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STRAIN-RATE SENSITIVITY OF THREE TITANIUM-ALLOY SHEET MATERIALS AFTER PROLONGED EXPOSURE AT 550° F (561° K)

by Robert M. Baucom

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STRAIN-RATE SENSITIVITY OF THREE TITANIUM-ALLOY SHEET MATERIALS AFTER PROLONGED EXPOSURE AT 550° F (561° K)

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SUMMARY

Results are presented of an investigation of the effects of strain rate on three titanium-alloy sheet materials before and after prolonged exposure without stress at 550° F (561° K). The strain-rate sensitivity of the three alloys, Ti-8Al-1Mo-1V, Ti-4Al-3Mo-1V, and Ti-6Al-4V, was determined from the results of tensile tests performed at three strain rates on smooth and V-notched specimens. Little change in the tensile properties of smooth and V-notched specimens was observed at any given strain rate during accumulated exposure times up to 22 000 hours. This result indicates that the alloys under investigation are apparently stable for the exposures noted. The effect of an increase in strain rate on the tensile properties was generally a moderate increase in strength for each of the alloys. The sensitivity of Ti-8Al-1Mo-1V and Ti-4Al-3Mo-1V to sharp notches tended to decrease with an increase in strain rate.

INTRODUCTION

The skin materials for a Mach 3 transport will experience cumulative exposure to elevated temperature up to about 30 000 hours (ref. 1) during the expected service life of the airplane. Such exposures can possibly lead to changes in mechanical properties of the skin materials. In addition, the skin materials will experience a wide range of loading rates in flight and during landing. Investigations of the effects of exposure to elevated temperature and of loading rate on mechanical properties of selected titanium-alloy and stainless-steel sheet have been undertaken at the Langley Research Center. Some results obtained for exposures up to 22 000 hours at 550° F (561° K) on the stability of these materials were reported in reference 2.

As a continuation of the Langley research on supersonic-transport materials, this report presents results of an investigation of the effects of exposures up to 22 000 hours at 550° F (561° K) on the strain-rate sensitivity of Ti-8Al-1Mo-1V, Ti-4Al-3Mo-1V, and Ti-6Al-4V titanium-alloy sheet. Tensile properties of notched and smooth specimens (for elastic strain rates of 0.00002, 0.1, and 5.0 per second) were determined at room temperature after exposure to elevated temperature.

The units used for the physical quantities appearing in this paper are given in both the U.S. Customary Units and the International System of Units, SI. (See ref. 3.) Factors relating the two systems are given in appendix A.

MATERIALS AND SPECIMENS

Materials

The titanium-alloy sheet materials selected for this investigation were Ti-8Al-1Mo-1V (mill annealed), Ti-4Al-3Mo-1V (solution treated and aged), and Ti-6Al-4V (mill annealed). These alloys were chosen because they were among the most promising of the titanium alloys considered in a screening program to select suitable materials for structural use in supersonic vehicles. (See ref. 4.) Heat-treating processes for the materials are given in table I, and the tensile properties of the materials in this investigation in the as-received condition are given in table II (obtained from ref. 2).

Specimens

The three tensile specimens used in this investigation are shown in figure 1. Duplicate specimens were machined from the sheet material in the direction of rolling (longitudinal) and perpendicular to the direction of rolling (transverse) for each exposure and strain-rate combination. The ASTM standard specimen (ref. 5) was used to determine the tensile properties at normal testing speeds, which corresponded to an elastic strain rate of 0.00002 per second. The modified ASTM standard specimen, which was used for the tests at strain rates of 0.1 and 5.0 per second, has the same test section as the ASTM standard specimen. The shoulder area of this specimen was modified to be compatible with grips in the 10 000-lbf-capacity (44.5 kN) high-speed pneumatic tensile testing machine at the Langley Research Center. The V-notched specimen, recommended by a special ASTM committee (ref. 6), was tested at each of the three strain rates. The holes in the ends of this specimen accommodated bearing pins through which the load was applied. The notch-root radii for these specimens varied from about 5×10^{-4} to 7×10^{-4} inch (13 to 18 μm); therefore, the theoretical stress concentration factor was about 22.

All specimens were cleaned before exposure to elevated temperature. An outline of the cleaning procedure is presented in appendix B.

TESTING PROCEDURES AND EQUIPMENT

Exposure

Test specimens were placed in furnaces and exposed with no applied load to temperatures of $550^\circ \pm 10^\circ$ F ($561^\circ \pm 6^\circ$ K). At predetermined exposure times of 2000, 4000, 7000, 10 000, 14 000, 18 000, and 22 000 hours, specimens were removed and subjected to tensile tests at room temperature. The maximum accumulated exposure time for each of the specimen types is given in table III.

Normal-Loading-Rate Tests

The tensile tests at the normal loading rate were performed in the 100 000-lbf-capacity (445 kN) hydraulic testing machine at the Langley Research Center. For tensile tests of smooth specimens, load-strain curves were obtained with an x-y recorder. Differential-transformer strain gages were clamped to both sides of the specimens to measure strain over a 1-inch (2.54-cm) gage length up to approximately 0.015. Conducting the tests at a constant loading rate through yield resulted in a strain rate of 0.00002 per second in the elastic region and a strain rate of approximately 0.00008 per second through yield. The loading rate was then increased to provide a strain rate of approximately 0.0008 per second to failure. The notched specimens were tested at a nominal strain rate of 0.00002 per second (based on the net section) in the same hydraulic testing machine used for the tensile tests of the standard smooth specimens. No attempt was made to determine load-strain curves for the notched specimens at any of the strain rates.

Rapid-Loading-Rate Tests

The rapid-loading tests were performed in the 10 000-lbf-capacity (44.5 kN) high-speed pneumatic tensile testing machine at the Langley Research Center shown in figure 2. The operation of this machine is described in detail in reference 7. The load was applied to the specimen by differential air pressure acting on a piston. Testing speed was varied by using different valve systems to exhaust air from the pressure chamber. For this investigation, pilot- and ball-valve assemblies were used to obtain the intermediate and fast testing speeds, respectively.

The loads during tests were measured by a specially designed stiff weigh bar attached to the bottom grip. The weigh bar was machined from 17-4 PH stainless steel and instrumented with four p-type-semiconductor strain gages. These gages provided approximately 60 times the output of conventional foil or wire strain gages at a given applied voltage and strain level. This feature permitted a reduced strain level in the load-sensing element for the same output as a standard load cell of the same capacity.

The stiffer bar increased the natural frequency of oscillation of the weighing system and eliminated the spurious load oscillations which were encountered during testing with a conventional load cell (ref. 7).

The strains were measured with conventional foil strain gages mounted in the test section of the smooth specimens after exposure. A special adhesive designed for high-strain-rate applications was used to bond the gages to the specimens. After the gage leads were attached, a moisture-proof coating was applied to the gage surface.

The recording system for the high-speed testing machine (fig. 2) consisted of a time-delay circuit, strain-gage amplification units, dual-trace storage oscilloscope with camera attachment, and power supplies. The adjustable time-delay circuit was regulated from prior calibration data to allow the sweep on the storage oscilloscope to be triggered at the correct time so that complete test information was recorded. The storage oscilloscope displayed the load and strain time histories on the screen of the cathode-ray tube and retained the traces until a record was obtained with a camera attachment.

RESULTS AND DISCUSSION

In the following sections, discussion is presented on load-time, strain-time, and stress-strain curves, and the effects of exposure and strain rate for Ti-8Al-1Mo-1V, Ti-4Al-3Mo-1V, and Ti-6Al-4V alloys.

Load- and Strain-Time Characteristics

Representative load and strain time histories obtained from tests conducted in the 10 000-lbf-capacity (44.5 kN) high-speed pneumatic tensile testing machine for smooth and notched specimens are shown in figure 3. An exception to the representative data is the load time history presented in figure 4, which was obtained only with the transverse Ti-4Al-3Mo-1V notched specimens at a strain rate of 5.0 per second.

For smooth specimens (fig. 3(a)) at an elastic strain rate of approximately 5.0 per second, the load and strain signals began smoothly. Approximately 2 milliseconds after loading began, the load and strain signals became essentially linear until the yield strength of the material was reached. At this point, rapid plastic deformation sheared the foil strain gages from the specimen and the strain signal disappeared from the oscilloscope screen. After an upper yield strength was reached, the load leveled off for the remainder of the test. At an elastic strain rate of approximately 0.1 per second, the load and strain signals became irregular about 10 milliseconds after the test began, after which the curves became approximately linear until the fracture point was almost reached. The strain gages remained intact for strain levels up to 0.012 so that stress-strain curves could be plotted through the yield region. The load-time curve for this strain rate does not demonstrate the abrupt yield behavior observed in tests at 5.0 per second.

For the notched specimens at an elastic strain rate of 5.0 per second, loading became nearly linear with time about 2 milliseconds after loading began. The load signal terminated abruptly when the rupture load was reached. The notched specimens tested at an elastic strain rate of 0.1 per second exhibited load-time characteristics similar to the characteristics for smooth specimens tested at this strain rate except that the load signal is terminated after a shorter testing time.

A representative load-time history for Ti-4Al-3Mo-1V transverse notched specimens tested at an elastic strain rate of 5.0 per second is shown in figure 4. Except for these specimens, the loads required for failure of all specimens in this program were below 5500 pounds (24.5 kN) and no irregularities in loading were encountered. For loads above 5500 pounds applied to these specimens, however, the loading curve dips downward (fig. 4) before resumption of loading to specimen failure. About 4.5 milliseconds are required for the load to return to the level at which the drop in loading began. This loading irregularity has been attributed to a testing-machine characteristic. Because of this variation, a large spread in test times was experienced for the Ti-4Al-3Mo-1V notched specimens at the highest strain rate.

Stress-Strain Properties of Smooth Specimens

Typical stress-strain curves for smooth Ti-8Al-1Mo-1V and Ti-4Al-3Mo-1V specimens are shown in figure 5. Curves for the tests conducted at an elastic strain rate of 0.00002 per second were plotted directly on an x-y recorder and those for the tests at 0.1 and 5.0 per second were drawn from the load- and strain-time oscilloscope traces. At the highest strain rate, the shape of the stress-strain curves in the yield region for these materials could not be determined precisely because the strain gages sheared off the specimen as plastic deformation began. Therefore, the dashed portion of the curves was estimated from load-time histories.

In figure 5(a), the longitudinal Ti-8Al-1Mo-1V specimens exhibited a slightly higher yield stress than the transverse specimens at strain rates of 0.00002 and 0.1 per second. At 5.0 per second, the load at fracture was approximately the same as the upper yield load, as discussed in reference 8.

Stress-strain curves for Ti-4Al-3Mo-1V are shown in figure 5(b). This material is considerably stronger in the transverse direction than in the longitudinal direction for the three strain rates. The shapes of the stress-strain curves are nearly the same for the three rates, except for the transverse direction at the highest strain rate. As was true for the Ti-8Al-1Mo-1V alloy tested at this rate, the strain gages were sheared off the specimen as plastic flow began.

Effect of Exposure

The effect of exposure at 550° F (561° K) up to 22 000 hours on tensile properties of the titanium alloys is shown in figure 6. Ultimate tensile strength, notch strength, and elongation are shown for Ti-8Al-1Mo-1V (fig. 6(a)) and Ti-4Al-3Mo-1V (fig. 6(b)) at room temperature for the three strain rates. Notch strength for Ti-6Al-4V is shown in figure 6(c).

In general, exposure does not produce a consistent increase or decrease in tensile properties of the three alloys at any of the strain rates for the test range of exposure times. Notice that data are not available to 22 000 hours for all specimens. Additional information on the effect of exposure up to 22 000 hours on the tensile properties of Ti-6Al-4V obtained at low strain rates may be obtained from reference 2. Results presented therein also showed no significant effect of exposure on tensile properties.

Effect of Strain Rate

Tensile and notch strengths.- The effect of an increase in strain rate on the tensile (i.e., referring to smooth specimens) and notch strengths for Ti-8Al-1Mo-1V, Ti-4Al-3Mo-1V, and Ti-6Al-4V titanium alloys is shown in figure 7. The data points on the curves represent the average of the test results for all exposure times for a particular strain rate and grain direction. The scatter bands attached to each data point present the highest and lowest strength values recorded over the entire exposure range. The tensile and notch strengths of Ti-8Al-1Mo-1V (fig. 7(a)) increased moderately with strain rate. The results for the longitudinal direction were slightly higher than those for the transverse direction, except at the lowest strain rate, where the tensile strengths for both directions were very nearly the same. For Ti-4Al-3Mo-1V (fig. 7(b)), the transverse tensile and notch strengths were higher than the strengths of the longitudinal specimens at each of the three strain rates. The same pattern of increasing strength was displayed for both specimen grain directions, with the notched specimens exhibiting a slightly greater increase than the smooth specimens as the strain rate was increased. The notch strength of Ti-6Al-4V (fig. 7(c)) increased with increasing strain rate for both specimen grain directions. At each of the three strain rates, the transverse strengths were higher than the longitudinal strengths. No data on the effect of strain rate on the tensile strength were obtained.

Relation between yield, notch, and tensile strengths.- The effect of strain rate on the yield and notch strength ratios is shown in figure 8. The data points on the curves represent the average of strength data for all exposures at each strain rate. The effect of strain rate on the yield strength ratio (the ratio of yield strength to ultimate tensile strength) for Ti-8Al-1Mo-1V and Ti-4Al-3Mo-1V is shown in figure 8(a). For both alloys, the yield strength increased more rapidly with strain rate than the tensile strength. The yield strength ratio for Ti-8Al-1Mo-1V and Ti-4Al-3Mo-1V (based on the upper or initial yield stress) varied from about 0.92 at a strain rate of 0.00002 per second to about 0.98 at 5.0 per second. The fact that at the highest rate of 5.0 per second the yield strength ratio for both alloys approached unity indicates that the yield strength was very nearly the same as the ultimate tensile strength.

The effect of strain rate on the notch strength ratio (the ratio of notch strength to ultimate tensile strength) of Ti-8Al-1Mo-1V and Ti-4Al-3Mo-1V is shown in figure 8(b). For both Ti-8Al-1Mo-1V and Ti-4Al-3Mo-1V, the notch strength increased more rapidly with strain rate than the tensile strength. The ratio for Ti-4Al-3Mo-1V varied from about 0.95 at a strain rate of 0.00002 per second to 1.00 at a strain rate of 5.0 per second. The notch strength ratio for Ti-8Al-1Mo-1V varied from about 0.78 at 0.00002 per second to 0.99 at 5.0 per second. The increase in notch strength ratio with strain rate for both materials indicates that the alloys appear to be less notch sensitive at a higher strain rate even though the tensile strengths are greater.

CONCLUDING REMARKS

An investigation was performed to determine the effects of exposure up to 22 000 hours at 550° F (561° K) on the strain-rate sensitivity of Ti-8Al-1Mo-1V (mill annealed), Ti-4Al-3Mo-1V (solution treated and aged), and Ti-6Al-4V (mill annealed) sheet. These effects were determined from changes in tensile properties of smooth and V-notched specimens obtained (before and after exposure) at strain rates that ranged from 0.00002 to about 5.0 per second. No significant change was observed in tensile properties of either the V-notched or the smooth alloy specimens at any of the strain rates after exposures up to 22 000 hours at 550° F (561° K). This result indicates that there was no material deterioration due to the exposure. The effect of increasing strain rate on the alloys was generally a corresponding moderate increase in the tensile (i.e., referring to smooth specimens) and notch strengths. For Ti-8Al-1Mo-1V and Ti-4Al-3Mo-1V, the yield and notch strengths increased more rapidly with increasing strain rate than did the ultimate tensile strength.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 13, 1968,
129-03-06-05-23.

APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The conversion factors required for units used herein are taken from reference 3 and presented in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Force	lbf	4.448	newtons (N)
Length	in.	0.0254	meters (m)
Stress	ksi = $\frac{1000\ \text{lbf}}{\text{in}^2}$	6.895×10^6	newtons/meter^2 (N/m^2)
Temperature	($^{\circ}$F + 459.67)	5/9	degrees Kelvin ($^{\circ}$K)

*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
mega (M)	10^6
kilo (k)	10^3
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}

APPENDIX B

CLEANING PROCEDURE FOR TITANIUM ALLOYS

Markings such as crayon or the manufacturer's stamp were removed with acetone and a cloth. Alkaline cleaning, which utilized a separate tank for each solution or rinse, was accomplished as follows:

1. Alkaline cleaner (sodium hydroxide base): 6 ounces per gallon $(45\ kg/m^3)$ of water at temperatures from 180° F to 200° F (355° K to 366° K); immersion time, 10 minutes
2. Hot water rinse; immersion time, 2 to 3 minutes
3. Nitric acid dip: 1 part concentrated nitric acid to 4 parts water, by volume; immersion time, 30 seconds
4. Hot water rinse, agitated
5. Cold water rinse, agitated
6. Cold water rinse, agitated, with a continuous supply of fresh water

The specimens were then dried with a clean cloth or paper wipers and packaged in clean containers.

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TABLE I.- MATERIALS AND HEAT TREATMENTS

Alloy	Condition	Nominal thickness		Heat treatment
		in.	cm	
Ti-8Al-1Mo-1V	Mill annealed	0.040	0.102	Annealed 8 hours at 1450° F (1061° K) and furnace cooled by producer
Ti-4Al-3Mo-1V	Solution treated and aged	.040	.102	Solution treated for 20 minutes (1200 seconds) at 1650° F (1172° K) and water quenched by producer; aged 4 hours at 1050° F (839° K); air cooled
Ti-6Al-4V	Mill annealed	.040	.102	Annealed 1 hour at 1475° F (1075° K), furnace cooled to 1300° F (977° K), and air cooled by producer

TABLE II.- TENSILE PROPERTIES FOR AS-RECEIVED TITANIUM-ALLOY SHEET

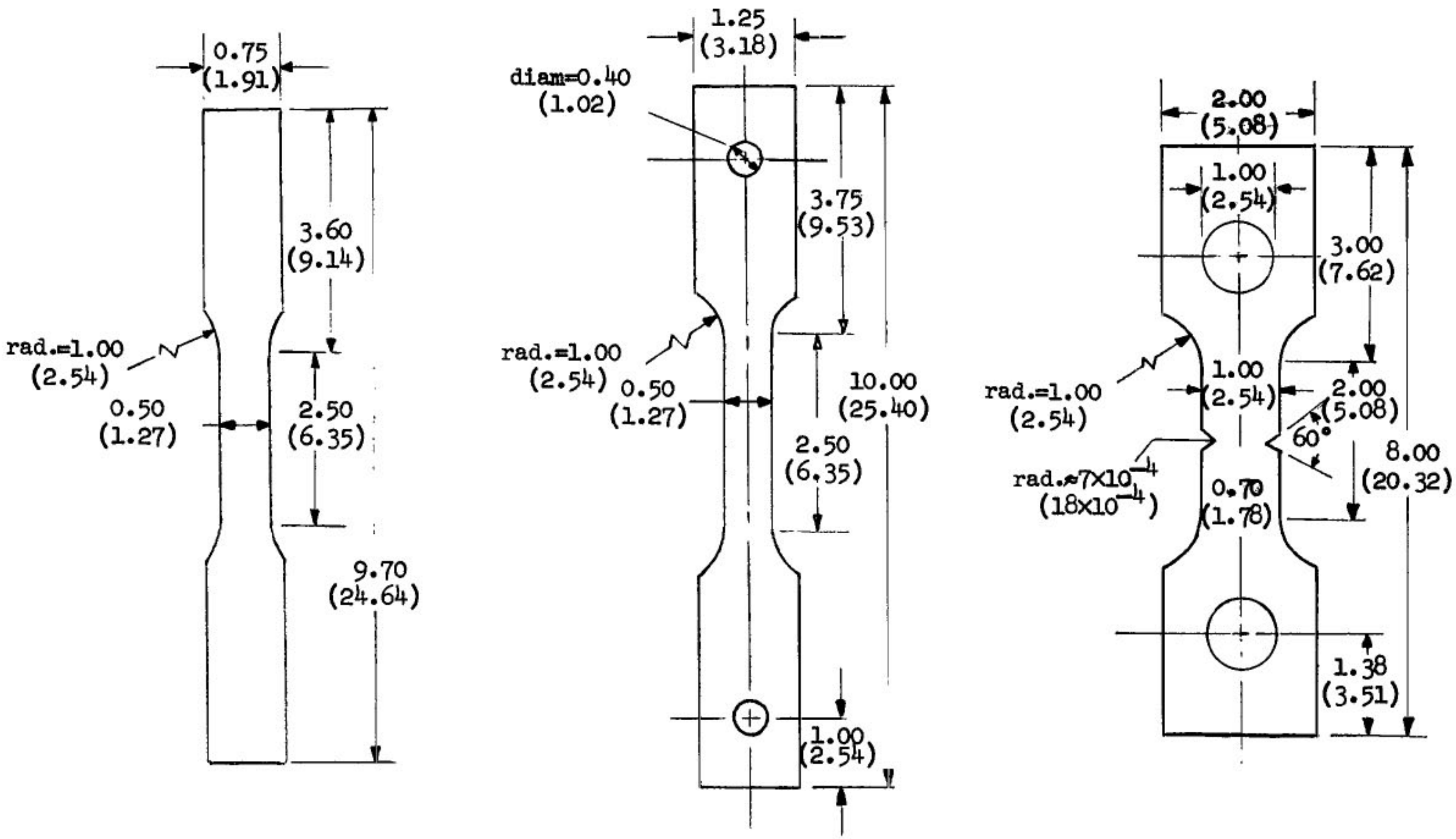
[Strain rate, 0.00002 per second]

Alloy	Grain direction	Tensile strength		Yield strength		Elongation in 2 in., percent	Notch strength[a]	
		ksi	MN/m^2	ksi	MN/m^2		ksi	MN/m^2
Ti-8Al-1Mo-1V	Longitudinal	156	1076	146	1007	18.0	127	876
	Transverse	159	1096	147	1014	16.0	112	772
Ti-4Al-3Mo-1V	Longitudinal	137	945	120	827	11.0	130	896
	Transverse	159	1096	148	1020	8.0	153	1055
Ti-6Al-4V	Longitudinal	145	1000	138	951	13.0	140	965
	Transverse	146	1007	140	965	13.0	147	1014

[a] A description of the notched specimen is presented in the section entitled "Materials and Specimens."

TABLE III.- STRAIN RATE AND MAXIMUM EXPOSURE TIMES FOR TITANIUM-ALLOY SHEET

Material	Specimen type	Testing speed	Elastic strain rate, per sec	Maximum exposure, hr	
				Longitudinal	Transverse
Ti-8Al-1Mo-1V	Smooth	Slow	0.00002	22×10^3	22×10^3
		Intermediate	.10	22	22
		Fast	5.0	22	22
	Notched	Slow	.00002	22	22
		Intermediate	.10	22	22
		Fast	5.0	22	22
Ti-4Al-3Mo-1V	Smooth	Slow	.00002	10	10
		Intermediate	.10	7	7
		Fast	5.0	10	10
	Notched	Slow	.00002	14	14
		Intermediate	.10	22	22
		Fast	5.0	22	22
Ti-6Al-4V	Notched	Slow	.00002	14	14
		Intermediate	.10	14	4
		Fast	5.0	14	4



ASTM standard — Modified ASTM standard — V-notched

Figure 1.- Tensile-specimen configurations for strain-rate tests. All dimensions are in inches (centimeters).

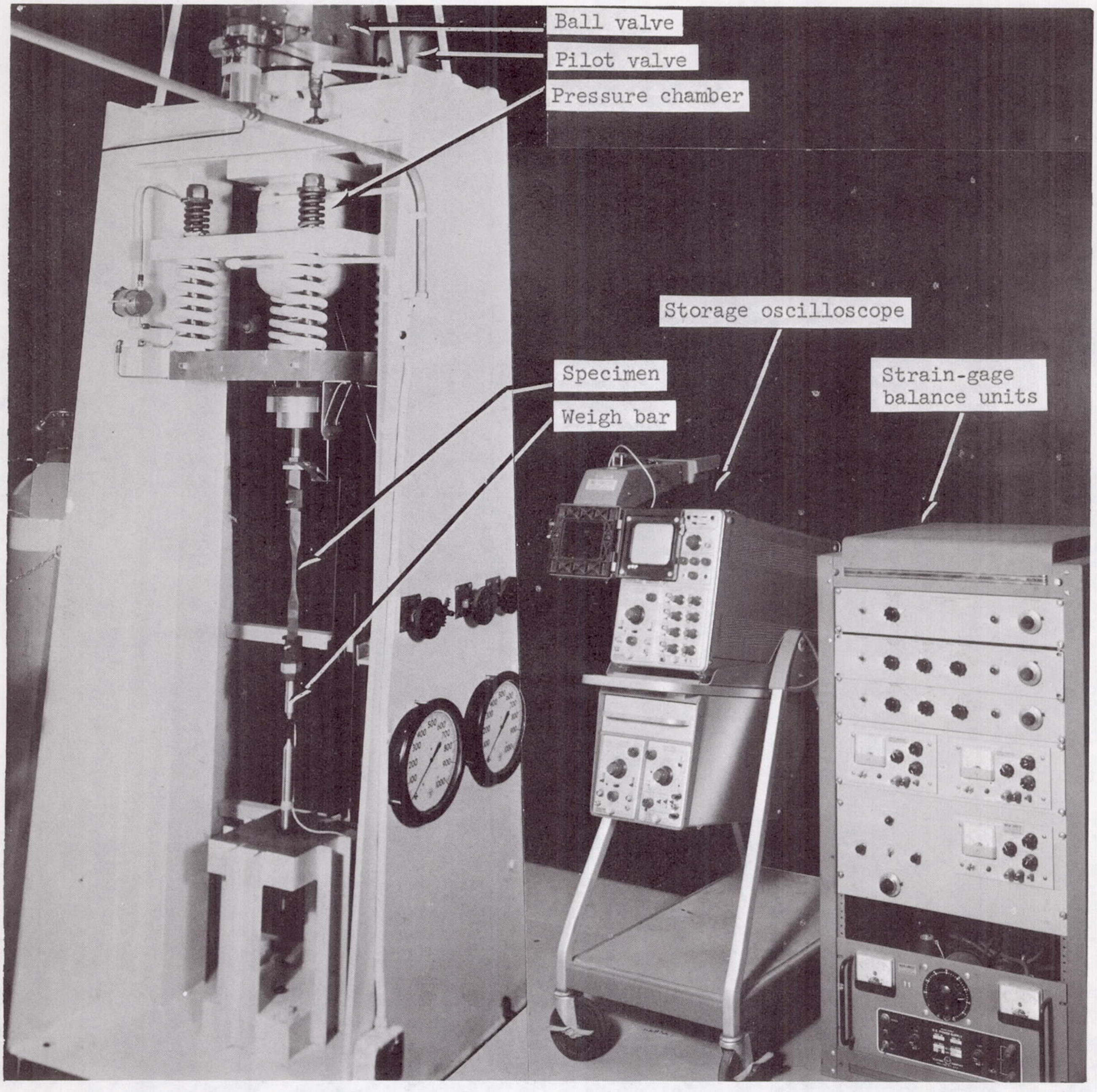
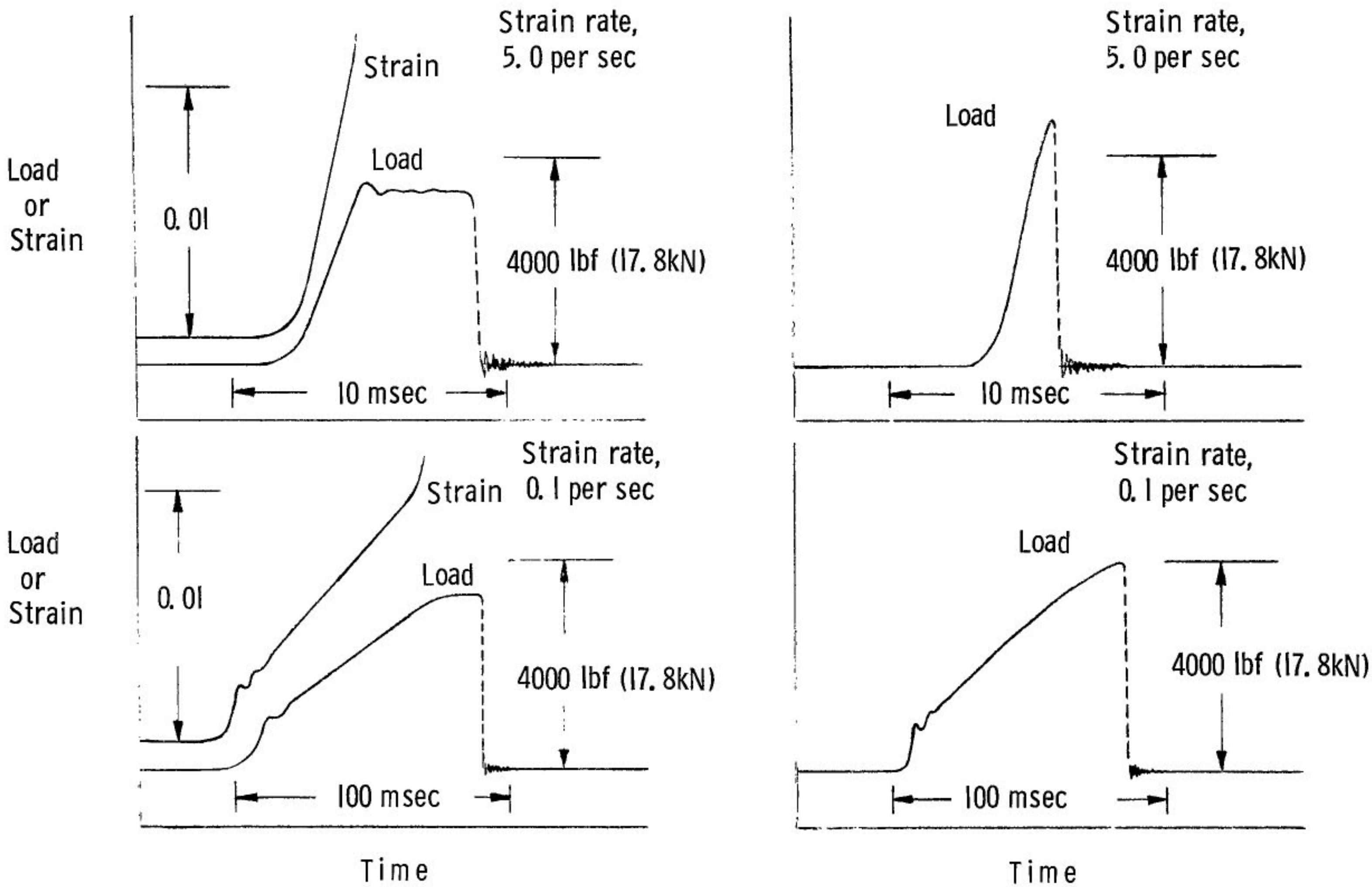


Figure 2.- The 10 000-lbf-capacity (44.5 kN) high-speed pneumatic tensile testing machine and the recording system. L-68-10,001



(a) Smooth specimen.

(b) Notched specimen.

Figure 3.- Representative load and strain time histories for smooth and notched specimens.

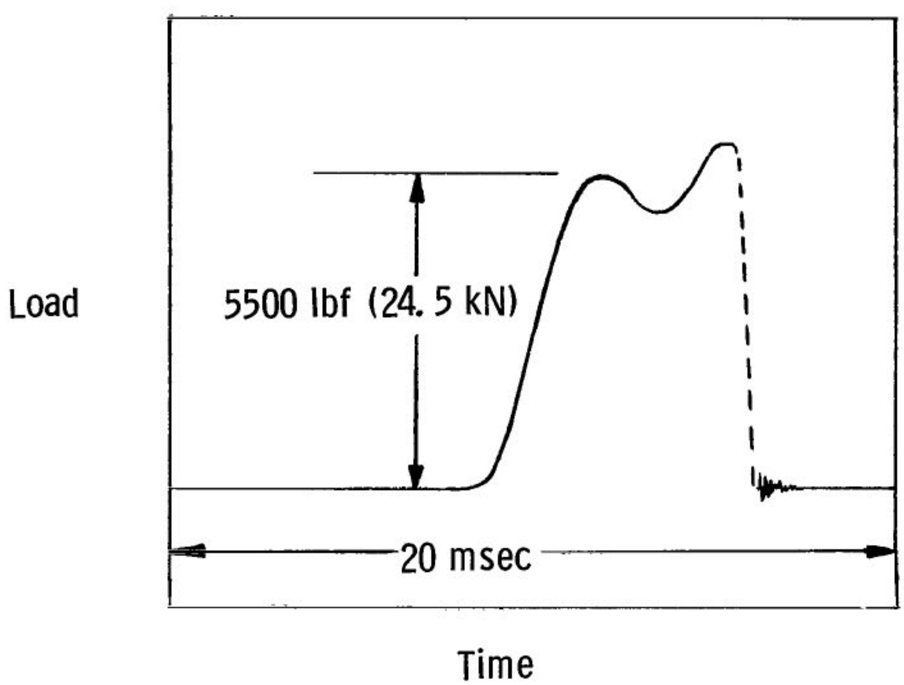
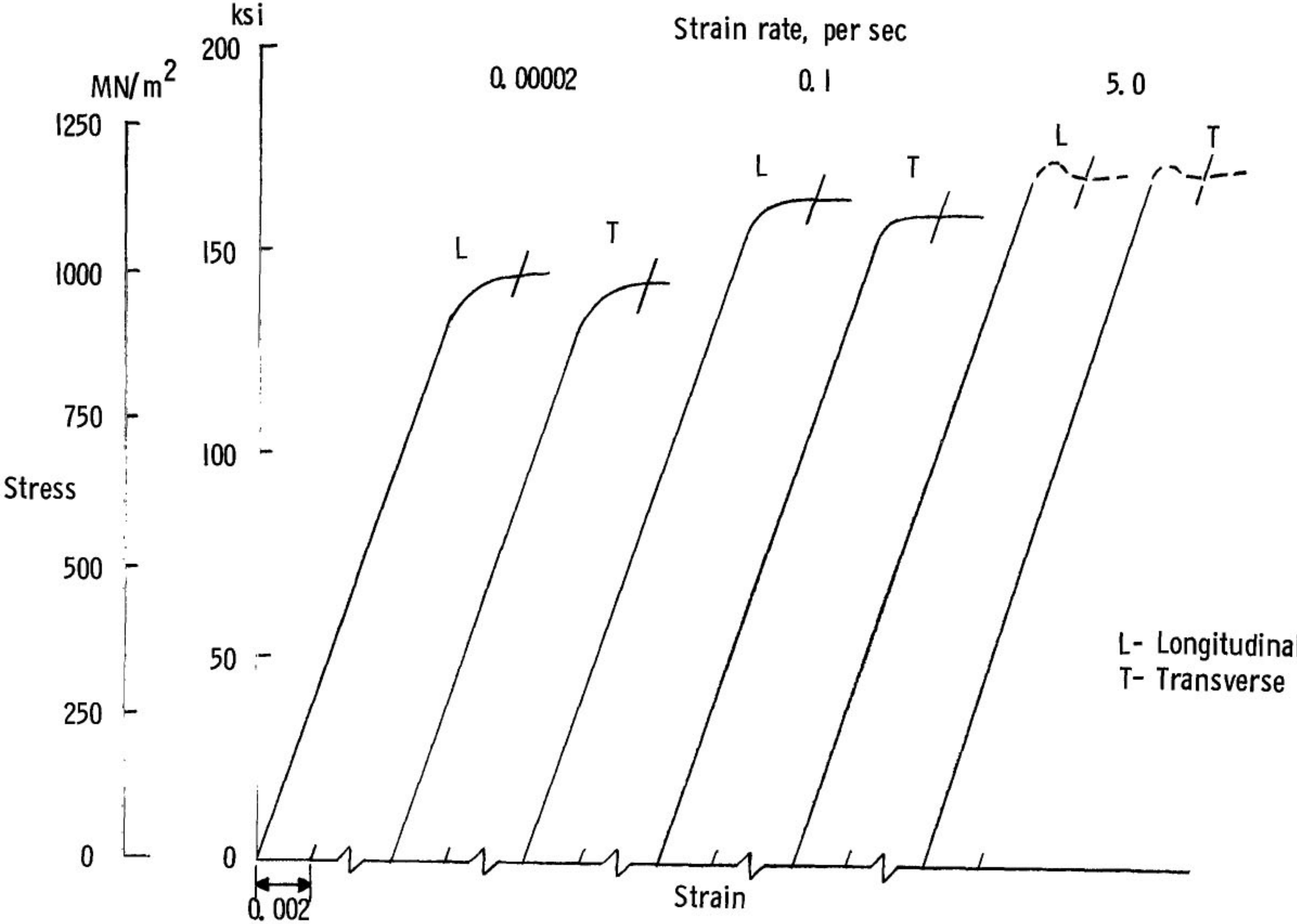
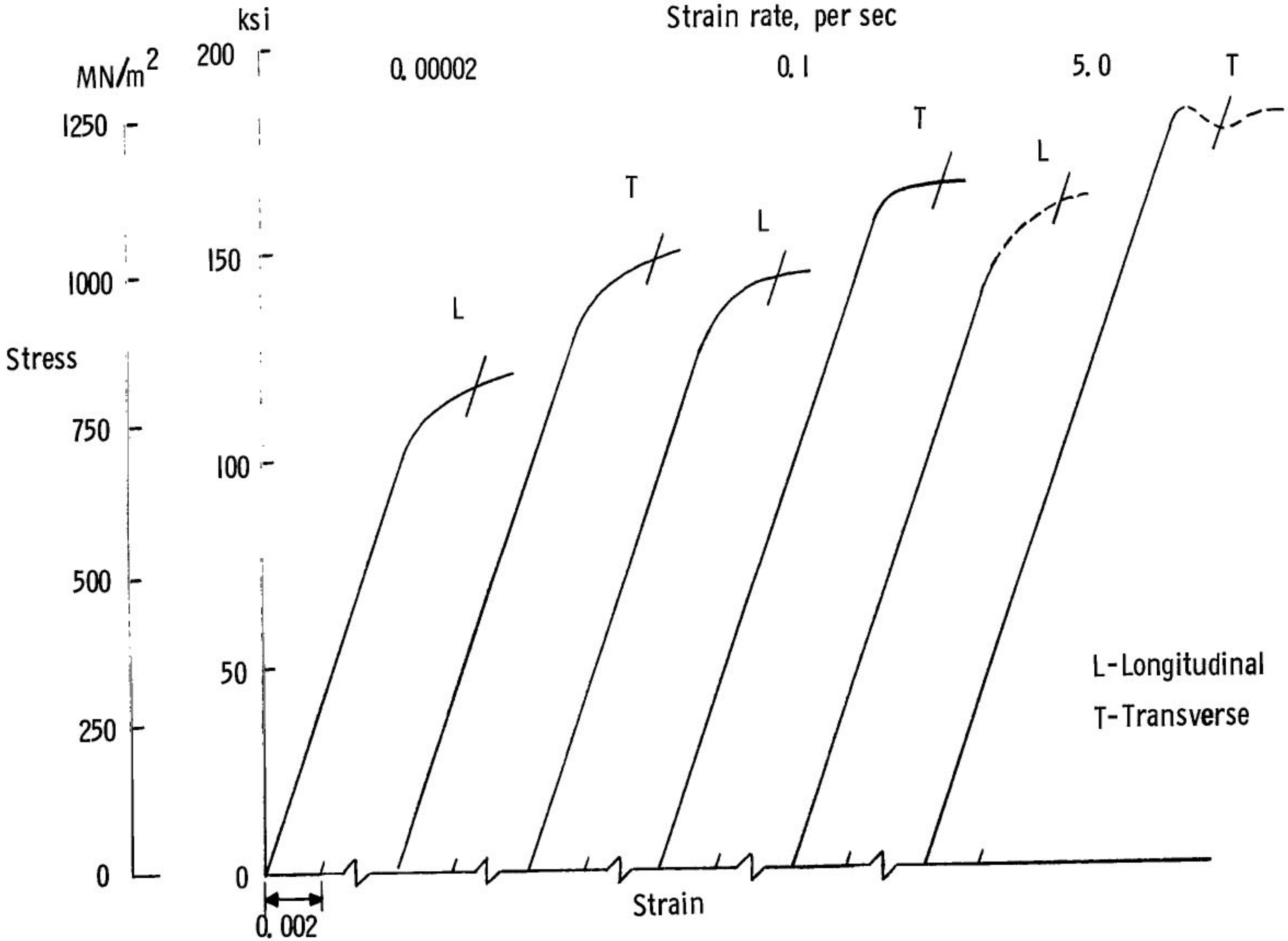


Figure 4.- Representative load time history for transverse Ti-4Al-3Mo-1V notched specimen at a strain rate of 5.0 per second.



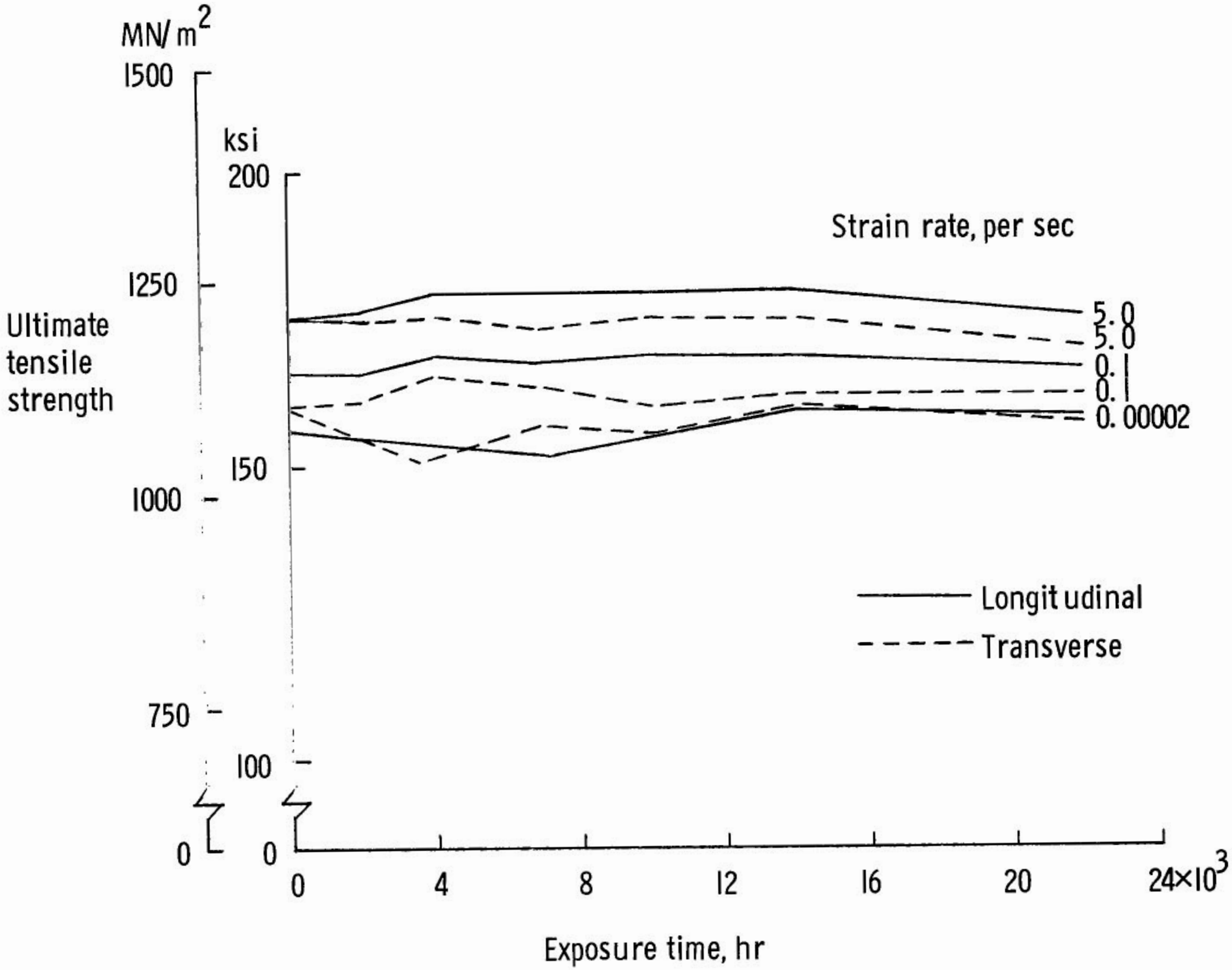
(a) Ti-8Al-1Mo-1V.

Figure 5.- Typical stress-strain curves for smooth titanium-alloy specimens.



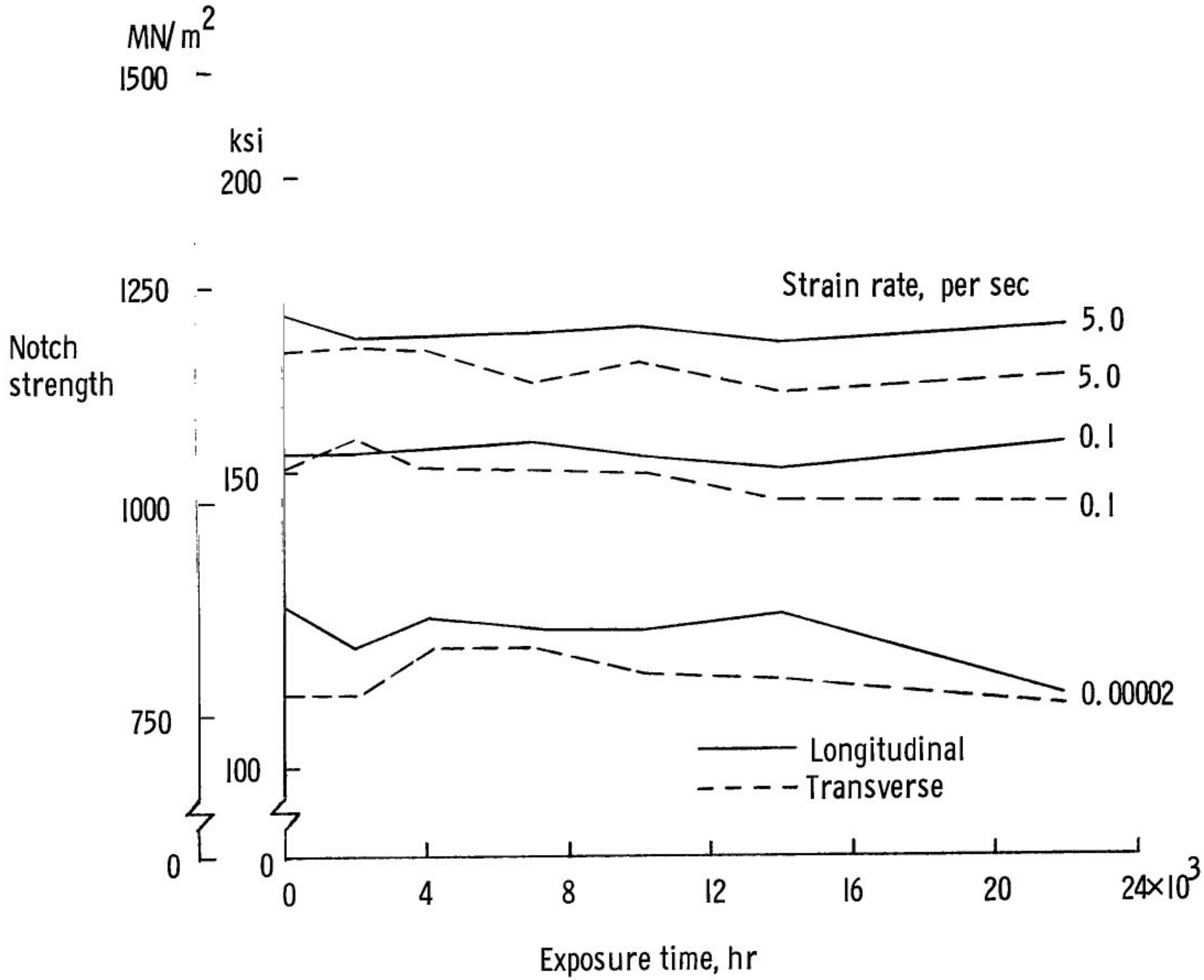
(b) Ti-4Al-3Mo-1V.

Figure 5.- Concluded.



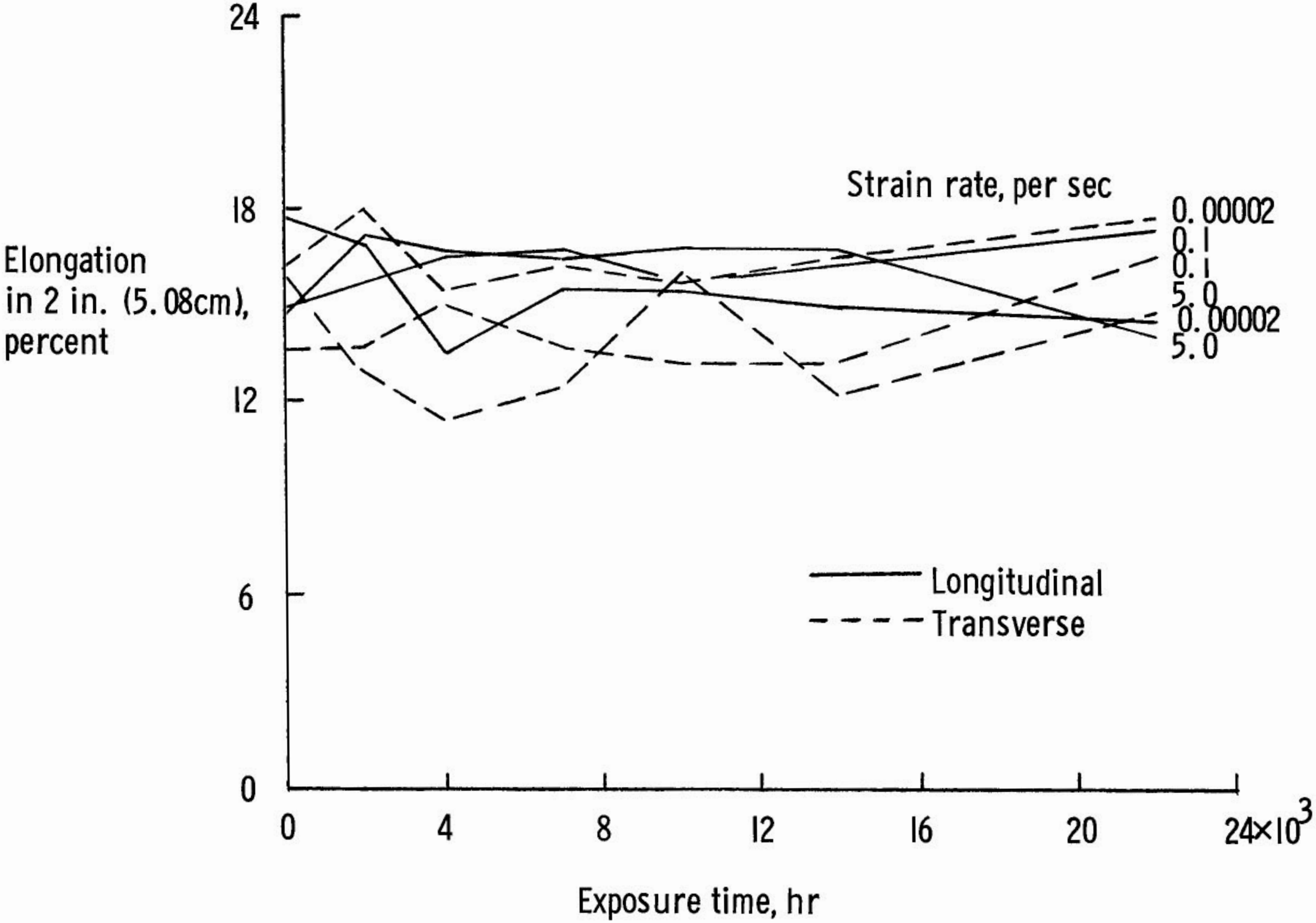
(a) Ti-8Al-1Mo-1V.

Figure 6.- Effect of exposure on tensile properties of titanium alloys.



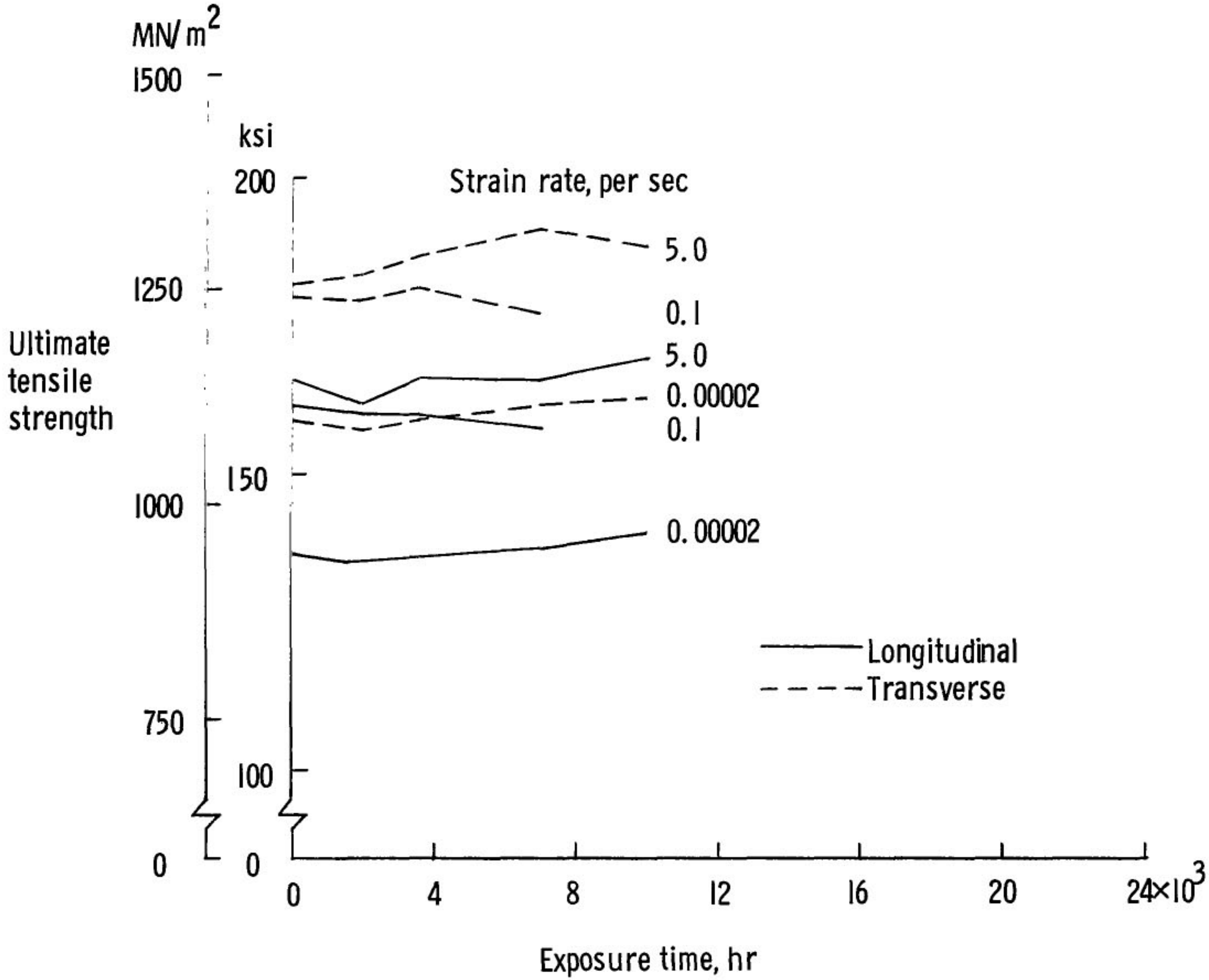
(a) Continued.

Figure 6.- Continued.



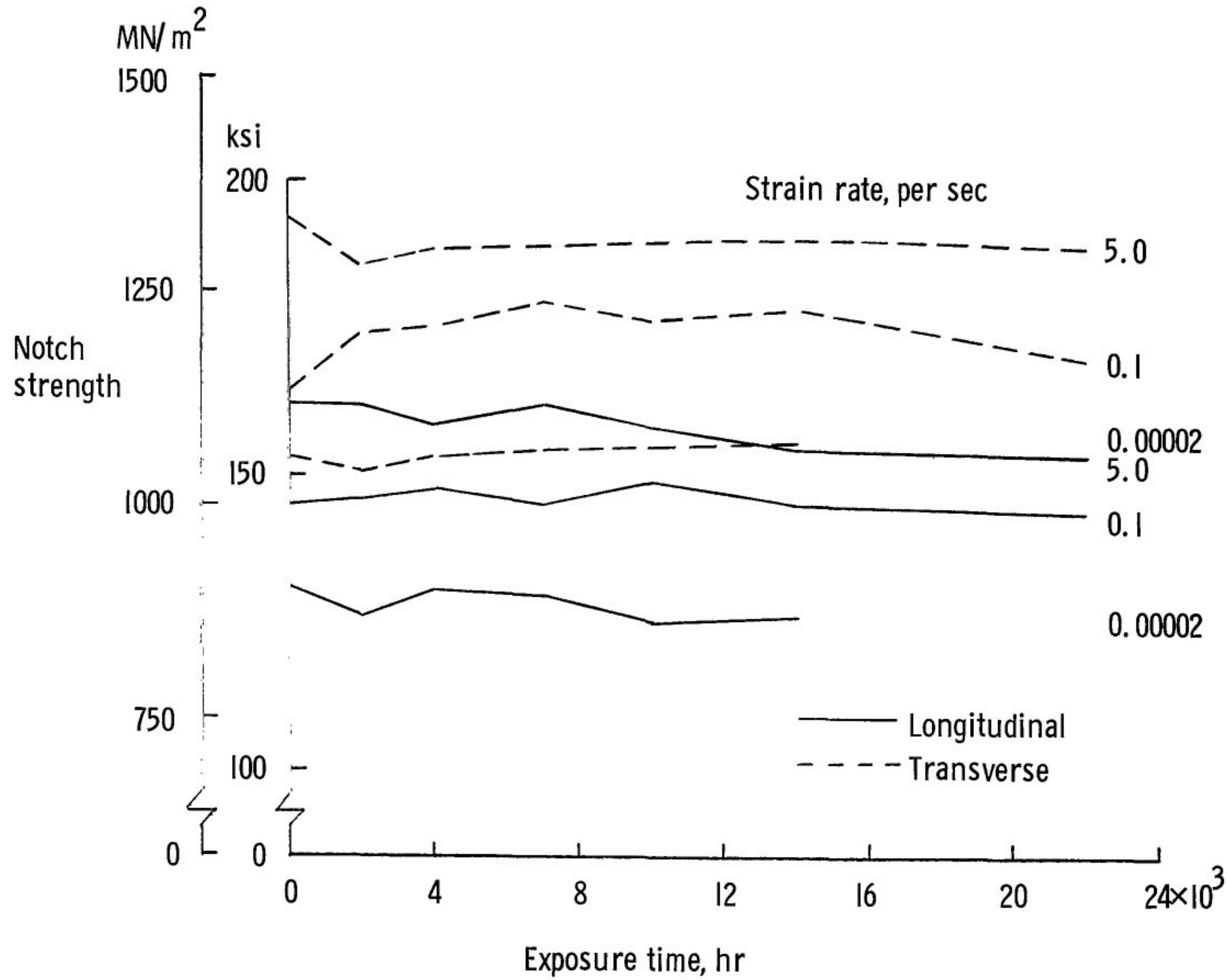
(a) Concluded.

Figure 6.- Continued.



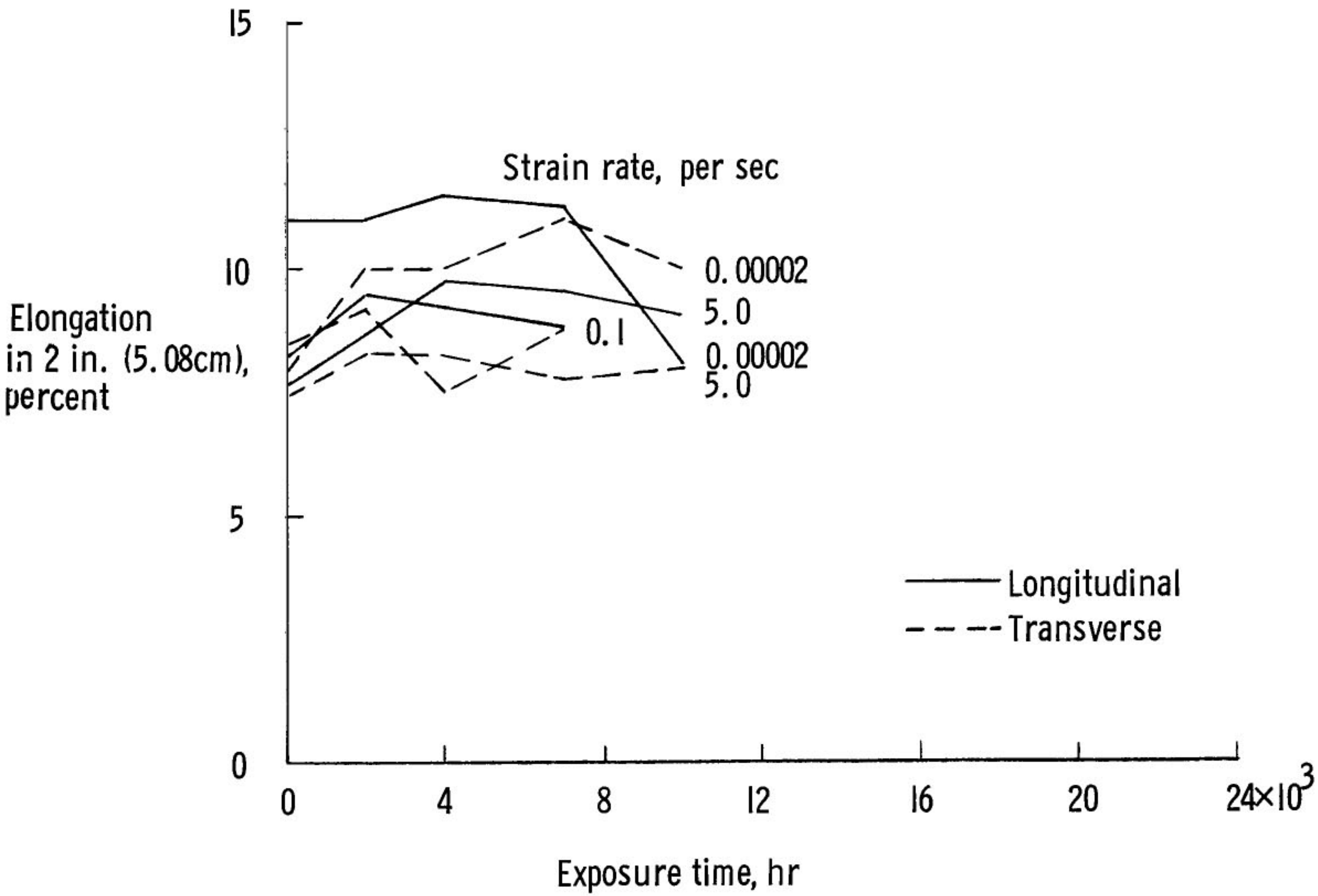
(b) Ti-4Al-3Mo-1V.

Figure 6.- Continued.



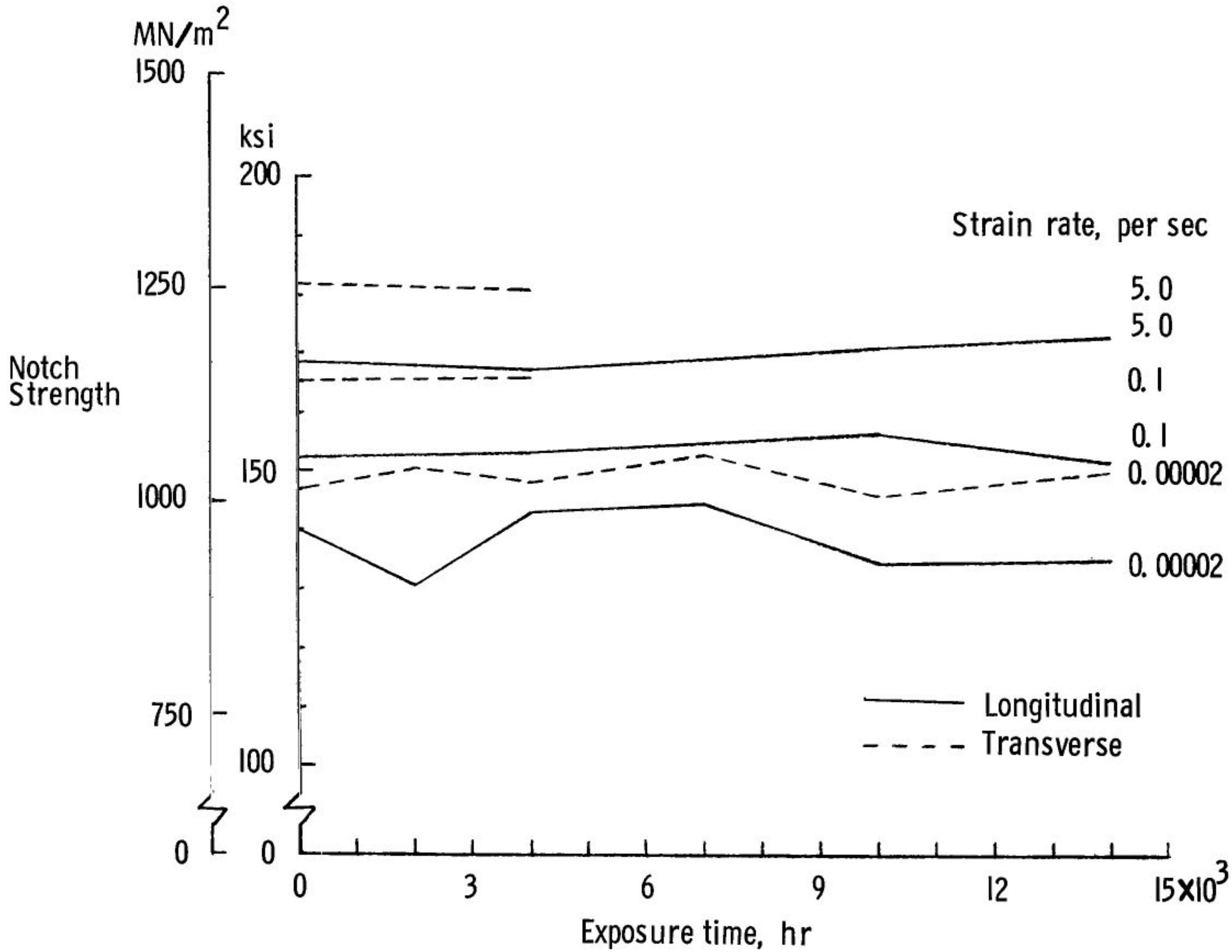
(b) Continued.

Figure 6.- Continued.



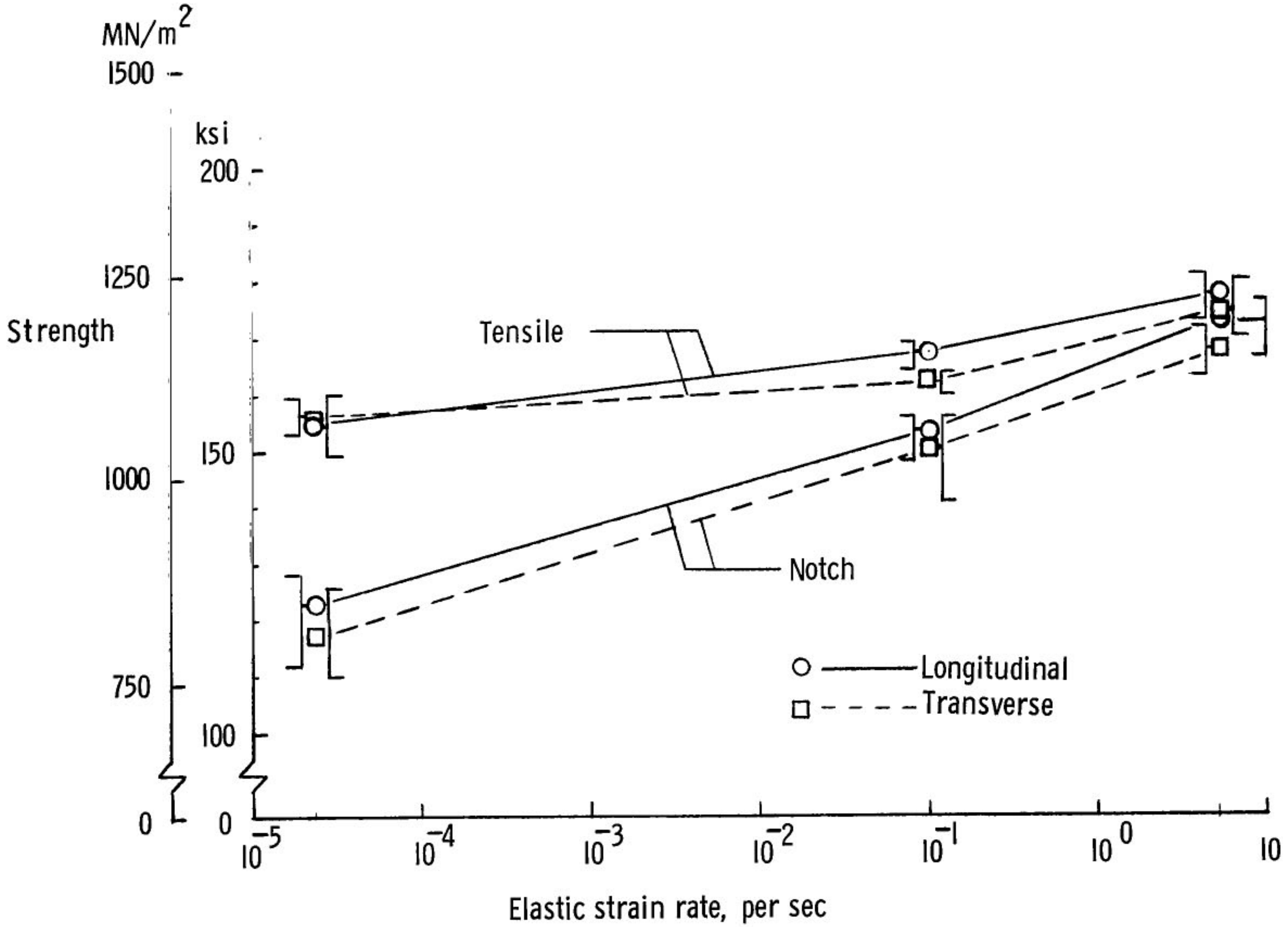
(b) Concluded.

Figure 6.- Continued.



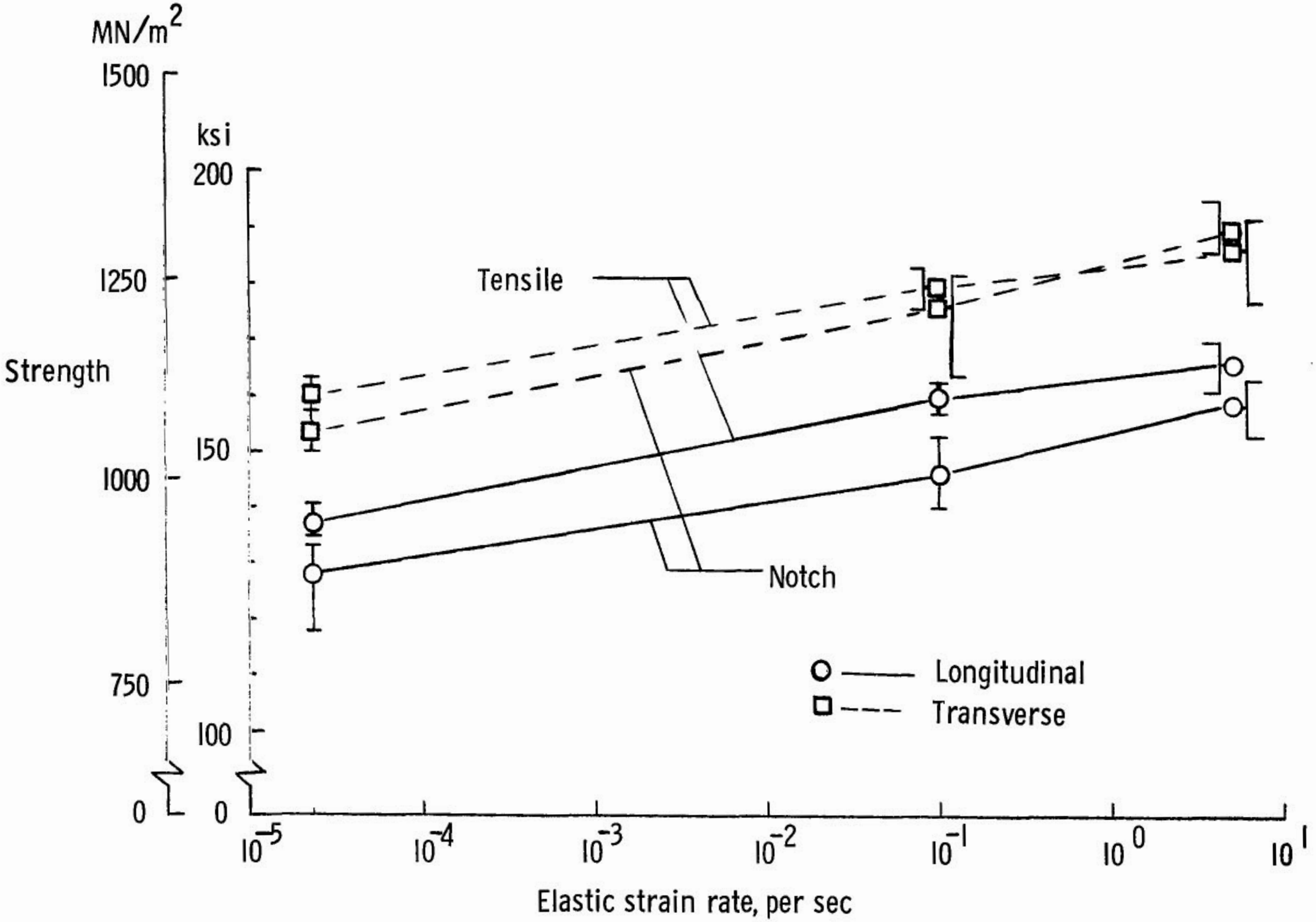
(c) Ti-6Al-4V.

Figure 6.- Concluded



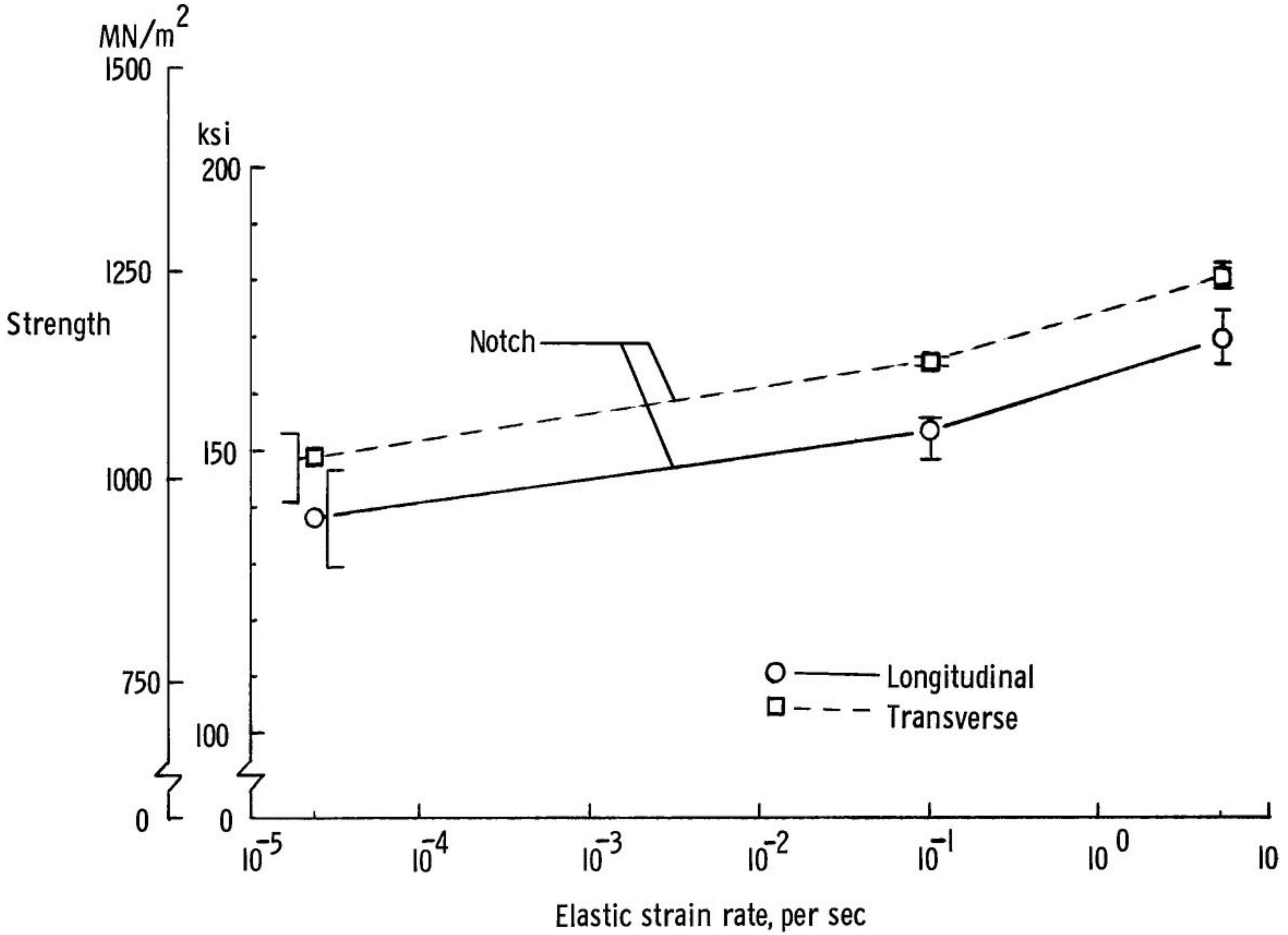
(a) Ti-8Al-1Mo-1V.

Figure 7.- Effect of strain rate on tensile and notch strengths of titanium alloys. (Strain rate for notched specimen is based on average stress rate in net section.)



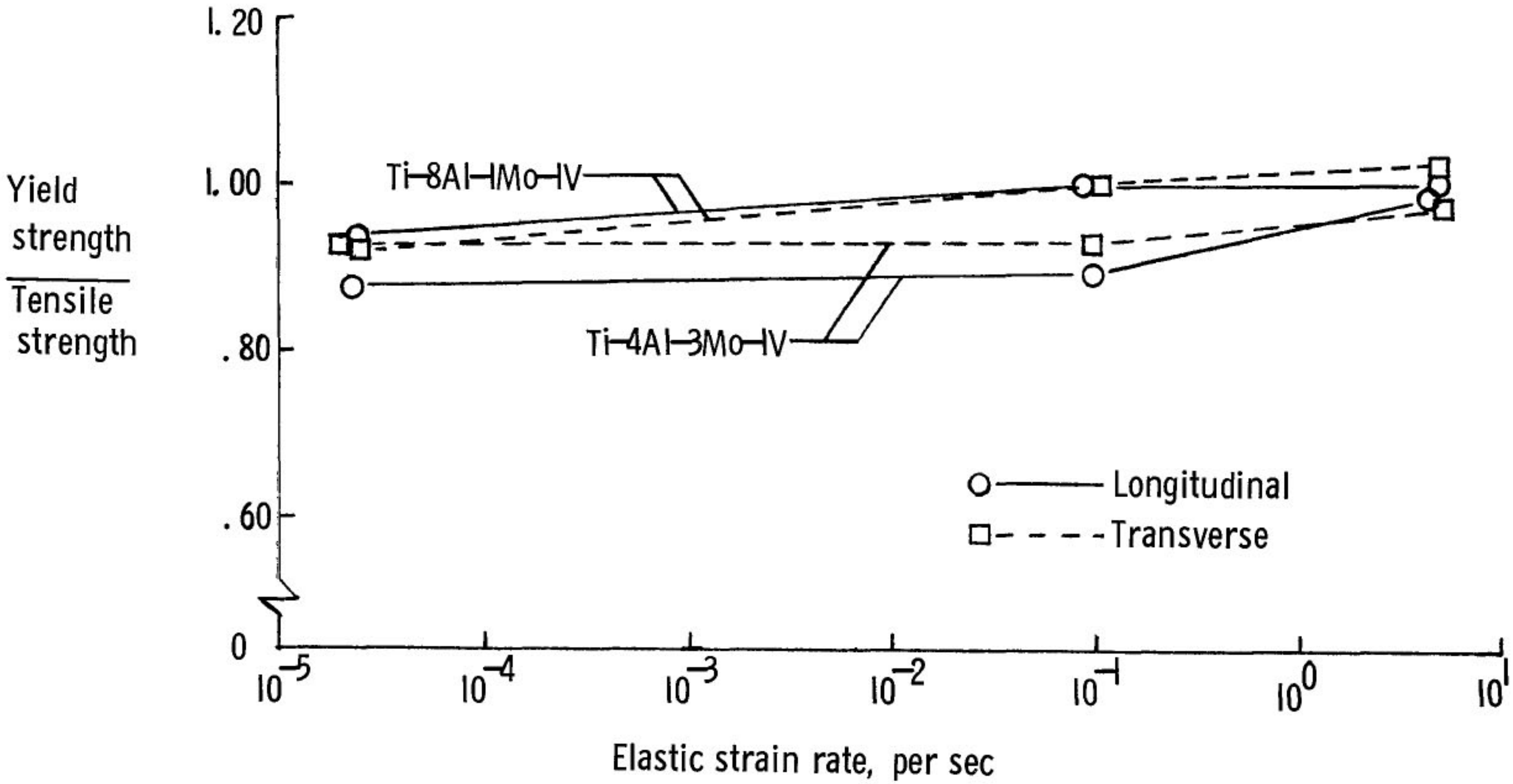
(b) Ti-4Al-3Mo-1V.

Figure 7.- Continued.



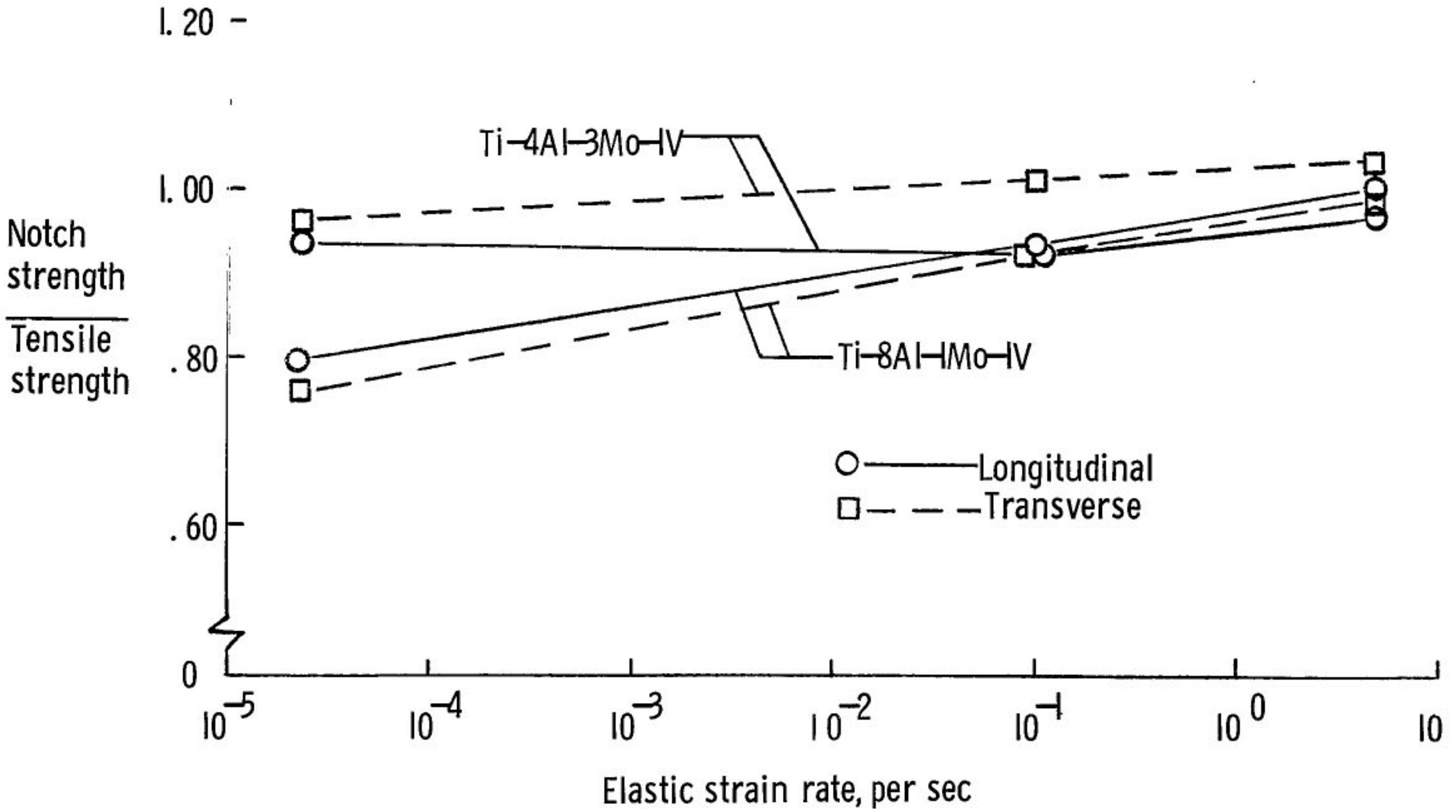
(c) Ti-6Al-4V.

Figure 7.- Concluded.



(a) Effect on ratio of yield strength to tensile strength.

Figure 8.- Effect of strain rate on strength ratios of Ti-8Al-1Mo-1V and Ti-4Al-3Mo-1V sheet material.



(b) Effect on ratio of notch strength to tensile strength.

Figure 8.- Concluded.

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