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EFFECT OF PRIOR CREEP ON THE MECHANICAL PROPERTIES OF A HIGH-STRENGTH HEAT-TREATABLE TITANIUM ALLOY, Ti-16V-2.5Al

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FOREWORD

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ABSTRACT

A study was carried out of the effect of exposure to elevated temperature creep conditions on the short-time mechanical properties of a high-strength, heat-treatable titanium alloy, Ti-16V-2.5Al. Exposures were conducted for 10 or 100 hours either unstressed or at stresses causing up to 2-percent creep deformation at temperatures between 600° and 900°F. The specimens were taken parallel to the sheet rolling direction.

Following the exposures, short-time tension, compression or tension-impact tests were run at room temperature or the temperature of exposure. Prior creep at 600°F raised the ultimate tensile strength and tensile yield strength considerably and the compressive yield strength and tensile elongation were substantially decreased. Exposure to temperature alone caused increases in strength indicative of an age-strengthening reaction. The changes in mechanical properties are attributed mainly to a combination of stress-accelerated age-strengthening and a Bauschinger effect. A lesser change in properties was noted for creep exposures conducted at 700°F. Peak properties from the age-strengthening reaction were noted in the unstressed exposures conducted at 800°F and overaging with a consequent drop-off in strength was obtained from the 900°F creep-exposures. Metallographic evidence tended to confirm the presence of stress-accelerated aging.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

W. J. TRAPP
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INTRODUCTION

An investigation was conducted to study the effects of prior creep-exposure at elevated temperature on the short-time mechanical properties of a high strength, heat-treatable titanium sheet alloy, Ti-16V-2.5Al. This material is one of a series of aircraft structural metals investigated under a program sponsored at the University of Michigan by the Materials Laboratory, Wright Air Development Center, U. S. Air Force, under Contract No. AF33(616)-3368 and its accompanying Supplemental Agreements.

Other materials studied in this investigation have included 2024-T86 aluminum alloy (Ref. 1), C110M titanium alloy (Refs. 2 and 3), and 17-7PH stainless steel in the TH 1050 condition (Ref. 4) and the RH 950 condition (Ref. 5).

The Ti-16V-2.5Al alloy which contains 16-percent vanadium and 2.5-percent aluminum was developed by the Mallory-Sharon Metals Corporation and produced under the auspices of the Department of Defense Titanium Sheet Rolling Program as one of a group of "second generation" titanium alloys suitable for production in sheet form. The inclusion of this alloy in the present investigation made possible the comparison of two titanium alloys of widely differing composition inasmuch as C110M was a binary alloy containing 8-percent manganese.

The purpose of these studies of structural metals is to provide the necessary background information to aid in the formulation of principles for the prediction of creep damage to short-time mechanical properties. The need for stable short-time properties has become important as flight vehicle design and performance requirements have progressed to the point where creep conditions are attained during a portion of the normal operating cycle. It is not only important that creep strength be sufficient to withstand these conditions but the subsequent short-time properties must also not be adversely affected. The short-time properties are of primary concern in connection with such events as high-intensity stresses of brief duration or the thermal stresses encountered in either heating or cooling.

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EXPERIMENTAL PROGRAM

The creep-exposures of the Ti-16V-2.5Al alloy were conducted principally at 600°, 800°, and 900°F with some additional studies conducted on specimens crept at 700°F. Specimens were exposed for 10, 50 or 100 hours without stress or for 10 or 100 hours at stresses selected to produce nominal creep deformations of 0.2, 0.5, 1.0, and 2.0 percent in the desired time period.

Creep deformation is defined as all deformation occuring between the completion of loading and the end of the test period. The creep deformation therefore does not include either the elastic or plastic deformation, if any, of loading.

The creep stresses used were those which had been determined by a series of preliminary tests to give, on the average, the desired amount of creep. Since the time, temperature, and stress of testing were fixed, the inherent scatter of creep properties produced actual deformations that were sometimes greater or less than the desired value. Time-elongation data were taken for all tests and all correlations were based on the actual amounts of deformation obtained. The deformation data were tabulated as follows: Total loading deformation, plastic loading deformation (if any), creep deformation, total plastic deformation (both loading and creep), and total deformation (all deformation elastic and plastic occuring during the application of the load and during the creep period).

After the exposures, the following mechanical property tests were carried out:

1. Tension tests at room temperature and the exposure temperature. The data reported are the ultimate tensile strength, 0.2-percent offset yield strength, elongation, reduction of area, and the elastic modulus. While the reduction of area data are reported, the accuracy of such measurements on thin sheets is questionable. The modulus values were computed from the slopes of the stress-strain curves and should not be regarded as precise determinations.

2. Compression tests at room temperature and the exposure temperature. The data reported are the 0.2 percent offset yield strength and the elastic modulus.

3. Tension-impact tests at room temperature for specimens exposed 10 hours at each temperature and at the exposure temperature for specimens exposed for 10 hours at 600 or 900°F. The data reported are the tension-impact strength, elongation, and reduction of area.

4. Hardness determinations on representative tensile specimens. Metallographic examination was also carried out on selected test specimens.

Most of the test specimens were taken from the sheets in the direction parallel to rolling. This was believed to be weaker than the transverse direction of the material. A few additional tests were conducted on specimens taken transverse to the rolling direction.

The properties of specimens subjected to creep-exposure were compared to the average properties of the as-treated material as established by a series of tests performed to define the normal scatter of each property. In most cases only single specimens were tested for each exposure condition. Significant effects were defined as those which resulted in short-time properties outside the scatter band for the original material. The conditions used to fix the base properties were inadequate to fix realistic confidence limits by statistical methods. Under these conditions the information gained from the study of simple trends is probably as effective as that which would have been gained using the statistical approximations necessary with the small sample sizes. Duplicate exposure tests were, however, run in several instances in order to give more confidence in the results.

TEST MATERIAL AND SPECIMENS

The Ti-16V-2.5Al alloy used in the present investigation was allocated from the Department of Defense Titanium Sheet Rolling Program.

Three sheets, identified as Sheets No. 0084-1, 0084-2, and 0084-7 from Heat No. M-22154, were received from the Mallory-Sharon Metals Corporation during July of 1958. The material was of nominal 0.063-inch thickness by 36 inches wide by 92 to 105-inches long.

The material had been solution heat treated and aged by the producer according to the following schedule: solution treated 1/2-hour at 1380°F; water quenched; aged 4 hours at 990°F; air cooled.

The following chemical analysis was reported:

Element	Percent (wt.)
C	0.02
N_2	0.014
H_2	0.0076
Fe	0.27
Al	2.56
V	15.79

In addition, the producer furnished mechanical property data for the three sheets:

Sheet No.	Direction	Room Temperature Properties: Ult. Tensile (psi)	Yield Strength (psi)	Elongation (%)	H_2 ppm
0084-1	L	167,000	153,800	7.3	76
	L	167,100	155,700	6.8	
	T	167,800	156,300	6.0	
	T	167,500	156,700	6.0	

Sheet No.	Direction	Room Temperature Properties: Ult. Tensile (psi)	Yield Strength (psi)	Elongation (%)	H_2 ppm
0084-2	L	178,000	164,600	6.5	76
	L	178,900	165,000	6.5	
	T	184,100	164,600	4.5	
	T	184,500	165,000	5.0	
0084-7	L	169,700	153,200	7.0	78
	L	169,400	155,800	6.5	
	T	175,300	160,900	5.0	
	T	175,900	161,000	5.0	

Examination of these data revealed good agreement in properties between Sheets 0084-1 and 0084-7, while Sheet 0084-2 was slightly stronger and less ductile. While the deviation was not considered excessive, it was decided to set aside Sheet 0084-2 for the time being and conduct the creep-exposure studies on the two sheets showing closer correspondence in properties.

The plan used for sampling specimen blanks is illustrated in Figure 1. With few exceptions the specimens were taken in the direction of rolling. Each sheet was divided into one-inch wide strips running the length of the sheet. The strips were numbered consecutively from 1 to 36 from one edge of the sheet to the other. The length of the sheet was divided into four sections (A, B, C, and D) approximately 26-inches long in the case of Sheet 0084-1 which was 105-inches in length and 23-inches long in the case of Sheet 0084-7 which was only 92-inches in length.

As the individual specimens were sheared from each blank they were stamped with a code number identifying their source: thus a specimen labeled 1CL17T is a tensile specimen taken in the longitudinal direction on strip 17, section C, of Sheet Number 0084-1. Compression specimens were coded "C" and tension-impact specimens were coded "M". The transverse samples were coded with a "T" instead of an "L" following the sheet number and section letter, while the transverse strips were identified as 1, 2, 23, 25 or 26, depending on the side of the section from which they were taken. Tension-impact and compression specimen blanks were cut from tensile blanks. In some cases tensile specimens of less than the normal 22-inch length were prepared from the material remaining after sampling the compression blanks. These specimens were used only for tests of base properties or unstressed exposure where furnace clearance was not critical. In all respects except overall length the short specimens were identical to the standard specimens.

The configurations and dimensions of the test specimens are illustrated in Figure 2. All specimens were designed so that they could be machined from the creep specimens following the desired exposure. For exposure to creep, the width of the gage section was machined 0.030-inch over the 0.5-inch nominal width. The excess was machined off after exposure and thus permitted the measurement of the properties of the material to be made without interference from the particular edge effects, if any, associated with the exposure of the specimen.

For convenience and uniformity in machining, jigs were constructed so that five or six specimens could be made concurrently. The blanks were milled to rough dimensions and then the shoulder radii and gage sections were ground to the finished dimensions.

TEST EQUIPMENT AND PROCEDURES

Detailed discussion of the development of the test equipment and procedures has been previously given (Refs. 1 and 4) and will not be repeated in the present report. Wherever applicable, ASTM Recommended Practices were adhered to in test procedures.

The creep-exposure tests were carried out in individual creep-testing machines with heating provided by a wire wound resistance furnace fitting over the specimen assembly. Strain measurements were accomplished using a modified Martens optical extensometer system.

Tensile and compression tests were conducted in a Baldwin-Southwark hydraulic tensile machine equipped with a strain pacer to give a strain rate of 0.005-inches per inch per minute. A recording extensometer system employing a micro-former strain gage was employed to give a continuous plot of the test results. A special compression testing fixture which included a loading ram and a pair of guide blocks to restrain lateral buckling of the specimen was constructed for use in this investigation.

Specimens prepared for electron microscope examination were mounted in bakelite and wet ground on rotating laps using a series of silicon carbide papers through 600 mesh. Final polishing was carried out first with fine diamond compound and then on a Syntron vibratory polisher in an acqueous media of Linde "B" polishing compound. The polished samples were etched with "R" etch--composed of 13.5 gm Benzalkonium Chloride, 35 ml Ethanol, 40 ml Glycerine, and 25 ml Hydrofluoric acid (20%)--by swabbing for 3-4 seconds.

For electron microscope examination, collodion replicas were made from the surface of the etched specimens. The replicas were shadowed with palladium to increase contrast and reveal surface contours. Polystyrene latex spheres of approximately 3400 Å diameter were placed on the replicas prior to shadowing to indicate the angle and direction of shadowing and provide an internal standard for the measurement of magnification. The micrographs reproduced in this report are direct prints from the original negatives; consequently the polystyrene spheres appear black and the shadows appear white. Since the latex spheres are raised in the replica, a phase casting a shadow opposite to that cast by the latex spheres is in relief on the metal specimen; conversely, areas casting shadows in the same direction as cast by the latex spheres are depressions in the surface of the metal specimen and represent a phase that was attacked by the etchant.

EXPERIMENTAL RESULTS

The experimental results are presented in the form of tabulations of the test data and such graphical representations as are needed to clearly delineate the effects observed. The data are organized both by type of short-time test conducted and the prior exposure condition. Following the discussion of the base properties, the effects of unstressed exposures and creep exposures are considered for each mechanical property. The metallographic studies are presented after the mechanical property data.

BASE PROPERTIES BEFORE CREEP EXPOSURE

Tension, compression, and tension-impact tests were conducted in order to establish the average strength of the as-treated material at both room temperature and at the temperatures of creep-exposure. Two specimens each were taken at random from the two sheets studied and the results were averaged to provide the basis for comparison with the properties following the creep-exposures.

Tension Properties

The results of tension tests at room temperature, 600°, 800°, and 900°F are summarized in Table 1. A plot of the effect of test temperature on the ultimate tensile and yield strengths and elongation is presented in Figure 3.

Fairly good agreement in the tensile and yield strengths was obtained both within sheets and between sheets. Most of the values fell within 5-percent of the average value while in only two cases was the deviation as much as 8 percent. Both the tensile and yield strengths decreased to the same extent as the temperature increased.

The elongation underwent little change between room temperature and 600°F, remaining at about 8-percent. At 800° and 900°F it increased, reaching a value of about 25 percent at 900°F.

The average room temperature ultimate tensile and tensile yield strengths determined at the University were within 2.5-percent of the values reported by the producer. A slightly higher value of elongation was obtained at the University.

Compression Properties

The compression test data for the room temperature and elevated temperature tests are presented in Table 2 and plotted as a function of temperature in Figure 4.

The yield strength in compression decreased with test temperature. The fall-off in strength was more rapid than was noted for the tensile properties. The compressive yield strength at room temperature was approximately equal to the ultimate tensile strength while at 900°F it had fallen below the level of the tensile yield strength. At room temperature the compressive yield strength was 112-percent of the tensile yield strength while at 900°F it was 93-percent of the tensile yield strength.

At all the test temperatures except 800°F, the variation between tests and between sheets was slight and was not over 2 to 3-percent from the average value. Two tests at 800°F, one from each sheet, deviated from 7 to 8-percent from the average at 800°F.

The modulus values observed in compression averaged slightly higher than the corresponding values observed in tension.

Tension-Impact Properties

The results of the room temperature and elevated temperature tension-impact tests are summarized in Table 3 and plotted in Figure 5.

The tension-impact strength decreased somewhat with increasing test temperature while the reduction of area was slightly increased. The elongation, on the other hand, did not change significantly with the test temperature.

Fairly good agreement was obtained both between sheets and within sheets.

Transverse Properties

In addition to the complete tests of longitudinal specimens a few check tests were made on transverse specimens of Ti-16V-2.5Al. A comparison of the as-treated short-time properties of the two directions follows:

Test Direction	Type of Test	Ult. Tensile (psi)	Yield Strength (psi)	Elong. (%)	R.A. (%)	Modulus (x 10^6psi)
Trans.	Tensile	165,200	152,000	6.5	18.6	14.2
Long.	Tensile(Sht. 1)	167,600	152,650	8.8	20.5	14.6
Trans.	Comp.	---	175,000	-	--	18.6
Long.	Comp.(Sht. 1)	---	169,000	-	--	15.3

Note: Transverse tests were run on specimens from Sheet 1. Comparative longitudinal data is the average for Sheet 1.

The tensile strengths in the transverse direction showed good agreement with those for the longitudinal direction, while the elongation was slightly less. This observation agrees with the data furnished by the producer (p. 4).

The apparently increased compression yield strength in the transverse direction may not be real inasmuch as the deviation was only slightly more than the experimental variation noted in duplicate tests of longitudinal samples. An effect of test direction on compression modulus was noted for previous tests of the C110M titanium alloy (Ref. 3). This may also have been the case in the present alloy.

Hardness Properties

The hardness of solution treated and aged Ti-16V-2.5Al was determined to be Rockwell "C" 36.8. This value is the average of five determinations each on four room temperature tensile specimens.

ESTABLISHMENT OF EXPOSURE STRESSES

The stresses for the creep-exposure tests were determined from curves of creep deformation established at 600°, 800°, and 900°F. It was the aim of these tests to establish the curves for 0.2, 0.5, 1.0 and 2.0 percent creep deformation in periods up to 100 hours. The nominal stresses for the creep exposures were then taken as the intersection of these curves with the ordinates at 10 or 100 hours. In some cases, further experience with the creep exposure tests necessitated readjustment of the stresses. This additional information was also used to revise the creep deformation relationships.

The data for these tests are summarized in Table 4 and plotted in Figure 6. The tests were usually discontinued once the limit of useful information had been reached although one specimen each was allowed to run until fracture at 800° and 900°F. The unfractured creep specimens were tensile tested at room temperature in order to gain some indication of the effect of creep-exposure.

In the 600°F creep tests considerable difficulty was encountered in fixing the curves for 1.0 and 2.0 percent creep deformation. The stresses required to reach this deformation in a short time were quite close to the ultimate strength and two tests were even run successfully at 140,000 psi, a stress above the 139,250 psi determined by short-time testing to be the average strength at this temperature. A large amount of short-time plastic deformation occurred during loading of a number of the 600°F creep specimens. This was a consequence of using test stresses above the proportional limit in order to reach the desired amount of creep deformation.

In the tests conducted at 800° and 900°F the required amounts of creep deformation were generally obtained without the necessity of using stresses above the yield strength. The creep deformation relationships at these temperatures were establish with little difficulty.

Tension tests at room temperature of the discontinued creep specimens revealed changes in the strength and ductility from the as-treated condition.

In Figure 7 the ultimate tensile strength, tensile yield strength, and elongation are plotted as a function of the total plastic strain in the creep test. The creep time is indicated for each point. Since these data represent a wide range of creep time as well as deformations no attempt was made to draw correlation curves.

The specimens crept at 600°F for periods between 10 and 1030 hours all had increased tensile strength and yield strength and decreased ductility from the as-treated condition. The increase in tensile strength ranged from 6-percent to 35-percent over the base value; the increase in yield strength ranged from 18 to 35-percent over the base value; while the absolute value of the elongation dropped from nearly 9-percent down to only one percent. It appeared that the change in properties from 600°F creep was more a function of the amount of prior creep than of the time of exposure.

The specimens crept at 800°F had increased ultimate tensile strength and tensile yield strength and slightly decreased ductility. The increase in tensile strength was moderate and reached only 9 percent over the base value while the yield strength increased as much as 20 percent. The lowest elongation observed was 4.3-percent. Again there was an indication that the properties after exposure were affected by the amount of prior creep.

The specimens crept at 900°F all had a decreased ultimate tensile strength and exhibited little or no change in the tensile yield strength with increased creep. The decrease in ultimate strength ranged from 6 to 12 percent of the base value while the variation in the tensile yield strength was only 5 percent of the base value. This is within the variability of the base condition. In two of the four specimens crept at 900°F the elongation was slightly higher than the base condition; in the other two it was reduced.

The specimens crept at 600 or 800°F had an increased hardness of up to 3 points Rockwell "C" while the specimens crept at 900°F had either an unchanged or slightly decreased hardness.

TENSION AND COMPRESSION PROPERTIES AFTER EXPOSURE

Unstressed Exposure

Room Temperature Tension Tests. Tension tests were conducted at room temperature on specimens exposed without stress for 10, 50 or 100 hours at 600°, 800°, and 900°F. Additional tests were later conducted on specimens exposed at 700°F for 10 or 100 hours. The test data are tabulated in Table 5 and plotted as a function of exposure time and temperature in Figure 8.

The effect of the unstressed exposures on the room temperature properties was small but showed some consistency. The ultimate strength curves fell within a range of ± 5 percent of the base condition while the yield strengths were either unaffected or increased up to 15 percent above the base value depending on the exposure temperature and time. Little or no change was observed in the elongations of these specimens.

Exposure at 600°F had little effect on the ultimate tensile or tensile yield strengths, while the 700° and 800°F exposures produced increased strengths. The exposure at 900°F caused the strengths to drop back close to the original values. A cross plot of these data at an exposure time of 100 hours shows the effect more clearly (Figure 9) and indicates that the material increased in strength as a result of further aging up to 800°F and was probably overaged at 900°F. The hardness data in Table 5 tend to confirm this.

Elevated Temperature Tension Tests. The results of tension tests conducted at the exposure temperature following unstressed exposure are summarized in Table 5 and plotted in Figure 10.

The effects of the unstressed exposure on the elevated temperature properties were generally small. The ultimate strength at 600°F after 100 hours exposure and the ultimate strengths after all the exposures at 800° or 900°F were increased about 6-8 percent. The increases in the yield strength were slightly greater and reached 10 to 15 percent for the 50 hour exposures at 800° or 900°F. The ductilities, however, were apparently unaffected. Only the specimens tested at 800°F showed any increase in hardness.

Room Temperature Compression Tests. The results of room temperature compression tests on specimens subjected to unstressed exposure are summarized in Table 6 and plotted in Figure 11.

All of the unstressed exposures caused some increase in the compressive yield strength. The increase in strength ranged from 4 percent above the base value for 10 hours exposure at 600°F to 14 percent for 100 hours exposure at 800°F. The increased strength appeared to be principally dependent on temperature with the time of exposure a minor factor. A cross plot of the data for 100 hours exposure is included in Figure 9 and shows that the compressive yield strength behaved in a manner similar to the ultimate tensile and tensile yield strengths as a function of the exposure temperature. The strength was increased with temperature and reached a peak for the exposure at 800°F. It then dropped off somewhat at 900°F. This behavior is again indicative of an aging reaction.

Elevated Temperature Compression Tests. The data for the elevated temperature compression tests following unstressed exposure are summarized in Table 6 and plotted in Figure 12.

Unlike the elevated temperature tensile properties, the compressive strength was significantly affected by the unstressed exposure. Although the 600°F strength was increased only 8 percent above the base value at 600°F, the 800°F strengths were increased up to 30 percent and the 900°F strengths were increased up to 44 percent. The greatest part of the increased strength at 800° and 900°F occurred in the first 10 to 20 hours of the exposure period. The slight increase in strength occurring at 600°F took place over the entire test period.

Creep Exposure

Room Temperature Tests. Creep-exposure tests were run for 10 or 100 hours at 600°, 800°, and 900°F. Some additional tests were then run at 700°F in order to clarify the initial results. The room temperature tension test data from these exposures are summarized in Table 7 and the room temperature compression test data are summarized in Table 8. Plots of the effect of prior creep on the short-time properties are presented in Figures 13 to 17 for each exposure time and temperature.

Creep-exposure at 600°F had quite a substantial effect on the strength and ductility of the Ti-16V-2.5Al sheet (Figure 13). The ultimate strength and the tensile yield strength were increased and the compression yield strength and elongation were decreased as the amount of creep was increased. Similar effects were noted in both the 10 and 100 hour exposures.

Reference to Table 7 shows that short-time plastic deformation was obtained during loading of most of the specimens exposed at 600°F. This came about since most of the loads required to reach the desired amounts of creep were above the proportional limit. In the 10 hour tests, the short-time loading strain ranged from 30 to 50-percent of the total plastic strain, while in the 100 hour tests, the short-time strain ranged from zero to 30 percent of the total strain. Some trouble with inconsistent premature failure was encountered with several specimens loaded to high stresses at 600°F. For this reason the data only cover creep deformation of up to one percent in 100 hours.

Research carried out in another phase of this investigation (Ref. 3) indicated that there was no apparent difference in the relative influence of short-time strain and creep strain in cases where the short-time strain ranged up to 30 percent of the total plastic strain and where there was no opportunity for a no-load recovery period during the test. These conditions were substantially fulfilled during the present exposures to 600°F.

Figure 14 presents a correlation of the 600°F creep-exposure data in terms of total plastic strain. These curves had the same shapes as the curves in Figure 13 which were based on creep deformation. There was no apparent difference in the time dependency revealed by either method of correlation.

The increase in the ultimate strength after 600°F creep-exposure ranged up to 20 percent above the base value, while the tension yield strength was increased as much as 35 percent. The compression yield strength was reduced to as much as 20 percent. One percent total strain caused the absolute value of the elongation to drop from 8.8 percent down to about one to two percent. The hardness of these specimens was increased only 2-3 points Rockwell "C".

Creep-exposures conducted at 700°F had a similar but less severe effect on the tension and compression strength than did the 600°F exposures while the ductility was not particularly decreased. (Figure 15). In these tests virtually all the plastic deformation was obtained during creep and there was no need to consider separately the effect of total plastic strain. The increase in the ultimate strength was barely outside the limit of variability established by the base property tests. The yield strengths, however, were affected to a greater degree. The tension yield strength was increased by a creep deformation of one percent approximately 10 to 12 percent above the value established by exposure to temperature alone, while the compression yield strength was decreased about 22 percent in the 10 hour exposure and only 7 percent in the 100 hour exposure to one percent creep. It will be recalled that both the tension and compression yield strengths were increased about 11 percent over the base value by the exposure at 700°F without stress. For none of the 700°F creep exposures was the elongation reduced below 6.5 percent.

The creep-exposures at 800°F had very little effect of significance on the ultimate strength and the elongation and only slight effects on the tension and compression yield strength (Figure 16). The tension yield strength was increased up to about 5 percent by creep in the 10 hour tests while the compression yield strength was reduced up to 8 to 15 percent with increased creep.

As was the case in the 700°F exposures, 10 hours creep caused a greater decrease in the compression yield strength than did 100 hours creep. The changes in elongation following 800°F creep-exposure were small and may have been due to experimental variability. Hardness was increased up to 4 points Rockwell "C".

Figure 17 shows the effects of creep-exposure at 900°F on the room temperature tension and compression properties of Ti-16V-2.5Al. Again there was very little change in either the ultimate tensile strength or the ductility while the tension and compression yield strengths were affected slightly. The tension yield strength was increased about 9 percent by one percent creep in 10 hours, but less than 4 percent by the same amount of creep in 100 hours. Conversely, the compression yield strength was decreased only 3-4 percent by one to two percent of creep in 10 hours, while the decline in the 100 hour test results was as much as 10 percent. However, most of this decrease was indicated by one test point and the possibility of experimental variability should not be ruled out. Thus the indicated decline may be spurious. The hardness of these samples was increased from one to three points Rockwell "C" above that of the as-treated condition.

A clearer understanding of the effects of creep-exposure on the room temperature tension and compression properties of Ti-16V-2.5Al can be gained from Figure 18. In this figure the mechanical properties are plotted as a function of the exposure temperature for both 100 hours unstressed exposure and for exposure to one percent creep (total plastic strain in the case of the 600°F data) in 100 hours. This figure shows that at 600°F the creep caused a large change in the ultimate tensile and yield strength over that caused by the exposure to temperature alone. The effects of creep on the tensile strength were maintained to a limited extent at 700°F, however, the ductility was not particularly affected. There was a significant difference in compression yield strengths up to 800°F.

The increase in tension yield strength and decrease in the compression yield strength with increased creep in the 600°F and 700°F exposures is a manifestation of a Bauschinger effect, while the behavior of the ultimate strength and ductility is due principally to the effect of stress-accelerated age-strengthening. These concepts will be discussed in greater detail in a later section of the report. (pp. 21-24)

Creep-Exposure of Transverse Specimens. Creep-exposure tests at 600°F were carried out on two specimens of Ti-16V-2.5Al taken in the transverse direction to rolling in order to check the previous results on the longitudinal specimens (Table 7). The data from the transverse tests is summarized in Table 9 and plotted as a function of creep deformation or total plastic strain in Figure 19.

The results of these tests were similar to the corresponding tests of longitudinal specimens. The ultimate tension strength and tension yield strength were increased with creep and the compression yield strength and the elongation were decreased. The relative extent of the changes was about the same for either test direction.

Elevated Temperature Tests. The results of the short-time tests run at the temperature of creep exposure following exposures for 10 or 100 hours at 600°, 800°, or 900°F are summarized in Tables 10 and 11 and plotted in Figures 20-22. In general, the effects noted in the elevated temperature tests were similar to those found in the corresponding tests at room temperature.

Creep-exposure at 600°F caused an increase in the ultimate tensile strength and the tensile yield strength, a large decrease in the compressive yield strength, and a moderate decrease in the ductility.

(Figure 20). The necessity of using loads low enough to avoid premature fracture at 600°F limited the amount of creep deformation obtained. The maximum increase in the ultimate strength was only about 5 percent in contrast to the 20 percent found in the room temperature tests. The tension yield strength was increased from 16 to 25 percent depending on the exposure time and the compression yield strength was decreased from 20 to 25 percent. These changes were slightly less than the corresponding effects in the room temperature tests.

On the other hand, the elongation in the 600°F tests was not reduced as severely as in the room temperature tests. Most of the elongations of these specimens remained above 5 percent. The only exception was a specimen whose reduction of area, however, was not affected. Thus, the low elongation indicated for this specimen may have been due to experimental variability. The hardnesses of the 600°F specimens were very slightly increased above the as-treated hardness.

Creep-exposures at 800°F produced little or no change in the 800°F tensile properties but did cause some decrease in the compression yield strength. (Figure 21). The slight changes in the ultimate tensile strength, the tensile yield strength and the elongation were generally within the limits established by the base property tests. There was a slight indication of increased tensile yield strength for one of the specimens exposed to creep for 100 hours. This increase was about 12 percent over the value for the exposure to temperature alone. The compressive yield strength after 10 or 100 hours creep-exposure to one percent deformation was decreased about 12 percent from the value for unstressed exposure. Hardness increases of one to two points Rockwell "C" were noted in these samples.

In contrast to the results of the 800°F tests, the creep-exposures at 900°F caused apparently significant changes in the 900°F properties (Figure 22). The ultimate tensile strength and tensile yield strength were increased from 10 to 20 percent above the base condition by the application of one to two percent creep. Accompanying the increases in the tensile strength was a decrease in the ductility from an original value of 25 percent down to about 15 percent.

The compressive yield strength remained well above the base value, being decreased in the 100 hours exposure only 8 percent from the increased strength that resulted from unstressed exposure.

Scatter in the compression test results for the 10 hours exposure made it difficult to correlate the results. This was the only test condition studied for this alloy in which testing scatter made the results uncertain. Apparently, creep exposure for 10 hours at 900°F either increased the 900°F compression yield strength or did not change it.

In any event, the changes in the elevated temperature properties after creep-exposure at 800° or 900°F were not large. In no case was the strength reduced below the value for the as-treated material and the ductilities all remained high. At 600°F, however, the compression yield strength was decreased below the value for the as-treated material while the tension yield strength was substantially increased., These changes in strength were obtained with only a moderate decrease in ductility.

TENSION-IMPACT PROPERTIES AFTER EXPOSURE

Unstressed Exposure

Room Temperature Tests. Data from the room temperature tension-impact tests following unstressed exposure is summarized in Table 12 and plotted in Figure 23. Most of the test points fall within the range obtained for the base property tests of the as-treated material. The 100 hour exposure at 600°F fell slightly below this range while the 50 and 100 hour exposures at 900°F were slightly above the range. The only additional condition showing a large decrease in ductility was the one specimen exposed for 10 hours at 700°F. This may have been due to experimental variability.

It appears generally that the unstressed exposure at 600° to 800°F had little effect on the tension-impact properties while the 900°F exposures may have caused some increase in the tension-impact strength.

Elevated Temperature. The results of the tension-impact tests conducted at the exposure temperature following unstressed exposure are summarized in Table 12 and plotted in Figure 24. The data indicate no apparent change in tension impact strength as the result of exposure. The elongations were also not affected significantly. Although some variations were obtained in the reduction of area data they were not consistent and no significance is attached to the variation.

Creep Exposure

Room Temperature Tests. The test results for specimens subjected to creep and then tension-impact tested at room temperature are summarized in Table 13 and plotted in Figure 25. Because of the lack of effect found in the unstressed exposure tests, the creep-exposures were confined to 10 hours.

Creep-exposure at 600°F reduced both the tension-impact strength and ductility of Ti-16V-2.5Al. Creep of up to one percent caused the tension-impact strength to be reduced by about 50 percent from the base value, while both the elongation and reduction of area were reduced to absolute values of about two percent.

Test scatter complicated the interpretation of the data for the 700°F creep-exposures. It is possible that the data for the unstressed exposure at 700°Farein error. The correlation curve for this temperature was drawn on the assumption that the unstressed exposure should have produced little change in properties from the base condition. In any event, the loss in tension-impact strength was less than that obtained at 600°F and the ductility does not appear to have been reduced significantly below that of the base condition.

The creep-exposure at 800°F caused some decrease in the tension-impact strength but no significant reduction in the ductility. The maximum decline in the strength was about 30 percent below the base condition. This compares fairly well with the test points for the 700°F exposure.

Following creep-exposure at 900°F there was a small increase in the tension-impact strength. It is doubtful that this was a real effect. Neither the elongation nor the reduction of area were affected by the 900°F exposures.

It appears, therefore, that creep exposure in the range from 600° to 800°F caused a reduction in the tension-impact strength of Ti-16V-2.5Al that was somewhat dependent on the amount of prior creep. The maximum reduction in strength ranged from 30 to 50 percent of the base condition. The ductility of the material was only reduced significantly by the 600°F exposures.

Elevated Temperature Tests. Tension-impact properties for specimens tested at the temperature of prior creep are summarized in Table 13 and plotted in Figure 26. These results are limited to creep-exposures conducted at 600° and 900°F.

In the tests at 600°F very little change was found in the tension-impact strength as the result of creep-exposure. The ductilities of the specimens were decreased however as the amount of creep was increased.

Following creep-exposure at 900°F the tension-impact strength was increased and the ductility was decreased. This behavior was quite similar to that found in the tensile tests at 900°F following creep at 900°F (Figure 22).

The extent of the losses in ductility following prior creep was about the same in both the 600° and 900°F tests.

METALLOGRAPHIC EXAMINATION OF TI-16V-2.5Al.

Metallographic examination of the Ti-16V-2.5Al alloy was made of a number of specimens after creep-exposure. Optical examination of the material was complicated by its extremely fine structure and susceptibility to staining. For example, Figure 27 illustrates the difficulties encountered in trying to interpret optical micrographs of the solution treated and aged condition. A number of the more common titanium etchants were tried with uniformly poor results in attempts to minimize the staining problem. Little success was also had with a 50%H_2O_2, 1%HF, 2%HNO_3 plus water, brightening solution suggested by The Mallory-Sharon Metals Corporation.

Quite good results were, however, obtained with the use of the electron microscope to examine replicas of the stained surfaces. The as-treated structure is shown at 3500x magnification in Figure 28 and at 8200x magnification in Figures 29 and 30. Figure 29 shows the longitudinal face of the material (i.e., in the direction of rolling) while Figure 30 shows the transverse section (across the thickness of the sheet). The structure consisted of inter-connected, blocklike primary alpha grains in a beta matrix. A very fine alpha precipitate appears throughout the matrix.

Changes in the structure as the result of creep-exposure were apparently confined to possible further precipitation and the growth and coalesence of the alpha phase. This shown by Figures 31 and 32, which are the longitudinal and transverse faces of a specimen crept to 1 percent total plastic strain in 100 hours at 600°F. The room temperature tensile elongation of this sample was only 2 percent in contrast to the 8.2 percent elongation of the as-treated condition.

The short-time test results indicated that it was the deformation rather than the exposure time that governed properties after exposure at 600°F. Figures 33 for 10 hours exposure and 34 for 1030 hours exposure show that there was some tendency for a reduction in the amount of the fine precipitate in the matrix as the exposure time was increased and an increase in the amount of the primary alpha in both structures as compared to the as-treated condition.

Figures 35 and 36 show respectively the structures of specimens that had good ductility after unstressed exposure for 100 hours at 800°F or stressed exposure for 10 hours at this temperature. The ductility of these samples was close to the as-treated value, however, the structures apparently were not markedly different from the samples exhibiting brittle behavior after 600°F exposure.

Perhaps the greatest change in appearance from the as-treated condition was noted in a specimen crept to one percent deformation in 428 hours at 900°F. (Figures 37 and 38) The fine precipitate in the matrix in the transverse view (Figure 38) particularly showed a considerable amount of growth and agglomeration in comparison to the as-treated condition. The 5.5 percent elongation of this specimen was somewhat below the 8.2 percent of the as-treated condition, however, it was appreciably higher than the elongation of the specimens crept at 600°F.

It appears, therefore, that the age-hardening of this material was not complete in the original heat treatment in 4 hours at 990°F. Further transformation probably occurred under the influence of the creep stress at 600°F or at the higher temperatures. It was not clear from the data whether the reaction was a simple one or included a secondary aging peak. It is probable, however, that the sample crept for 428 hours at 900°F was overaged.

DISCUSSION

The results of this investigation indicate that creep-exposures particularly at 600° or 700°F, had a significant effect on the short-time strength and ductility of solution treated and aged Ti-16V-2.5Al alloy. The changes found were an increased ultimate tensile strength and tensile yield strength and a decreased compressive yield strength and tensile elongation. The effects appear to be more dependent on the amount of prior creep than on the time of exposure.

These property changes were the result of two mechanisms:

1. A structural instability of the material resulting in further age-strengthening during testing.

2. The effect of the super-imposed plastic strain of creep which accelerated the age-strengthening, caused the Bauschinger effect and may have produced a slight amount of strain hardening.

A good understanding of these effects can be gained from Figure 18 which shows the effect of testing temperature on the mechanical properties following unstressed exposure for 100 hours or exposure to one percent creep in 100 hours.

The unstressed exposure caused an increase in the ultimate strength and the tensile and compressive yield strengths that reached a peak at 800°F. This increase in strength was not especially large--amounting only to about 5 percent for the ultimate strength and about 14 percent for the yield strengths. Furthermore, the increased strength was accompanied by little sacrifice in ductility. The original 8.8 percent elongation was only reduced to about 8 percent by the exposure at 800°F. The exposure at 900°F caused a reduction in strength characteristic of over-aging.

The addition of creep strain to the 600°F exposures caused quite a substantial increase in the ultimate tensile strength and tensile yield strength above the level for the unstressed exposure. In addition, the compression yield strength was lowered and the elongation was substantially reduced.

This behavior was caused by a combination of the two factors mentioned above. Most of the increase in tensile strength was due to stress-accelerated aging. The changes in the yield strength resulted from Bauschinger effects produced by the plastic strain. While only a few percent of plastic strain are required to produce Bauschinger effects, the amount obtained in this investigation was well below that normally required to cause appreciable strain hardening.

The Bauschinger effect is defined as "the phenomenon by which plastic deformation of a metal raises the yield strength in the direction of plastic flow and decreases the yield strength in the opposite direction." (Ref. 6) Another report to be issued under this contract deals with the creep-induced Bauschinger effect. (Ref. 3) Consequently, the discussion of the effect in the present report will be limited.

The yield strengths measured in this investigation following creep-exposure at 600°F are net strengths. The compressive and tensile yield strengths were both increased by the exposure to temperature while the tensile yield strength was increased and the compressive yield strength was decreased by the Bauschinger effect. The observed tensile yield strength is comprised of a plus component from the Bauschinger effect and a plus component from age-strengthening. The observed compressive yield strength is comprised of a plus component from age-strengthening and a minus component from the Bauschinger effect. Furthermore, the ultimate tensile strength was increased mainly by age-strengthening while the adverse effect on ductility followed from the same cause.

Since the ductility was not significantly reduced by the unstressed exposure at 600°F, then stress-accelerated age-strengthening must have played a role in reducing the ductility following the 600°F creep exposure. Ordinarily, strain-hardening might be considered to be a minor factor since the existence of a Bauschinger effect implies the presence of residual plastic strain which of course is a requisite of strain hardening. However, appreciable strain hardening requires more than the few percent of plastic deformation obtained in these creep exposures.

In the 700°F exposures all these factors were operative, however. The higher temperature resulted in less residual plastic strain and the age-strengthening was the major factor affecting the properties. This was evident from the fact that the net compression yield strength after 700°F exposure was considerably higher than the strength following the 600°F exposure.

Following the peak age-strengthening effect at 800°F the properties became dependent principally on the temperature of exposure. As mentioned previously, the 900°F results indicate that the material was over-aged and the ductility data for the 900°F creep-exposures again suggest that the over-aging was stress-accelerated since the ductility was slightly increased.

These observations are in fairly good agreement with both the hardness data and the metallographic studies, however, because of the interaction of the effects, it is impossible to establish just what fraction of the net observed change in strength is due to each factor.

The behavior of the Ti-16V-2.5Al alloy was different in several respects from that previously observed for C110M titanium (a binary alloy containing 8 percent manganese). (Ref. 2) The first difference was that the C110M was tested in the hot-rolled and annealed condition and consequently precipitation-hardening or age-strengthening during testing was not much of a factor. There was, however, some breakdown of the beta phase under the influence of the exposure conditions (Ref. 3) that may have resulted in a minor amount of strengthening. In the C110M alloy, the Bauschinger effect was found to be at its maximum for the creep exposures at 700°F, while for the Ti-16V-2.5Al the effect was most marked after the 600°F exposure.

It should be noted, however, that the lowest exposure temperature studied for C110M was 650°F. It is possible that larger effects might have been observed if creep-exposures had been conducted at 600°F.

In most respects, however, it appeared that the stress-accelerated transformation of the Ti-16V-2.5Al made it susceptible to a greater number of changes in properties than the C110M was capable of. Thus, the higher strength of the Ti-16V-2.5Al alloy was obtained at some sacrifice of stability.

It should be remembered, however, that the low ductility conditions of Ti-16V-2.5Al were obtained after creep that was accompanied by a substantial amount of short-time plastic loading strain. In actual practice it is unlikely that loads would be used that were above the yield strength or proportional limit at 600° or 700°F. Thus, these changes in properties may be more of academic interest than of practical concern.

CONCLUSIONS

Exposure of solution treated and aged Ti-16V-2.5Al sheet to temperatures between 600° and 900°F and creep deformations of up to 2 percent in 100 hours resulted in changes in mechanical properties that were due to both the structural instability of the material and to the super-imposed plastic strain of creep. Increased tensile strength and decreased elongation after creep exposure at 600°F was attributed mainly to stress-accelerated age-strengthening. An increased tensile yield strength and decreased compressive yield strength were manifestations of the Bauschinger effect caused by the plastic strain from the creep exposure. Exposure to temperature alone caused changes in properties indicative of age-strengthening. A lesser change in properties was noted for creep exposures conducted at 700°F.

Peak properties from the age-strengthening reaction were noted in the unstressed exposures conducted at 800°F and a drop in strength from overaging was observed following the 900°F exposures. The application of stress caused little additional effects in the 800° and 900°F exposures beyond those noted for the exposure to temperature alone.

Metallographic evidence supported the existence of an age-strengthening reaction.

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TABLE I

TENSILE TEST DATA FOR TI-16V-2.5Al

Test Temp. (°F)	Specimen No.	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Reduction of Area (%)	Modulus, E x 10^6(psi)	Hardness R"C"
Room	1AL17T	162,000	149,000	9.0	24.0	14.1	36
	1CL4T	173,200	156,300	8.5	17.0	15.1	37
		167,600	152,650	8.8	20.5	14.6	36.5
	7BL35T	175,300	152,500	9.0	14.5	15.5	37.3
	7CL14T	180,000	149,000	8.5	14.1	14.0	37.2
		177,650	150,750	8.8	14.3	14.8	37.2
Average - 4 tests		172,625	151,700	8.8	17.4	14.7	36.8
600	1AL20T	134,000	112,000	10.0	28.0	12.8	
	1DL31T	142,000	120,000	7.0	15.0	12.6	
		138,000	116,000	8.5	22.5	12.7	
	7AL2T	137,000	117,000	7.0	37.0	12.2	
	7BL30T	144,000	122,000	9.0	30.0	12.7	
		140,500	119,500	8.0	33.5	12.4	
Average - 4 tests		139,250	117,750	8.2	28.0	12.6	
800	1CL3T	130,000	111,000	9.0	25.0	12.0	
	1DL32T	124,000	105,000	15.0	29.0	11.3	
		127,000	108,000	12.0	27.0	11.6	
	7AL6T	123,500	108,000	11.0	39.5	11.2	
	7CL17T	122,000	97,000	20.0	38.1	11.1	
		122,750	102,500	15.5	38.8	11.2	
Average - 4 tests		124,875	105,250	13.8	32.9	11.4	
900	1AL18T	92,700	79,300	20.0	44.0	11.9	
	1DL30T	103,000	78,300	27.0	43.0	11.6	
		97,850	78,800	23.5	43.5	11.8	
	7AL7T	93,600	77,300	30.0	64.8	10.0	
	7CL24T	97,000	82,000	24.5	60.6	9.9	
		95,300	79,650	27.2	62.7	10.0	
Average - 4 tests		96,575	79,225	25.4	53.1	10.9	

TABLE 2

COMPRESSION TEST DATA FOR TI-16V-2.5Al

Test Temp. (°F)	Specimen No.	0.2% Offset Yield Strength, psi	Modulus, E x 10^6(psi)
Room	1AL14C	168,000	15.6
	1CL3C	172,000	15.2
	1DL35C	167,000	15.1
		169,000	15.3
	7AL7C	171,000	15.4
	7BL25C	168,000	16.5
	7CL13C	172,000	16.0
		170,300	16.0
Average - 6 tests		169,700	15.6
600	1AL13C	126,000	13.2
	1DL30C	128,000	13.2
		127,000	13.2
	7AL11C	126,000	14.8
	7CL14C	132,000	15.0
		129,000	14.9
Average - 4 tests		128,000	14.0
800	1AL18C	109,000	12.2
	1DL26C	100,000	12.7
		104,500	12.4
	7AL2C	108,000	12.2
	7CL18C	115,000	12.0
		111,500	12.1
Average - 4 tests		108,000	12.3
900	1AL22C	73,000	11.5
	1DL32C	72,700	12.4
		72,850	12.0
	7BL31C	72,000	11.1
	7CL23C	72,700	12.5
		72,350	11.8
Average - 4 tests		72,600	11.9

TABLE 3

TENSION-IMPACT TEST DATA FOR TI-16V-2.5Al

Test Temp. (°F)	Specimen No.	Tension-Impact Strength, ft-lb.	Elongation (%)	R. A. (%)
Room	1CL15-3	55	6.5	18.4
	1CL17-1	41	6.3	14.8
	Average	48	6.4	16.6
	7AL25-3	40	7.5	21.5
	7AL26-3	38	---	20.4
	Average	39	7.5	21.0
Average - 4 tests		43.5	6.8	18.8
600	1CL15-2	33	6.3	27.0
	1CL17-3	29	7.0	29.0
	Average	31	6.6	28.0
	7AL26-1	34	7.5	30.0
Average - 3 tests		32	6.9	28.7
800	1C16-2	27	6.8	23.0
	7AL26-2	27	6.0	24.0
Average - 2 tests		27	6.4	23.5
900	1CL16-3	28	6.3	23.0
	7AL25-1	25	6.5	25.0
	7AL25-2	26	7.0	25.0
	Average	25.5	6.8	25.0
Average - 3 tests		26.3	6.7	27.7

TABLE 4

RUPTURE AND CREEP DEFORMATION DATA FOR TI-16V-2.5Al ALLOY

(1380°F-1/2 hour-WQ; 990°F-4 hours-AC)

Test Temp. (°F)	Specimen No.	Stress (psi)	Rupture Time (hrs, if any)	Elong. (%)	R.A. (%)	Hardness After Test R"C"	Total Loading Def. (%)	Plastic Loading Def. (%)	Time to Reach Indicated Creep Deformation (hrs) 0.2	0.5	1.0	2.0	Final Creep Def. (%)	Total Plastic Def. (%)	Room Temperature Tensile Properties of Unfractured Creep Specimens: Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elong. (%)	R.A. (%)	Modulus, E x 10^6, psi
600	1CL5T	140,000	>1030.1*	--	--	40.0	2.29	1.25	---	0.02	0.04	3.5	6.10	7.35	230,000	---	1.0	4.0	14.0
	1ALT6 **	140,000	> 10.0*	--	--	38.4	3.78	2.80	0.2	0.45	0.8	7.3	2.22	5.02	204,000	(204,000)	1.5	12.3	13.7
	7CL33T**	138,000	> 10.0*	--	--	36.6	1.52	0.53	0.4	0.95	20(est)	---	0.79	1.32	196,700	196,700	2.5	8.3	15.1
	7AL18T	138,000	0.01	8.0	29.0	35.4	2.35	1.30	---	----	----	---	--	--	---	----	---	----	----
	1ALT3 **	135,000	> 9.9*	--	--	36.5	1.66	0.86	0.9	4.0	----	---	0.63	1.49	186,500	186,500	3.0	18.8	14.7
	1ALT1 **	125,000	> 100.0*	--	--	--	1.17	0.26	9.5	78.0	----	---	0.59	0.85	191,200	191,200	3.2	9.7	14.2
	1AL19T	120,000	> 325 *	--	--	--	1.49	0.45	8.5	63.0	196	---	1.29	1.74	202,200	198,500	3.0	14.2	15.1
	1DL34T	110,000	> 676.1*	--	--	--	0.79	nil	26.0	144.0	----	---	1.07	1.07	202,500	200,500	3.5	7.4	14.5
	7AL9T	100,000	> 263.8*	--	--	40.0	0.76	nil	24.0	145.0	540(est)	---	0.71	0.71	191,000	188,000	5.0	15.0	15.0
	7AL8T	90,000	> 171.1*	--	--	38.4	0.66	nil	93.0	320(est)	----	---	0.29	0.29	183,000	179,000	7.3	15.1	14.6
800	1CL8T	70,000	251.9	32.7	53.7	40.0	0.54	0.02	0.6	1.5	5.0	17.5	>> 5.6	--	---	----	---	----	----
	1DL33T	55,000	> 336.9*	--	--	41.0	0.45	nil	1.8	4.5	14.5	54.0	5.57	5.57	178,000	174,000	4.3	20.6	15.1
	7BL33T	45,000	> 171.1*	--	--	--	0.34	nil	1.7	9.5	39.5	168.5	1.99	1.99	188,800	183,000	6.5	17.5	15.2
	7BL32T	35,000	> 171.2*	--	--	40.0	0.24	0.02	4.6	20.5	100.0	---	1.21	1.23	181,000	174,000	8.8	16.0	14.6
	7AL4T	20,000	> 340.3*	--	--	--	0.13	nil	12.5	137.0	----	---	0.68	0.68	174,800	170,000	9.5	25.0	16.0
	1AL24T**	14,000	> 100.0*	--	--	38.3	0.11	nil	30.0	----	----	---	0.30	0.30	175,000	169,000	12.0	18.9	14.9
900	1DL28T	25,000	226.0	44.3	82.0	34.7	0.23	nil	1.4	3.4	7.4	21.5	>>3.5	--	---	----	---	----	----
	7AL12T	20,000	> 142.9*	--	--	36.0	0.17	nil	1.0	6.5	21.0	64.0	3.81	3.81	163,000	160,000	7.5	18.6	14.8
	7CL16T	15,000	> 362.3*	--	--	36.3	0.13	nil	4.4	25.0	94.0	260.0	2.57	2.57	161,500	157,000	11.0	29.5	14.7
	7AL5T	10,000	> 428.5*	--	--	35.6	0.21	nil	10.0	66.0	357.0	---	1.10	1.10	153,000	152,000	5.5	22.6	14.9
	1AL21T	5,000	> 325.0*	--	--	37.0	0.03	nil	99.0	----	----	---	0.37	0.37	152,000	152,000	11.0	28.0	14.9

\> Greater than.
\>> Much greater than.
* Test stopped before rupture.
** Data from stress-exposure test.
(est) Estimated.

TABLE 5

EFFECT OF UNSTRESSED EXPOSURE ON TENSILE PROPERTIES OF TI-16V-2.5Al

	Exposure Conditions			Tensile Properties After Exposure							
Specimen No.	Temp. (°F)	Stress (psi)	Time (hrs)	Test Temp. (°F)	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	R.A. (%)	Modulus, E x 10^6(psi)	Hardness R"C"
7BL36T	600	none	10	room	175,000	161,500	7.5	16.0	14.3	38.3
1DL26T		none	50	room	170,700	155,900	11.0	11.3	14.3	--
1AL13T		none	100	room	166,200	152,500	9.5	22.1	14.0	34.6
7CL13T	700	none	10	room	180,000	163,900	10.5	21.0	15.0	39.5
7AL3T		none	100	room	177,000	165,000	8.3	29.7	14.7	--
7AL1T	800	none	10	room	176,300	166,500	10.0	22.0	15.0	39.2
1AL14T		none	50	room	170,000	--	9.5	26.3	14.1	38.4
7BL26T		none	50	room	183,500	174,000	8.5	14.7	15.3	--
7CL18T		none	100	room	182,000	173,500	8.0	23.4	14.8	36.7
1AL15T	900	none	25	room	166,400	159,000	11.0	25.8	14.9	36.9
7BL25T		none	50	room	167,200	159,500	10.0	18.9	15.0	--
1DL29T		none	100	room	163,500	158,500	8.0	26.5	15.5	37.9
1CL10T	600	none	10	600	142,000	120,000	8.0	22.6	13.1	37.3
7AL11T		none	50	600	136,800	117,000	7.0	39.2	12.5	36.1
7CL23T		none	100	600	148,500	126,000	7.5	29.3	12.5	36.5
1CL12T	800	none	10	800	133,800	113,700	11.0	23.2	11.9	39.9
7BL34T		none	50	800	134,200	119,000	13.5	30.3	11.3	41.3
1DL25T		none	100	800	132,600	112,500	12.0	28.6	13.7	38.2
7BL31T	900	none	10	900	104,000	86,100	28.0	51.0	10.3	--
7AL10T		none	25	900	99,800	87,200	24.0	48.0	10.3	35.5
1CL11T		none	50	900	104,000	93,500	27.0	50.8	10.6	38.1
7CL15T		none	100	900	102,800	81,400	24.0	50.4	10.5	37.4
7AL22T	Inadvertently heated to 1500°F for 1/2-hour - Air Cooled.			room	137,000	129,000	5.0	28.1	14.7	

TABLE 6

EFFECT OF UNSTRESSED EXPOSURE ON COMPRESSION PROPERTIES OF TI-16V-2.5Al

Exposure Conditions				Compression Properties After Exposure		
Specimen No.	Temp. (°F)	Stress (psi)	Time (hrs)	Test Temp. (°F)	0.2% Offset Yield Strength (psi)	Modulus, E x 10^6, psi
1CL94C	600	none	10	room	174,200	15.3
7BL26C		none	50	room	179,000	15.4
1CL97C		none	100	room	180,500	15.7
1CL98C	700	none	10	room	186,000	16.5
1CL96C		none	100	room	187,500	15.4
7AL6C	800	none	10	room	186,000	17.6
1DL36C		none	50	room	186,500	16.4
7CL17C		none	100	room	192,000	16.3
1CL10C	900	none	25	room	178,900	15.4
7BL34C		none	50	room	183,800	16.2
1AL23C		none	100	room	179,500	16.4
7CL24C	600	none	10	600	133,000	14.0
1DL27C		none	50	600	133,200	13.8
7CL15C		none	100	600	138,000	15.1
1CL12C	800	none	10	800	131,000	13.3
1CL93C		none	10	800	131,700	13.2
7AL10C		none	50	800	136,900	13.6
1DL31C		none	100	800	138,000	16.4
1CL91C	900	none	10	900	92,000	12.5
7AL1C		none	25	900	103,100	12.8
1AL15C		none	50	900	80,300	11.9
		none	50	900	103,000	11.4
1CL92C		none	100	900	105,000	12.8

TABLE 7

EFFECT OF PRIOR CREEP ON ROOM TEMPERATURE TENSILE PROPERTIES OF TI-16V-2.5Al

Nominal Exposure Conditions: Temp. (°F)	Time (hrs)	Creep Def. (%)	Specimen No.	Actual Exposure Conditions: Time (hrs)	Stress (psi)	Total Load Def. (%)	Plastic Load Def. (%)	Creep Def. (%)	Total Plastic Def. (%)	Total Def. (%)	Room Temperature Tensile Properties After Exposure: Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elong. (%)	R.A. (%)	Modulus, E x 10^6, psi	Hardness R"C"
600	10	0.2	1CL7T	10.0	118,000	0.91	0.09	0.18	0.27	1.09	174,300	174,300	5.0	16.4	14.3	38.8
		0.5	1ALT3	9.9	135,000	1.66	0.86	0.63	1.49	2.29	186,500	186,500	3.0	18.8	14.7	36.5
		1.0	7CL33T	10.0	138,000	1.52	0.53	0.79	1.32	2.31	196,700	196,700	2.5	8.3	15.1	36.6
		2.0	1ALT6	10.0	140,000	3.78	2.80	2.22	5.02	6.00	204,000	204,000	1.5	12.3	13.7	38.4
	100	0.2	1DL36T	100.0	89,000	0.60	nil	0.17	0.17	0.77	177,700	167,500	9.0	13.5	13.3	39.5
		0.5	7CL19T	100.0	110,000	0.84	0.04	0.40	0.44	1.24	184,000	182,500	5.0	15.4	14.0	39.6
		1.0	1ALT1	100.0	125,000	1.17	0.26	0.59	0.85	1.76	191,200	191,200	3.2	9.7	14.2	--
		2.0	7CLT32	100.0	130,000	1.14	0.28	0.72	1.00	1.86	199,800	199,800	2.0	9.1	13.9	37.3
			1CL26T	nil	135,000	Broke on loading.										
700	10	0.2	7CL9T	10.0	75,000	0.51	nil	0.27	0.27	0.78	180,000	171,200	8.5	20.0	14.4	38.4
		1.0	1AL32T	10.0	100,000	0.81	0.07	0.84	0.91	1.65	176,000	176,000	8.5	20.5	14.3	39.6
			7AL35T	10.0	106,000	0.83	0.10	0.98	1.08	1.81	186,000	186,000	6.5	16.0	14.2	--
	100	0.5	1BL34T	100.0	57,000	0.41	nil	0.61	0.61	1.02	179,000	169,000	8.8	21.8	16.5	--
		1.0	7AL19T	100.0	80,000	0.61	nil	1.28	1.28	1.89	186,000	181,000	7.8	20.3	14.4	--
800	10	0.2	7CL34T	9.9	23,000	0.19	nil	0.26	0.26	0.45	184,000	174,000	9.0	18.9	15.0	39.5
		0.5	1AL22T	10.0	44,000	0.35	0.01	0.58	0.59	0.93	169,100	161,500	5.5	24.7	14.6	39.5
		1.0	1CL6T	10.0	61,000	0.50	nil	1.15	1.15	1.65	177,500	171,300	8.0	24.9	14.2	40.4
		2.0	7BL29T	10.0	76,000	0.52	nil	1.85	1.85	2.37	181,500	175,000	7.5	14.9	16.3	39.4
	100	0.2	1AL24T	100.0	14,000	0.11	nil	0.30	0.30	0.41	175,000	169,000	12.0	18.9	14.9	38.3
		0.5	7CL22T	100.0	22,000	0.15	nil	0.48	0.48	0.63	182,700	174,900	8.0	14.3	14.7	39.5
		1.0	1DL35T	100.0	35,000	0.28	nil	1.06	1.06	1.34	179,800	171,500	10.5	13.3	14.9	40.4
		2.0	1AL16T	100.0	50,000	0.38	nil	1.84	1.84	2.22	177,000	171,500	9.5	21.2	15.1	40.5
900	10	0.2	1CL2T	10.0	10,000	0.10	nil	0.21	0.21	0.31	172,600	160,000	8.0	16.0	14.3	38.9
		0.5	7BL27T	10.0	18,000	0.17	0.01	0.50	0.51	0.67	175,000	167,000	9.5	21.0	14.6	40.0
		1.0	7CL21T	10.0	24,000	0.21	nil	0.90	0.90	1.11	173,800	166,300	8.0	16.5	14.1	38.7
		2.0	7CL36T	10.0	29,500	0.28	nil	1.45	1.45	1.73	185,000	177,800	8.5	11.6	14.6	--
			1CL28T	10.0	31,500	0.28	0.03	1.87	1.90	2.15	166,000	160,000	8.0	23.6	15.8	--
	100	0.2	7CL25T	100.0	5,000	0.04	nil	0.21	0.21	0.25	170,500	164,200	7.5	20.0	15.7	37.7
		0.5	1AL5T	100.0	9,000	0.11	nil	0.45	0.45	0.56	163,200	157,000	9.5	34.2	15.8	37.3
		1.0	7CL35T	100.0	14,500	0.13	nil	1.07	1.07	1.20	170,000	163,900	10.5	20.6	14.9	38.5
		2.0	1CLT1	100.0	19,000	0.22	0.01	1.84	1.85	2.06	168,000	163,000	10.0	24.3	14.6	37.9

TABLE 8

EFFECT OF PRIOR CREEP ON ROOM TEMPERATURE COMPRESSION PROPERTIES OF Ti-16V-2,5Al

Nominal Exposure Conditions			Actual Exposure Conditions								Compression Properties After Exposure		
Temp. (°F)	Time (hrs)	Creep Def. (%)	Specimen No.	Time (hrs)	Stress (psi)	Total Load Def. (%)	Plastic Load Def. (%)	Creep Def. (%)	Total Plastic Def. (%)	Total Def. (%)	Test Temp. (%)	0,2% Offset Yield Strength (psi)	Modulus, E x 10[6](psi)
600	10	0,2	7BL28T	10,0	125,000	1,01	0,15	0,24	0,39	1,25	room	156,000	13,9
		0,5	7CL30T	10,0	131,000	1,47	0,46	0,39	0,85	1,86	room	139,500	15,3
		1,0	7CL26T	10,0	138,000	2,30	1,30	0,54	1,84	2,84	room	140,500	15,3
			1AL23T	nil	139,000	Fractured on loading.							
		2,0	1AL35T	10,0	140,000	2,35	1,75	Fractured immediately after loading.					
			7AL14T	10,0	140,000	2,3(est.)	1,7(est.)	0,69	2,4(est.)	3,0(est.)	room	117,000	15,8
	100	0,2	1AL25T	100,0	91,000	0,65	nil	0,24	0,24	0,89	room	176,000	17,0
		0,5	1ALT4	100,0	114,000	1,03	0,25	0,59	0,84	1,62	room	165,000	18,2
		1,0	1BL26T	100,1	131,000	2,07	0,16	1,19	1,35	3,26	room	137,000	14,9
		2,0	1ALT26	nil	137,750	Fractured on loading.							
700	10	0,2	1BL24T	10,0	80,000	0,58	nil	0,34	0,34	0,92	room	151,000	15,3
		1,0	7BL2T	10,0	105,000	0,86	nil	0,99	0,99	1,85	room	144,000	15,7
	100	0,5	7AL17T	100,0	57,000	0,44	nil	0,59	0,59	1,03	room	172,500	14,4
		1,0	1CL31T	100,0	80,000	0,62	0,02	1,26	1,28	1,88	room	175,500	14,3
800	10	0,2	1ALT11	10,0	23,000	0,18	nil	0,20	0,20	0,38	room	175,000	15,9
		0,5	7CL27T	10,0	37,449	0,29	0,04	0,39	0,43	0,68	room	179,000	16,2
			1ALT8	10,0	50,500	0,38	0,05	0,61	0,66	0,99	room	174,500	15,7
		1,0	1AL27T	10,0	61,000	0,48	nil	1,00	1,00	1,48	room	173,000	16,4
		2,0	1BL28T	10,0	76,500	0,64	0,07	1,73	1,80	2,37	room	153,000	15,2
			7AL20T	10,0	77,000	0,66	0,02	2,54	2,56	3,20	room	160,900	14,6
	100	0,2	1AL36T	100,0	14,000	0,12	nil	0,28	0,28	0,40	room	170,000	15,8
		0,5	7CLT31	100,0	22,000	0,17	nil	0,55	0,55	0,72	room	201,000	16,8
			1CL29T	100,0	22,000	0,10	nil	0,32	0,32	0,42	room	176,000	16,2
		1,0	7CL5T	100,0	35,000	0,25	nil	1,18	1,18	1,43	room	177,000	16,0
		2,0	1ALT12	100,0	51,000	0,41	nil	2,16	2,16	2,57	room	176,900	16,2
900	10	0,2	1ALT7	10,0	10,000	0,08	nil	0,18	0,18	0,26	room	172,000	15,8
		0,5	7CL29T	10,0	18,000	0,18	nil	0,49	0,49	0,67	room	150,500	16,4
		1,0	1AL28T	10,0	24,500	0,23	nil	0,98	0,98	1,21	room	170,200	16,7
		2,0	1ALT10	10,0	30,500	0,28	0,04	1,88	1,92	2,16	room	171,000	16,1
	100	0,2	1AL31T	100,0	5,000	0,05	nil	0,21	0,21	0,26	room	180,000	17,2
		0,5	7CL28T	100,1	9,000	0,08	nil	0,47	0,47	0,55	room	179,200	15,5
		1,0	1ALT9	100,0	14,500	0,15	nil	1,12	1,12	1,27	room	176,200	16,3
		2,0	7CL8T	100,0	19,500	0,19	0,01	2,11	2,12	2,30	room	161,000	16,7

TABLE 9

EFFECT OF CREEP EXPOSURE ON MECHANICAL PROPERTIES OF TRANSVERSE SPECIMENS OF TI-16V-2.5Al

	Exposure Conditions								Tensile or Compression Properties After Exposure							
Specimen No.	Temp. (°F)	Time (hrs)	Stress (psi)	Plastic Load Def. (%)	Total Load Def. (%)	Creep Def. (%)	Total Plastic Def. (%)	Total Def. (%)	Test Temp. (°F)	Type Of Test	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elong. (%)	R.A. (%)	Modulus, E x 10^6(psi)
1BT-T1	As produced.		---	--	--	--	--	--	room	Tensile	165,200	152,000	6.5	18.6	14.2
1BT-T11	600	10.0	none	--	--	--	--	--	room	Tensile	170,000	156,000	5.8	12.0	15.2
1C-T1	600	10.0	132,000	0.62	1.49	0.62	1.24	2.11	room	Tensile	186,000	186,000	1.5	11.8	14.0
1BT-C5	As produced		---	--	--	--	--	--	room	Compression	---	175,000	-	--	18.6
1BT-C7	600	10.0	none	--	--	--	--	--	room	Compression	---	175,000	-	--	16.7
1BT-T25	600	9.9	132,000	0.80	1.72	0.84	1.64	2.57	room	Compression	---	127,000	-	--	14.9

TABLE 10

EFFECT OF PRIOR CREEP ON ELEVATED TEMPERATURE TENSILE PROPERTIES OF TI-16V-2.5Al

Nominal Exposure Conditions				Actual Exposure Conditions							Tensile Properties After Exposure						
Temp. (°F)	Time (hrs)	Creep Def. (%)	Specimen No.	Time (hrs)	Stress (psi)	Total Load Def. (%)	Plastic Load Def. (%)	Creep Def. (%)	Total Plastic Def. (%)	Total Def. (%)	Test Temp. (°F)	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elong. (%)	R.A. (%)	Modulus, E x 10^6(psi)	Hardness R"C"
600	10	0.2	1DL27T	10.6	130,000	1.79	0.70	0.27	0.97	2.06	600	143,700	138,500	8.0	17.3	12.6	36.2
		0.5	7CL7T	10.0	131,000	1.40	0.49	0.46	0.95	1.86	600	151,000	145,000	5.8	30.0	12.6	37.2
		1.0	7BL1T	10.0	137,889	2.15	1.17	0.48	1.65	2.63	600	151,000	149,000	15.0	28.9	12.8	38.7
		2.0	7AL16T	nil	140,000	1.34	0.28	Ruptured on loading.									
	100	0.2	1AL30T	100.0	91,000	0.65	nil	0.20	0.20	0.85	600	144,000	125,000	7.3	24.5	14.2	37.6
		0.5	7CL4T	100.0	114,000	0.89	0.08	0.48	0.56	1.37	600	156,000	145,000	6.0	21.3	12.0	39.9
		1.0	1BL31T	100.0	131,000	2.15	1.16	1.14	2.30	2.15	600	155,500	---	3.0	23.5	12.4	--
800	10	0.2	7CL10T	10.0	23,000	0.18	nil	0.20	0.20	0.38	800	131,000	113,000	10.0	23.4	12.0	39.1
		0.5	1BL23T	10.0	44,000	0.33	0.02	0.55	0.57	0.88	800	128,000	116,000	9.5	27.7	11.2	37.4
		1.0	1AL33T	10.0	61,000	0.47	0.02	1.35	1.37	1.82	800	132,000	115,000	10.0	43.0	11.3	39.1
		2.0	7AL13T	10.0	76,500	0.50	nil	2.39	2.39	2.89	800	130,000	118,000	12.0	30.3	11.2	40.6
	100	0.5	1CL25T	100.0	22,000	0.20	nil	0.57	0.57	0.77	800	132,000	115,000	10.5	30.0	11.4	--
		2.0	7AL32T	100.0	51,000	0.39	nil	2.21	2.21	2.70	800	138,000	125,000	7.8	19.0	12.6	--
900	10	0.2	1CL13T	10.0	10,000	0.10	nil	0.20	0.20	0.30	900	105,000	91,300	28.2	50.2	10.5	37.3
		0.5	7CL6T	10.0	18,000	0.06	nil	0.44	0.44	0.50	900	107,400	88,800	20.5	50.0	10.8	38.9
		1.0	1ALT2	10.0	28,000	0.24	nil	1.10	1.10	1.34	900	107,800	99,300	19.0	44.4	10.7	38.3
		2.0	1BL25T	10.0	30,500	0.27	nil	1.59	1.59	1.86	900	108,000	93,500	15.5	43.2	10.7	37.8
	100	0.5	7AL36T	100.0	9,000	0.10	nil	0.44	0.44	0.54	900	110,000	87,500	16.5	49.0	11.9	--
		1.0	7AL31T	100.0	14,500	0.11	0.01	1.14	1.15	1.25	900	113,000	90,000	17.5	46.8	11.1	--
		2.0	1CL23T	100.0	19,000	0.19	nil	2.11	2.11	2.30	900	120,500	105,000	14.0	30.3	13.0	--

TABLE 11

EFFECT OF PRIOR CREEP ON ELEVATED TEMPERATURE COMPRESSION PROPERTIES OF TI-16V-2.5Al

Nominal Exposure Conditions			Actual Exposure Conditions								Compression Properties After Exposures		
Temp. (°F)	Time (hrs)	Creep Def. (%)	Specimen No.	Time (hrs)	Stress (psi)	Total Load Def. (%)	Plastic Load Def. (%)	Creep Def. (%)	Total Plastic Def. (%)	Total Def. (%)	Test Temp. (°F)	0.2% Offset Yield Strength (psi)	Modulus, E x 10^6 (psi)
600	10	0.2	1AL34T	10.0	118,000	1.05	0.23	0.22	0.45	1.27	600	101,000	14.3
		0.5	1BL27T	9.9	132,000	2.20	1.97	0.56	2.53	2.76	600	100,000	13.8
		1.0	7CL1T	10.0	137,500	2.10	1.11	0.58	1.69	2.68	600	105,000	14.3
	100	0.2	1BL33T	100.0	91,000	0.66	0.05	0.20	0.25	0.86	600	>114,000	15.2
		0.5	7CL3T	100.0	114,000	0.86	0.04	0.45	0.49	1.31	600	127,000	13.4
		1.0	1BL31T	99.8	131,000	2.34	1.32	1.22	2.54	3.56	600	110,000	13.3
800	10	0.2	7CL11T	10.0	23,000	0.18	0.01	0.24	0.25	0.42	800	125,400	12.5
		0.5	7CL12T	10.0	44,000	0.38	nil	0.54	0.54	0.92	800	123,000	12.3
		1.0	1AL29T	10.0	61,000	0.43	nil	0.98	0.98	1.41	800	113,000	12.8
		2.0	1BL32T	10.0	77,000	0.57	nil	2.03	2.03	2.60	800	116,000	13.3
	100	0.5	7AL33T	100.0	22,000	0.17	nil	0.51	0.51	0.68	800	123,000	13.4
		2.0	1CL22T	100.0	51,000	0.38	nil	2.07	2.07	2.45	800	123,000	12.5
900	10	0.2	1CL14T	10.0	10,000	0.10	nil	0.23	0.23	0.33	900	108,000	11.9
		0.5	7CLT2	10.0	18,000	0.17	nil	0.50	0.50	0.67	900	118,000	12.6
			1CL34T	10.0	18,000	0.16	0.02	0.52	0.54	0.68	900	92,400	11.1
		1.0	1BL35T	10.0	24,500	0.23	nil	0.79	0.79	1.02	900	101,300	12.5
		2.0	1BL29T	10.0	30,500	0.25	0.02	1.55	1.57	1.80	900	97,000	12.1
	100	0.5	7AL34T	100.0	9,000	0.10	nil	0.50	0.50	0.60	900	98,000	9.9
		1.0	1CL24T	100.0	14,500	0.09	nil	1.09	1.09	1.18	900	96,500	11.0
		2.0	1CL21T	100.0	19,000	0.16	nil	2.26	2.26	2.42	900	97,500	11.7

TABLE 12

EFFECT OF UNSTRESSED EXPOSURE ON TENSION-IMPACT PROPERTIES OF TI-16V-2.5Al

Exposure Conditions			Tension-Impact Properties after Exposure			
Temp. (°F)	Time (hrs)	Specimen No.	Test Temp. (°F)	Tension-Impact Strength, ft-lb	Elongation (%)	R.A. (%)
600	10	1CL18-1	room	43	6.0	28.0
	50	1CL20-2	room	48	7.0	23.0
	100	7AL27-1	room	30	5.5	15.0
700	10	7AL29-3	room	27	1.5	2.0
800	10	1CL19-1	room	53	7.5	26.0
		7AL28-2	room	39	1.7	13.0
	50	7AL27-2	room	38	5.5	19.0
	100	7CL28-3	room	45	6.5	15.0
900	10	7AL27-3	room	35	5.3	15.0
		7AL30-1	room	39	4.5	20.0
	50	1CL18-2	room	58	5.5	19.0
	100	1CL20-1	room	58	8.5	21.0
600	10	7AL30-2	600	34	7.0	31.0
	50	7AL28-1	600	27	5.5	29.0
	100	1CL20-3	600	29	6.5	23.0
800	10	1CL19-2	800	29	6.3	23.0
	50	7AL29-1	800	30	6.0	35.0
	100	1CL19-3	800	28	6.8	18.5
900	10	1CL18-3	900	26	6.3	43.0
	50	7AL30-3	900	30	5.5	26.0
	100	7AL29-2	900	24	3.3	24.0

TABLE 13

EFFECT OF PRIOR CREEP ON TENSION-IMPACT PROPERTIES OF TI-16V-2.5Al

Nominal Exposure Conditions				Actual Exposure Conditions							Tension-Impact Properties after Exposure			
Temp. (°F)	Time (hrs)	Creep Def. (%)	Specimen No.	Time (hrs)	Stress (psi)	Total Load Def. (%)	Plastic Load Def. (%)	Creep Def. (%)	Total Plastic Def. (%)	Total Def. (%)	Test Temp. (°F)	Tension-Impact Strength, ft-lb	Elongation (%)	R.A. (%)
600	10	0.2	7AL15T	10.0	118,000	1.10	0.28	0.30	0.58	1.40	room	32	3.3	17.0
		0.5	7AL21T	10.0	131,000	2.30	1.30	0.85	2.15	3.15	room	25	3.0	21.0
		1.0	1CL33T	10.0	137,500	3.45	2.40	1.17	3.57	4.62	room	20	2.3	3.9
		2.0	7AL18T	nil	138,000	2.35	1.30	Ruptured just after loading.			-	-	-	-
700	10	0.2	1CL32T	10.0	75,000	0.54	nil	0.31	0.31	0.85	room	52	7.2	22.0
		1.0	1CL35T	10.0	105,000	0.86	0.10	1.09	1.19	1.95	room	31	4.0	22.0
800	10	0.5	1CL30T	10.0	44,000	0.36	nil	0.74	0.74	1.10	room	28	3.0	24.0
		1.0	7AL24T	10.0	61,000	0.50	0.04	1.08	1.12	1.58	room	26	2.0	21.0
		2.0	1BL36T	10.0	77,000	0.59	0.02	2.17	2.19	2.76	room	32	4.3	29.0
900	10	0.5	13C36T	10.0	18,000	0.16	nil	0.48	0.48	0.64	room	43	9.0	17.5
		1.0	7AL23T	10.0	24,500	0.23	0.01	0.97	0.98	1.20	room	36	4.7	23.5
		2.0	1CL27T	10.0	31,500	0.25	0.01	1.80	1.81	2.06	room	47	6.5	13.7
600	10	0.2	1BL5T	10.0	119,000	1.00	0.25	0.23	0.48	1.23	600	27		23.0
		0.5	7BL9T	10.0	130,000	1.44	0.87	0.69	1.56	2.13	600	34	1.0	19.0
		1.0	1BL11T	10.0	137,000	3.13	2.10	2.13	4.23	5.26	600	37	1.0	16.0
900	10	0.5	7BL15T	10.0	18,000	0.16	0.01	0.49	0.50	0.65	900	24	2.3	8.0
		1.0	1BL3T	10.0	24,500	0.22	nil	0.85	0.85	1.07	900	31	2.5	8.0
		2.0	7BL20T	10.0	31,500	0.25	nil	1.67	1.67	1.92	900	42	5.0	25.0

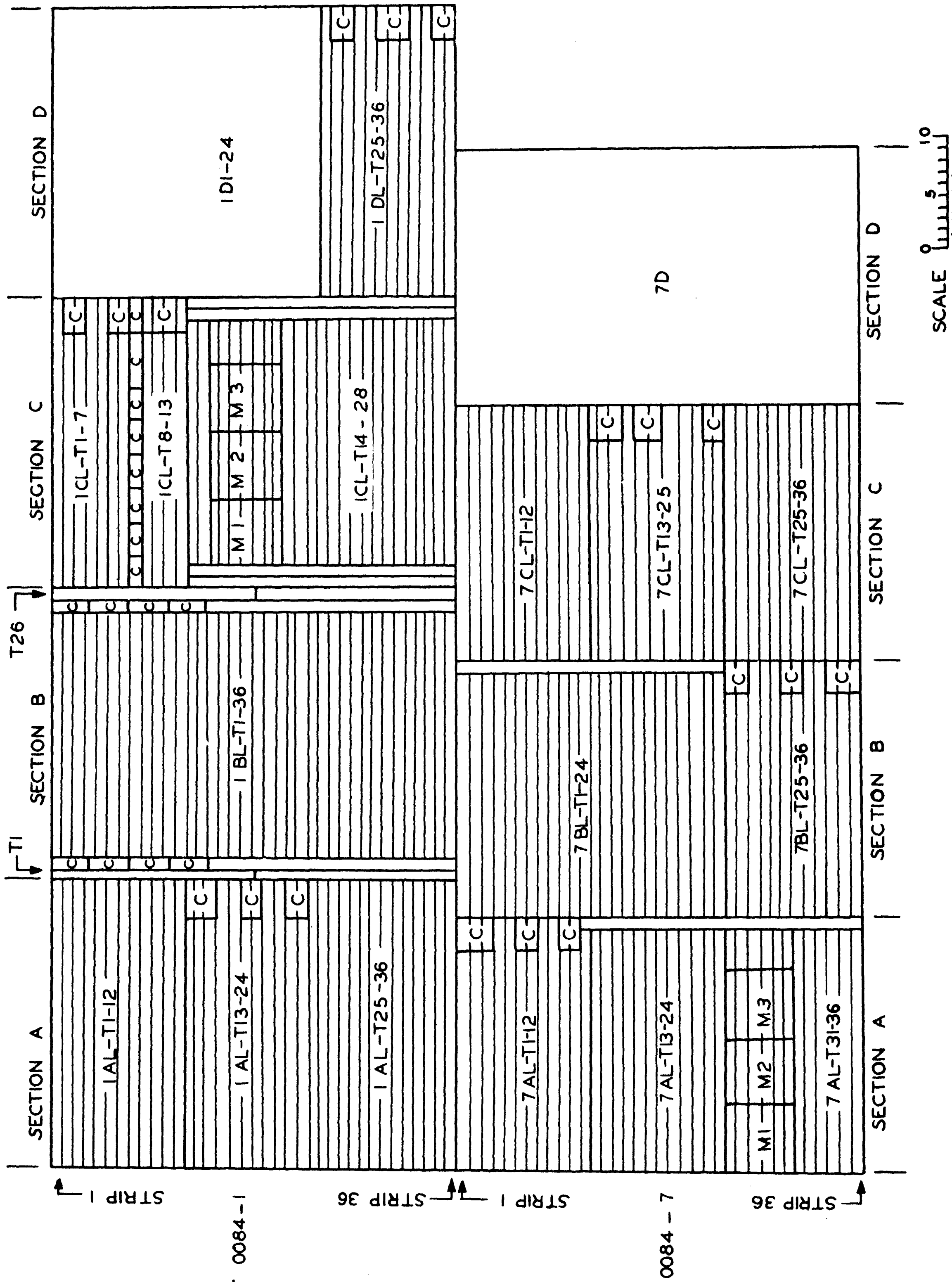

FIGURE 1 SAMPLING PROCEDURE FOR Ti 16V-2.5Al ALLOY

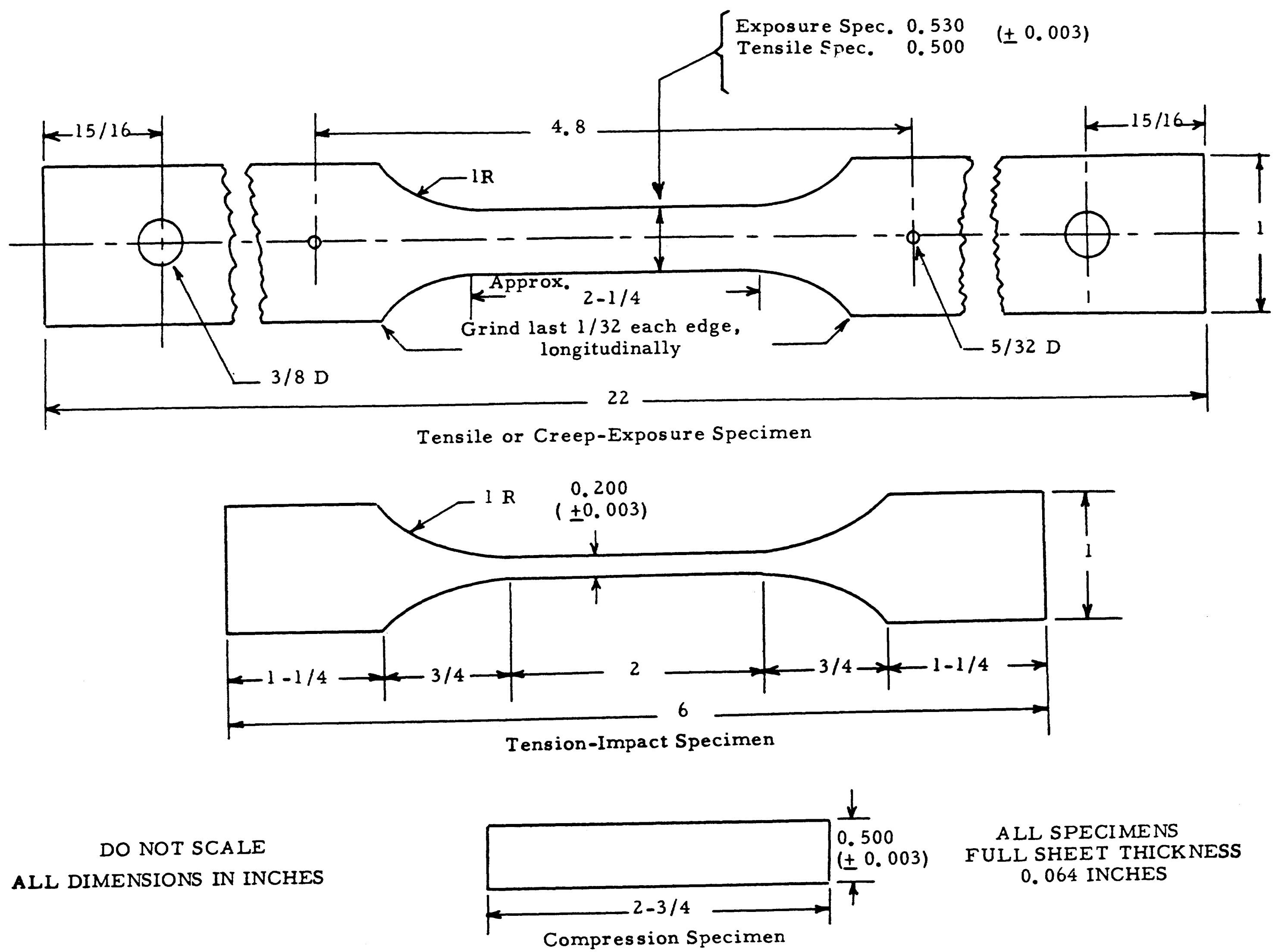

Figure 2. - Details of Test Specimens (Tension-Impact and Compression Specimens Designed to be Cut from Creep Specimens after Exposure).

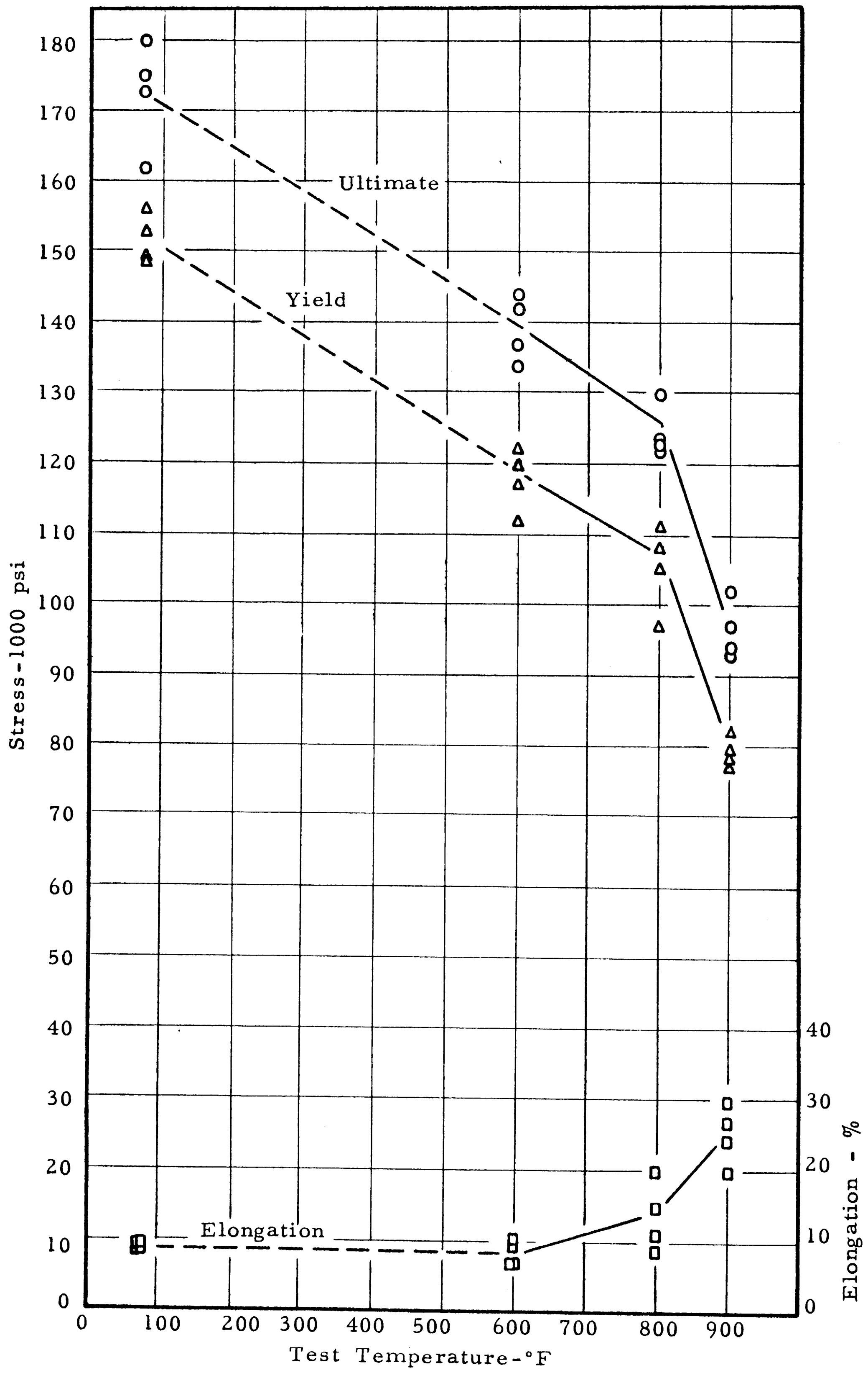

Figure 3. - Effect of Test Temperature on Tensile Properties of Ti-16V-2.5Al.

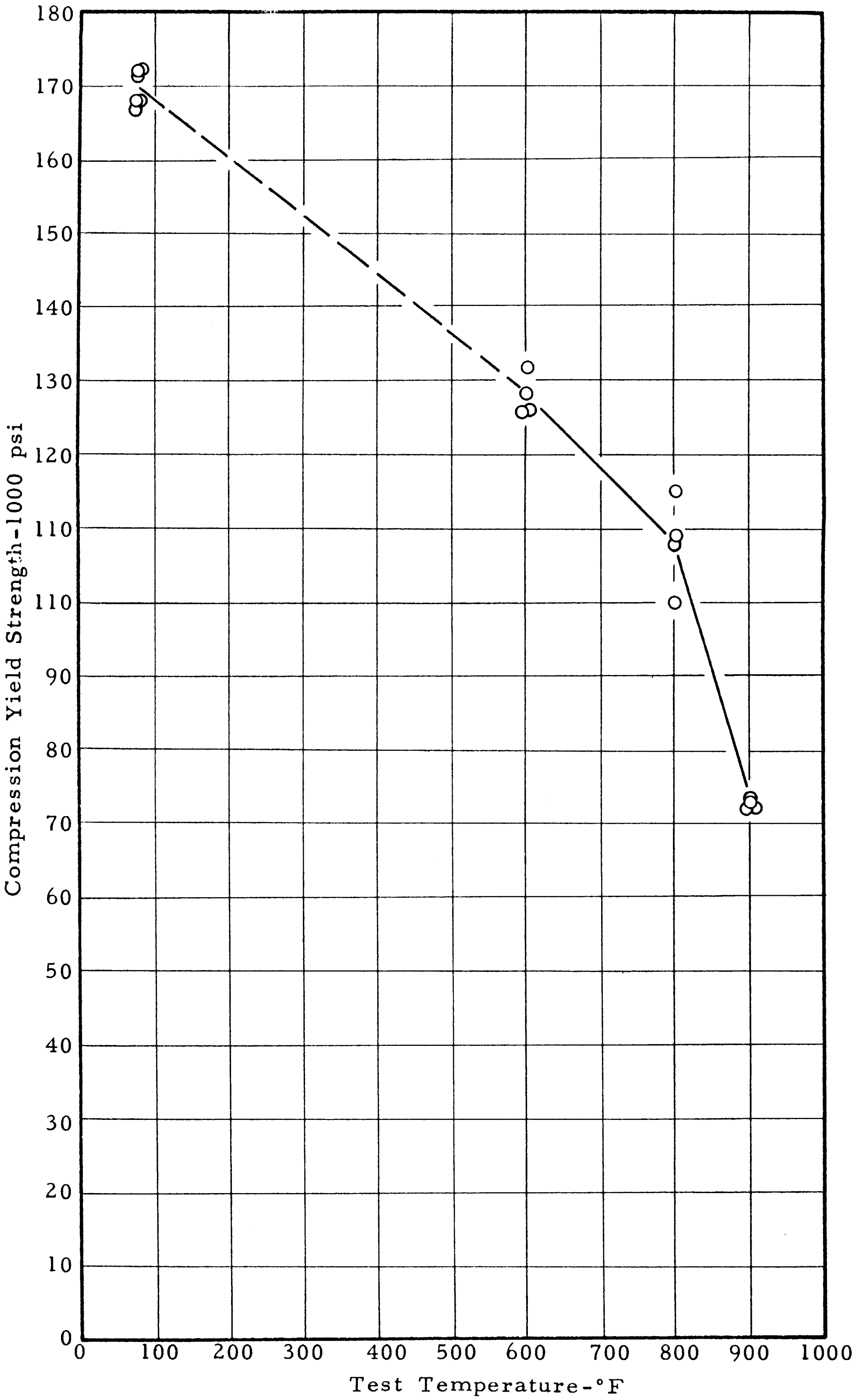

Figure 4. - Effect of Test Temperature on Compression Yield Strength of Ti-16V-2.5Al.

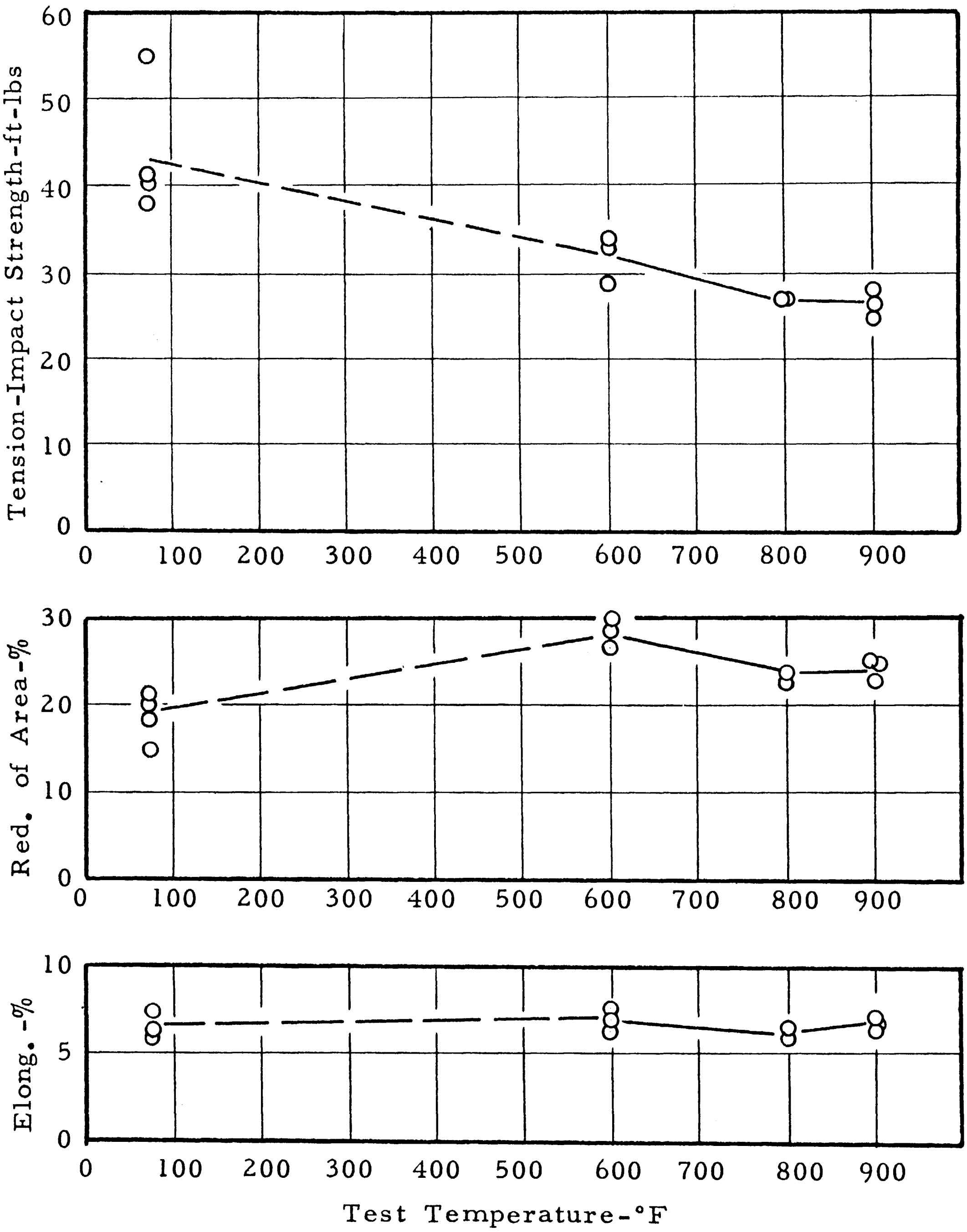

Figure 5 - Effect of Test Temperature on Tension-Impact Properties of Ti-16V-2.5Al.

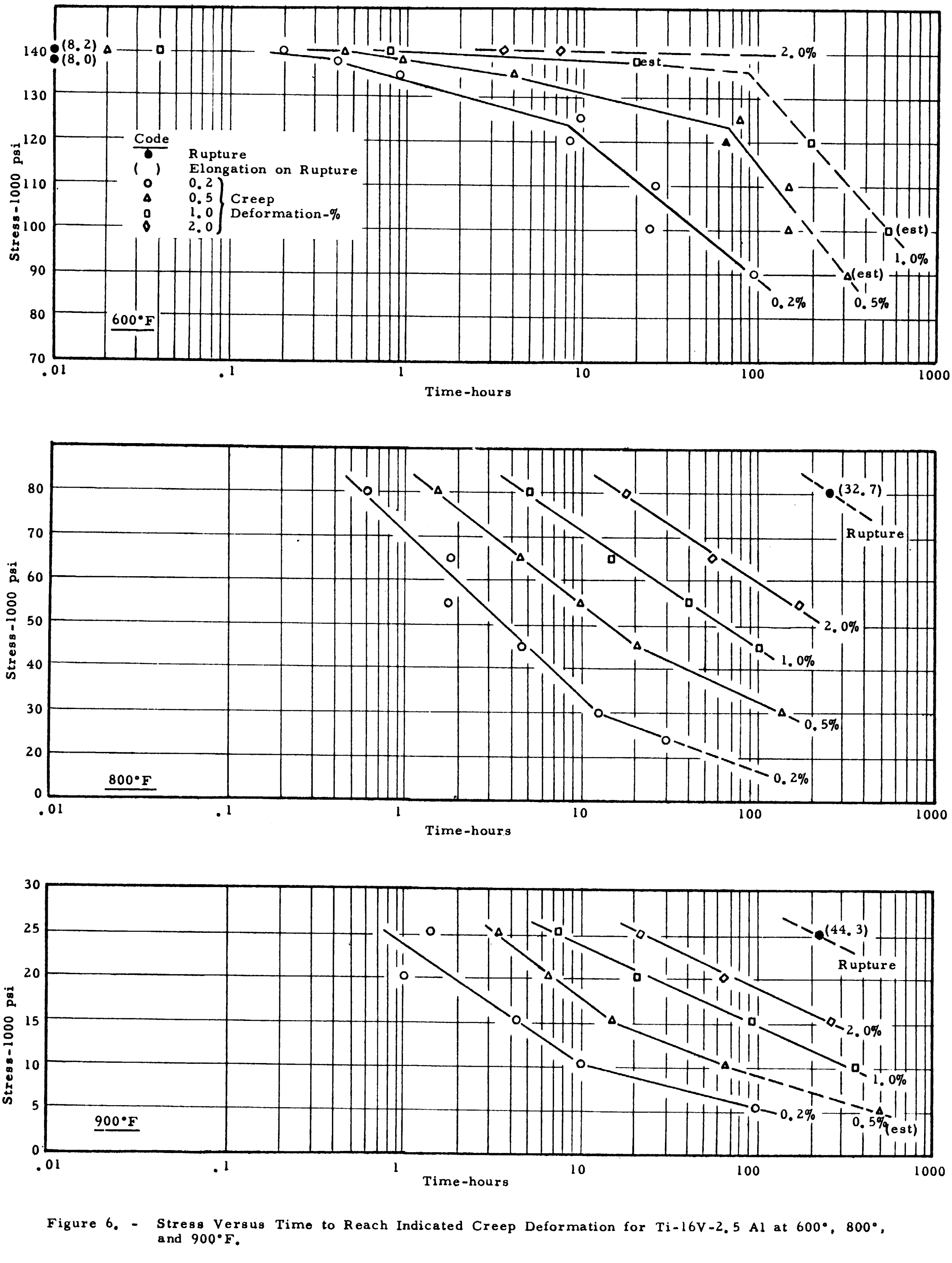

Figure 6. - Stress Versus Time to Reach Indicated Creep Deformation for Ti-16V-2.5 Al at 600°, 800°, and 900°F.

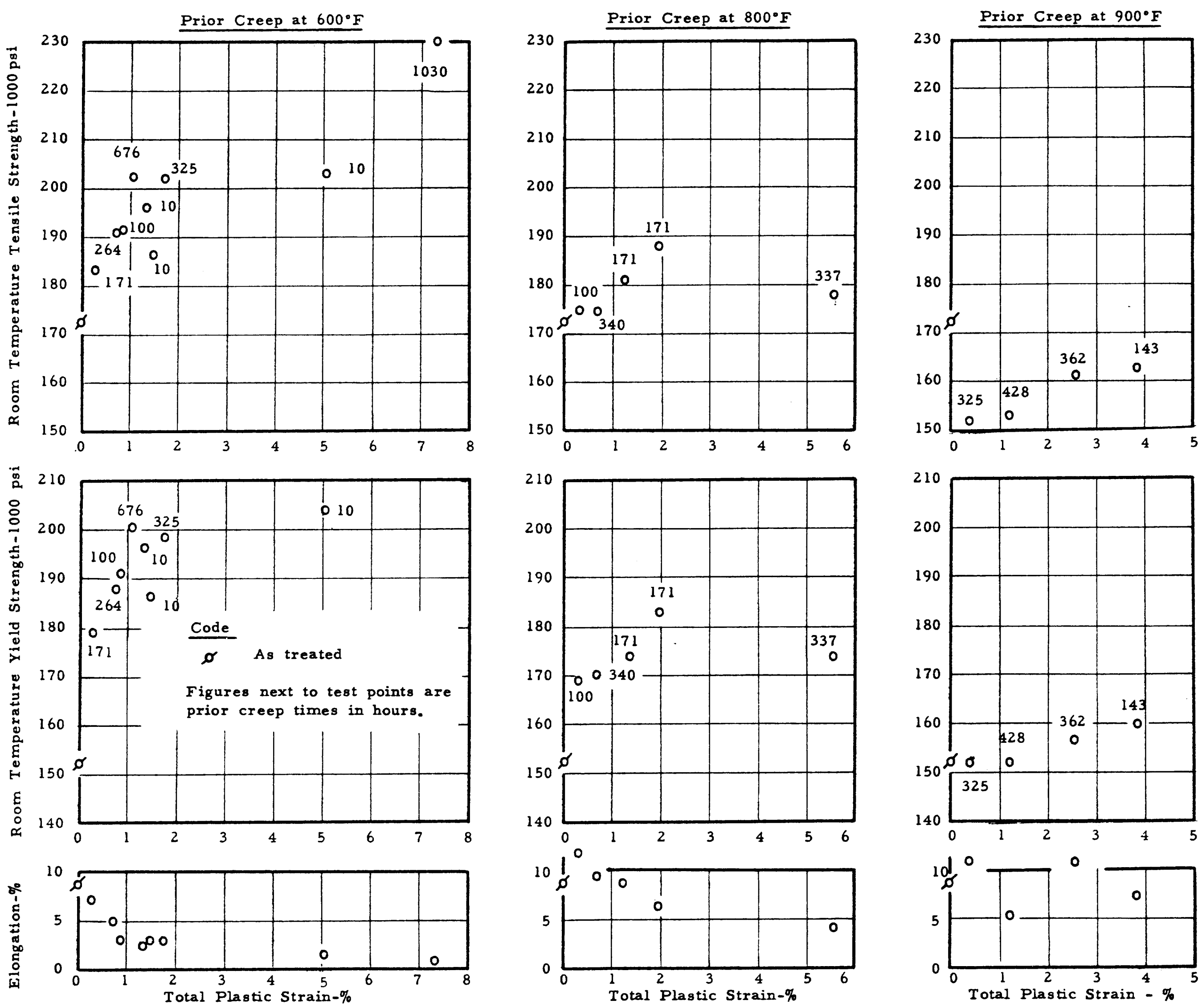

Figure 7. - Effect of Deformation in 10 hour to 1030 hour Creep Tests at 600°, 800°, and 900°F on Room Temperature Tensile Properties of Ti-16V-2.5Al.

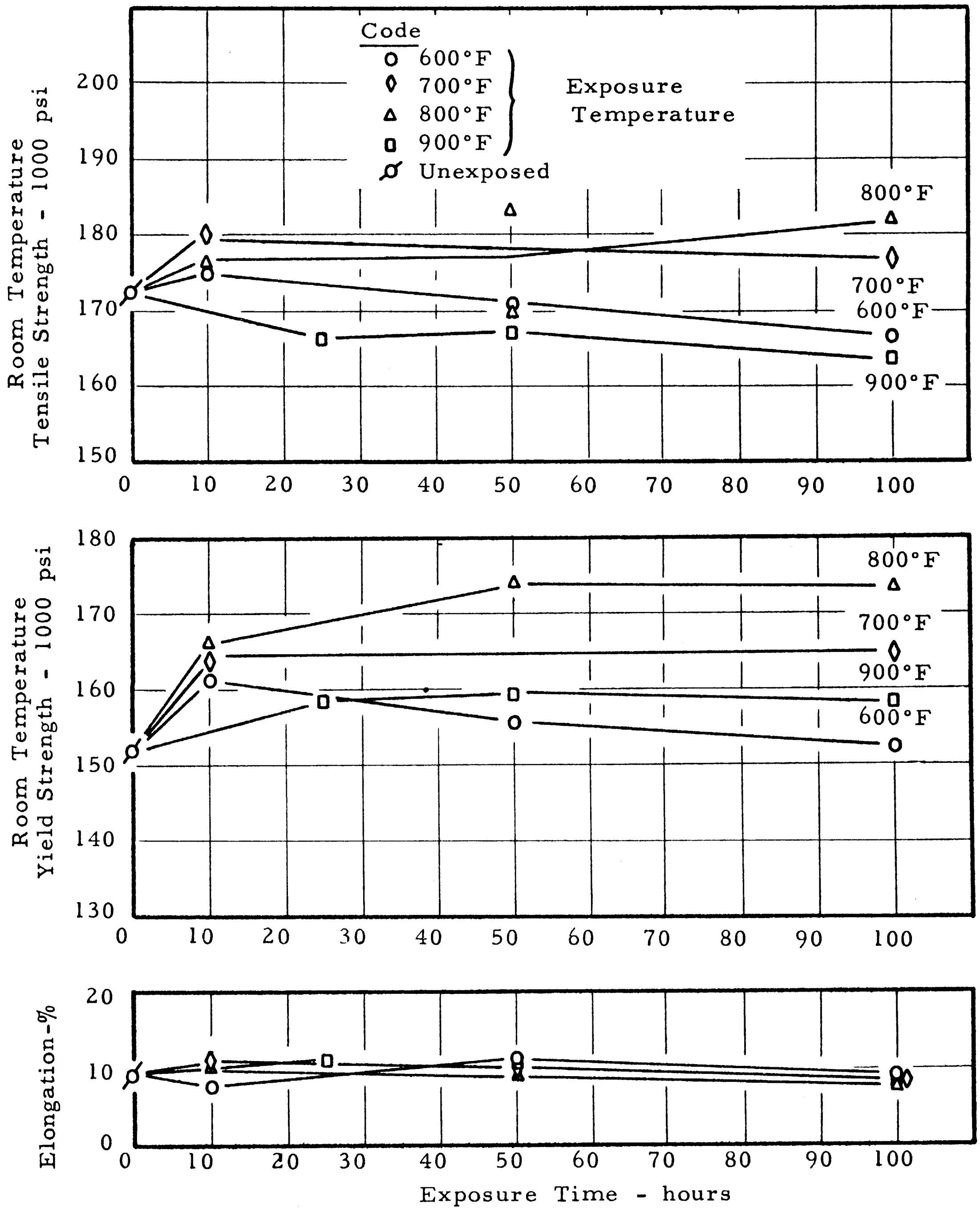

Figure 8. - Effect of Unstressed Exposure on Room Temperature Tensile Properties of Ti-16V-2.5Al.

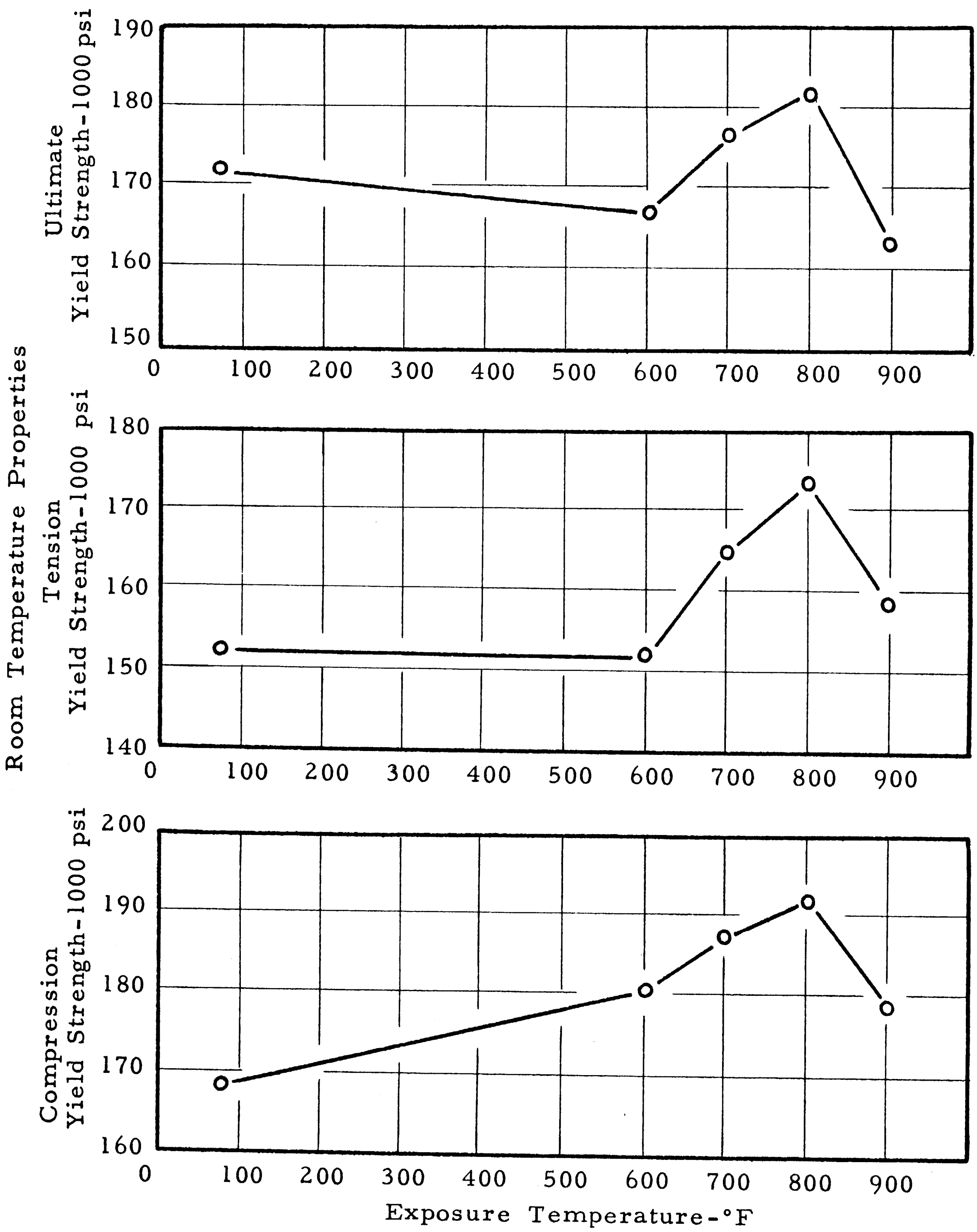

Figure 9. - Effect of 100 Hours Unstressed Exposure on Room Temperature Tension and Compression Strengths of Ti-16V-2.5Al.

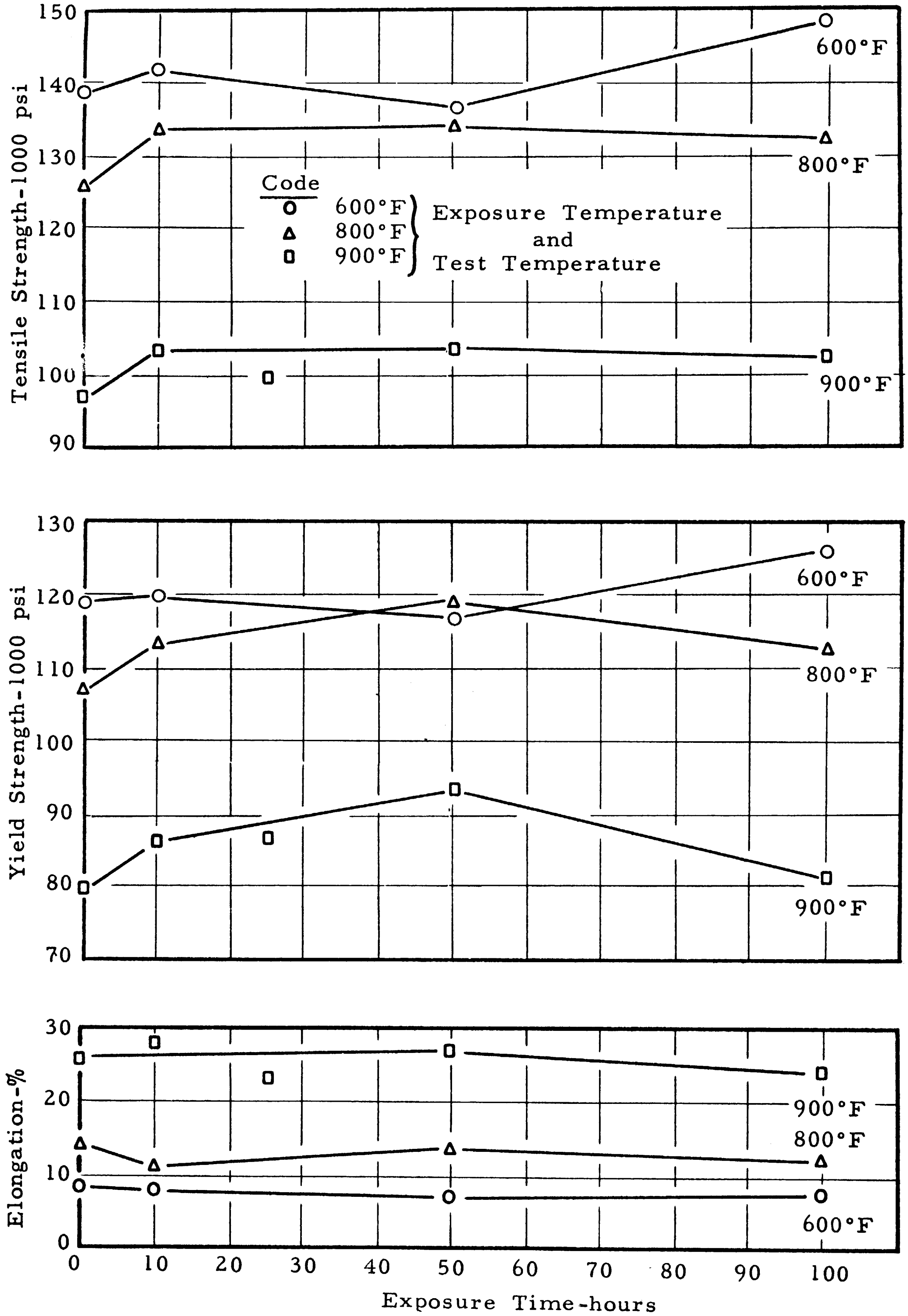

Figure 10. - Effect of Unstressed Exposure on Elevated Temperature Tensile Properties of Ti-16V-2.5Al.

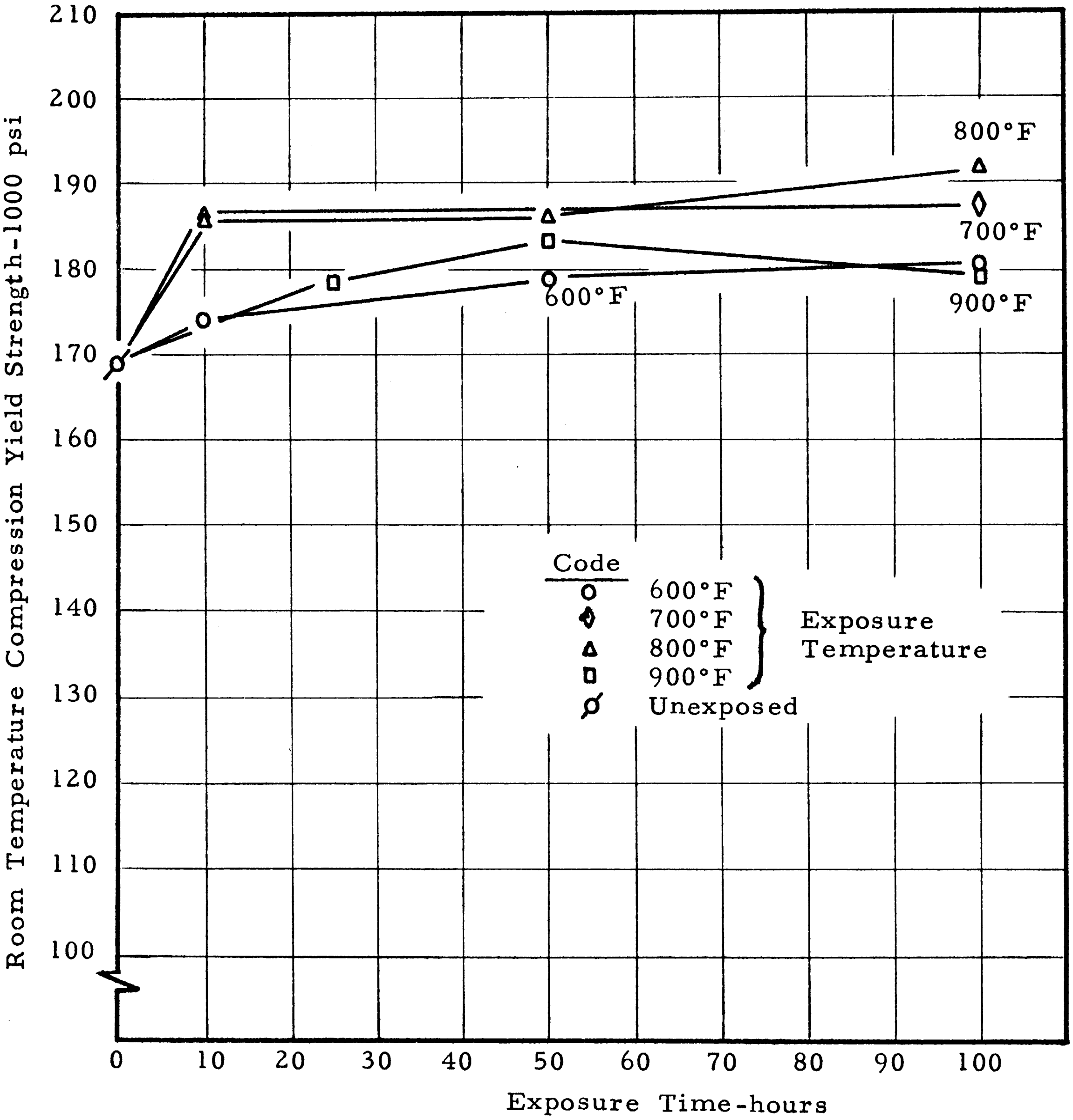

Figure 11. - Effect of Unstressed Exposure on Room Temperature Compression Yield Strength of Ti-16V-2.5Al.

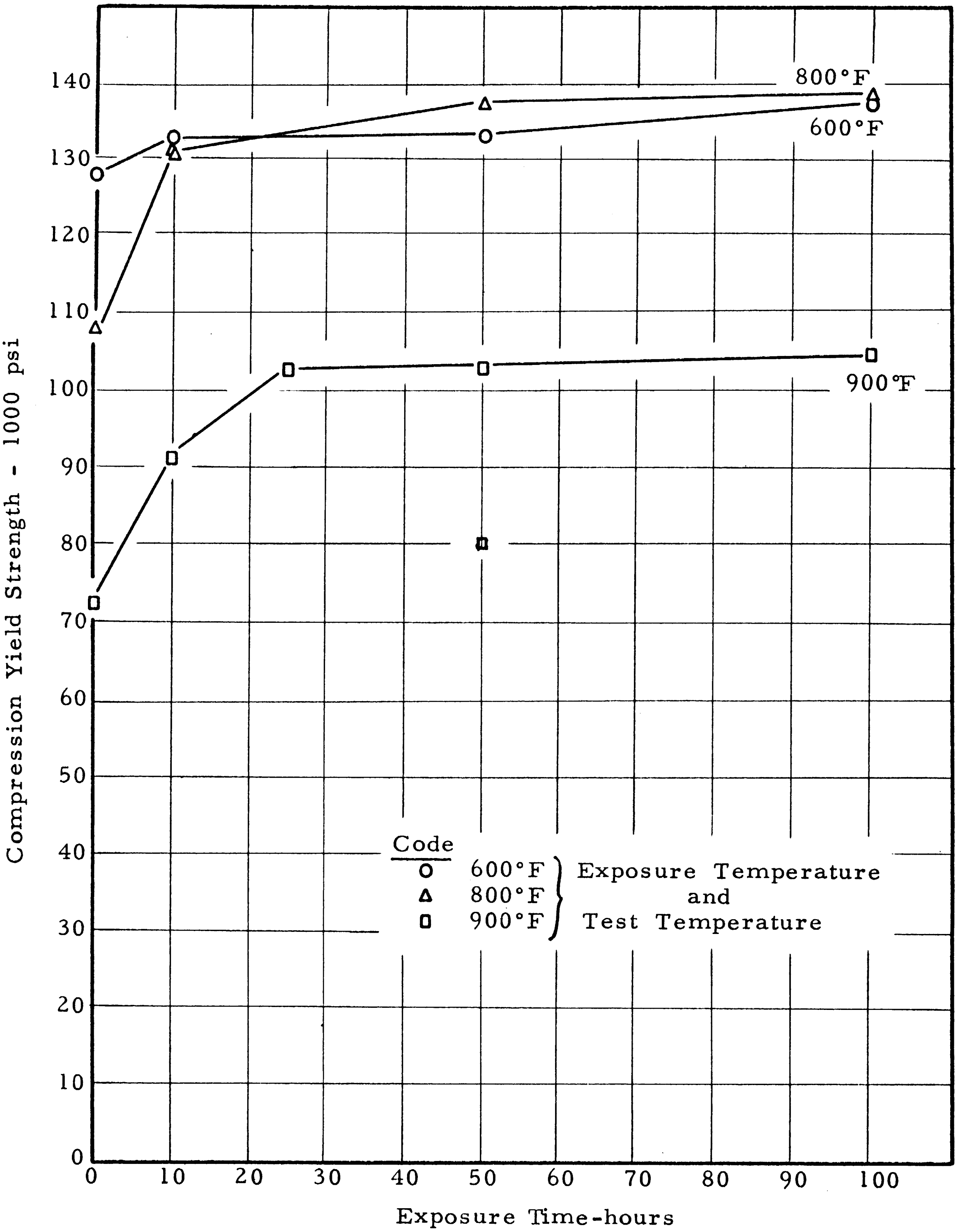

Figure 12. - Effect of Unstressed Exposure on Elevated Temperature Compression Yield Strength of Ti-16V-2.5Al.

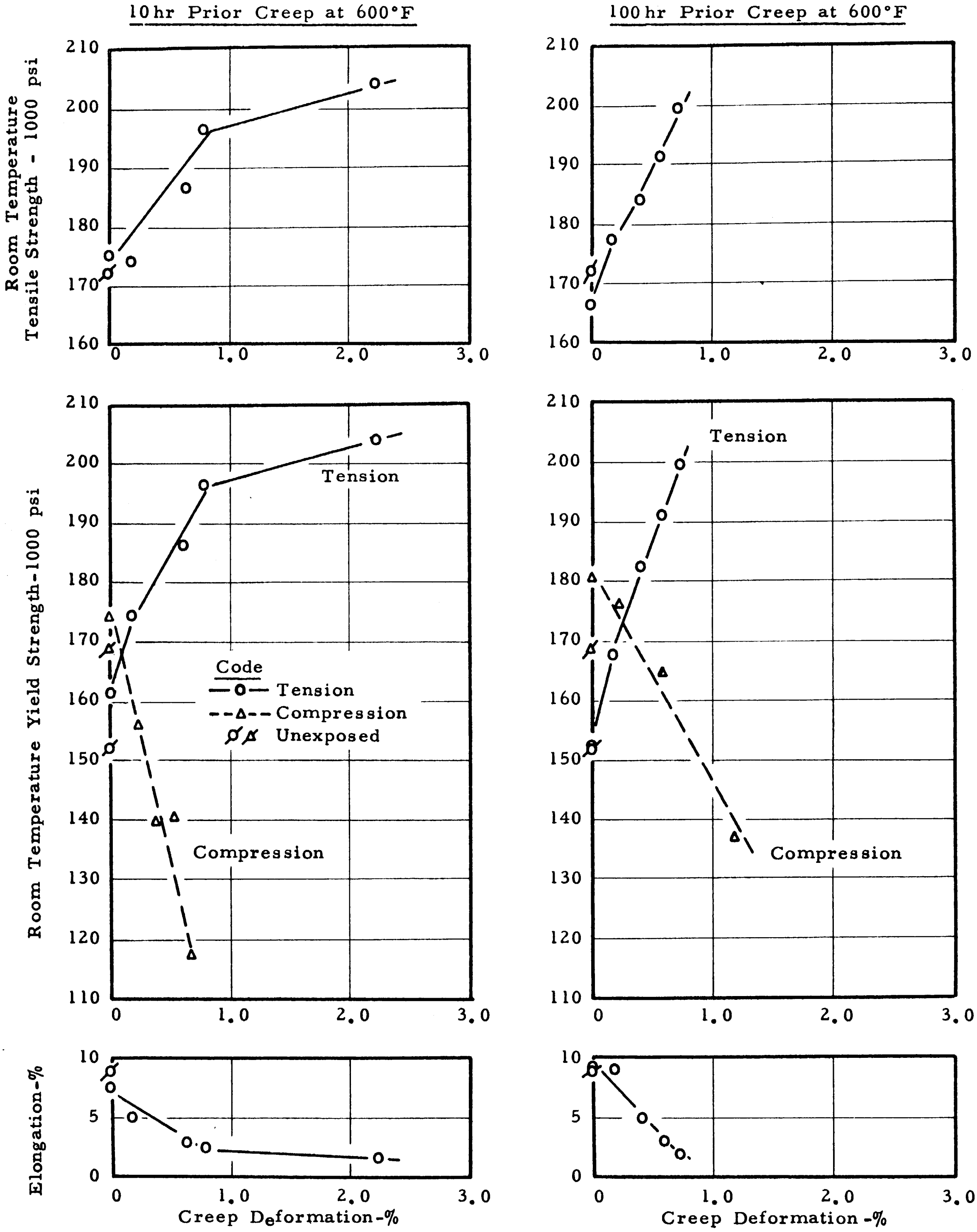

Figure 13. - Effect of Prior Creep Exposure at 600°F on Room Temperature Tension and Compression Properties of Ti-16V-2.5Al.

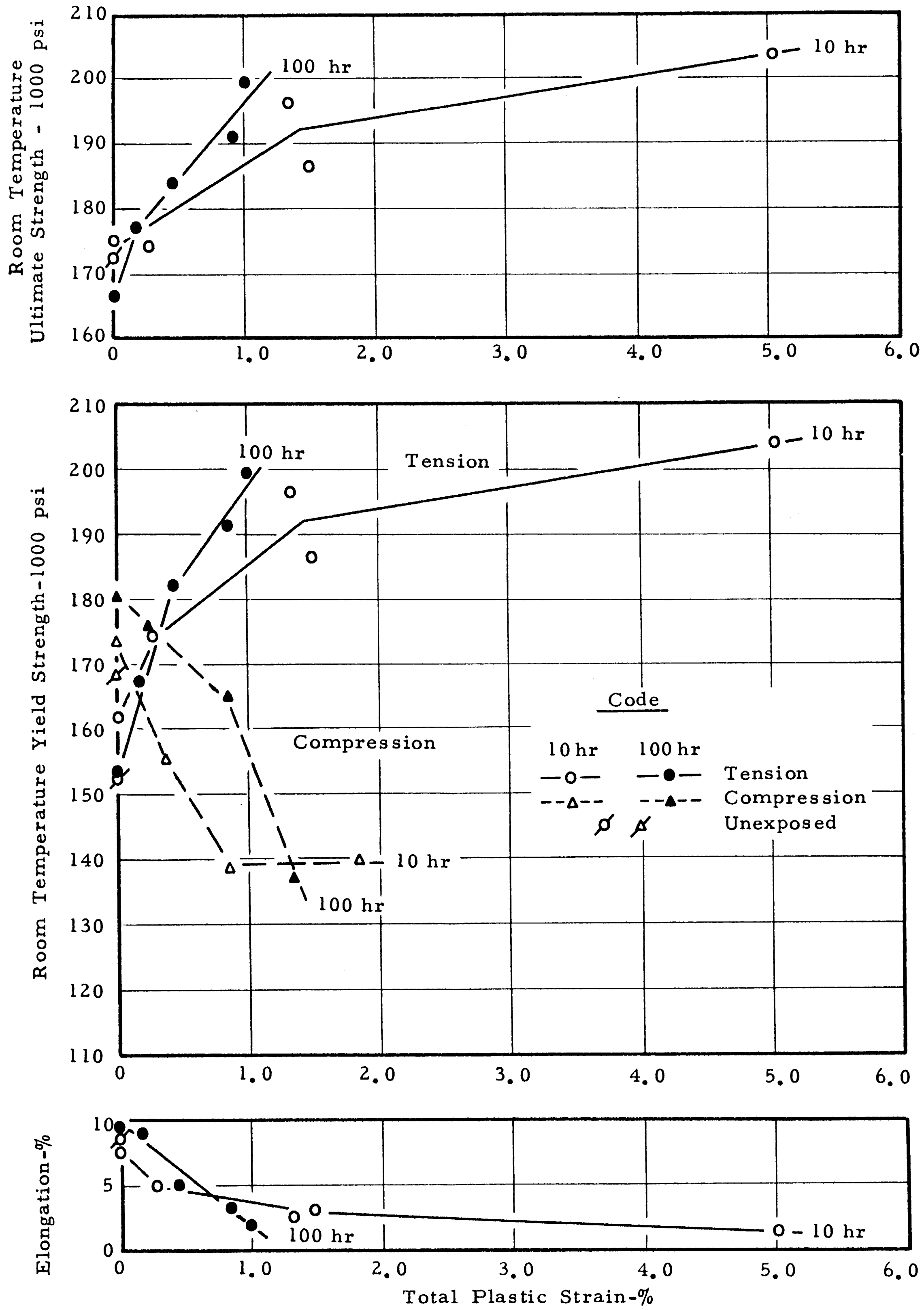

Figure 14. - Effect of Total Plastic Strain Reached in Creep-Exposure at 600°F on the Room Temperature Tension and Compression Properties of Ti-16V-2.5Al.

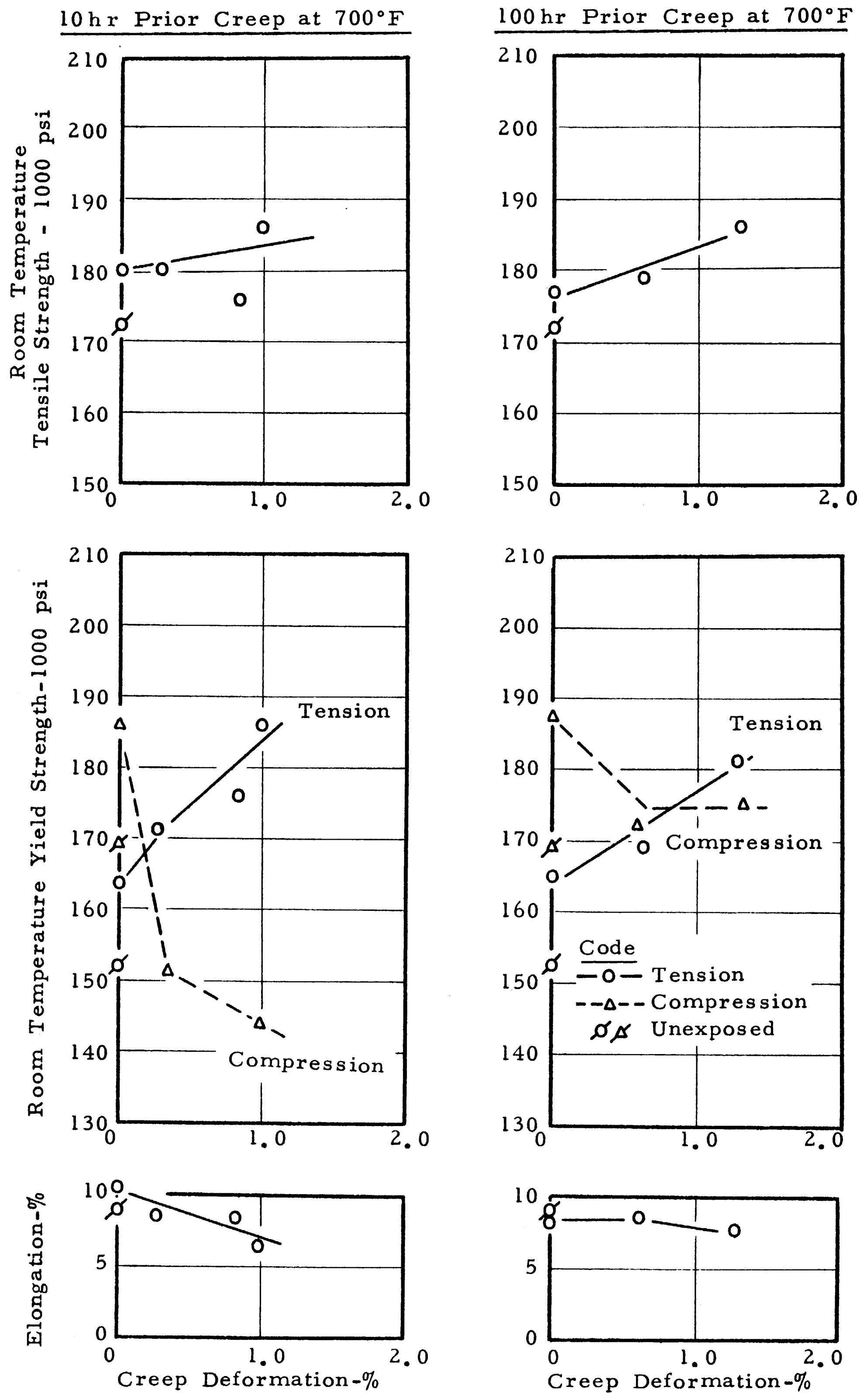

Figure 15. - Effect of Prior Creep Exposure at 700°F on Room Temperature Tension and Compression Properties of Ti-16V-2.5Al.

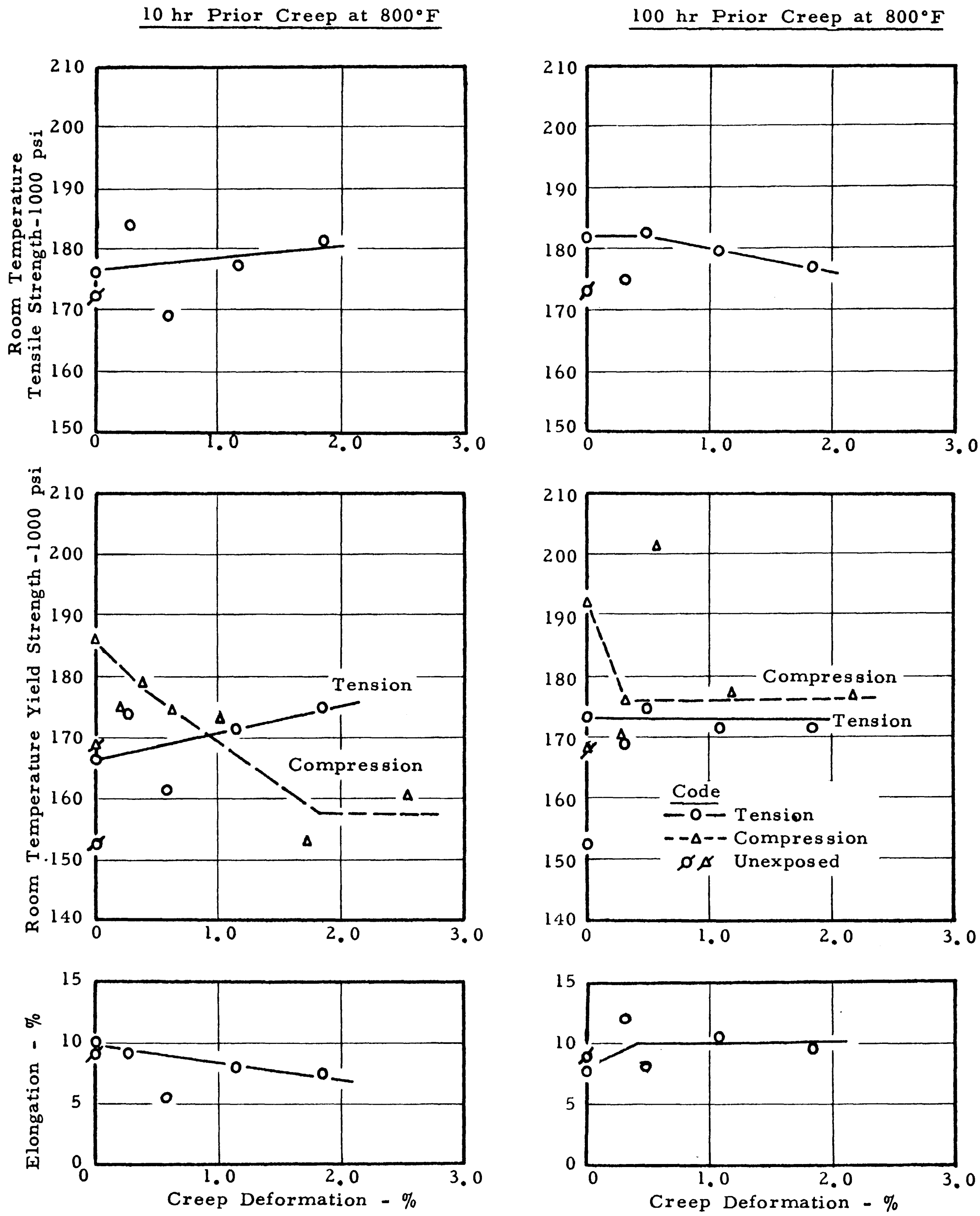

Figure 16. - Effect of Prior Creep Exposure at 800°F on Room Temperature Tension Properties of Ti-16V-2.5Al.

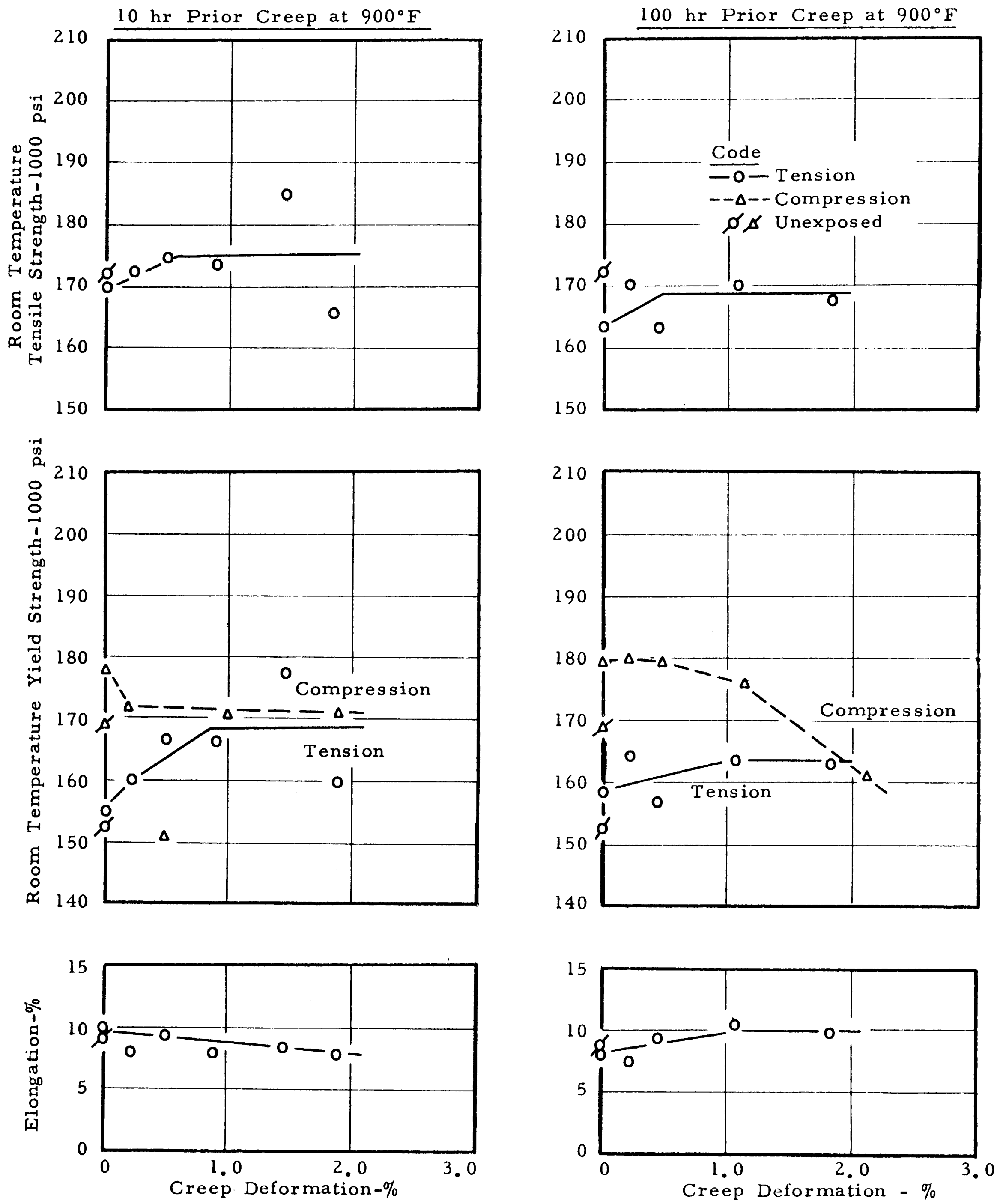

Figure 17. - Effect of Prior Creep Exposure at 900°F on Room Temperature Tension and Compression Properties of Ti-16V-2.5Al.

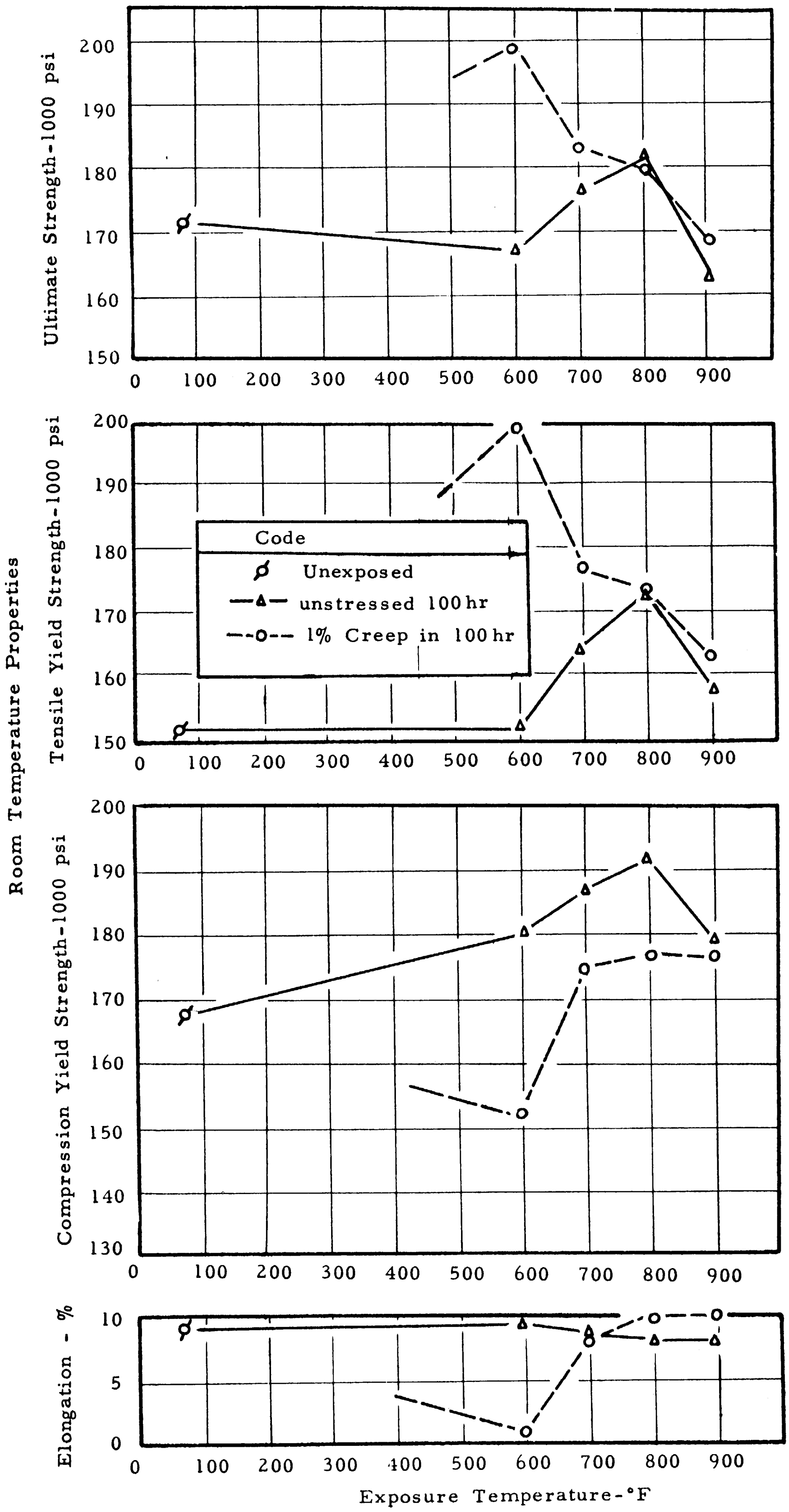

Figure 18. - Effect of 100-Hour Exposure at 600° to 900°F Either Unstressed or to 1% Creep on Room Temperature Tension and Compression Properties of Ti-16V-2.5Al.

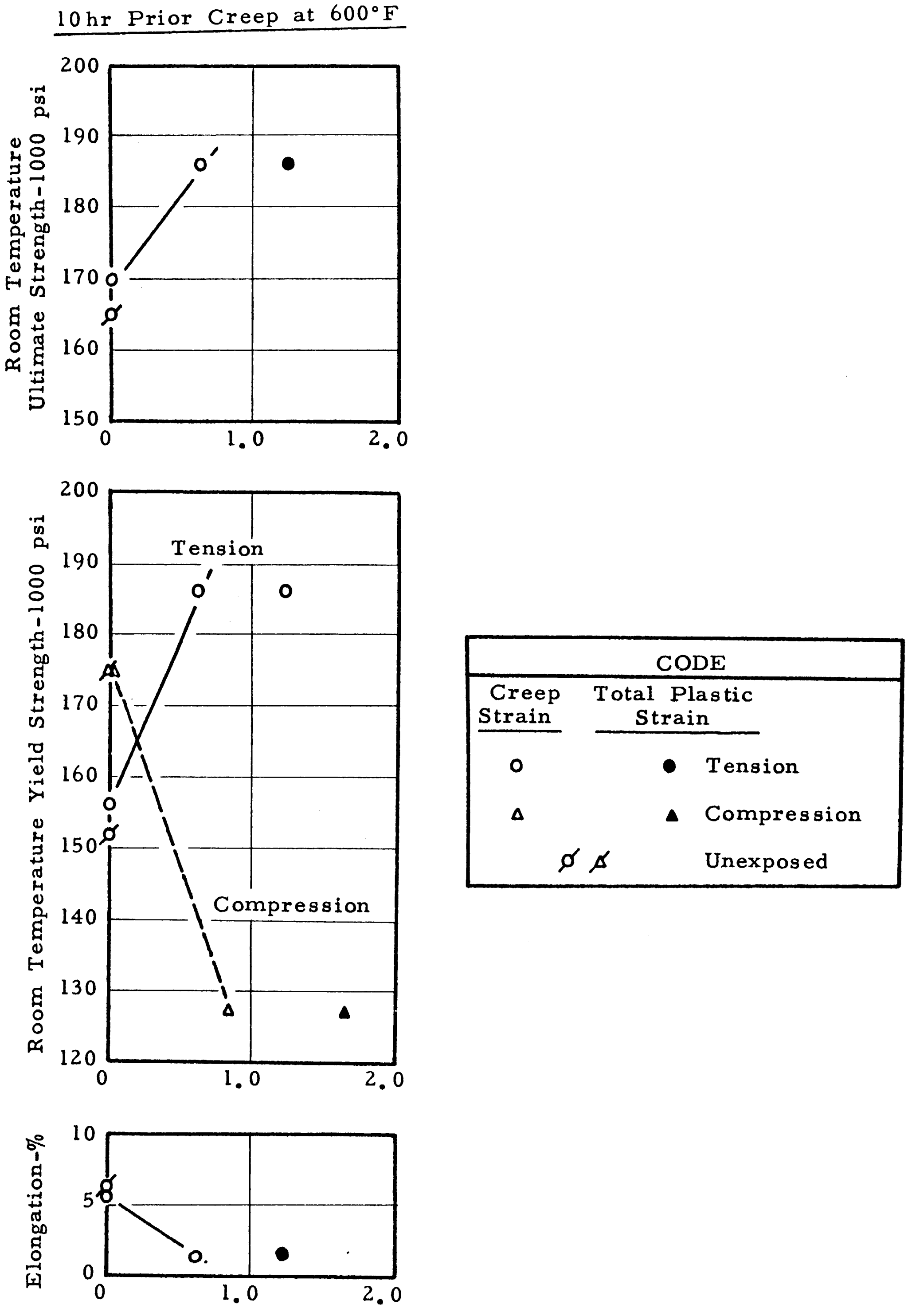

Figure 19. - Effect of 10-hr Creep Exposure at 600°F on Room Temperature Tension and Compression Properties of TRANSVERSE SPECIMENS of Ti-16V-2.5Al.

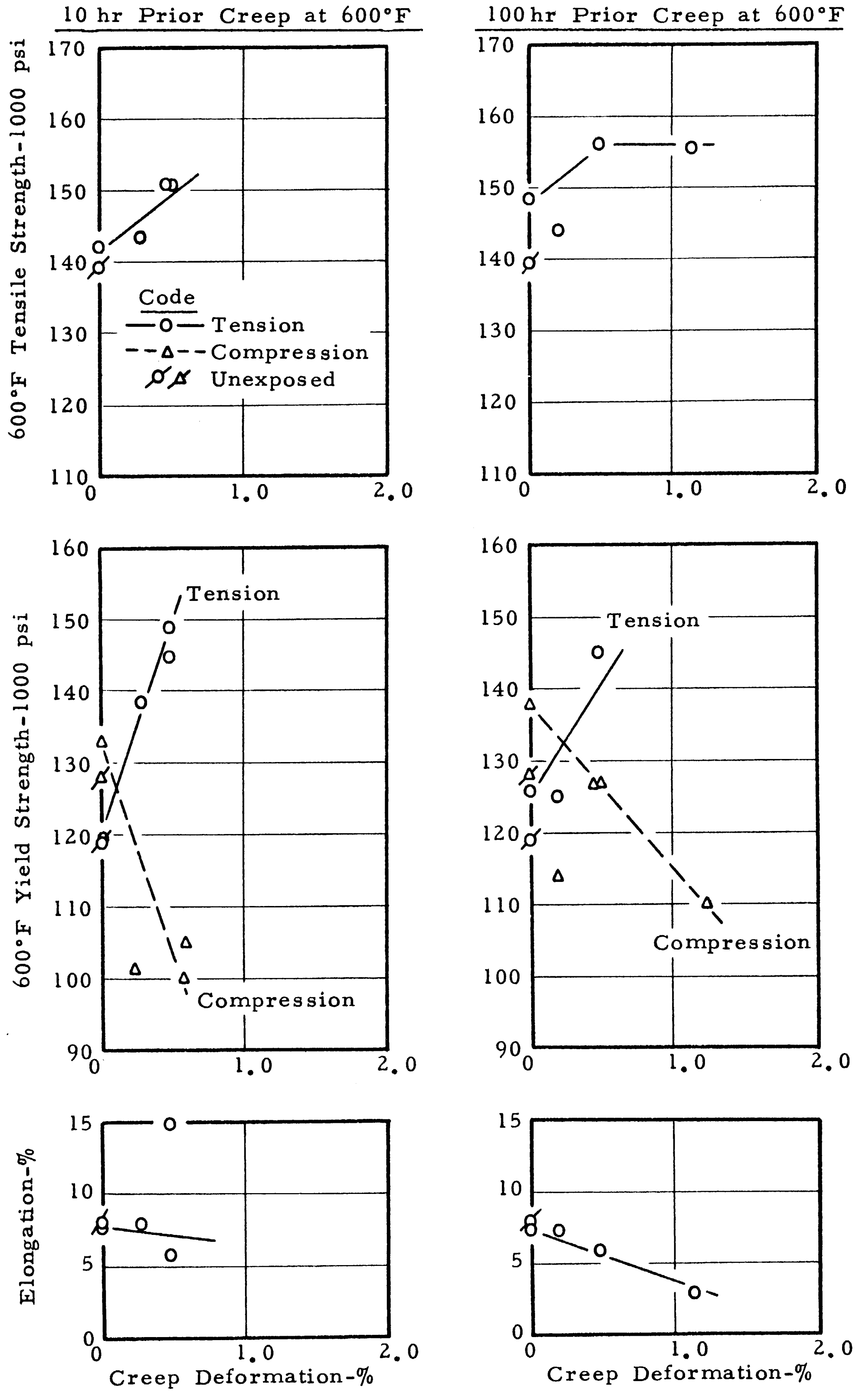

Figure 20. - Effect of Prior Creep Exposure at 600°F on Tension and Compression Properties of Ti-16V-2.5Al at 600°F.

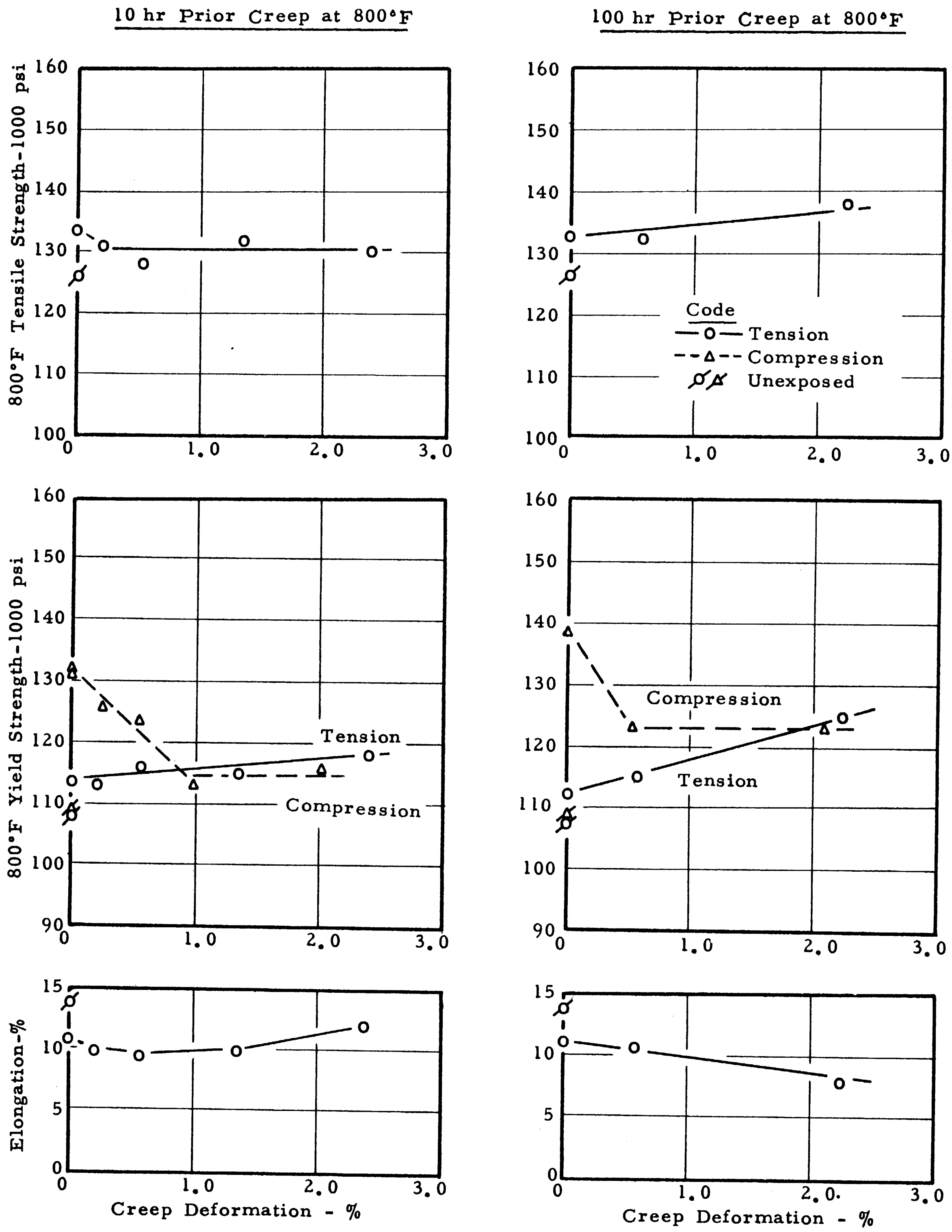

Figure 21. - Effect of Prior Creep Exposure at 800°F on Tension and Compression Properties of Ti-16V-2.5Al at 800°F.

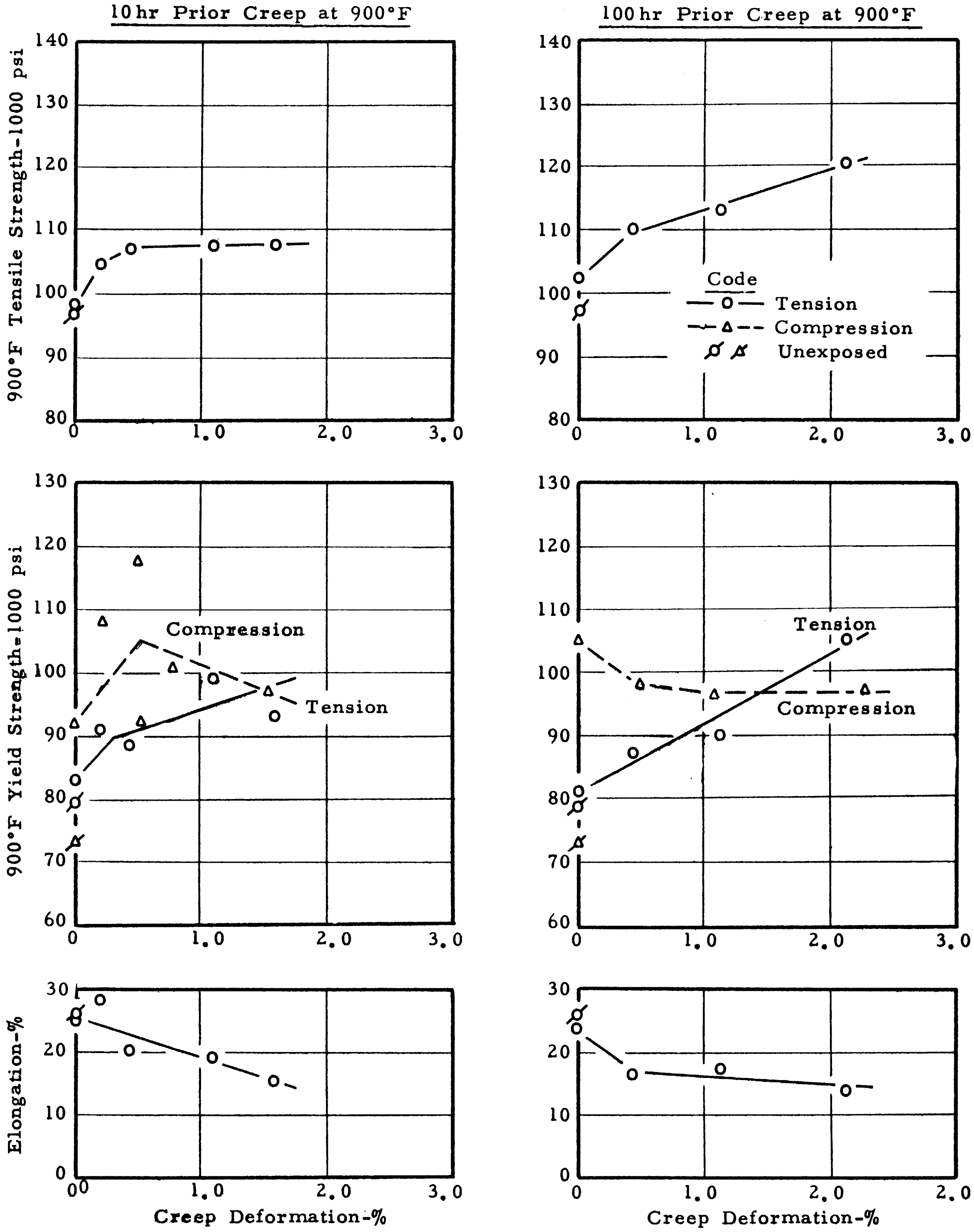

Figure 22. - Effect of Prior Creep Exposure at 900°F on Tension and Compression Properties of Ti-16V-2.5Al at 900°F.

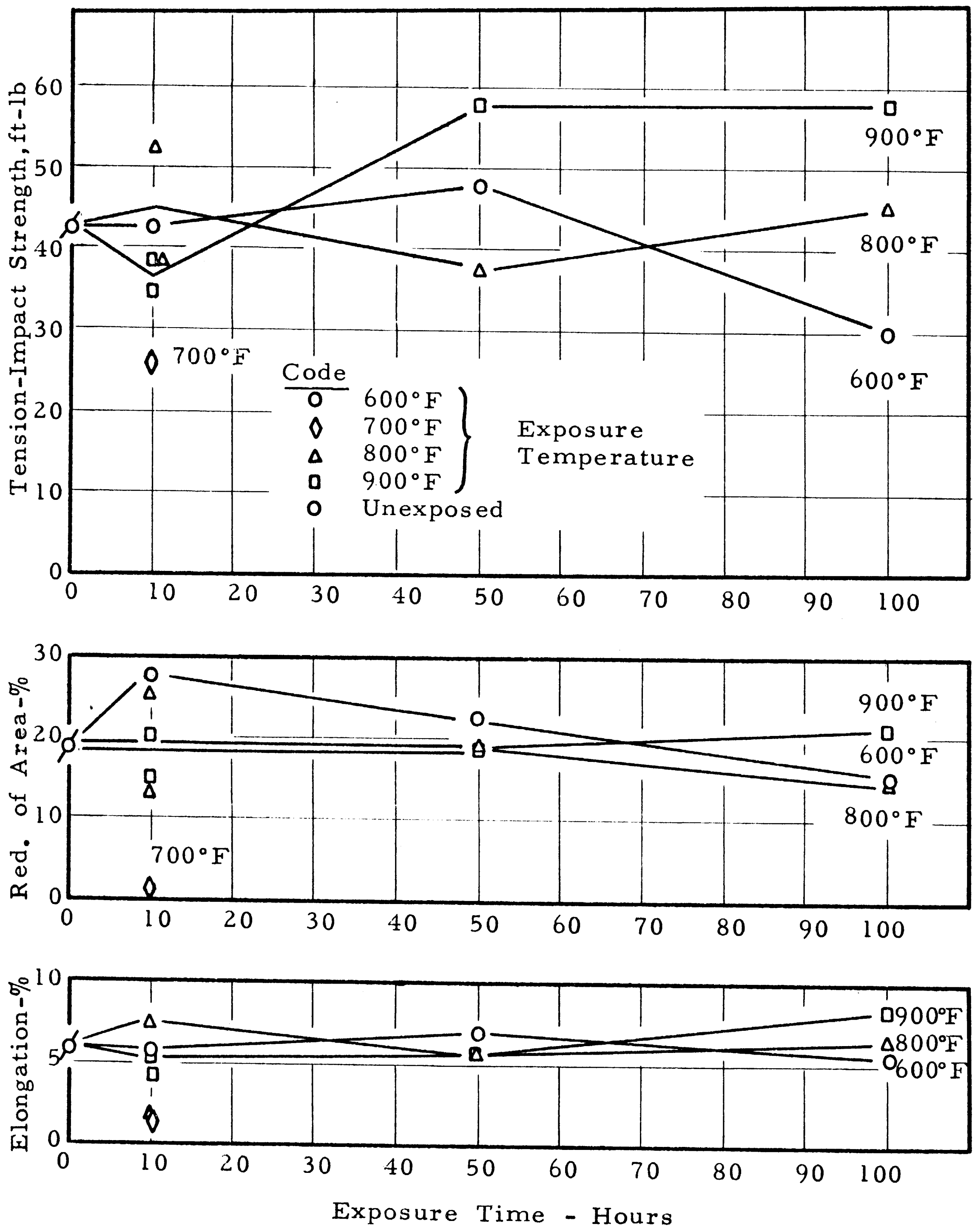

Figure 23. - Effect of Unstressed Exposure on Room Temperature Tension-Impact Properties of Ti-16V-2.5Al.

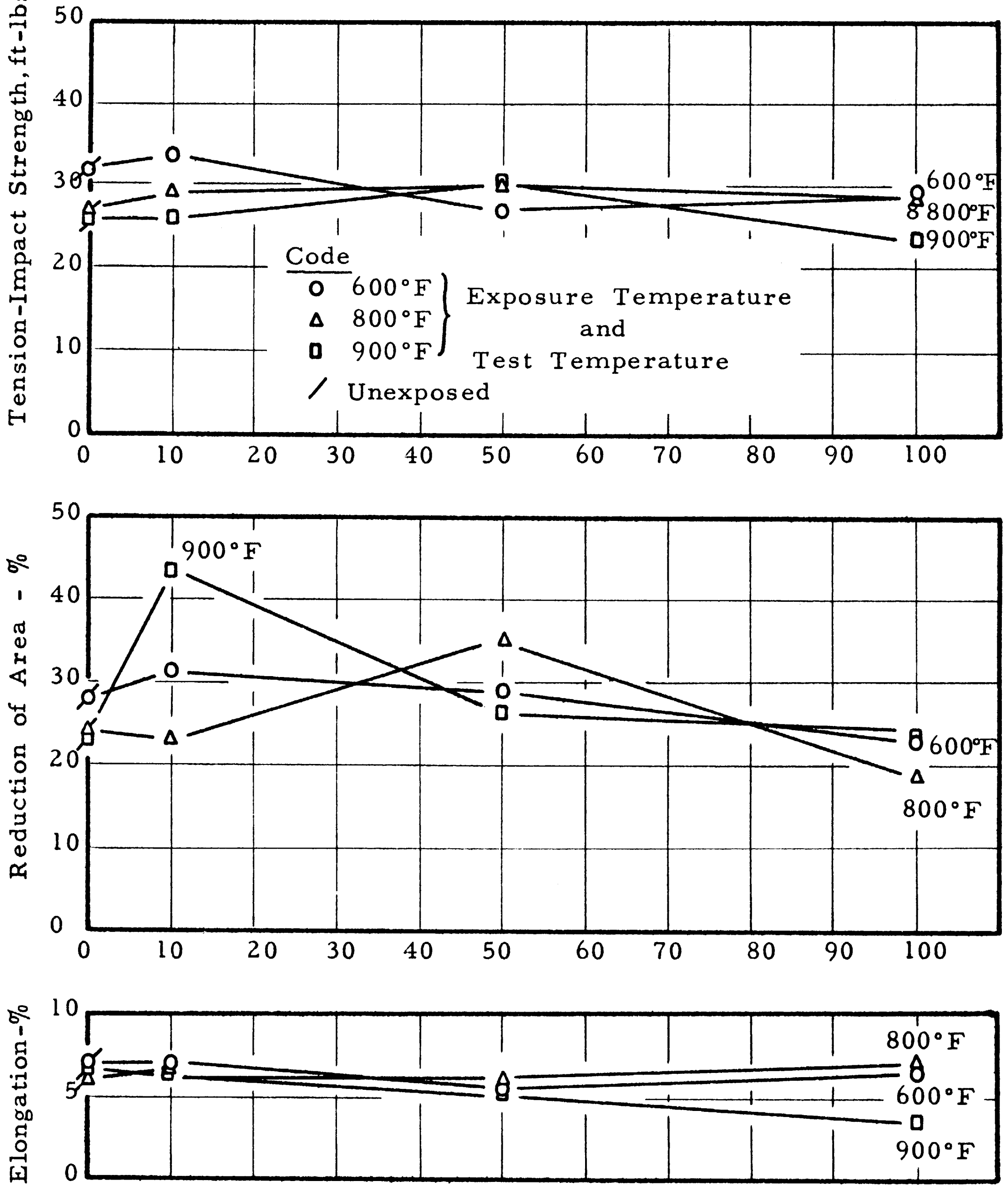

Figure 24. - Effect of Unstressed Exposure on Elevated Temperature Tension-Impact Properties of Ti-16V-2.5Al.

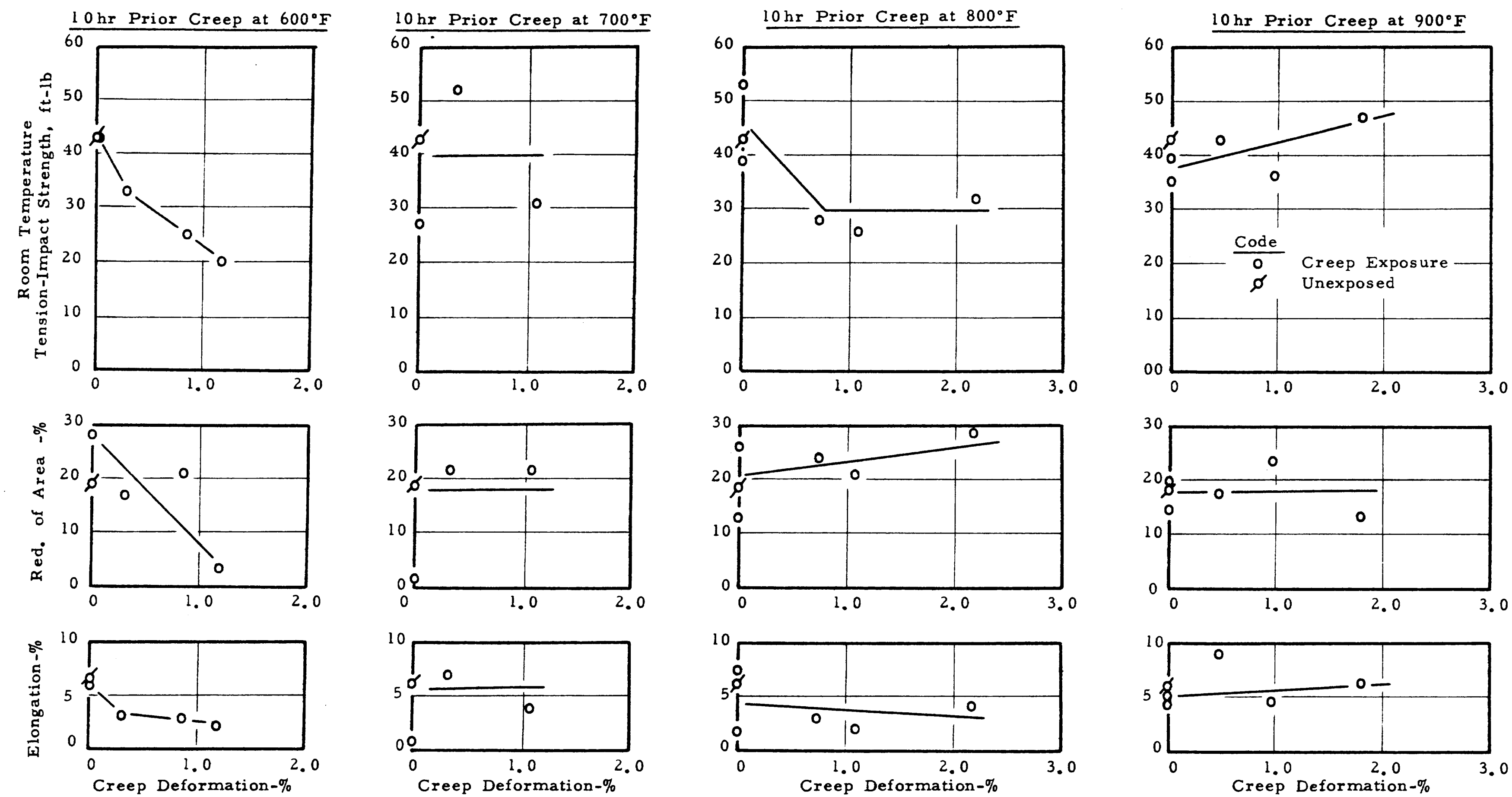

Figure 25. - Effect of Prior Creep Exposure on Room Temperature Tension-Impact Properties of Ti-16V-2.5Al.

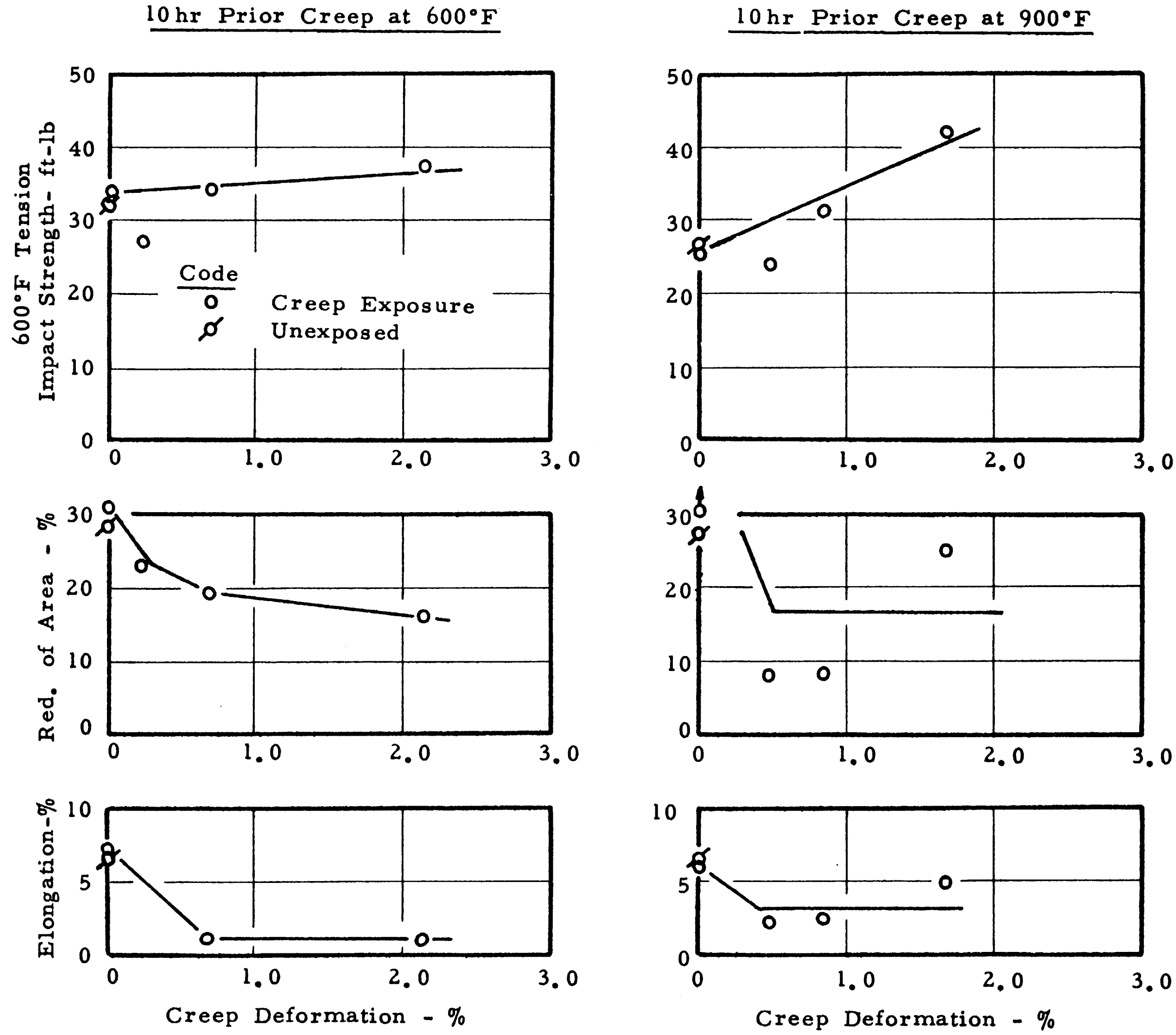

Figure 26. - Effect of Prior Creep-Exposure at 600° or 900°F on Elevated Temperature Tension-Impact Properties of Ti-16V-2.5Al.

Figure 27 x1000

As-Treated (Optical Micrograph)
(Transverse Section)

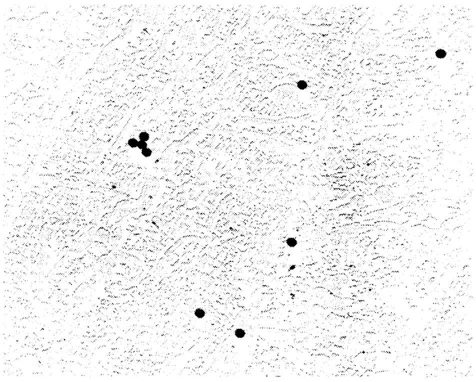

Figure 28 x3500

As-Treated (Electron Micrograph)
(Transverse Section)

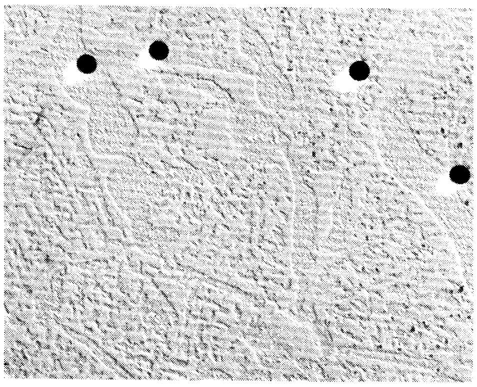

Figure 29 x8200

As-Treated (Longitudinal Surface)
RT Elong. 8.8%

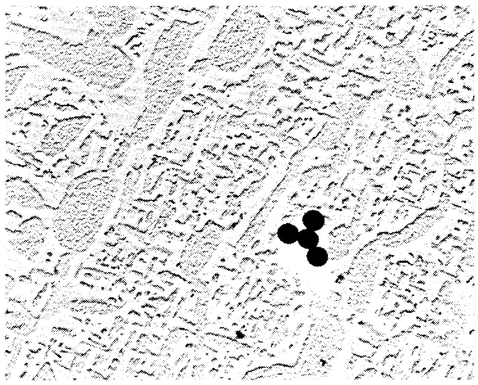

Figure 30 x8200

As-Treated (Transverse Section)
RT Elong. 8.8%

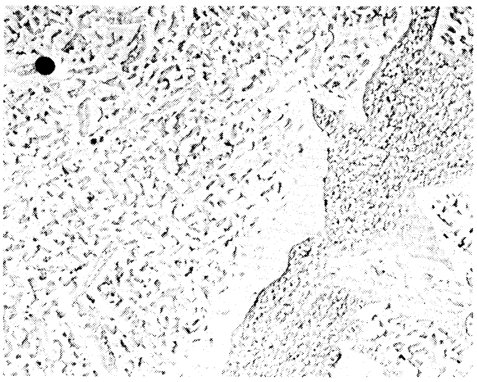

Figure 31 x8200
Creep Tested 100 hours at 600°F
to 1.0% deformation.
RT Elong. 2.0%
(Longitudinal Surface)

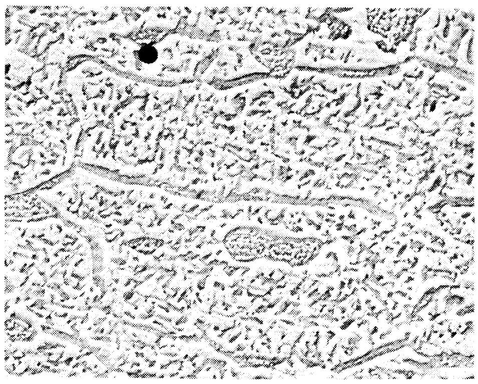

Figure 32 X8200
Same as Figure 31.
(Transverse Section)

Note: RT Elong. is elongation in room temperature tensile after indicated creep-exposure.

Figures 27-32. - Electron Micrographs of Ti-16V-2.5 Al Alloy.

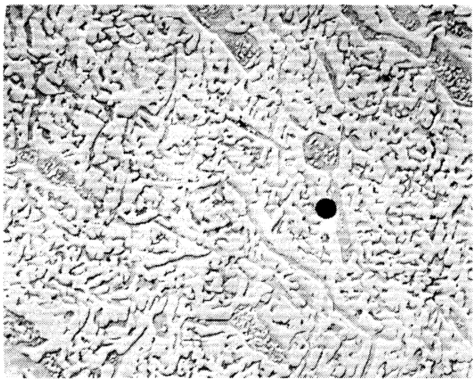

Figure 33 x8200

Creep Tested 10 hours at 600°F to 0.79% deformation. (Transverse Section) RT Elong 2.5%

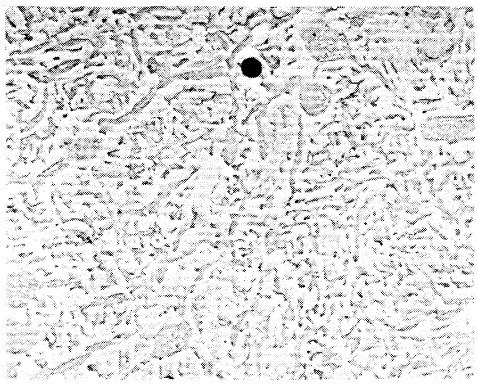

Figure 34 x8200

Creep Tested 1030 hours at 600°F to 7.4% deformation. (Transverse Section) RT Elong 1.0%

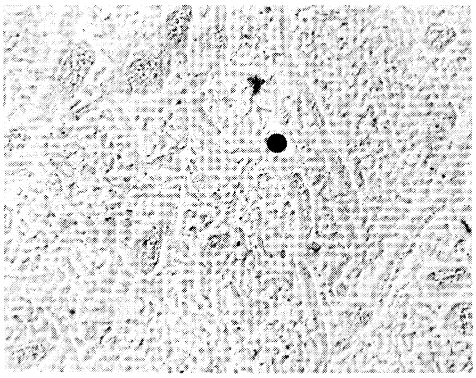

Figure 35 x8200

Exposed 100 hours at 800°F at no stress. (Transverse Section) RT Elong 8.0%

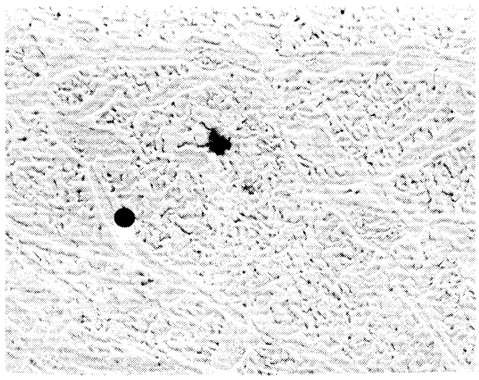

Figure 36 x8200

Creep Tested 10 hours at 800°F to 1.85% deformation. (Transverse Section) RT Elong 7.5%

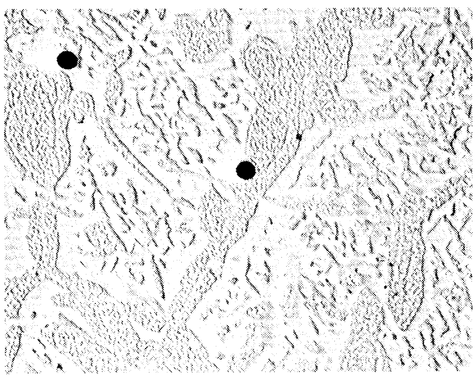

Figure 37 x8200
Creep Tested 428 hours at 900°F to 1.0% deformation. (Longitudinal Surface) RT Elong. 5.5%

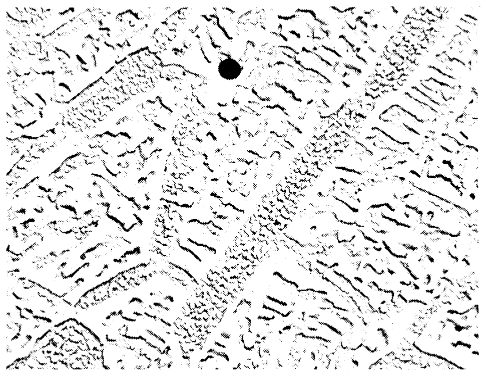

Figure 38 x8200
Same as Figure 37 (Transverse Section)

Note: RT Elong., is elongation in room temperature tensile test after indicated creep-exposure.

Figures 33-38. - Electron Micrographs of Ti-16V-2.5Al Alloy.

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The University of Michigan Research Institute, Ann Arbor, Michigan

EFFECT OF PRIOR CREEP ON THE MECHANICAL PROPERTIES OF A HIGH-STRENGTH HEAT-TREATABLE TITANIUM ALLOY, Ti-16V-2.5Al, by J. V. Gluck and J. W. Freeman. March 1959. 67p. incl. illus., tables, 6 refs. (Proj. 7360; Task 73604). (WADC TR 59-454). [Contract AF33(616)-3368].

Unclassified report (over)

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Unclassified report (over)

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The effect of creep to 2 percent in 10 or 100 hours at temperatures from 600° to 900°F was determined on the tension, compression, and tension-impact properties of Ti-16V-2.5Al at room temperature or the exposure temperature. Prior creep at 600°F raised ultimate tensile and yield strength. Lesser changes were found at higher temperatures. Changes in properties are attributed to a combination of stress-accelerated age-strengthening and a Bauschinger effect.

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