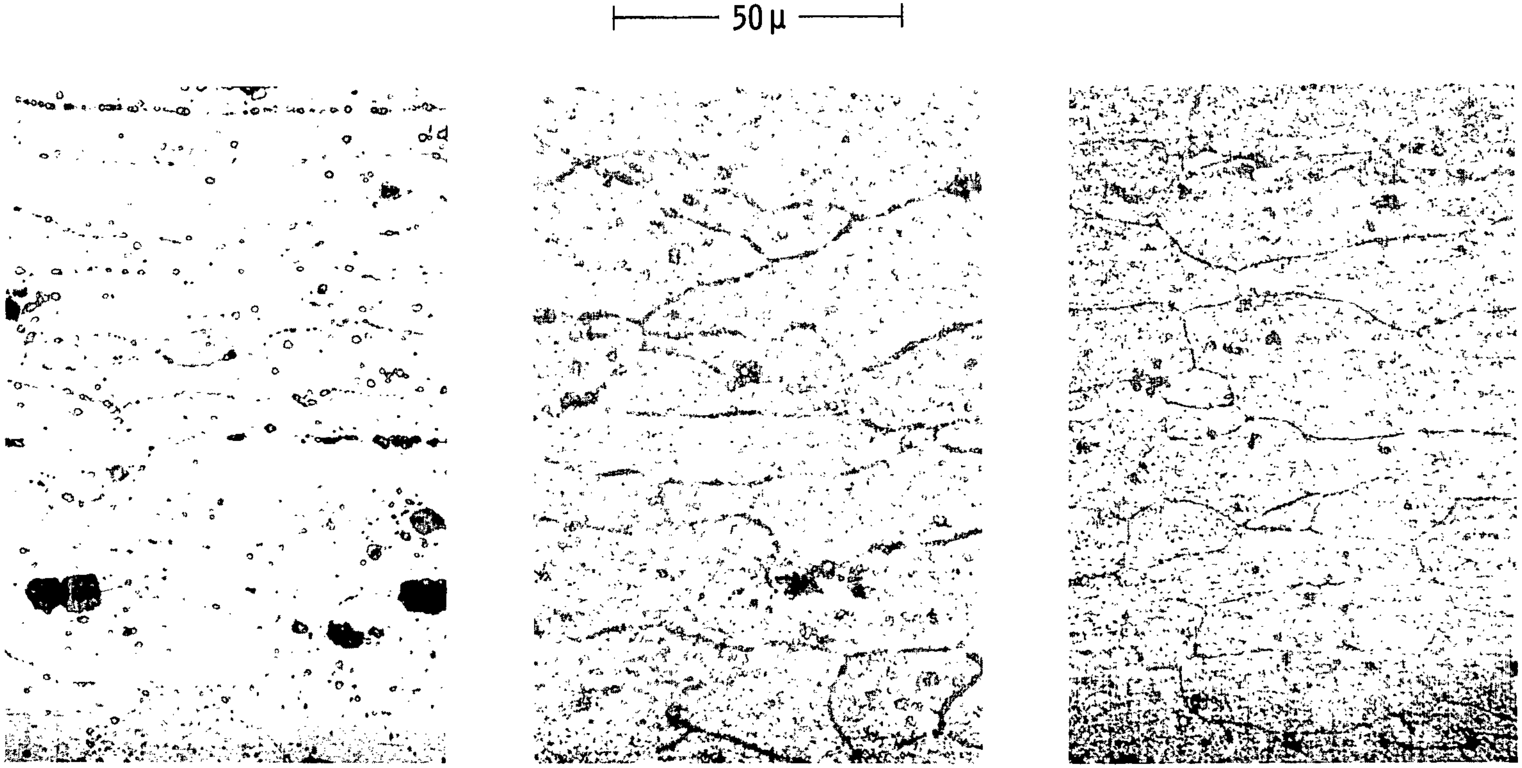
22 000 hours at 300° F (420° K), no exposure stress

14 521 hours at 350° F (450° K), 10-ksi (69-MN/m^2) stress

(a) Clad 2024-T81.

L-68-10,007

Figure 11.- Photomicrographs of aluminum-alloy sheet materials before and after exposure at 300° and 350° F (420° and 450° K).



As received

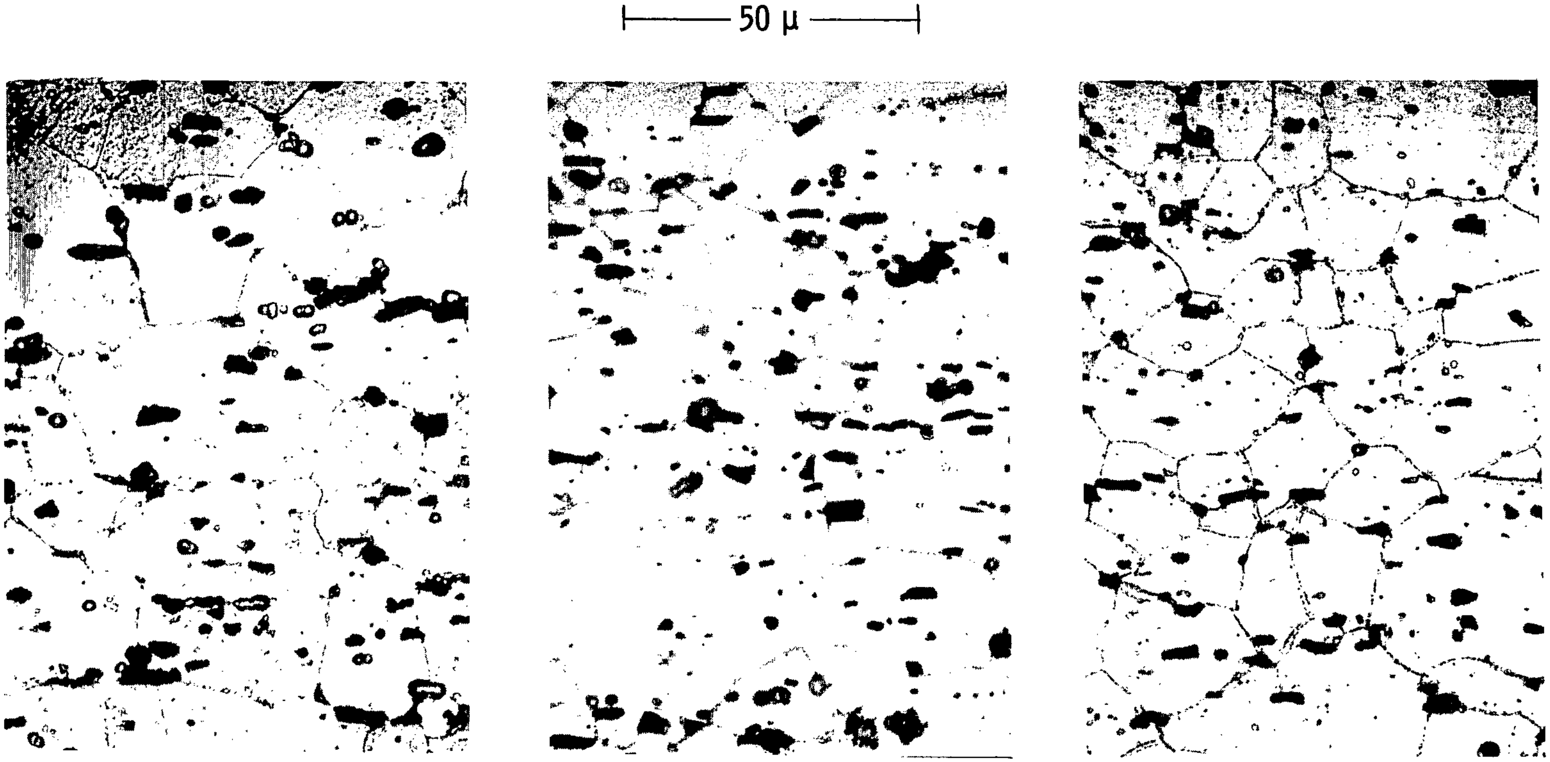
22 000 hours at 300° F (420° K), no exposure stress

12 751 hours at 350° F (450° K), 5-ksi (34-MN/m^2) stress

L-68-10,008

(b) X2020-T6.

Figure 11.- Continued.



As received

10 000 hours at 300° F (420° K), no exposure stress

4484 hours at 350° F (450° K), 9-ksi (62-MN/m^2) stress

(c) Clad RR-58.

L-68-10,009

Figure 11.- Concluded.

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> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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