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TENSILE PROPERTIES OF AIRCRAFT-STRUCTURAL METALS AT VARIOUS RATES OF LOADING AFTER RAPID HEATING

WILLIAM P. ROE
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SOUTHERN RESEARCH INSTITUTE

SEPTEMBER 1957

WRIGHT AIR DEVELOPMENT CENTER

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SEPTEMBER 1957

MATERIALS LABORATORY
CONTRACT NO. AF 33(616)-424
PROJECT NO. 7360

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
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FOREWORD

This report was prepared by Southern Research Institute under USAF Contract No. AF 33(616)-424. The contract was initiated under Project No. 7360, "Material Analysis and Evaluation Techniques," Task No. 73605, "Design and Evaluation Data for Structural Metals". It was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. Richard Klinger acting as project engineer.

This report covers work conducted from October 1956 to April 1957.

In addition to the authors, the following personnel at Southern Research Institute contributed significantly to the project:

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ABSTRACT

The purpose of the present phase of this program was to determine the effects of variations in strain rate and holding time at temperature on the tensile properties of several aircraft-structural metals after they had been heated within 10 sec to test temperatures approaching the melting points of the alloys involved. Major emphasis was placed on an accurate determination of these effects on the ultimate tensile strength and 0.2%-offset yield strength. The modulus of elasticity, percent elongation, and proportional limit were determined with less accuracy as by-products of the data for the purpose of establishing trends. This investigation covered strain rates from 0.00005 in./in./sec to 1.0 in./in./sec, holding times at test temperature from 10 sec to 1800 sec, and the following sheet materials over the range of test temperatures indicated:

Annealed Stellite-25, 1600°F - 2250°F
Heat-treated Inconel-X, 1600°F - 2250°F
Full-hard 301 stainless steel, 1600°F - 2250°F
Annealed A110-AT titanium alloy, 1200°F - 2770°F
Alclad 2024-T3 aluminum alloy, 800°F - 900°F

In general, the ultimate tensile strength and 0.2%-offset yield strength of all test materials increased appreciably with increasing strain rates at each test temperature. With only minor variations, the apparent modulus of elasticity showed a consistently increasing trend with increasing strain rates. The same was true for the percent elongation with the exception of annealed A110-AT titanium alloy, which showed a decreasing trend with increasing strain rates.

Because of atmospheric attack, the properties of the A110-AT alloy deteriorated with increasing times at the higher test temperatures. Holding times at test temperature had no significant effect on any of the properties of the other materials investigated.

At 2250°F, annealed Stellite-25 had the greatest strength, followed by heat-treated Inconel-X, annealed A110-AT titanium alloy, and full-hard 301 stainless steel.

The oxidation resistance of annealed Stellite-25 and heat-treated Inconel-X was good at 2250°F, full-hard 301 stainless was fair to poor, and annealed A110-AT titanium alloy was poor. Alclad 2024-T3 aluminum alloy showed good oxidation resistance at 900°F.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Richard R Kennedy

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Chief, Metals Branch
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TENSILE PROPERTIES OF AIRCRAFT-STRUCTURAL METALS AT VARIOUS RATES OF LOADING AFTER RAPID HEATING[1]

INTRODUCTION

Aircraft-structural materials are often subjected in service to high rates of loading after rapid heating and after short times at temperature. Knowledge of the strength properties of structural materials under these conditions is necessary for the proper design of high-speed aircraft and missiles. Since such conditions are not approached in ordinary testing, an investigation was undertaken to determine the effects of variations in temperature, holding time at temperature, and strain rate on the short-time tensile properties of aircraft-structural metals. In the work covered by this report, five sheet materials were tested — A110-AT titanium alloy, Alclad 2024-T3 aluminum alloy, full-hard 301 stainless steel, Inconel-X, and Stellite-25. The specimens were heated to test temperatures that approached the melting points within 10 seconds; after various holding times up to 30 minutes, the specimens were strained to failure at rates from 0.00005 to 1.0 in./in./sec.

This report covers the third phase of the project. The first phase included a literature survey, development of suitable test equipment, and testing of seven aircraft-structural sheet metals at temperatures up to 1200°F. Ten additional materials, several having been heat-treated under different conditions, were tested under similar conditions in the second phase. The results of both studies were reported in WADC Technical Reports 55-199, Parts 1 and 2.

In general, the results of the first and second phases of this program indicated that strength properties of the various alloys increased with increasing strain rates. Furthermore, the effect of strain rate was more pronounced with increasing temperatures. Structural changes such as precipitation and recrystallization, which are dependent on time and temperature, and blue brittleness, which is dependent on strain rate and temperature, cause significant variations in the properties of the unstable alloys. The effects of these changes were superimposed upon and sometimes obscured the inherent effects of temperature and strain rate.

1. Manuscript copy released by authors July 1957 for publication as a WADC Technical Report

TEST METALS AND CONDITIONS

The test conditions employed on the different test metals are shown in Table I, and the identifications and chemical compositions of the test alloys are outlined in Table II. All of the metals were tested in the form of sheet with a nominal thickness of 0.040 in. with the exception of Alclad 2024-T3, which had a nominal thickness of 0.064 in. Dimensions of the test specimens are shown in Figure 3.

Inconel-X was heat-treated by Southern Research Institute, whereas the remaining materials were supplied by the manufacturers in the desired conditions. All materials were machined to the proper specimen size after heat-treatment.

The highest test temperatures were the maximum temperatures that could be obtained for testing each alloy. Absorption of oxygen and nitrogen from the air limited the testing of A110-AT titanium alloy sheet to 2770°F and a holding time of 100 sec. After a 30-minute holding time at this temperature, the remaining material was so weak that it powdered readily in one's fingers. The same phenomenon, which occurred within a few seconds at 3000°F, obviated testing the titanium specimens at that temperature as previously planned.

Incipient melting of the other materials prevented testing at temperatures higher than those indicated. The reported test temperatures are those at the surface of the specimens. Since the specimens are resistance-heated, heat losses at the surface result in a temperature gradient, with the interior being somewhat hotter than the surface. Experience at Southern Research Institute has shown that testing is impossible when melting starts in the interior, since the specimen begins to sag and finally ruptures without any application of load.

TEST EQUIPMENT

In WADC Technical Reports 55-199, Parts 1 and 2, the equipment and techniques used in running tests and calibrations are described in considerable detail. The descriptions that follow are intended mainly as brief reviews. Since the previous reports, two major improvements in equipment have been made — a "clip-on" extensometer and a mechanical calibrator for the extensometer. These items are described in more detail.

The test equipment consisted of a screw-driven tensile machine, which was actuated by a DC motor through appropriate speed reducers. Tensile specimens were resistance heated by means of current supplied through a welding transformer. Specimen temperature was controlled by means of chromel-alumel thermocouples, which were flash-welded at the middle of the gage length, and

Table I

Alloys and Test Conditions

Alloy	Form	Specification	Strain Rates, In./In./Sec	Max. Heat-ing Time, Sec	Test Temp, °F	Holding Times, Sec[1]
Stellite-25 Annealed	0.040 In. Sheet	AMS-5537	0.00005-0.01-1.0	10	1600-2000-2250	10-100-1800
Inconel-X Heat-Treated[2]	0.040 In. Sheet	MIL-N-7786	0.00005-0.01-1.0	10	1600-2000-2250	10-100-1800
301 Stainless Full-Hard	0.040 In. Sheet	MIL-S-5059	0.00005-0.01-1.0	10	1600-2000-2250	10-100-1800
A110-AT Titanium	0.040 In. Sheet	-----	0.00005-0.01-1.0	10	1200-1600-2350-2770	10-100-1800
Alclad 2024-T3 Aluminum	0.064 In. Sheet	QQ-A-362a	0.00005-0.01-1.0	10	760-900	10-100-1800

1. Refers to holding time at temperature immediately before testing.
2. Tempered 20 hours at 1300°F and air cooled.

Table II

Identification and Analyses of Test Alloys

Stellite Sheet

Alloy	Source	Heat No.	C	Mn	Fe	S	Si	Ni	Cr	W	Co
Stellite-25 Annealed	Haynes-Stellite	L-1065	0.08	1.30	2.70	0.010	0.48	10.20	19.93	14.82	Bal.

Inconel Sheet

Alloy	Source	Heat No.	C	Mn	Fe	Si	Cr	Al	Ti	Ta and Cb	Ni
Inconel-X Heat-Treated[1]	Int'l. Nickel	HT3409X	0.04	0.73	6.48	0.39	15.86	0.88	2.61	0.84	Bal.

Stainless Steel Sheet

Alloy	Source	Heat No.	C	Mn	P	S	Si	Cr	Ni	Fe
Type 301 Full-Hard	Washington Steel Corp.	29795	0.102	1.22	0.029	0.19	0.48	17.86	7.39	Bal.

Titanium Alloy Sheet

Alloy	Source	Heat No.	C	N	Al	Sn	Ti
A110-AT Annealed	Rem-Cru	D41003	0.1	0.02	5.7	2.7	Bal.

Aluminum Alloy Sheet[2]

Alloy	Source	Lot No.	Mg	Si	Cr	Fe	Cu	Mn	Zn	Al
Alclad 2024-T3 Quenched	Alcoa	65396	1.8-1.2	0.5 Max.	0.10 Max.	0.5 Max.	4.9-3.8	0.9-0.3	0.10 Max.	Bal.

1. Tempered 20 hours at 1300°F and air cooled.
2. Alcoa did not supply analyses but certified that the composition met the specification limits.

a temperature recorder-controller working in conjunction with the resistance heating unit. Thermocouples, which actuated temperature recorders, were welded to the specimens at the gage points to facilitate control of temperature uniformity.

With resistance-heating of tensile specimens, heat losses to the shoulders tended to create a lower temperature in the ends of the gage length than in the center. At the lower test temperatures, it was necessary to direct a slight stream of air at the center of the specimen in order to effectively obtain temperature uniformity. As the air stream reduced the temperature at the specimen center, the control mechanism caused additional current to flow to maintain the center of the specimen at the control temperature. This extra current, in turn, caused the temperature at the ends of the gage length to increase. Temperature uniformity at the highest test temperatures was satisfactory without the use of an air stream.

Load was measured by a strain-gage load cell, and strain by a novel "clip-on" extensometer, which was actuated at the gage points of the specimen. The signals from these transducers were amplified and the output of the amplifier fed into a load-strain recorder. A cathode-ray oscilloscope in conjunction with a Polaroid Land Camera was used for recording load-strain curves. This oscilloscope had sufficient stability to permit the accurate recording of the slowest strain-rate tests as well as the fastest strain-rate tests. Calibrated timing markers were applied to each recorded trace to facilitate the accurate determination of the strain rate for each test. Stress-strain curves were recorded to approximately 1.5% strain. An electronic relay in the strain-amplifier channel was then actuated to short out the strain channel, so that only load was recorded beyond 1.5% strain.

A functional diagram of the test setup is displayed in Figure 1, and a schematic diagram of the loading frame with the load cell, extensometer, and specimen in place is shown in Figure 2.

Extensometer

A new extensometer was designed and utilized during this phase of the program. This extensometer, which clips on the specimen, is illustrated in Figure 3. Resistance-wire strain gages were bonded to both sides of the two flat springs. To both ends of the flat springs, ceramic contact pieces were rigidly fastened. The free distance between the knife-edge contact points was made 6% longer than the gage length between the lugs on the specimen. To attach the units to the specimen, the contact points are depressed slightly with the fingers and inserted between the lugs. The restoring force of the springs provides sufficient pressure at the knife-edge contact points to make the two halves of the extensometer self-supporting. As the specimen is strained, the extensometer relaxes. The four strain gages, which are connected in a bridge circuit, produce a signal that, for the small deflection of the springs, is proportional to the net strain within the gage length of the specimen. When the

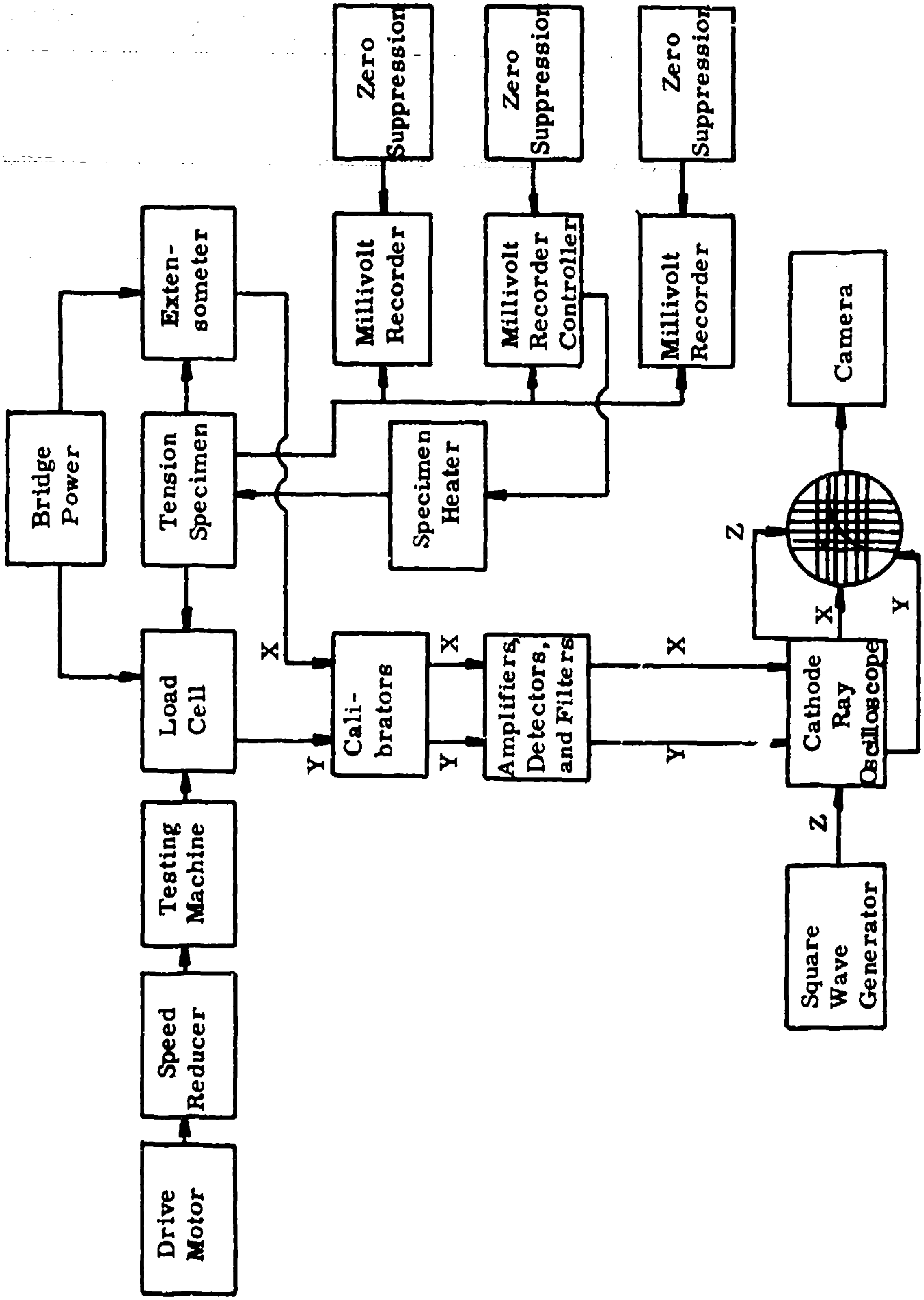

Figure 1. Functional diagram of testing equipment.

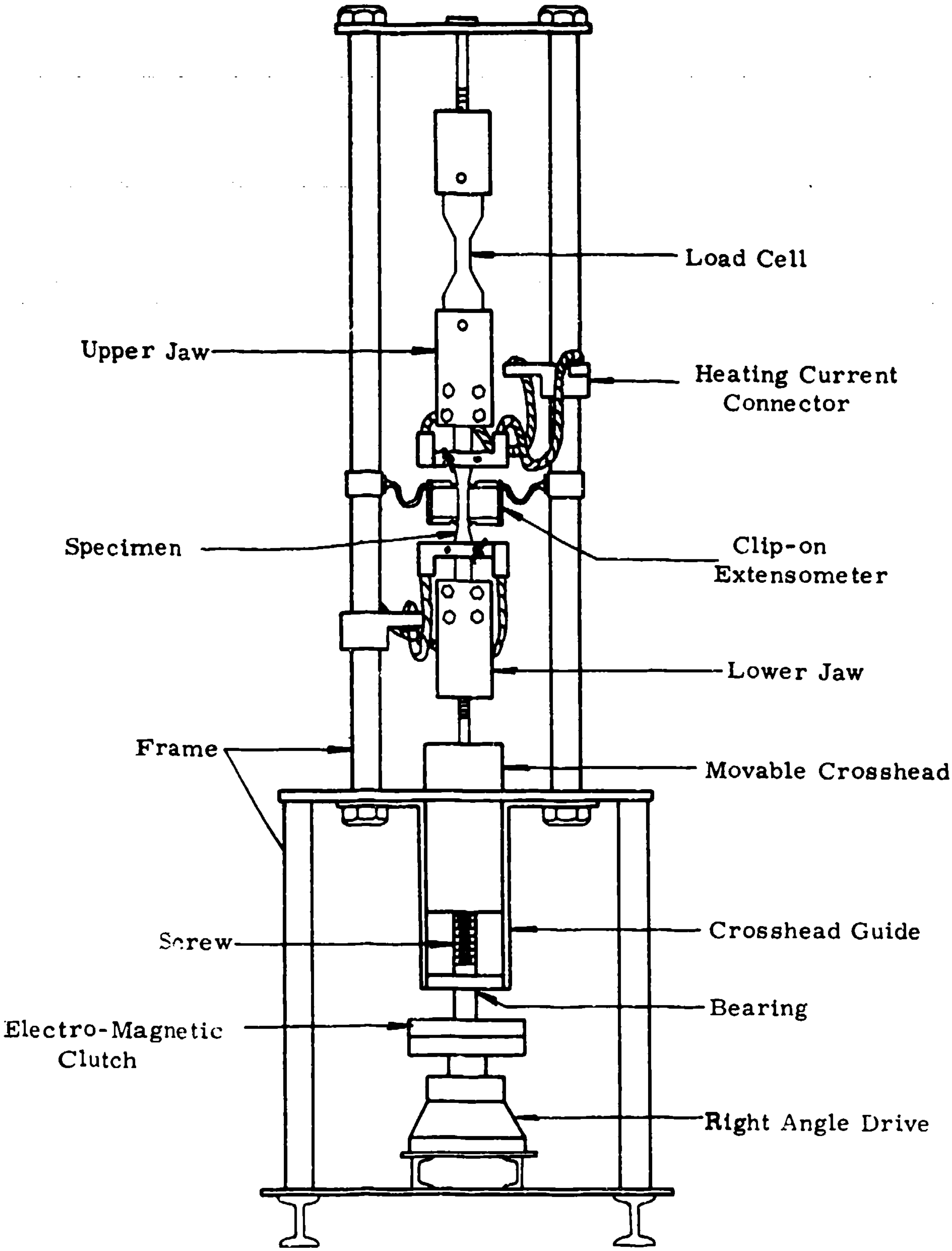

Figure 2. Schematic diagram of testing machine (front view).

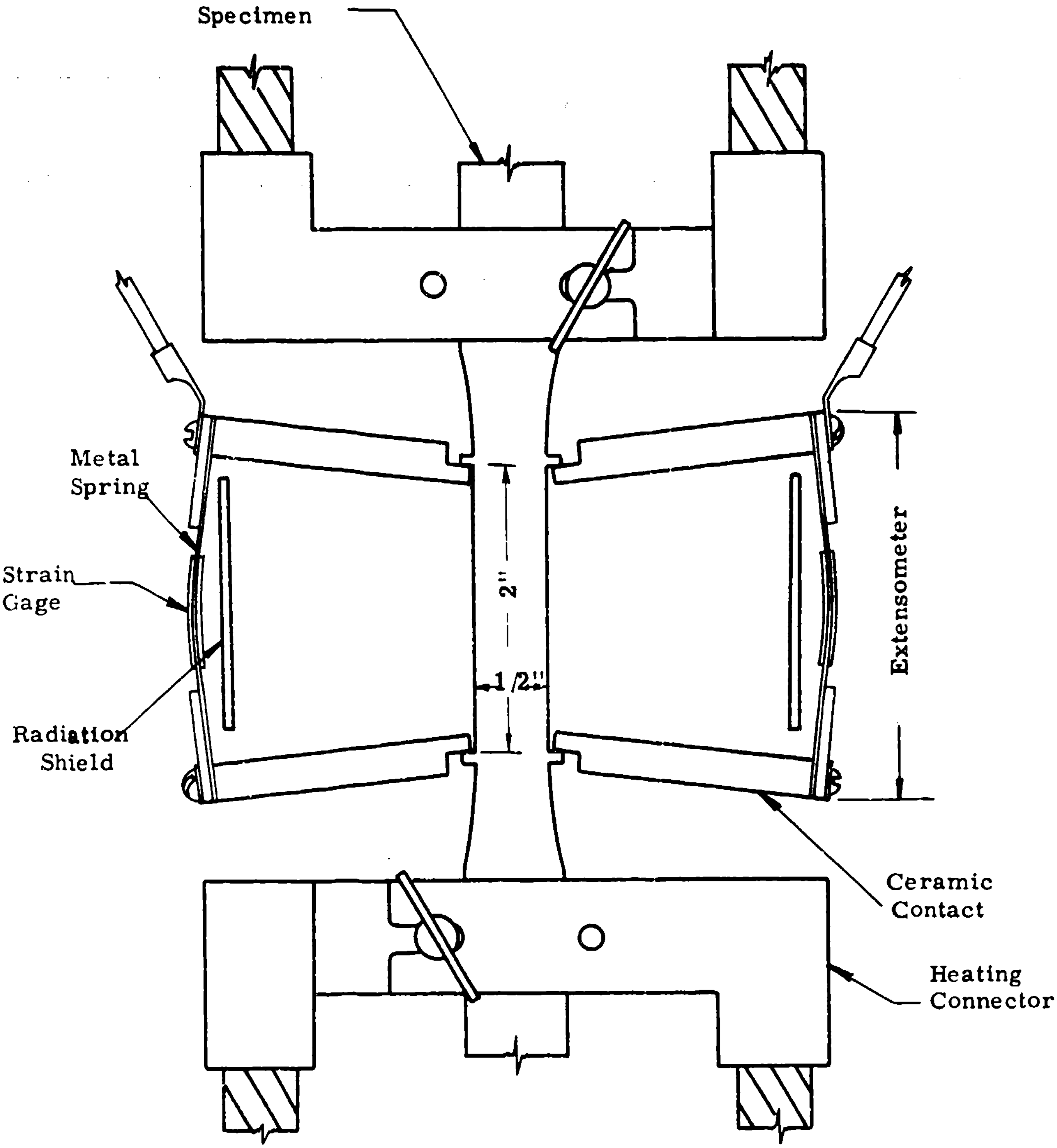

Figure 3. Specimen, Extensometer, and Heating Connectors.

specimen strain exceeds 6%, the extensometer is completely relaxed and swings free of the specimen for the remainder of the test.

Some of the advantages claimed for the clip-on extensometer over the cantilever-spring extensometer, which was formerly used, are (1) more accurate measurement of net strain between the gage points, (2) greater strain sensitivity, (3) better thermal and electrical insulation from the specimen, and (4) insensitivity to lateral movement of the specimen, which sometimes occurs with a slight re-alignment of the specimen holders as the load is first applied.

Mechanical Calibrator

A new mechanical extensometer calibrator was designed and constructed. This calibrator, as shown in Figure 4, quickly records a calibration curve on a strip-chart millivolt recorder, and saves much time over the old method, in which the extensometer was calibrated by comparing its output with the strain in a test specimen as measured by the output of strain gages attached directly to the specimen. The standard in the calibrator is a sensitive mechanical micrometer driven by a synchronous motor through a set of gears with fixed ratio. The chart is driven by another synchronous motor. As the extensometer is deflected by the movement of the micrometer, the output of the extensometer is so fed into the pen of the recorder that a plot of extensometer output vs deflection results. The outputs obtained at the five steps of the resistive calibrator, which was described in WADC TR 55-199 Pt 1, are entered onto this plot to obtain the calibration of the strain grid that is applied to the load-strain record.

ACCURACY OF TEST DATA

For a more complete analysis of the accuracy of the data and a discussion of the possible sources of error, reference is made to WADC Technical Report 55-199, Part 1, which covers the first phase of the project.

The main objective of this study was to obtain accurate information about the short-time strength properties of aircraft materials. In designing the test equipment, the major emphasis was directed toward the accurate determination of yield and ultimate strengths. Considerable time and effort would have been required to modify the equipment in order to obtain the proportional limit, modulus of elasticity, and elongation with the same degree of accuracy. These latter properties, which were determined from the test data more as by-products, were considered significant in denoting gross trends rather than absolute precise values. Therefore, consideration must be given to the methods used before making application of the data reported for the proportional limit, modulus of elasticity, and elongation. These compromises were considered justifiable in the interest of obtaining accurate yield- and ultimate-strength data within a reasonable length of time.

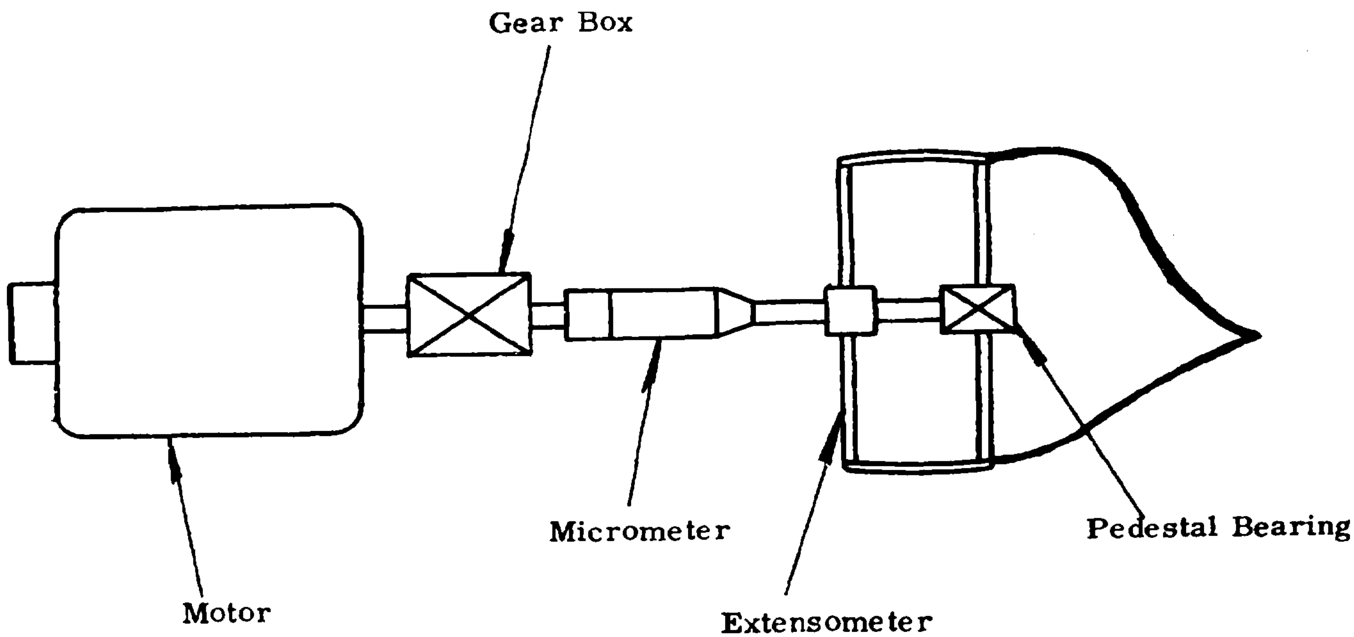

Figure 4. Schematic diagram of mechanical calibrator.

The calibrations of the load cells and extensometers were checked periodically throughout the project. The results of these checks indicated that load calibrations were reproducible within ± 2% and strain calibrations within ± 2.5% of the readings at any load and strain level. As a result of possible inaccuracies in the calibrations and in the interpretation of the load-strain curves, the maximum inaccuracy of the yield- and ultimate-strength data was ± 2.5% of each value, and that of the proportional limit values approximately ± 5%. Additional small negative errors were consistently introduced into the reported strength properties as a result of the slight tension applied by the extensometer at the start of the test. The maximum extent of this error was approximately 200 psi. The modulus-of-elasticity values for most tests are believed to be accurate within ± 10% of the true values. This degree of error in the modulus determinations was a result both of possible inaccuracies in the load and strain indications and of human inconsistencies in interpreting properly the slope of the load-strain curves.

Total elongation was determined with a divider and ruler to the nearest 0.01 in. Therefore, the measured percent-elongation values were accurate to within ± 0.25%. Because of the fact that the test specimens are resistance-heated, an inherent error may exist in the reported values for percent elongation. This error is introduced after the test specimen begins to neck-down. The increase in electrical resistance, as a result of the reduced cross-sectional area in the necked-down portion, tends to cause localized heating of the specimen. This localized heating may change the elongation characteristics of the test material. Since the specimens necked-down only after the ultimate load had been reached, the localized heating did not affect the strength and modulus determinations. Furthermore, the magnitude of the error introduced into the percent elongation values was probably negligible in the most rapid tests because there was not sufficient time for appreciable localized heating.

An investigation made during the first phase of the project indicated that the maximum error in the temperature indications was 2% of absolute temperature. Although higher test temperatures were used in the present work, methods for measuring and controlling temperature were the same, and it is believed that equivalent accuracy was obtained in the temperature measurements.

In previous phases of the work, which included testing at temperatures up to 1200°F, it was possible to measure the temperature gradients that existed between the interior and surface of the test specimens. These gradients were a result of convection and radiation at the surface. The temperature controller was adjusted to compensate for the gradients, and temperatures at the interior of the specimens were reported as the test temperatures. These gradients were rather small, amounting to a maximum of 15°F at 1200°F. In the present phase of the work, an attempt was made to measure the gradients at temperatures up to 2250°F by the method described in WADC TR 55-199, Part 1; however, very inconsistent and nonreproducible results were obtained. Therefore, the temperature control was not adjusted to compensate for the gradients during the tests, and all reported temperatures are those detected at the surface of the specimens. It is estimated that at temperatures between 2000°F and 3000°F, the gradient through the specimens was between 100°F and 150°F. This estimate is based upon the fact that incipient melting could be detected in the Inconel-X, Stellite-25, and 301 stainless steel when the indicated surface temperatures were between 100°F and 150°F below the liquidus temperature. Temperature nonuniformity between the center and ends of the specimen gage length was no more than ± 25°F throughout all tests until the specimens began to neck-down, after which excessive localized heating sometimes occurred.

Because of the two-position-type control, the specimen temperature varied within ± 10°F of the control setting during the tests at elevated temperatures.

TEST PROCEDURE

All elevated-temperature tensile tests were conducted on the sheet metals oriented in the directions as indicated:

Annealed Stellite-25	Transverse
Heat-Treated Inconel-X	Longitudinal
Full-Hard 301 Stainless Steel	Longitudinal
Annealed A110-AT Titanium Alloy	Longitudinal
Alclad 2024-T3 Aluminum Alloy	Transverse

These directions were chosen since it had been established from the preceding phases of this project that lower room-temperature strength properties resulted when the test metals were oriented as shown.

Tensile tests at each temperature were first run on each metal at the fastest and slowest strain rates after the maximum and minimum holding times, as shown in Table I. Tests at the intermediate strain rate and holding time were conducted only if the extreme conditions of strain rate and holding time at a given temperature produced differences greater than 10% in the yield strength. In general, tensile tests at the extreme conditions were carried out in triplicate, whereas those at intermediate conditions were carried out in duplicate.

The proportional limit, 0.2%-offset yield strength, and ultimate strength were determined from each calibrated load-strain record. Modulus of elasticity was measured from the slope of the elastic portion of the load-strain curve, and the maximum load on the initial straight-line section of the curve was interpreted as the proportional limit. Total elongation of each specimen was measured with a divider and scale, as discussed previously.

A strain rate for each test was calculated from the timing information on the load-strain curves. During each test the strain rate increased considerably when the load exceeded the proportional limit. The slower strain rate up to the proportional limit resulted from elastic deformation that occurred in the pull rods, load cell, specimen shoulders, and jaws as the load increased. This deformation of the machine parts takes up some of the movement of the crosshead, which travels at a constant rate. During plastic deformation of the specimen, however, the deformation of parts outside the gage length is negligible because the load increases much more slowly; therefore, almost all of the crosshead travel must be taken up by the specimen. Under all test conditions, the strain rate in the plastic region was approximately three times that in the elastic portion of the test. The strain rates reported in the test data are average rates from the start of loading to the 0.2%-offset yield strength.

The time that elapsed from the start of loading until the ultimate load was reached is reported for each material at all test conditions. These data were obtained in different ways, depending upon the rate of straining. At the intermediate and slowest strain rates, the loading trace on the load-strain records was observed during the tests, and the time to reach the ultimate load was measured with a stop watch.

At the fastest strain rate, the tests were too rapid to permit stop-watch measurements. For some materials and temperatures, the ultimate load was reached within 1.5% strain, and the time to ultimate load was determined from the load-strain records. For other materials and temperatures, an extra test was run at the fastest strain rate in order to determine the time to ultimate load. In these tests load-time curves, rather than load-strain curves, were recorded by photographing the oscilloscope trace with the Polaroid Land Camera. The internal sweep voltage of the oscilloscope was applied to the X-axis input, while the load signal was applied to the Y-axis input. Timing information was obtained by applying calibrated pulses to the Z-axis input to produce a broken-line trace.

In many of the tests, a large amount of plastic deformation occurred at or near the ultimate load, and an appreciable amount of time elapsed while the specimen was, apparently, at the ultimate load. It was difficult in these instances to interpret precisely the moment when the ultimate load was reached. In general, it appeared that the ultimate load was reached just before localized necking was observed in the specimens, at which time the load started to decrease. Therefore, the initiation of necking was used as an indication that the ultimate load had just been passed.

TEST RESULTS

The test results are tabulated in Tables III through VII and shown in Figures 6 through 45. The results for the various test alloys are arranged in the following order in the tables, figures, and discussion that follow: Stellite-25, Inconel-X, Type 301 full-hard stainless steel, A110-AT titanium alloy, and Alclad 2024-T3 aluminum alloy.

The yield strength, ultimate strength, modulus of elasticity, and percent elongation of each test alloy are shown graphically three different ways:

1. As functions of temperature with strain rate and holding time constant for each curve. These plots were made for all strain rates at a holding time of 1800 sec for all test materials with the exception of the A110-AT titanium alloy, for which the curves were plotted for the 10-sec holding time.

2. As functions of strain rate for all temperatures and holding times, which are constant for each curve.

3. As functions of holding times for all temperatures and strain rates, which are constant for each curve.

As mentioned previously, tests at intermediate conditions of strain rate and holding time were not run on a particular alloy if the difference in yield strengths determined at the extreme conditions was less than 10%. For this reason, certain points or portions of curves representing intermediate test conditions are not included in the figures.

Proportional-limit values were not plotted, but, in general, they followed the same trends as the yield-strength values with respect to temperature, strain rate, and holding time.

Families of typical stress-strain curves are also shown for each test material. These curves, which were accurately reproduced to a suitable scale from the original data, show the changes in stress-strain relationships for the extreme conditions of strain rate and holding time for each test temperature.

Annealed Stellite-25 Sheet

Test results for the annealed Stellite-25 sheet material are outlined in Table III and shown graphically in Figures 6 through 12.

Both the ultimate tensile strength and 0.2%-offset yield strength decreased continuously as test temperatures increased from 1600°F to 2250°F. In general, the same relationships were observed for the modulus of elasticity and the percent elongation with only minor exceptions; e.g., the modulus of elasticity at the fastest strain rate appeared to be relatively independent of temperature, and the percent elongation at the intermediate strain rate increased slightly with increasing temperature from 2000°F to 2250°F.

The ultimate tensile strength was particularly susceptible to strain rate changes, increasing significantly with increasing strain rates at each test temperature. The 0.2%-offset yield strength was unaffected by strain-rate changes at 1600°F, but increased with increasing strain rates at the higher test temperatures. Strain-rate effects on the modulus of elasticity were not significant at 1600°F, and differences in values obtained between the intermediate and fastest strain rates were probably not significant at the higher test temperatures. The apparent modulus values obtained in the slowest strain-rate tests were appreciably lower at 2000 and 2250°F. Percent elongation values increased in direct relation to the strain rate at each test temperature.

Holding time had practically no effect on any of the properties of this material.

Stress-strain curves have been plotted as families in Figure 12, showing the extreme conditions of strain rate and holding time for each test temperature. Effects of strain rate and temperature on the 0.2%-offset yield strength are readily apparent from these plots.

Figure 13 shows the surface condition of the annealed Stellite-25 sheet materials after tests at each temperature under the extreme conditions of strain rate and holding time. This material had relatively good oxidation resistance, and scale formation was not appreciable even at the longest holding time and highest temperature. This photograph shows clearly, however, the loss in ductility and brittle fractures obtained in the slowest strain-rate tests.

Heat-Treated Inconel-X Sheet

Test results for the heat-treated Inconel-X sheet are outlined in Table IV and plotted in Figures 14 through 20.

The ultimate tensile strength and 0.2%-offset yield strength decreased continuously with increasing temperature from 1600°F to 2250°F at each strain rate. The modulus of elasticity followed the same general trend, whereas the percent elongation increased as temperature was raised from 1600°F to 2000°F and then decreased with further increases in temperature.

Strain-rate effects were particularly noticeable with this material. Both the ultimate tensile strength and 0.2%-offset yield strength increased appreciably with increasing strain rates at each test temperature from 1600°F to 2250°F. Modulus of elasticity and percent elongation were generally unaffected at 1600°F, but increases were apparent at the higher test temperatures with increasing strain rates.

Slight increases in the ultimate tensile strength and 0.2%-offset yield strength were noted with increasing holding times at 1600°F at the intermediate and fast strain rates. This strengthening was probably a result of precipitation since Inconel-X is an age-hardening alloy. Holding-time effects at the remaining test temperatures were negligible. Modulus of elasticity and percent elongation were relatively unaffected by holding time variations, with the exception of a loss in ductility at 2250°F at the 1800-sec holding time and 1.0 in./in./sec strain rate.

Stress-strain families in Figure 20 represent typical data at the extreme conditions of holding time and strain rate for each test temperature. Decreases in yield strength with a decrease in strain rate and an increase in test temperature are quite apparent.

Inconel-X appeared to have good oxidation resistance, as shown in the photographs of test specimens in Figure 21. Scale formation was very minor even at the highest test temperature and longest holding time.

Full-Hard 301 Stainless Steel Sheet

Test results for the full-hard 301 stainless steel sheet are included in Table V and plotted in Figures 22 through 28.

The ultimate tensile strength and 0.2%-offset yield strength followed the usual trend of decreasing continuously with increasing temperature from 1600°F to 2250°F for each strain-rate condition. Similar behavior was noted for the modulus of elasticity and percent elongation, with the exception of one increase in a modulus value at 2250°F for the intermediate strain rate condition and one increase in an elongation value at 2000°F for the fastest strain rate condition.

Both the ultimate and yield strength increased significantly with increasing strain rates at each test temperature. In general, the modulus of elasticity and percent elongation showed a similar over-all dependence on strain rate.

Holding-time effects on the ultimate tensile strength and 0.2%-offset yield strength were negligible at all test conditions. They were also negligible for the modulus of elasticity and percent elongation, with the exception of a minor scatter in the results for both properties in some of the fastest strain-rate tests.

Stress-strain families have been plotted in Figure 28, and the effect of strain rate and temperature on the 0.2%-offset yield strength is readily apparent. The decrease in yield strength from 1600°F to 2000°F was especially large in comparison with the decrease from 2000°F to 2250°F.

Figure 29 contains photographs of specimens after testing under the extreme conditions of strain rate and holding time at each temperature. Oxidation resistance was fair. Scale formation was negligible at 1600°F, but increased with increasing test temperature and longer holding times. At 2250°F scale formation was appreciable on the specimen tested at a strain rate of 0.00005 in./in./sec after a holding time of 1800 sec.

Annealed A110-AT Titanium Alloy Sheet

Test results for the annealed A110-AT titanium alloy sheet are outlined in Table VI and plotted in Figures 30 through 36. Tests at 2350°F and 2770°F could not be completed at the slowest strain rate, and tests at 2770°F could not be completed at the longest holding times for the other strain-rate conditions. Oxidation and nitridation were so severe that the specimens retained no strength under these conditions.

The ultimate tensile strength and 0.2%-offset yield strength decreased in a continuous manner as test temperatures were increased from 1200°F to 2770°F.

The modulus of elasticity followed the same general trend, but the percent elongation was quite erratic. This property increased from 1200°F to 1600°F, decreased from 1600°F to 2350°F, and finally increased again at the highest test temperature.

Strength properties were sensitive to strain-rate changes. Ultimate tensile strength and 0.2%-offset yield strength increased significantly as strain rate increased at all test temperatures. The apparent modulus of elasticity increased slightly with increasing strain rates, whereas the percent elongation tended to decrease with increasing strain rates.

Stress-strain families are included in Figure 36, showing typical tensile curves under the extreme conditions of holding time and strain rate at different test temperatures. In general, the effects of strain rate and temperature on the ultimate tensile strength, 0.2%-offset yield strength, and modulus of elasticity can readily be observed.

Figure 37 shows the surface condition of typical specimens after testing under the various conditions of strain rate and holding time at each temperature. Oxidation resistance was only fair at 1200°F and became extremely poor at the higher test temperatures. A blue surface discoloration was apparent at 1200°F, and a white, loosely-adherent scale developed at 1600°F. This scale, which became quite heavy at higher test temperatures, apparently reacted with the underlying metal.

Alclad 2024-T3 Aluminum Alloy Sheet

Test results for the Alclad 2024-T3 aluminum alloy sheet are included in Table VII and shown graphically in Figures 38 through 44. A few of the low-temperature tests inadvertently were run at 760°F rather than 800°F, as shown in Figures 38 and 39. Corresponding values at 800°F were subsequently picked off these curves and used in the comparative plots shown in Figures 40 through 43.

The ultimate tensile strength, 0.2%-offset yield strength, modulus of elasticity, and percent elongation decreased for each strain-rate condition with increasing test temperature.

The ultimate tensile strength and 0.2%-offset yield strength were quite sensitive to strain-rate changes, both properties increasing markedly with increasing strain rates at each test temperature. The modulus of elasticity and percent elongation showed a similar trend as the strain rate increased from the slowest to the intermediate condition, but these properties then decreased as a rule at the fastest strain rate.

With only minor exceptions, holding time at any one temperature and strain rate appeared to have a negligible effect on the properties of this material.

Stress-strain families have been included in Figure 44. Strain-rate and temperature effects on the 0.2%-offset yield strength are readily apparent.

Surface conditions of four Alclad 2024-T3 aluminum sheet specimens after testing are shown in Figure 45. The oxidation resistance of this material was very good, no surface scale having formed under any of the test conditions. However, the actual fracture surfaces appeared discolored after testing had been completed at the longest holding time and slowest strain rate at 900°F.

DISCUSSION

As mentioned previously, yield- and ultimate-strength values were determined with a good degree of accuracy, whereas modulus of elasticity and elongation values were obtained more as by-products. Therefore, in the discussion that follows, major emphasis will be placed on the strength properties. Although time limitations prevented a complete analysis of the data, a number of trends and relationships were sufficiently evident and reproducible from the data to be of value to the design engineer.

The test results showed that tensile properties of the various test materials were strongly dependent on temperature and strain-rate changes, and only slightly dependent on changes in holding time.

As a general rule, strength properties and modulus of elasticity of all test materials decreased with increasing test temperatures. Isolated exceptions to this trend occurred in modulus-of-elasticity values. For example, a slight increase in the modulus of elasticity was observed at the intermediate strain rate for both heat-treated Inconel-X and full-hard 301 stainless steel as the temperature increased from 2000°F to 2250°F. In addition, the modulus of elasticity remained relatively constant at the fastest strain rate for annealed Stellite-25 at test temperatures from 1600°F to 2250°F.

Percent-elongation values varied erratically with increasing test temperature. A general decreasing trend was observed for annealed Stellite-25 and Alclad 2024-T3 aluminum alloy. Full-hard 301 stainless steel exhibited a similar behavior except at the fastest strain rate. At the fastest strain rate in full-hard 301 stainless and Inconel-X, percent-elongation values increased as temperature was increased from 1600°F to 2000°F and then decreased with further increases in temperature. Percent-elongation values of annealed A110-AT titanium alloy increased as temperature was increased from 1200°F to 1600°F, decreased at 2350°F, and then increased at 2770°F.

The ultimate tensile strength of all materials increased appreciably with increasing strain rate at each test temperature. The same was true for the 0.2%-offset yield strength of all materials with the exception of annealed Stellite-25 at 1600°F. The yield strength of this material remained practically constant for each strain rate at this temperature.

With only minor exceptions, the modulus of elasticity tended to increase slightly as strain rates increased at each test temperature for all materials. Percent-elongation values also tended to increase with increasing strain rate in most of the test materials. One exception to this trend occurred in A110-AT titanium alloy, which exhibited a general decrease in elongation as strain rates increased. Inconsistencies were noted in the Alclad 2024-T3 aluminum alloy in that some of the percent-elongation values at specific holding times decreased at the fastest strain rate after having increased at the intermediate strain rate.

The general effects of strain rate on tensile properties observed in this phase of the work were similar to those determined in previous phases; i.e., with increasing strain rates, strength properties usually increased, elongation varied unpredictably depending upon the temperature and material, and modulus of elasticity remained constant or apparently increased slightly. The increases of modulus of elasticity with increasing strain rate were more pronounced at the higher test temperatures. These changes in apparent modulus are not believed to be true variations in elastic properties, but rather are probably due to a small amount of creep that occurs at the slower strain rates during the elastic portion of the tests.

Variations in holding time from 10 sec to 1800 sec had little or no effect on the 0.2%-offset yield strength and ultimate tensile strength of the Stellite-25, Inconel-X, full-hard 301 stainless, or 2024-T3 at any of the test temperatures. At 1200°F and 1600°F, the A110-AT titanium alloy was not affected by variations in holding time; but as holding time was increased from 100 sec to 1800 sec at 2350°F and 2770°F, the strength deteriorated to zero and the ductility also decreased owing to oxidation and other atmospheric contamination. With changes in holding time in some of the other test materials, a few small variations were found in the modulus of elasticity and percent elongation. These variations were isolated and showed no consistent trends, making it difficult to ascribe any significance to them.

Annealed Stellite-25 and heat-treated Inconel-X were the alloys most resistant to oxidation at the test temperatures. Neither of these materials developed appreciable scale at the highest test temperature of 2250°F. Full-hard 301 stainless steel ranked next in oxidation resistance, although service at 2250°F could not be recommended because of the rapid deterioration and appreciable scale formation that occurred at this temperature. The oxidation of annealed A110-AT titanium alloy at 1200°F compared visually with that of full-hard 301 stainless steel at 1600°F. At higher test temperatures, the oxidation resistance of this titanium alloy was poor. A yellowish-white, loosely-adherent scale, presumably TiO_2, formed readily at 1600°F. At 2350°F and 2770°F, an extremely heavy scale formed and appeared to react with the underlying base metal. Alclad 2024-T3 aluminum alloy had good oxidation resistance up to its highest test temperature of 900°F.

Figures 46 and 47 show the effects of temperature on the strength properties of the test metals at the fastest and slowest strain rates after a holding time of 1800 sec at test temperatures. These comparative plots include data from previous phases of this program so that a continuous curve could be presented for each material tested in the present phase from room temperature to the highest test temperature.

Increases in ultimate and yield strengths as a result of an increase in the strain rate from 0.00005 to 1.0 in./in./sec were quite pronounced for most materials and test temperatures. On the basis of the tests at the fastest strain rate, heat-treated Inconel-X had the highest ultimate strength at 1600°F, followed by annealed Stellite-25, full-hard 301 stainless steel, and annealed A110-AT titanium alloy. This order at the fastest strain rate changed somewhat as the test temperature increased. Annealed Stellite-25 had the greatest ultimate strength at 2250°F, followed by heat-treated Inconel-X, annealed A110-AT titanium alloy, and full-hard 301 stainless steel. Annealed A110-AT titanium alloy was the only material that could be tested at higher temperatures. Although atmospheric contamination prevented testing at the slowest strain rate and longest holding time, this material still had an ultimate tensile strength at 2770°F of approximately 3000 psi at the fastest strain rate after a holding time of 100 sec.

The Alclad 2024-T3 aluminum alloy also showed large increases in ultimate strength with increasing strain rates even though the highest test temperature was only 900°F. This alloy had exhibited a higher ultimate strength at the slowest strain rate at temperatures up to 300°F, apparently as a result of aging effects. It is believed that similar precipitation and particle-growth phenomena were the cause of slight decreases in strength with increasing strain rate in heat-treated Inconel-X and annealed Stellite-25 at certain of the lower test temperatures. However, no such effects were detected in the ultimate strength of any of the materials tested above 1600°F.

As shown in Figure 47, heat-treated Inconel-X had the greatest yield strength by far at 1600°F at the fastest strain-rate, followed by annealed Stellite-25, annealed A110-AT titanium alloy, and full-hard 301 stainless steel. Similar to its previously noted behavior in regard to ultimate tensile strength, the heat-treated Inconel-X suffered a rapid loss in strength above 1600°F. At 2250°F, annealed Stellite-25 had the greatest yield strength at the fastest strain rate, followed by heat-treated Inconel-X, annealed A110-AT titanium alloy, and full-hard 301 stainless steel.

Alclad 2024-T3 aluminum alloy showed a considerable increase in yield strength with increasing strain rates at test temperatures of 800°F and 900°F. Previous comments on aging and particle-growth phenomena in regard to the ultimate strength also apply in general to the yield strength of this material as well as to that of heat-treated Inconel-X and annealed Stellite-25 at certain test temperatures.

Figures 48 through 51 show the effects of temperature on the strength properties of the test materials at the maximum and minimum holding times. These comparative plots, which include previous low-temperature results, show that the effects of holding time on the tensile properties of the test metals are, in general, not nearly so pronounced as those of strain rate. Minor fluctuations were evident as a result of aging phenomena at certain of the lower test temperatures for Alclad 2024-T3 aluminum alloy and heat-treated Inconel-X. As mentioned previously, atmospheric contamination resulted in a marked deterioration in A110-AT titanium alloy at 2350°F and 2770°F. Otherwise, holding times exerted little or no influence on strength properties.

A discussion of the qualitative correlation between tensile and creep properties was presented in WADC TR 55-199 Parts 1 and 2. It was pointed out that creep tests are analogous to tensile tests at very slow strain rates. Materials that are quite senstivie to changes in strain rate — i.e., their strength properties decrease greatly with decreases in strain rate — would not be expected to retain high strength when the strain rate is decreased to levels that are associated with creep tests. On the other hand, materials in which strength properties are relatively insensitive to changes in strain rate should have good creep strength since their strength will not decrease greatly as strain rates are reduced to creep levels. These relations are shown schematically in Figure 5.

This correlation between sensitivity to strain rate and creep properties is illustrated by the data plotted in Figure 52. This plot shows the percentage change that occurred in the ultimate strength of each material as the strain rate was increased from 0.00005 to 1.0 in./in./sec at different temperatures. For each material the effect of strain rate was relatively small up to a certain temperature and then increased sharply with further increases in temperature. As shown in Figure 52, the minimum temperatures at which the sensitivity to strain rate reached 100% in the different materials were as follows:

Alclad 2024-T3 aluminum alloy,	600°F
A110-AT titanium alloy,	1200°F
Full-hard 301 stainless steel,	1400°F
Heat-treated Inconel-X	1500°F
Annealed Stellite-25	1700°F

These temperatures correspond roughly to the maximum temperatures at which each material would be expected to exhibit reasonable creep resistance. At higher temperatures than those indicated, the ultimate strength of each of these materials showed a marked dependence on strain rate.

These results suggest that data of the type plotted in Figure 52 might be used to obtain a quick qualitative indication of the temperature range in which new and untested alloys could be expected to serve well in applications involving creep. A comparison of such plots for new alloys with the existing curves might show the relative merits of the new alloys for creep service.

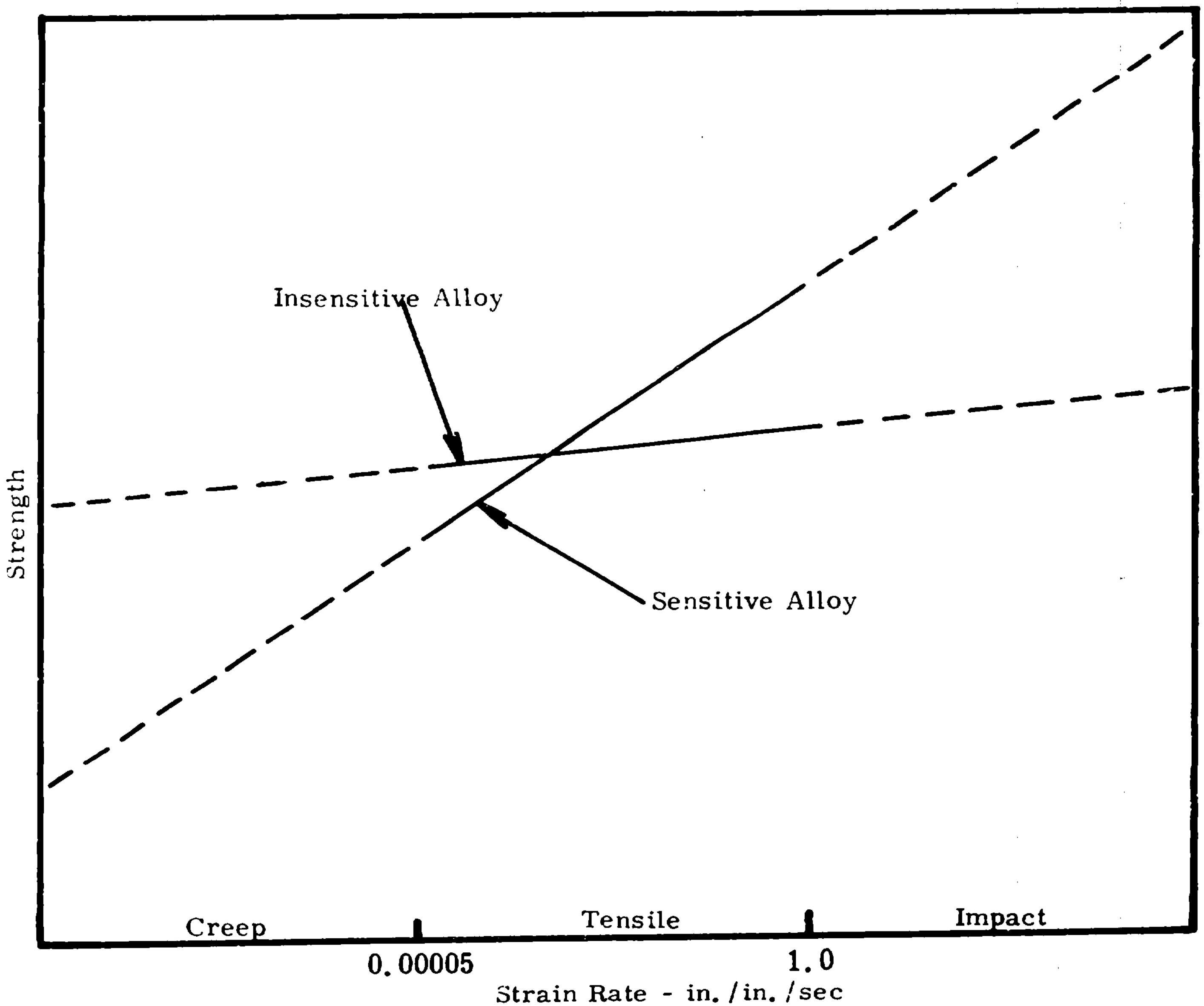

Figure 5. Schematic representation of strain-rate effects on one alloy in which strength is sensitive and another alloy in which strength is insensitive to changes in strain rate.

CONCLUSIONS

1. The ultimate tensile strength and 0.2%-offset yield strength of all test materials decreased continuously with increasing temperatures. These test temperatures were 800°F to 900°F for Alclad 2024-T3 aluminum alloy, 1600°F to 2770°F for annealed A110-AT titanium alloy, and 1600°F to 2250°F for heat-treated Inconel-X, annealed Stellite-25, and full-hard 301 stainless steel.

2. In general, the modulus of elasticity also decreased with increasing test temperatures for all materials. The percent elongation, however, varied erratically with increasing temperature.

3. Both the ultimate tensile strength and 0.2%-offset yield strength of all materials increased appreciably as strain rates increased at each test temperature with only one exception. The yield strength of annealed Stellite-25 at 1600°F was practically unaffected by strain-rate changes.

4. In general, as strain rates increased at each test temperature, both the apparent modulus of elasticity and percent elongation tended to increase. Although isolated variations were noted in the data, the only major exception to these trends was in the annealed A110-AT titanium alloy, which exhibited a decrease in the percent elongation as strain rates increased.

5. Variations in holding time at the test temperatures had no significant effect on the ultimate tensile strength, 0.2%-offset yield strength, modulus of elasticity, and percent elongation of the Stellite-25, Inconel-X, full-hard 301 stainless steel, and Alclad 2024-T3 aluminum alloy. At the higher test temperatures, the properties of the A110-AT titanium alloy deteriorated with increasing holding time due to atmospheric contamination.

6. Annealed Stellite-25 and heat-treated Inconel-X were the alloys most resistant to oxidation at the highest test temperatures, followed by full-hard 301 stainless steel and annealed A110-AT titanium alloy. Alclad 2024-T3 alloy exhibited good oxidation resistance at its highest test temperature of 900°F.

7. A qualitative correlation between creep and tensile properties was shown. The temperatures at which creep resistance falls off rapidly are roughly equivalent to those at which increases in strain rate resulted in a marked increase in the ultimate strength for each material. These temperatures were approximately 600°F for Alclad 2024-T3 aluminum alloy, 1200°F for annealed A110-AT titanium alloy, 1400°F for full-hard 301 stainless steel, 1500°F for heat-treated Inconel-X, and 1700°F for annealed Stellite-25.

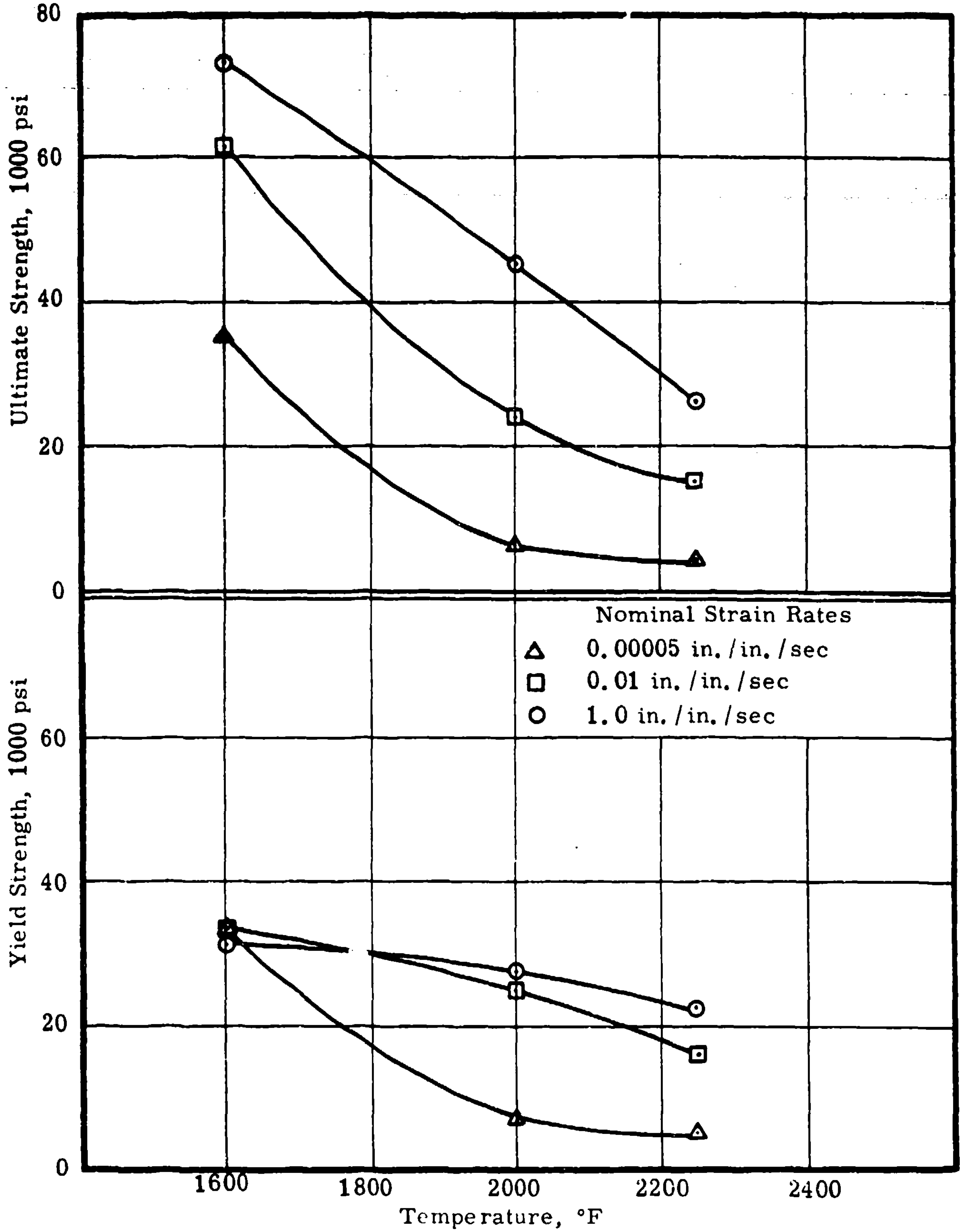

Figure 6. Effect of temperature, after 1800-sec holding time, on the 0.2%-offset yield strength and ultimate tensile strength of annealed Stellite-25 sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

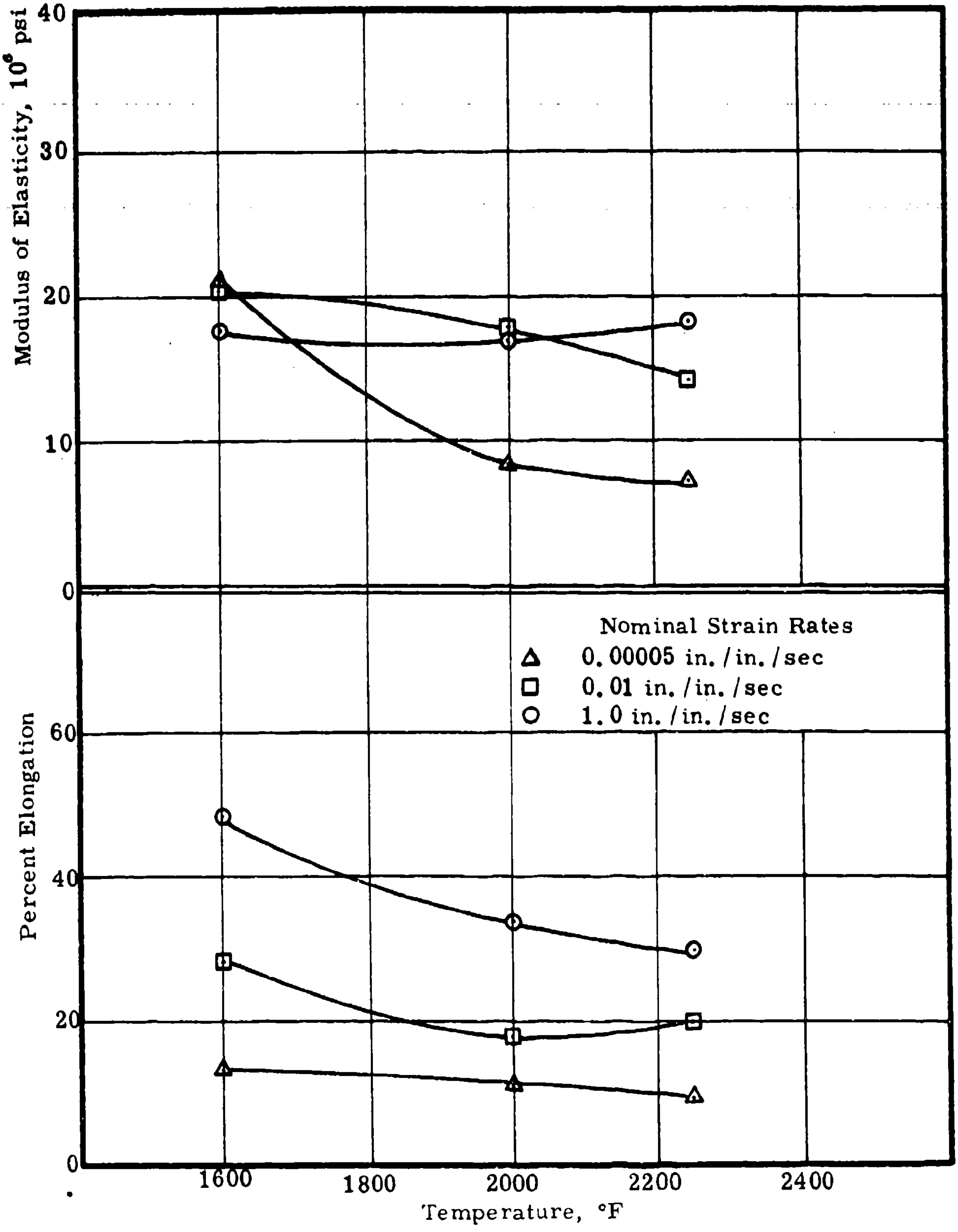

Figure 7. Effect of temperature, after 1800-sec holding time, on the percent elongation and modulus of elasticity of annealed Stellite-25 sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

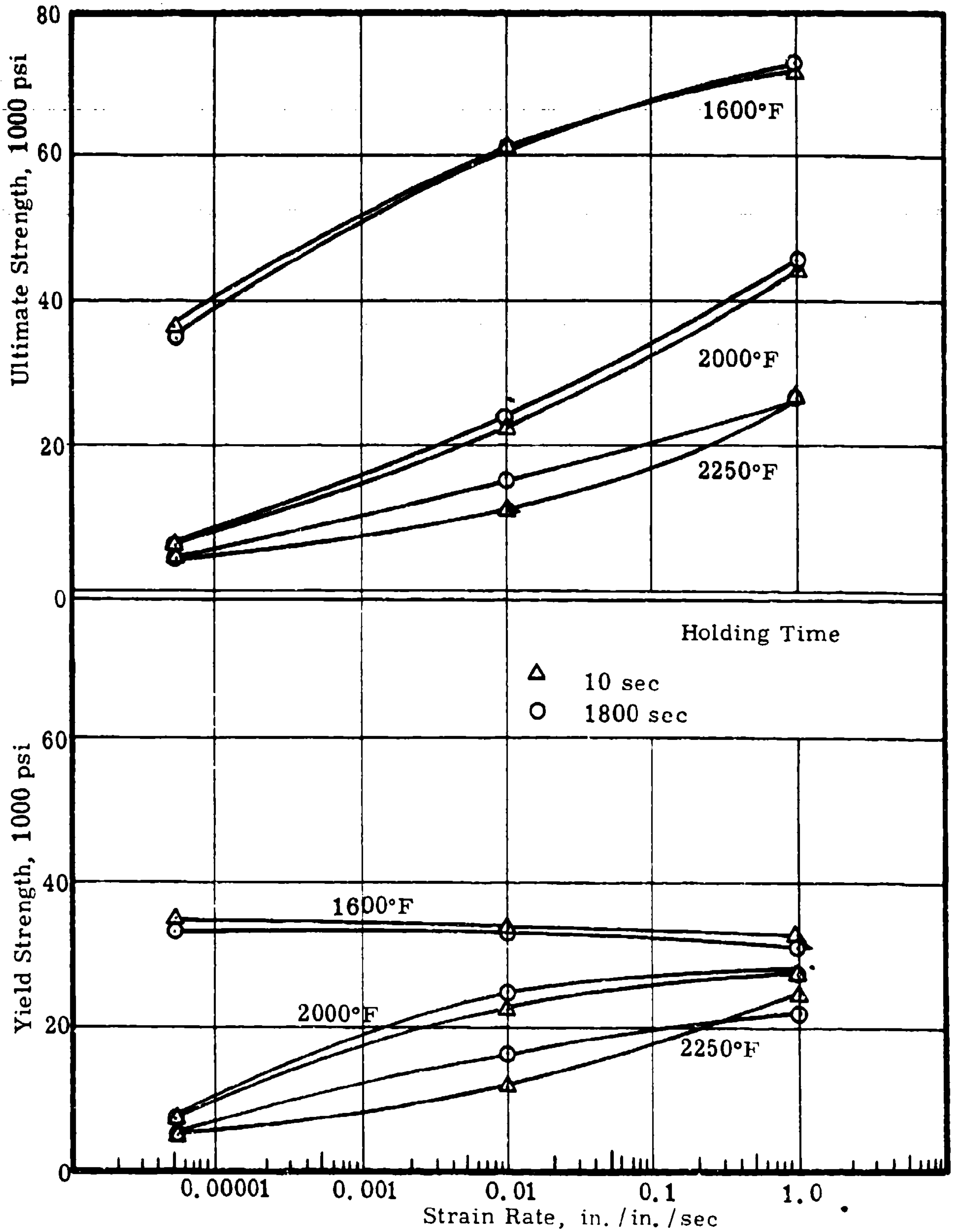

Figure 8. Effect of strain rate on the 0.2%-offset yield strength and ultimate tensile strength of annealed Stellite-25 sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

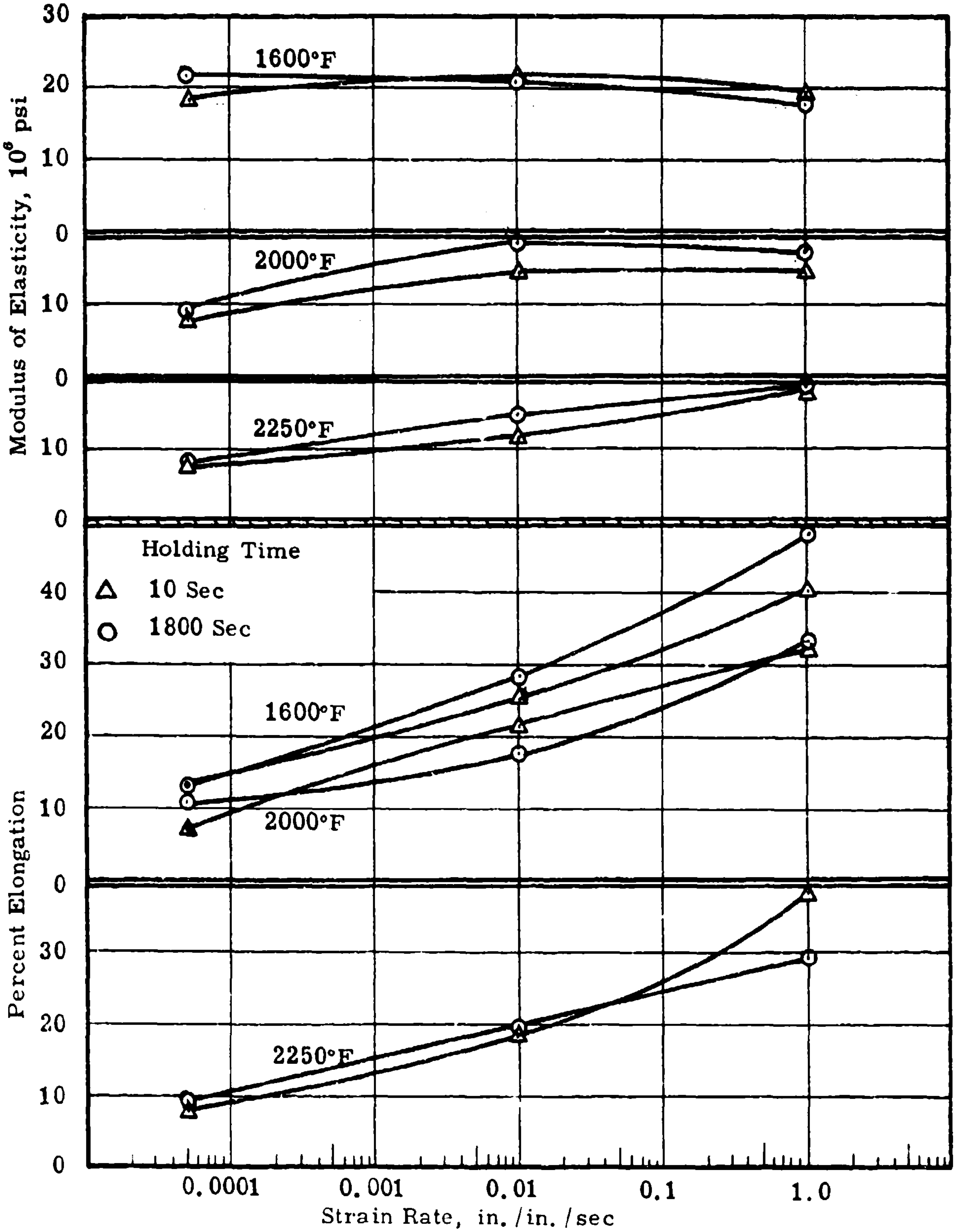

Figure 9. Effect of strain rate on the percent elongation and modulus of elasticity of annealed Stellite-25 sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

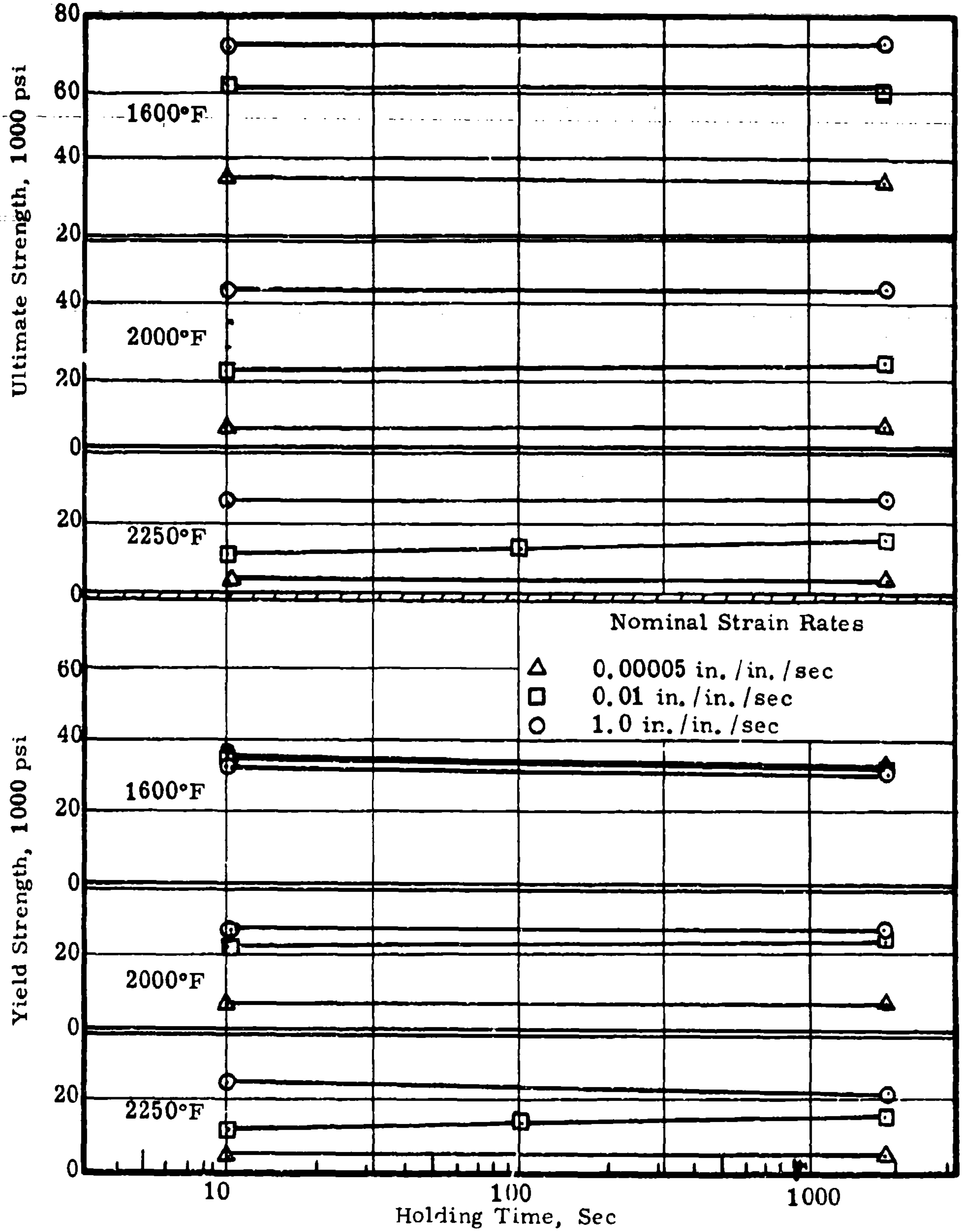

Figure 10. Effect of holding time on the 0.2%-offset yield strength and ultimate tensile strength of annealed Stellite-25 sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

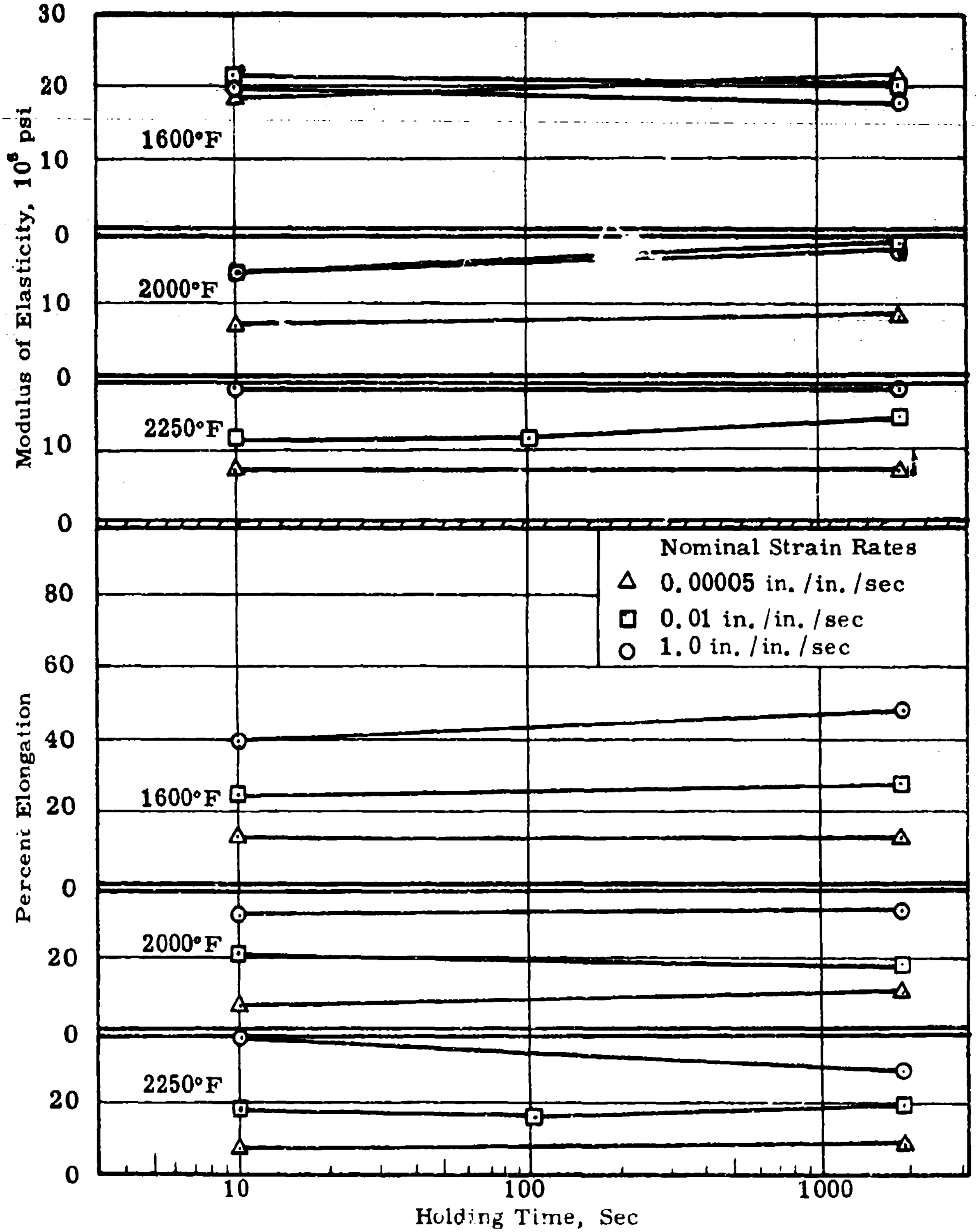

Figure 11. Effect of holding time on the percent elongation and modulus of elasticity of annealed Stellite-25 sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

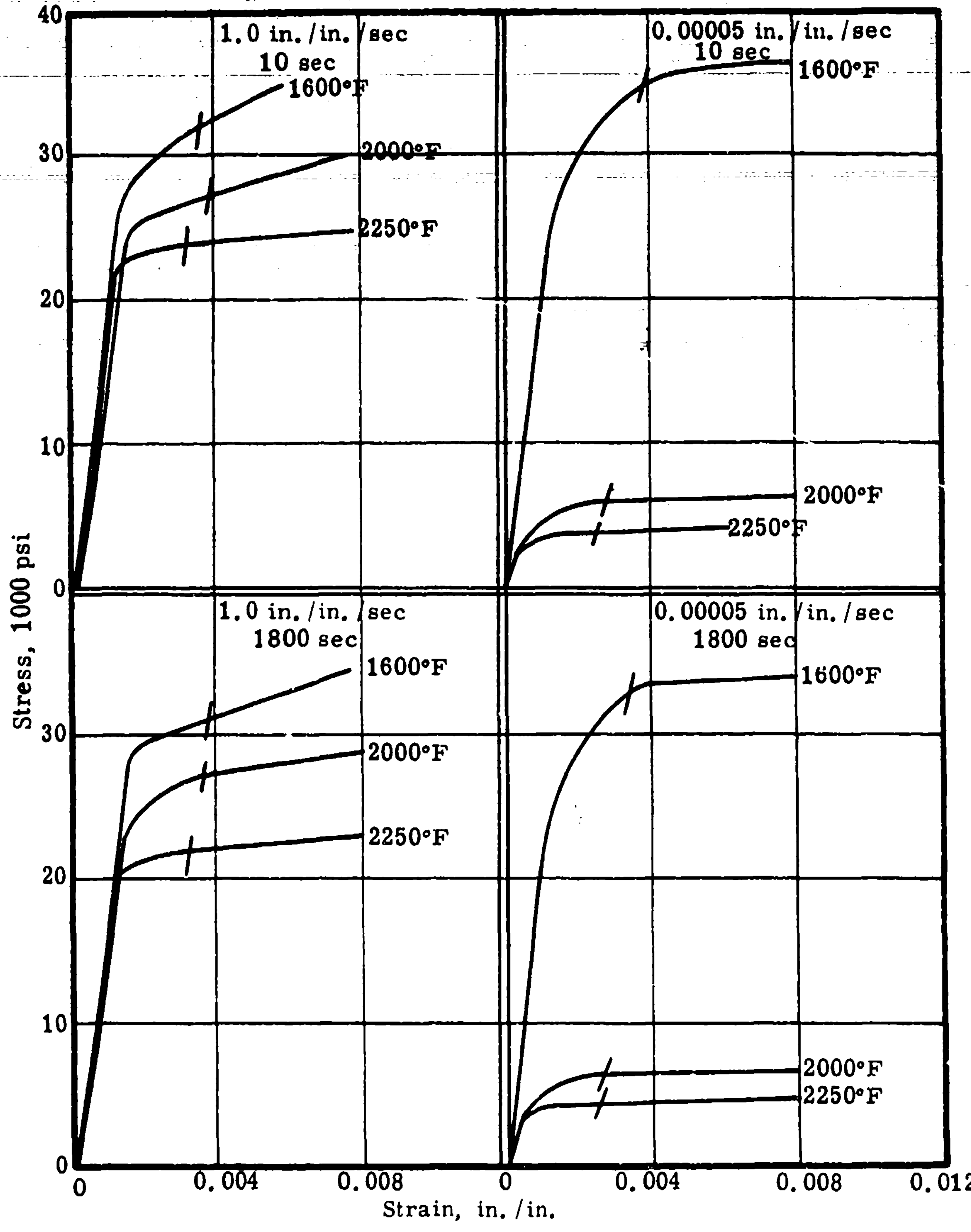

Figure 12. Stress-strain curves for annealed Stellite-25 sheet at different temperatures, strain rates, and holding times. Specimens were heated to test temperature within 10 sec.

Temp, °F	Strain Rate, In./In./Sec	Holding Time, Sec
1600	1.0	10
1600	0.00005	1800
2000	1.0	10
2000	0.00005	1800
2250	1.0	10
2250	0.00005	1800

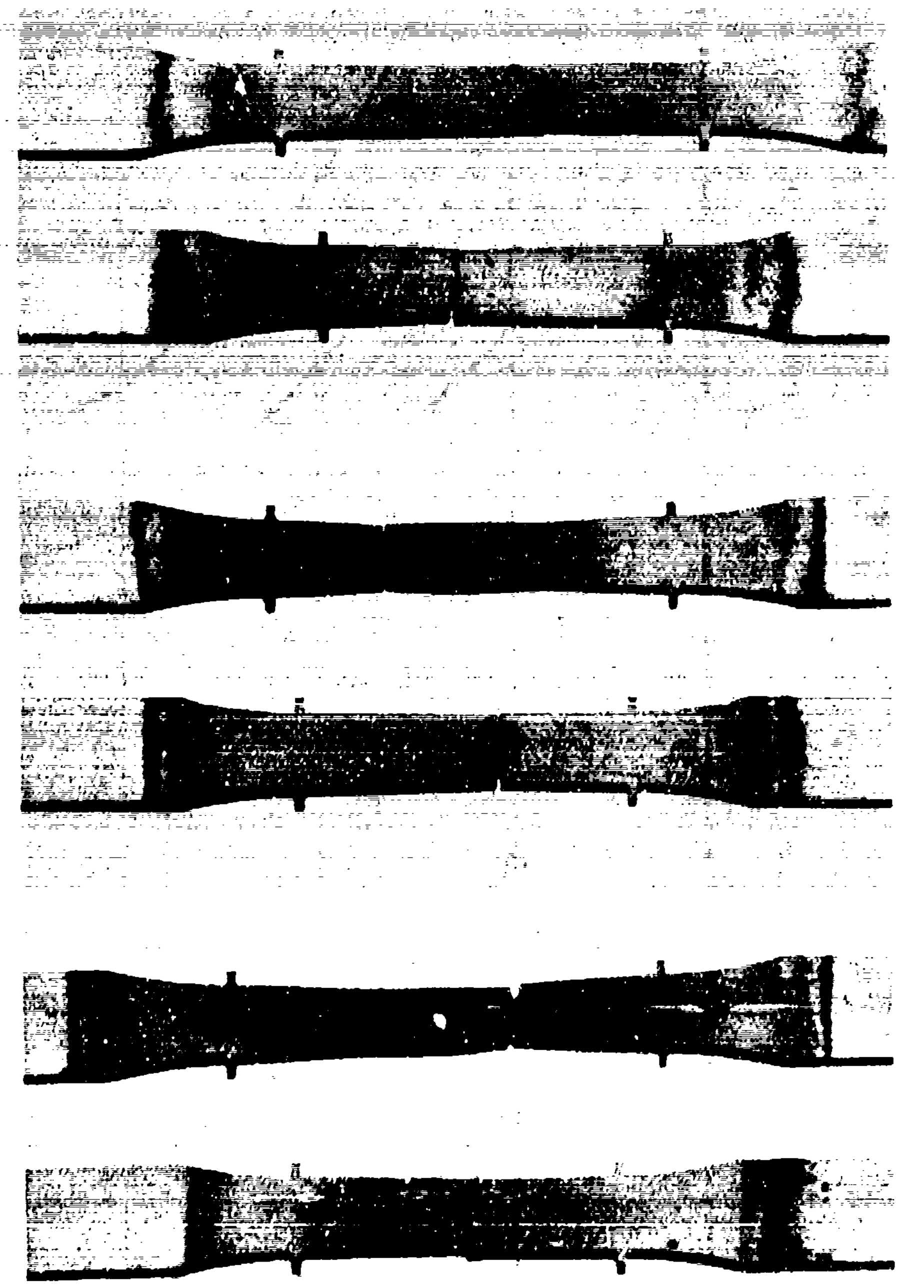

Figure 13. Surface condition of annealed Stellite-25 sheet after high-temperature testing.

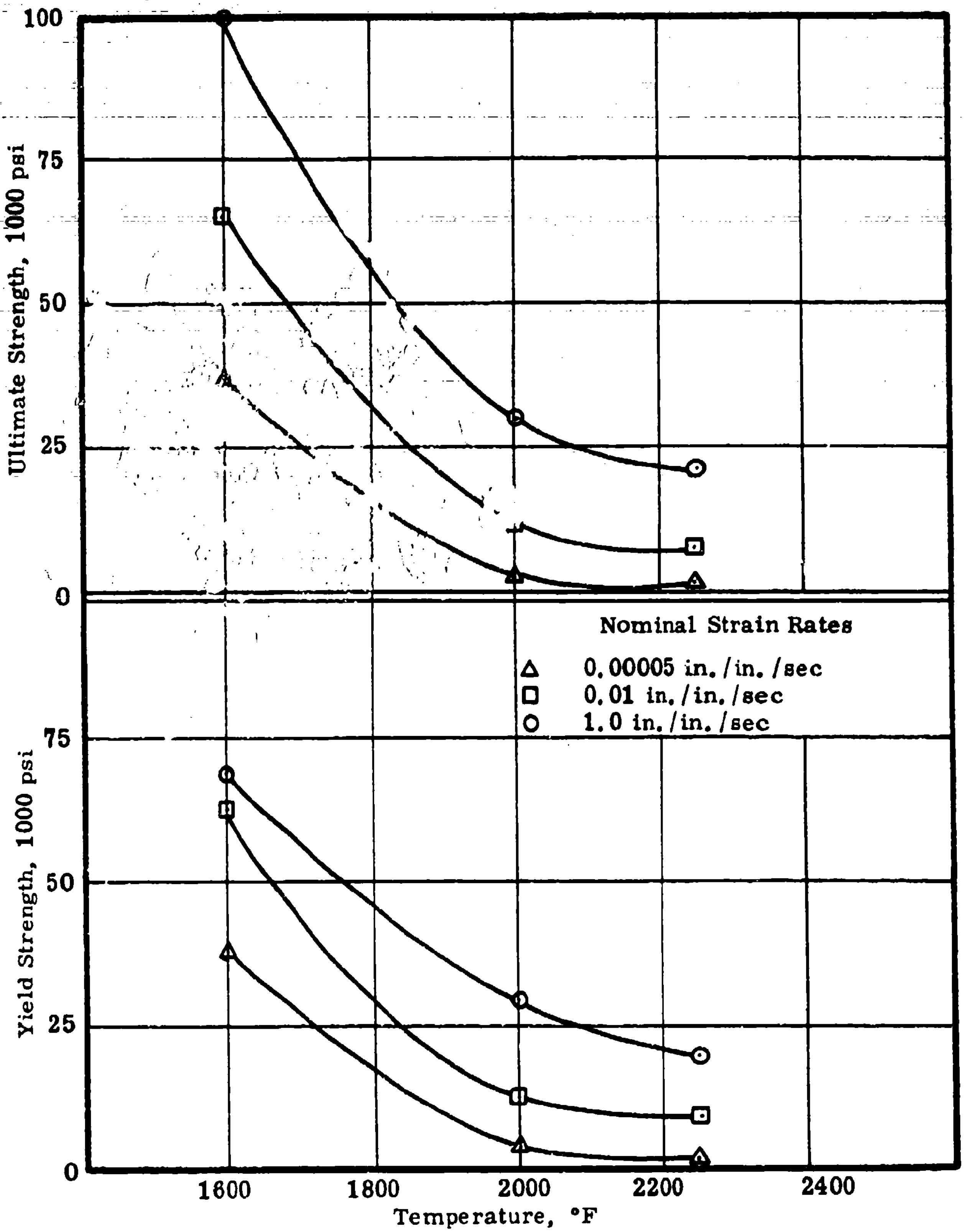

Figure 14. Effect of temperatu[illegible] after 1800-sec holding time, on the 0.2%-offset yield [illegible]ength and ultimate tensile strength of heat-treated Inconel-X sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

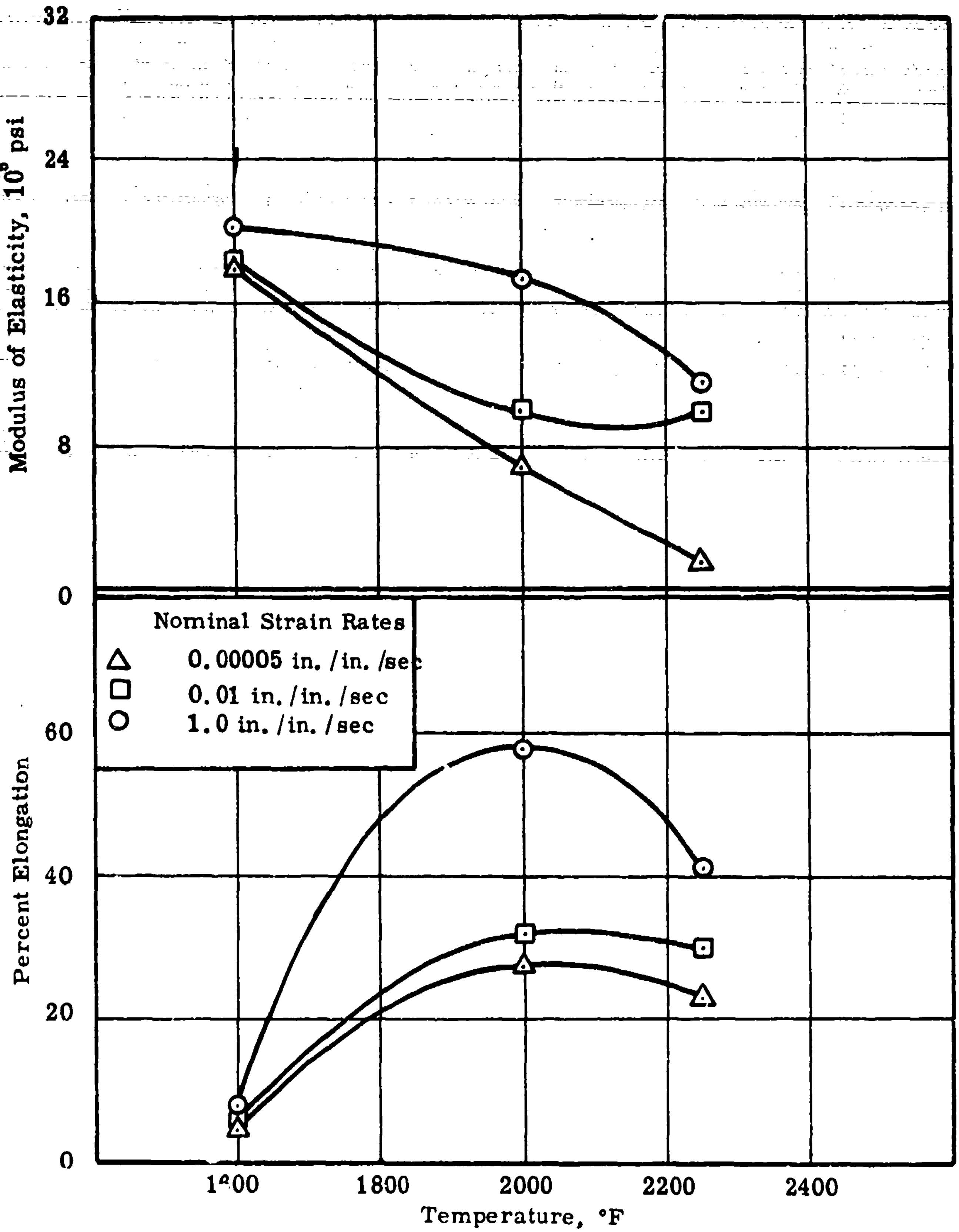

Figure 15. Effect of temperature, after 1800-sec holding time, on the percent elongation and modulus of elasticity of heat-treated Inconel-X sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

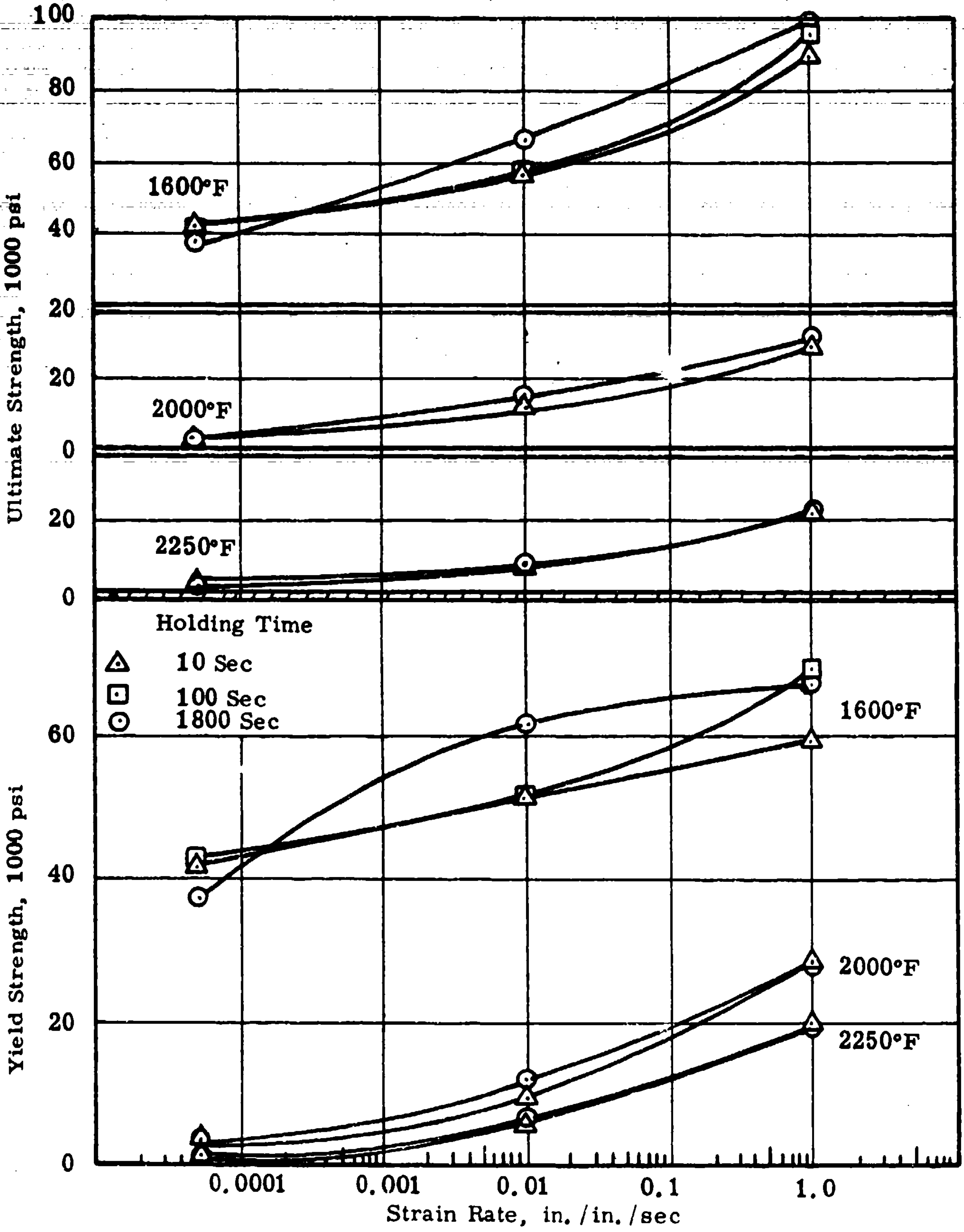

Figure 16. Effect of strain rate on the 0.2%-offset yield strength and ultimate tensile strength of heat-treated Inconel-X sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

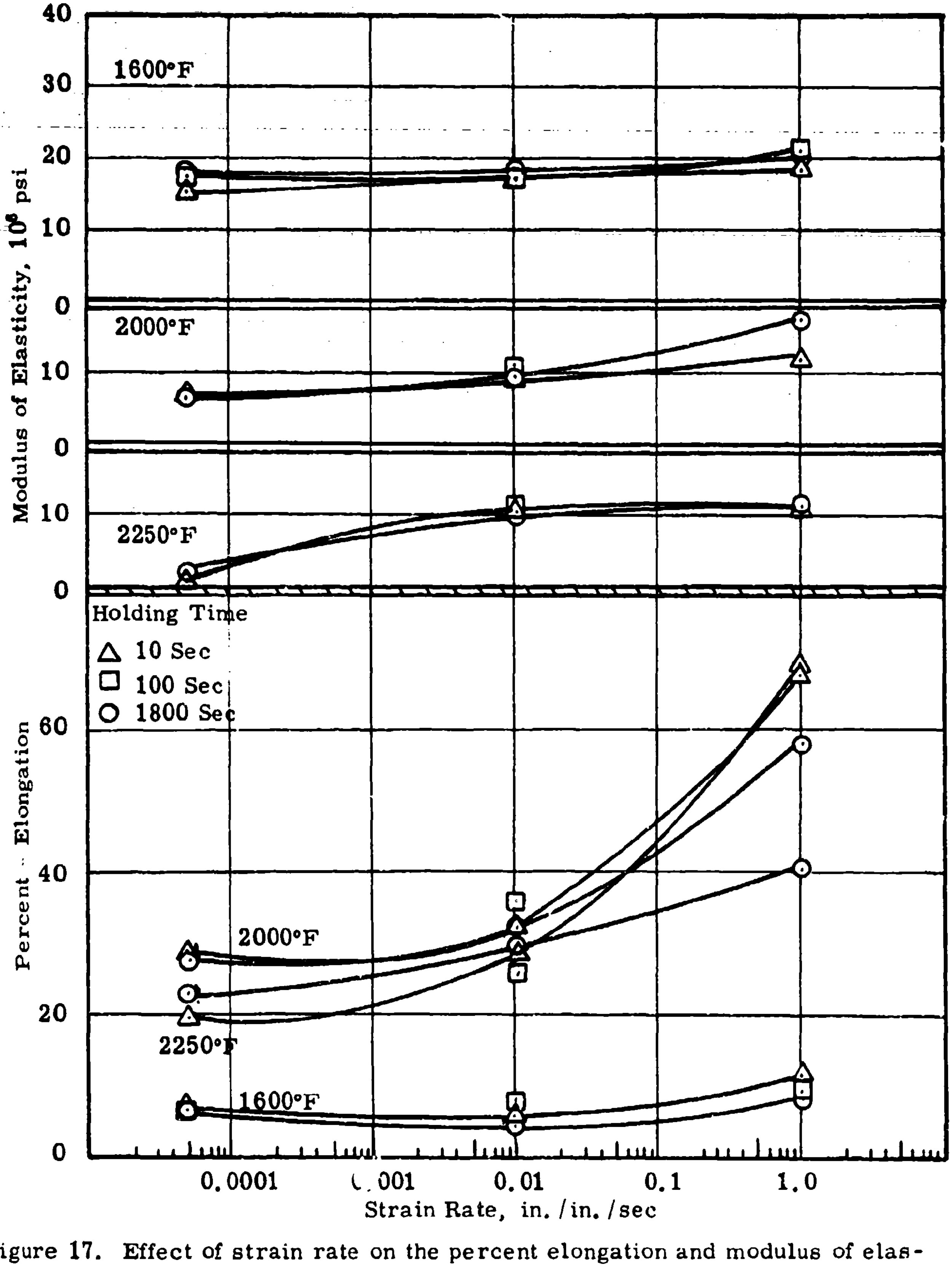

Figure 17. Effect of strain rate on the percent elongation and modulus of elasticity of heat-treated Inconel-X sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

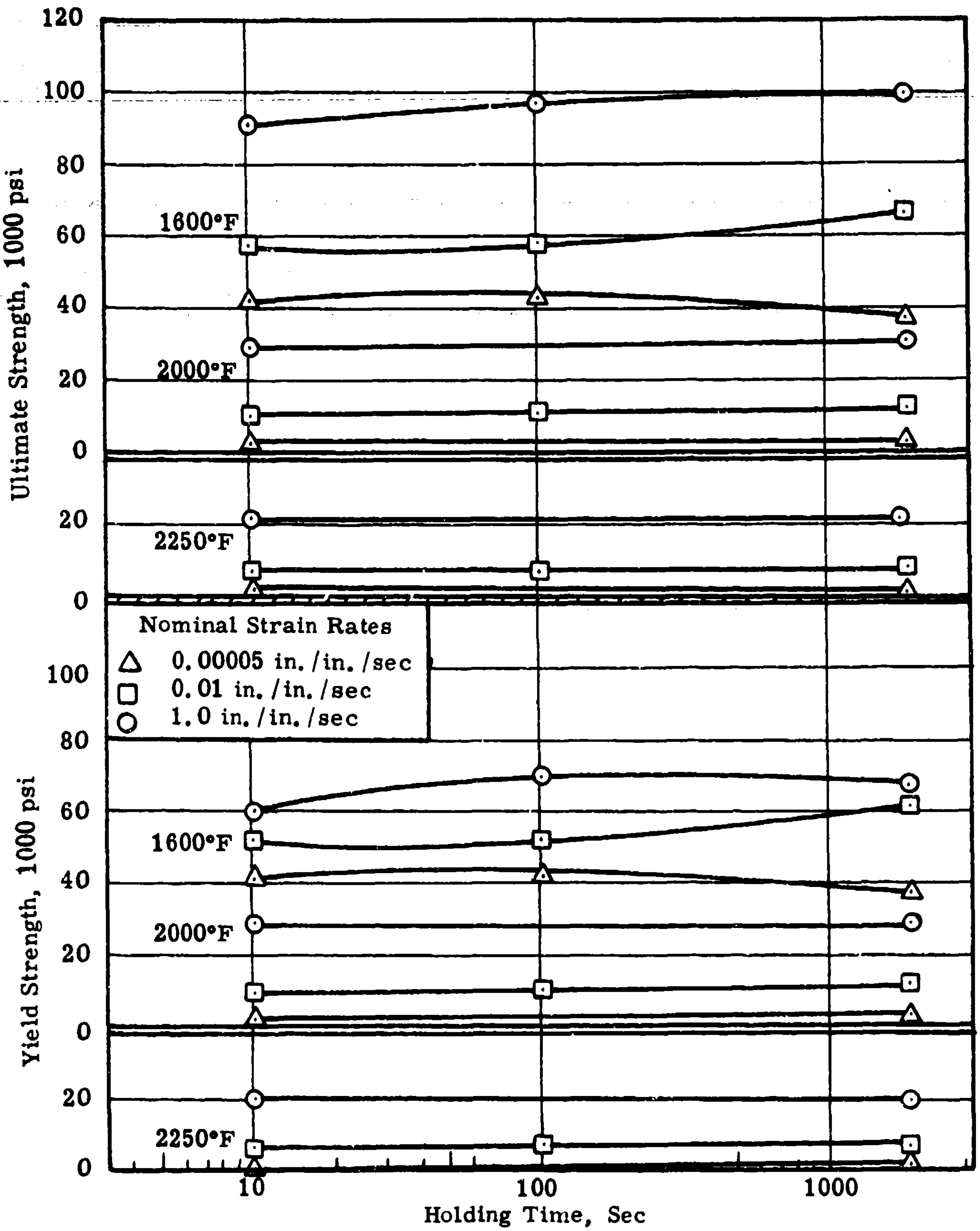

Figure 18. Effect of holding time on the 0.2%-offset yield strength and ultimate tensile strength of heat-treated Inconel-X sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

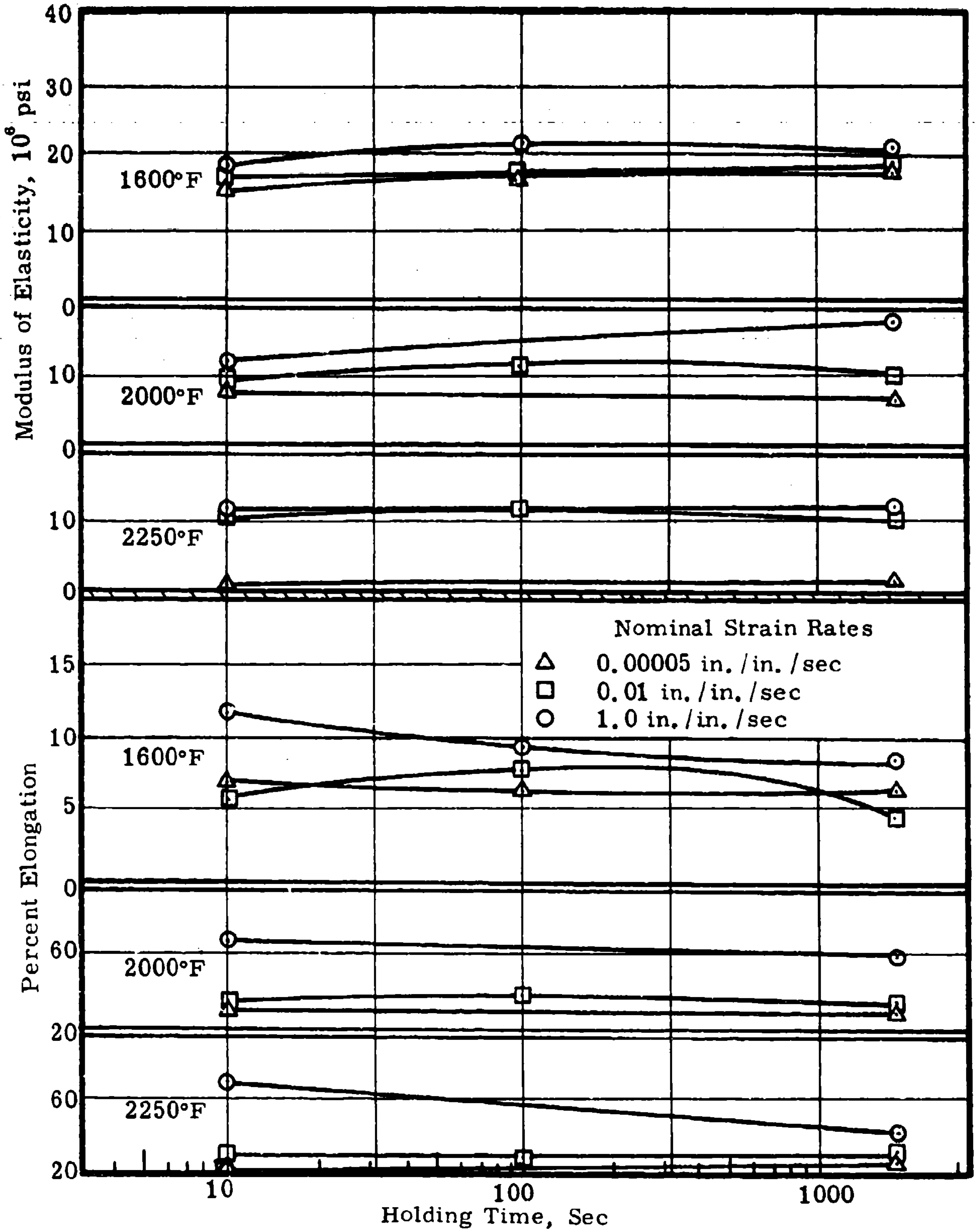

Figure 19. Effect of holding time on the percent elongation and modulus of elasticity of heat-treated Inconel-X sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

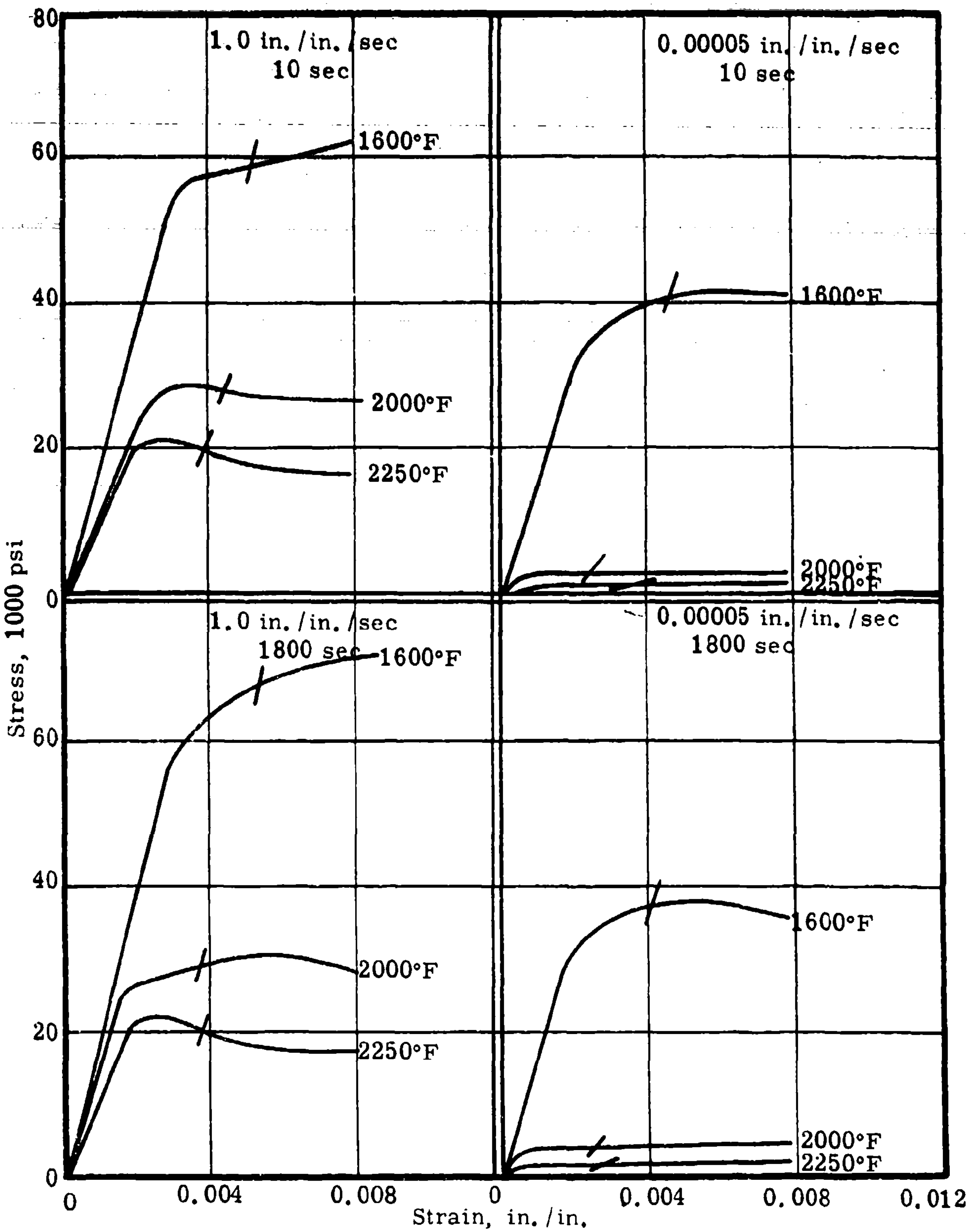

Figure 20. Stress-strain curves for heat-treated Inconel-X sheet at different temperatures, strain rates, and holding times. Specimens were heated to test temperature within 10 sec.

Temp, °F	Strain Rate, In. / In. / Sec	Holding Time, Sec
1600	1.0	10
1600	0.00005	1800
2000	1.0	10
2000	0.00005	1800
2250	1.0	10
2250	0.00005	1800

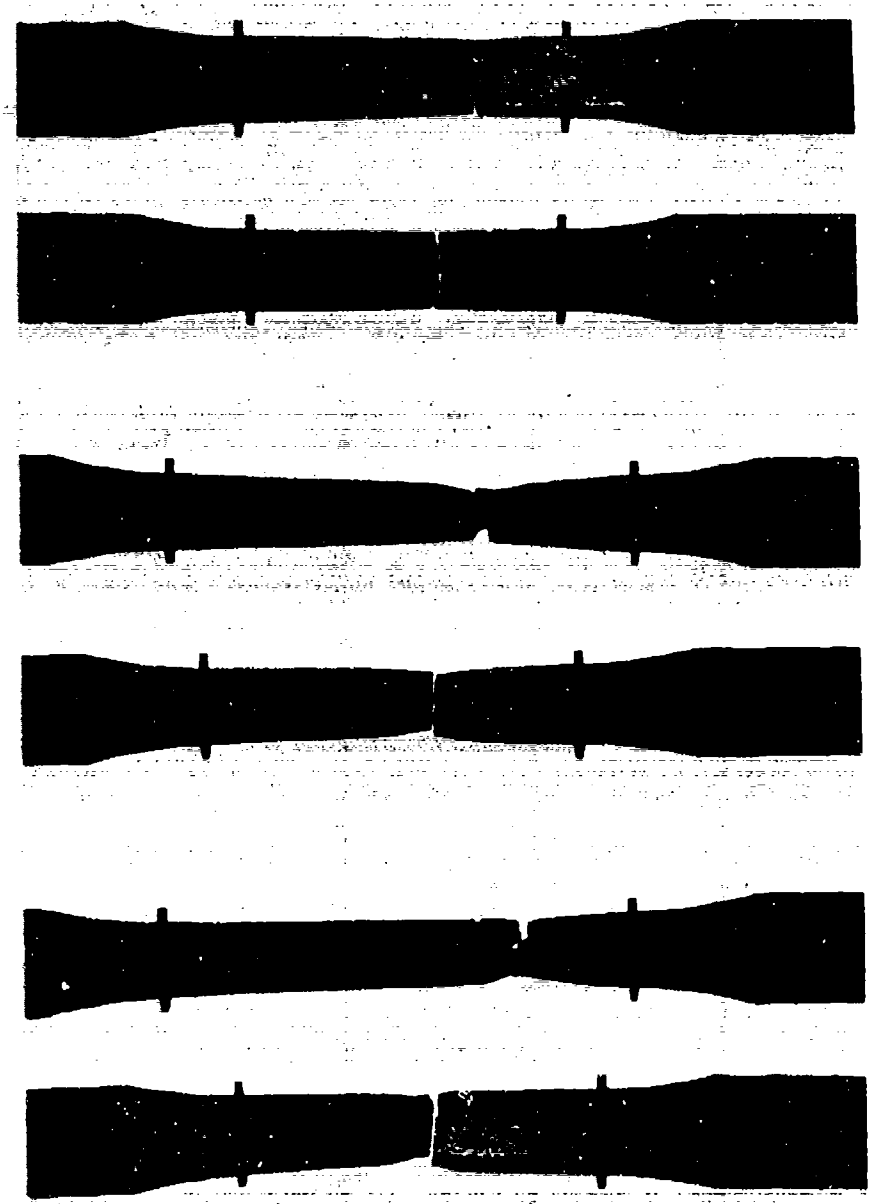

Figure 21. Surface condition of heat-treated Inconel-X sheet after high-temperature testing.

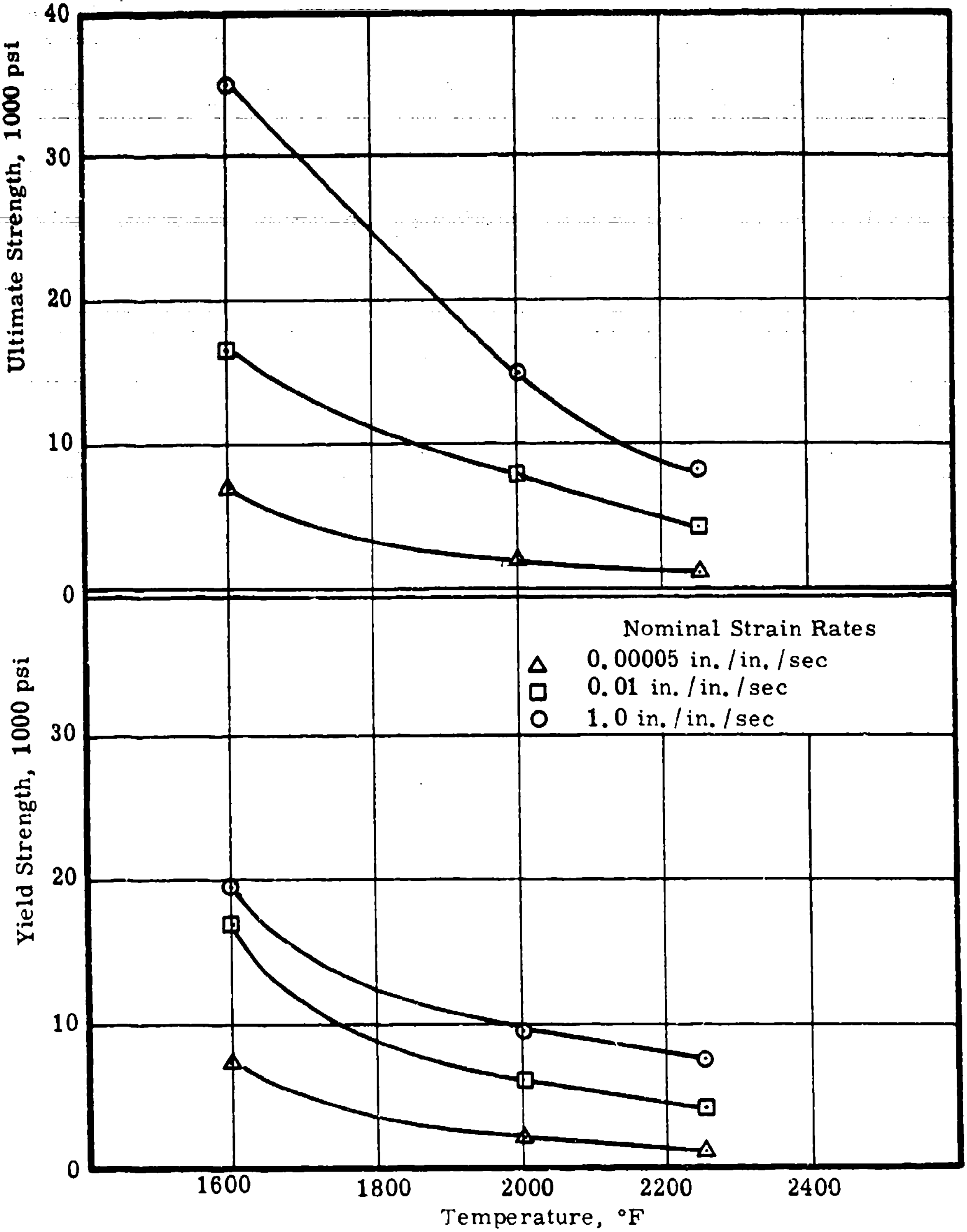

Figure 22. Effect of temperature, after 1800-sec holding time, on the 0.2%-offset yield strength and ultimate tensile strength of full-hard 301 Stainless Steel sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

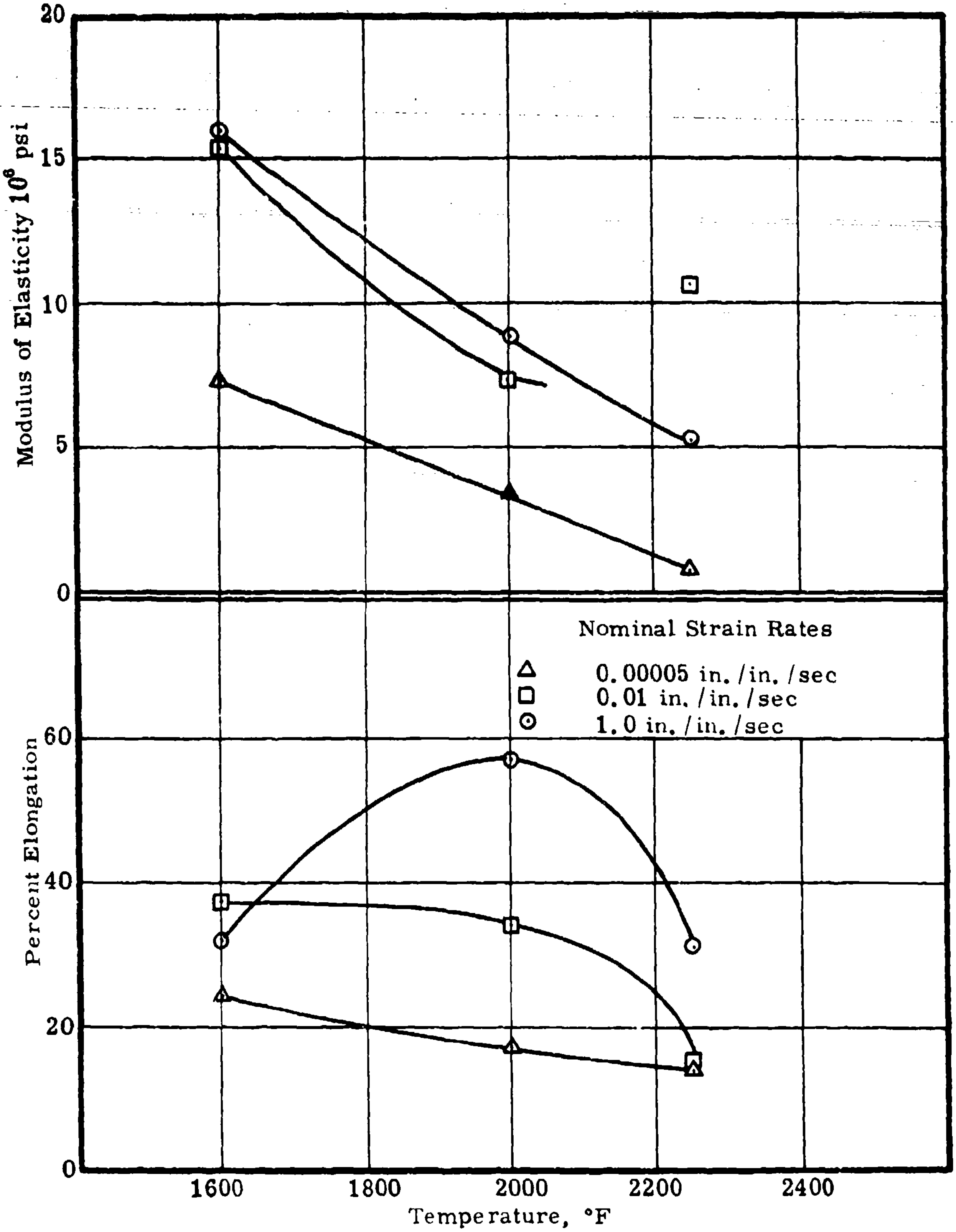

Figure 23. Effect of temperature, after 1800-sec holding time, on the percent elongation and modulus of elasticity of full-hard 301 Stainless Steel sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

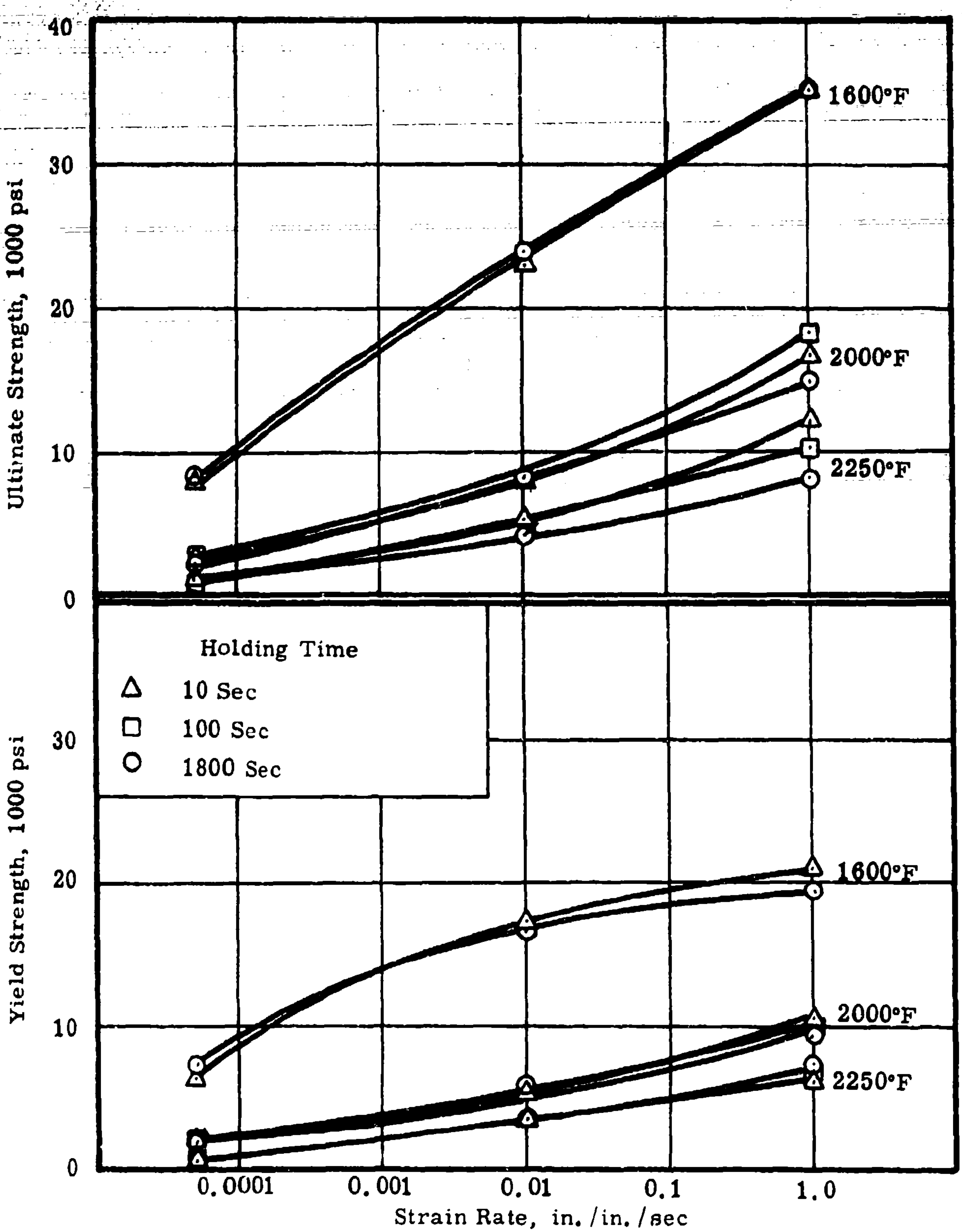

Figure 24. Effect of strain rate on the 0.2%-offset yield strength and ultimate tensile strength of full-hard 301 Stainless Steel sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

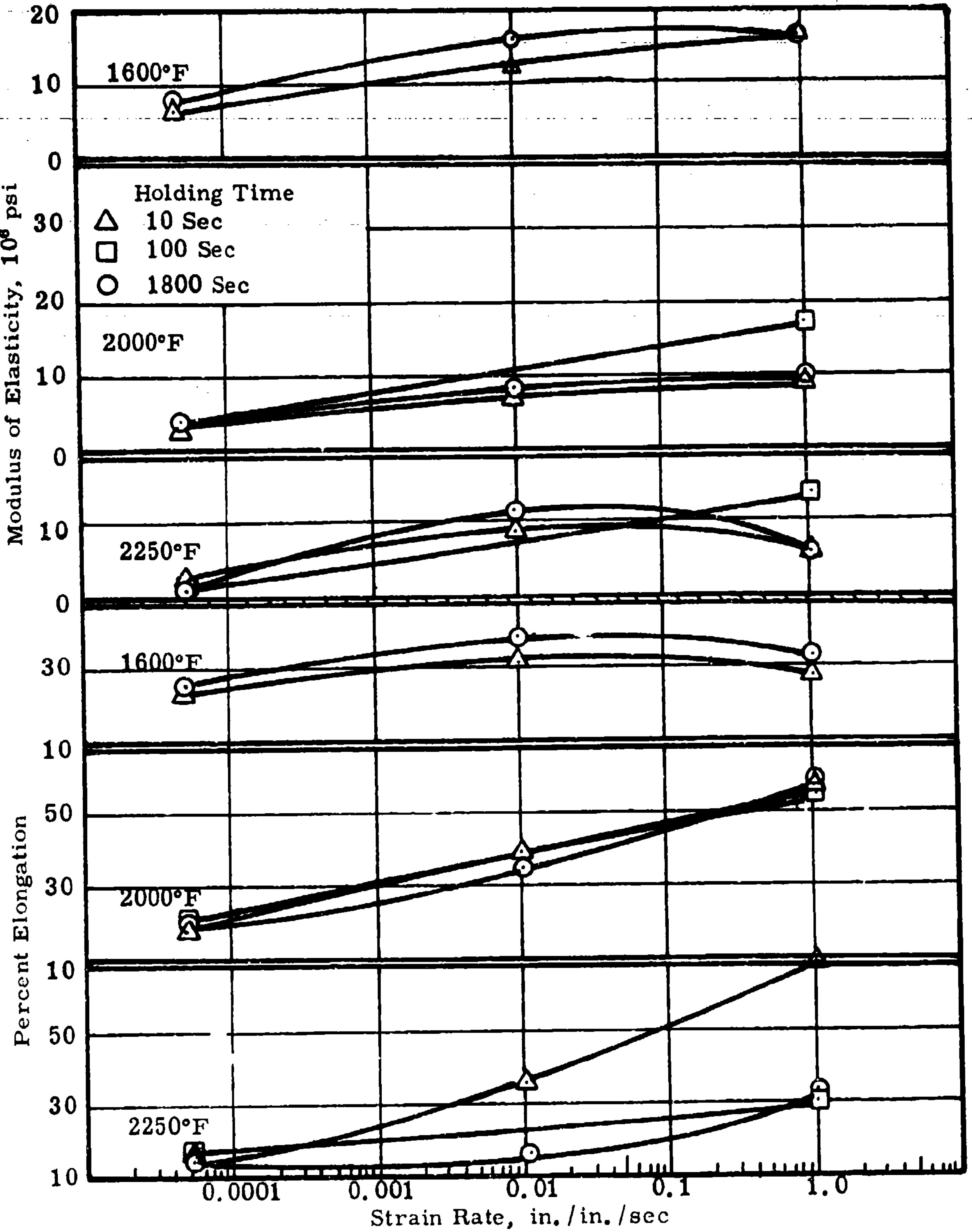

Figure 25. Effect of strain rate on the percent elongation and modulus of elasticity of full-hard 301 Stainless Steel sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

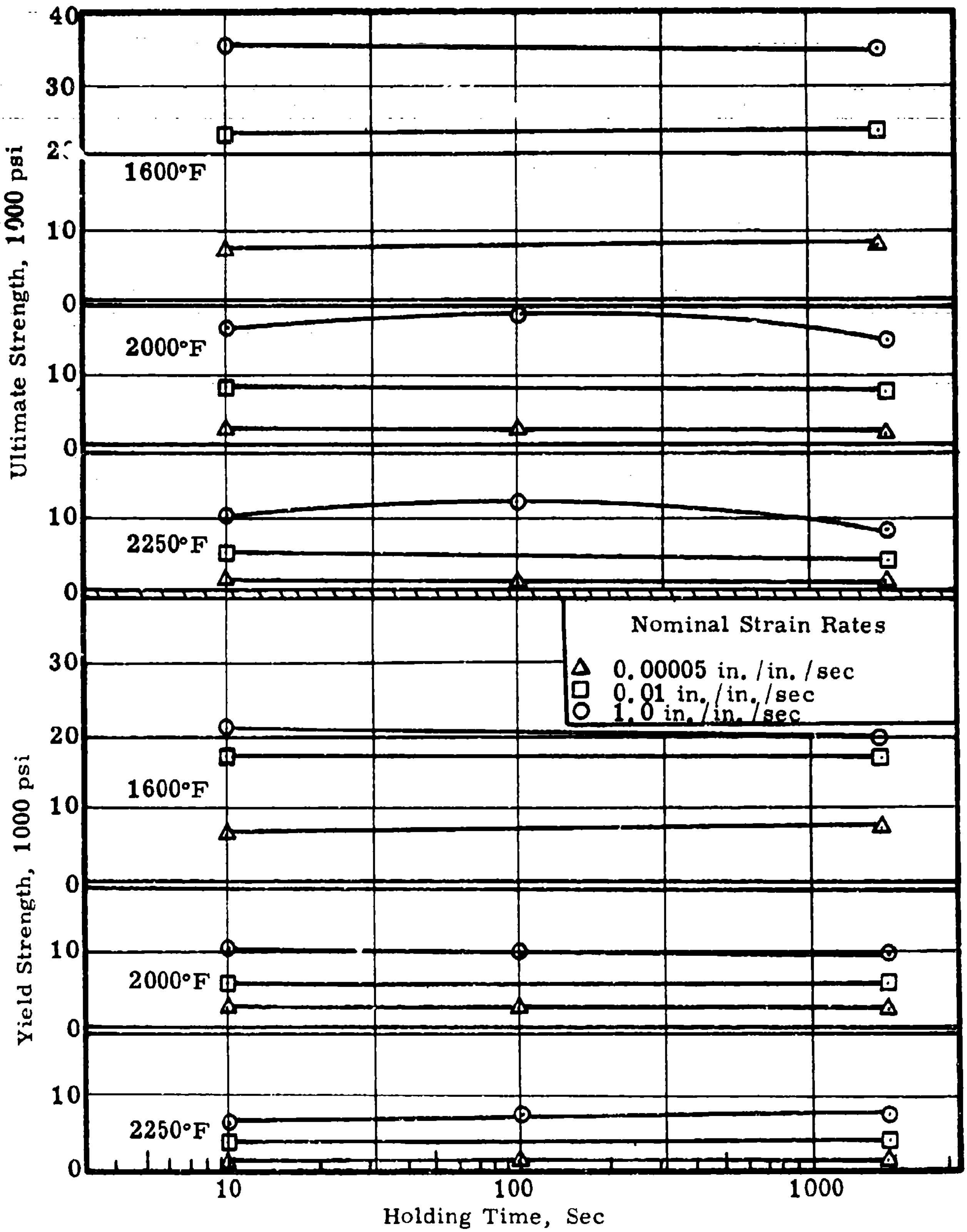

Figure 26. Effect of holding time on the 0.2%-offset yield strength and ultimate tensile strength of full-hard 301 Stainless Steel sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

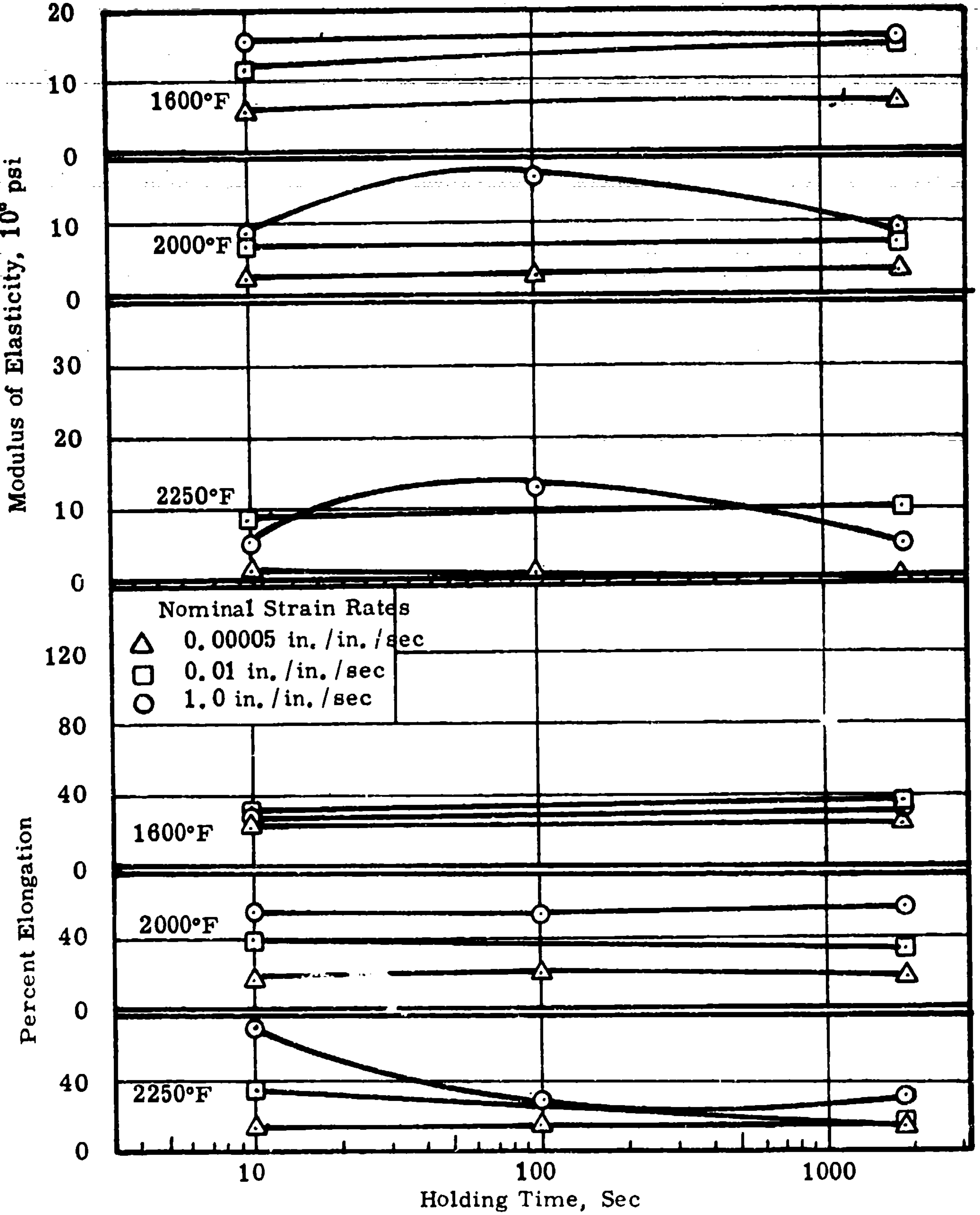

Figure 27. Effect of holding time on the percent elongation and modulus of elasticity of full-hard 301 Stainless Steel sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

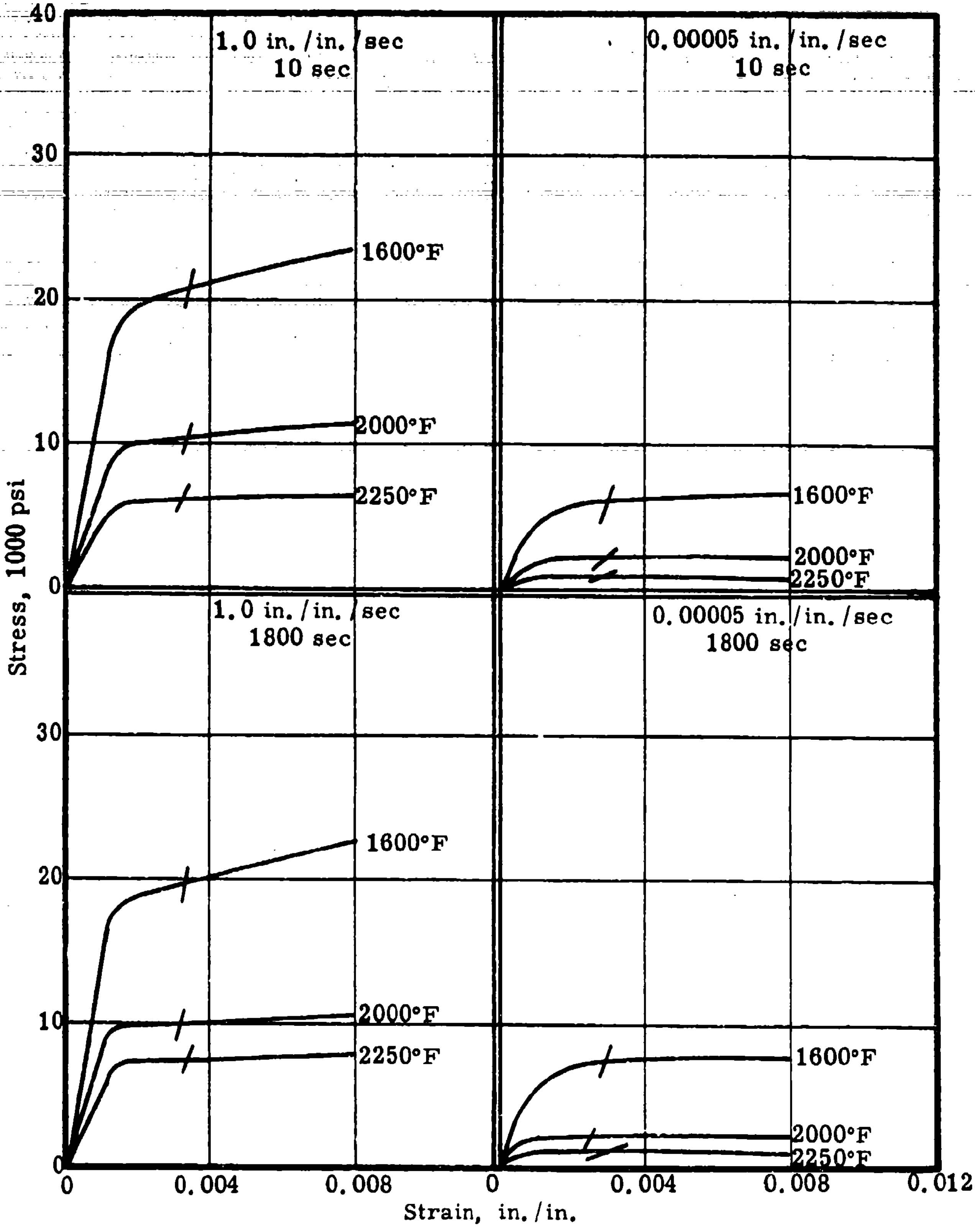

Figure 28. Stress-strain curves for full-hard 301 Stainless Steel sheet at different temperatures, strain rates, and holding times. Specimens were heated to test temperature within 10 sec.

Temp, °F	Strain Rate, In./In./Sec	Holding Time, Sec
1600	1.0	10
1600	0.00005	1800
2000	1.0	10
2000	0.00005	1800
2250	1.0	10
2250	0.00005	1800

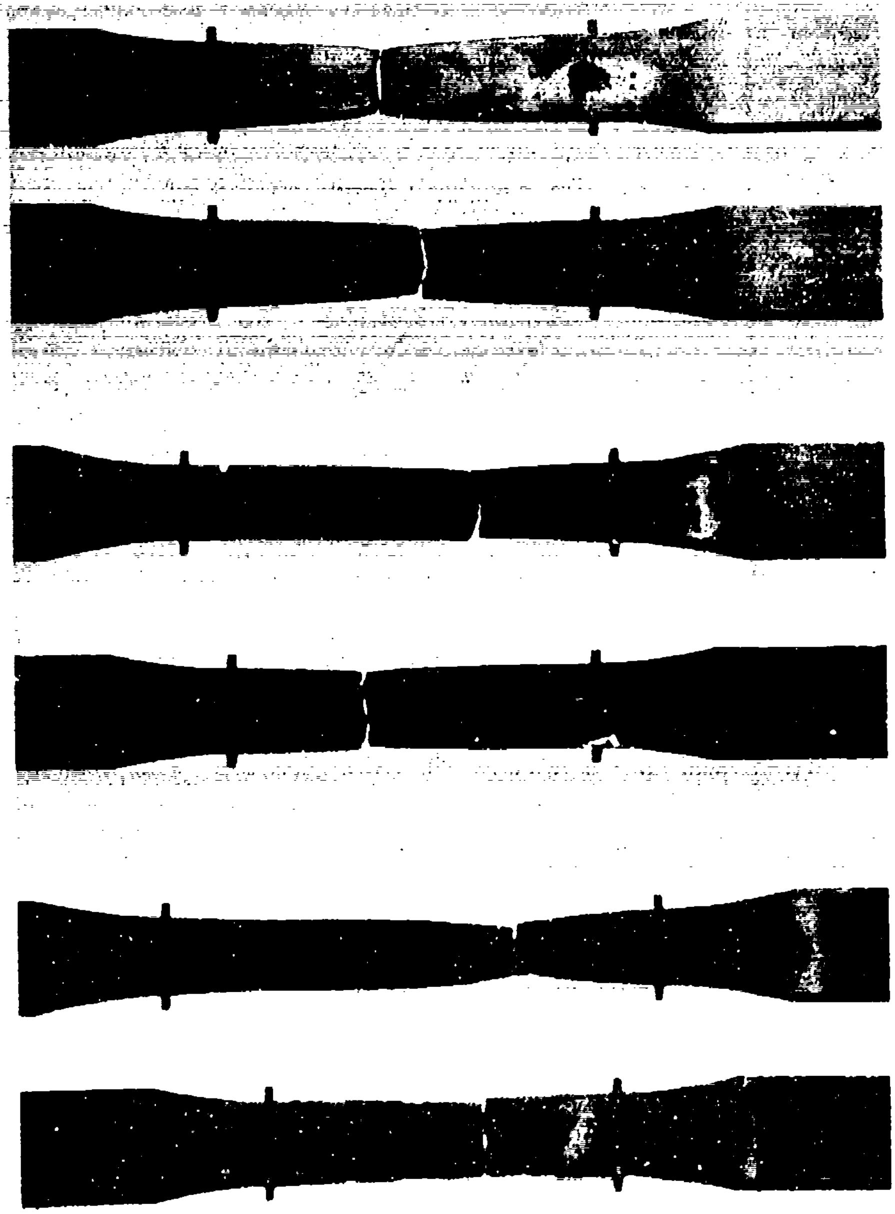

Figure 29. Surface condition of full-hard 301 Stainless Steel sheet after high-temperature testing.

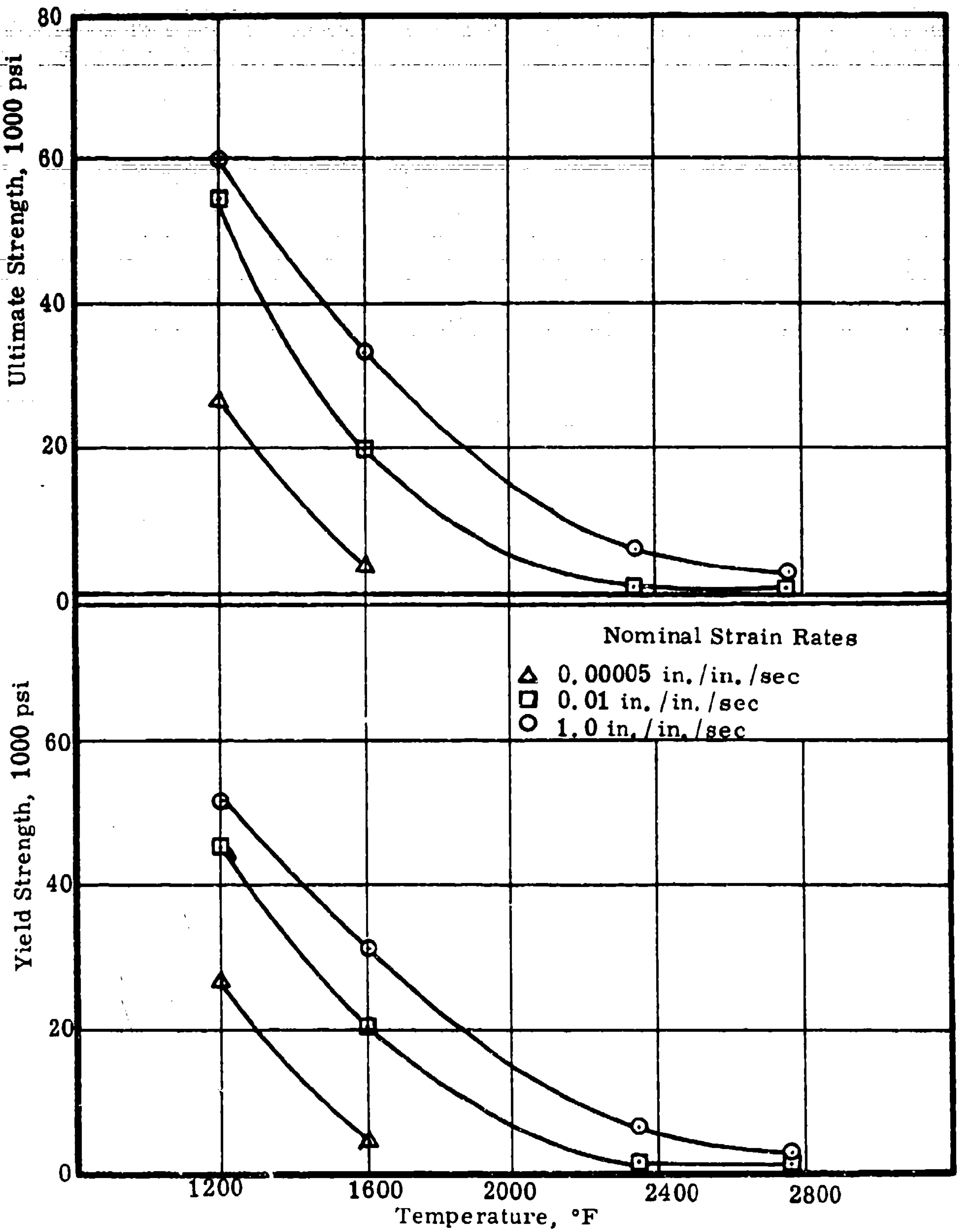

Figure 30. Effect of temperature, after 10-sec holding time, on the 0.2%-offset yield strength and ultimate tensile strength of annealed A110-AT Titanium-alloy sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

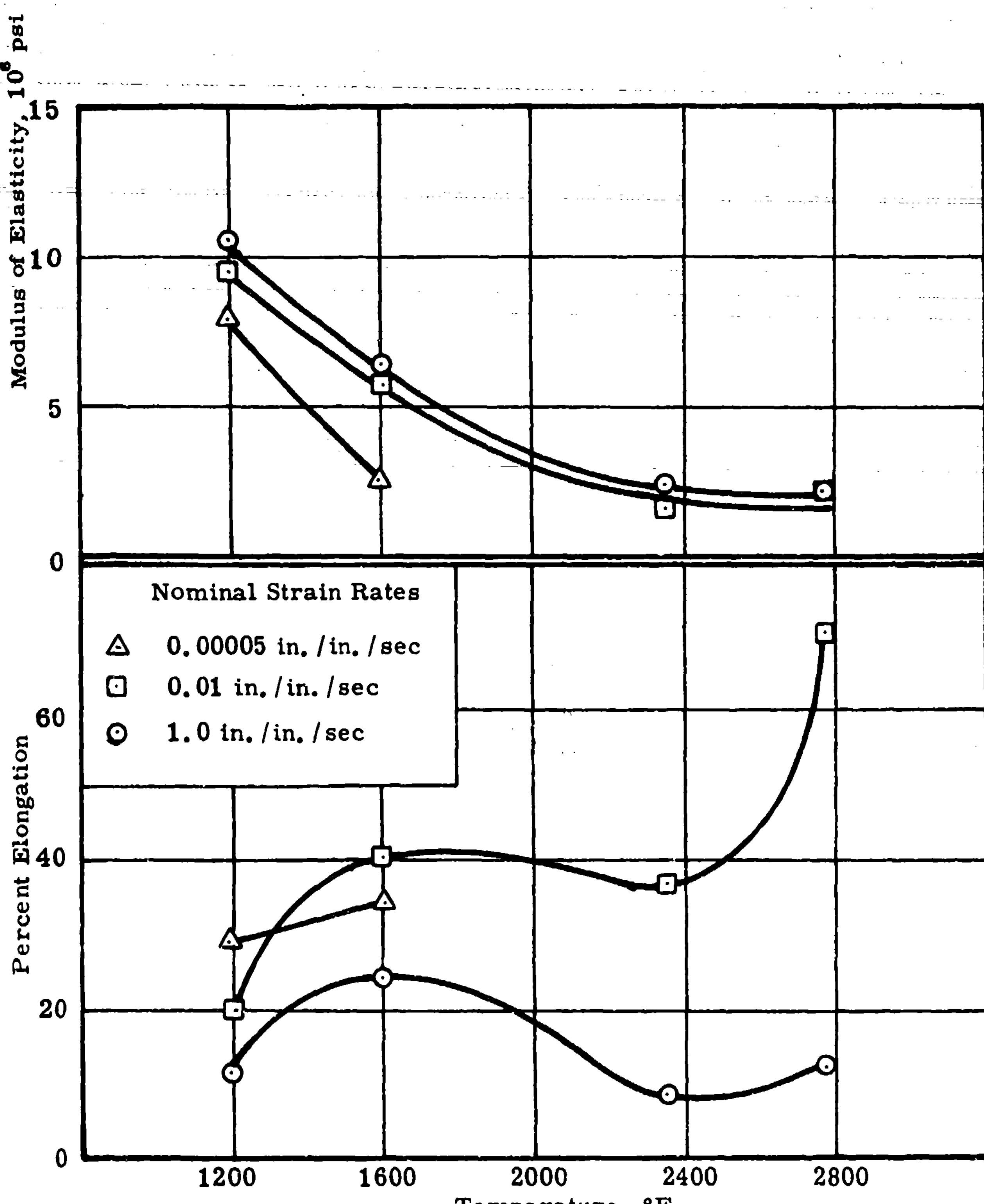

Figure 31. Effect of temperature, after 10-sec holding time, on the percent elongation and modulus of elasticity of annealed A110-AT Titanium alloy sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

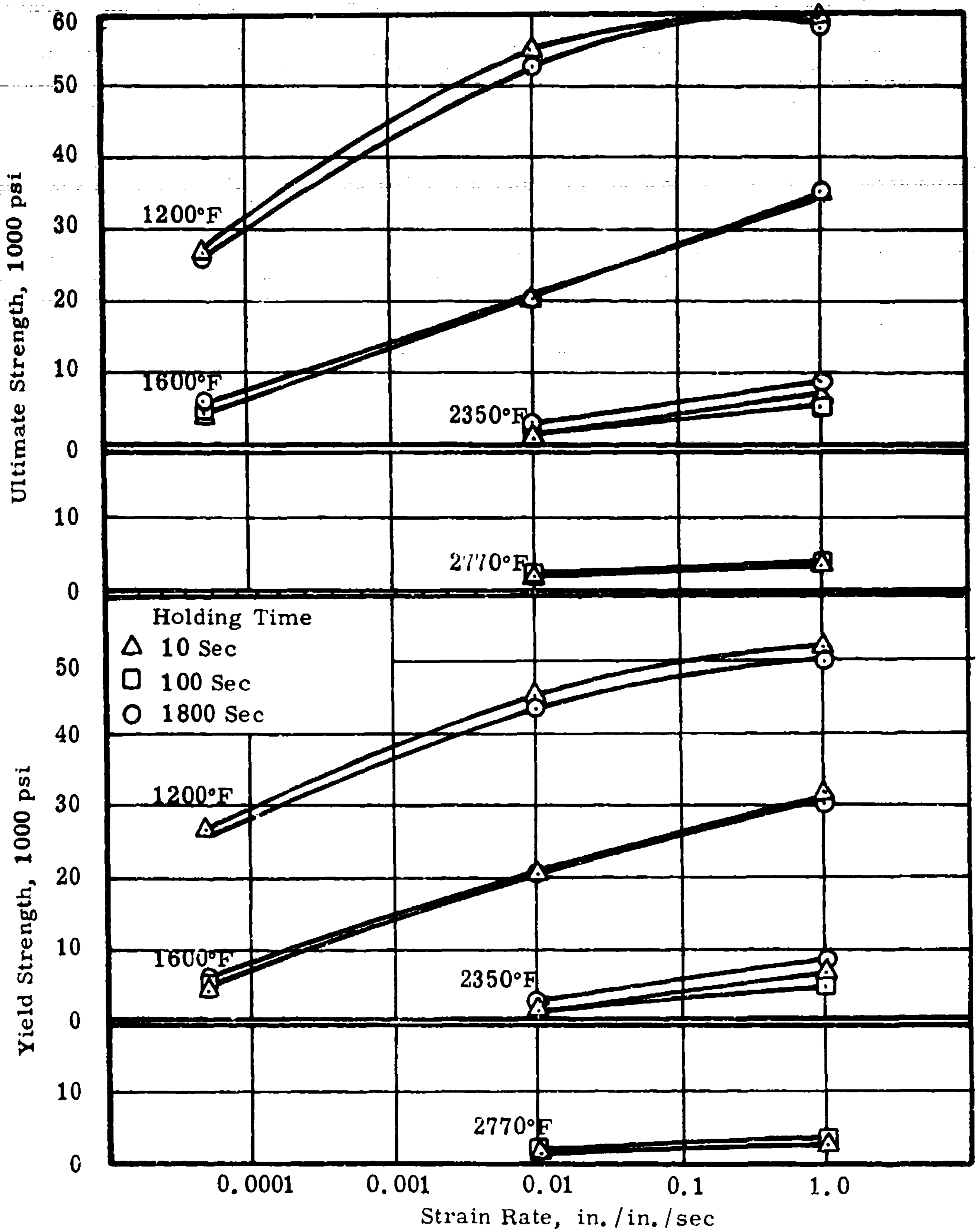

Figure 32. Effect of strain rate on the 0.2%-offset yield strength and ultimate tensile strength of annealed A110-AT Titanium alloy sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

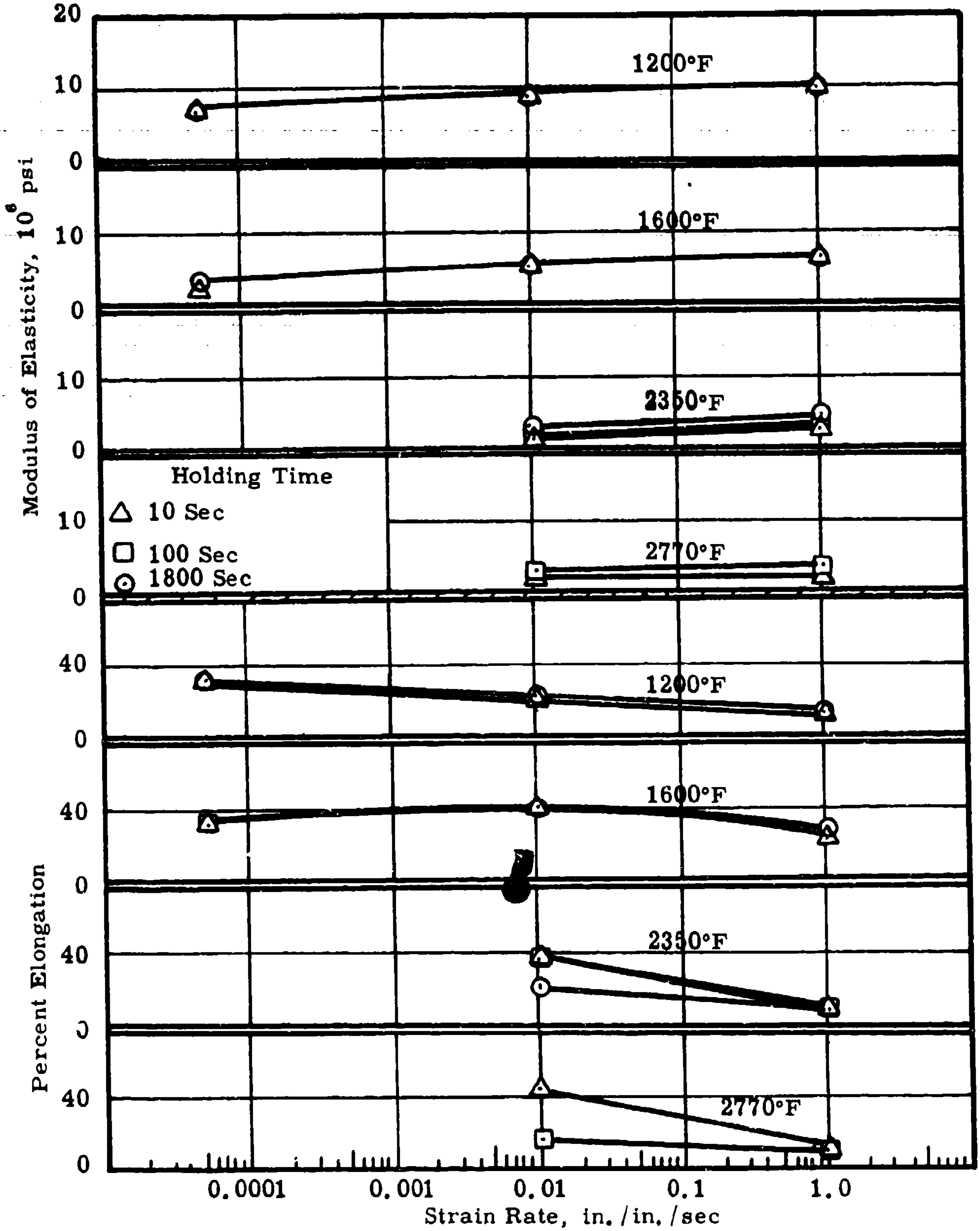

Figure 33. Effect of strain rate on the percent elongation and modulus of elasticity of annealed A110-AT Titanium alloy sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

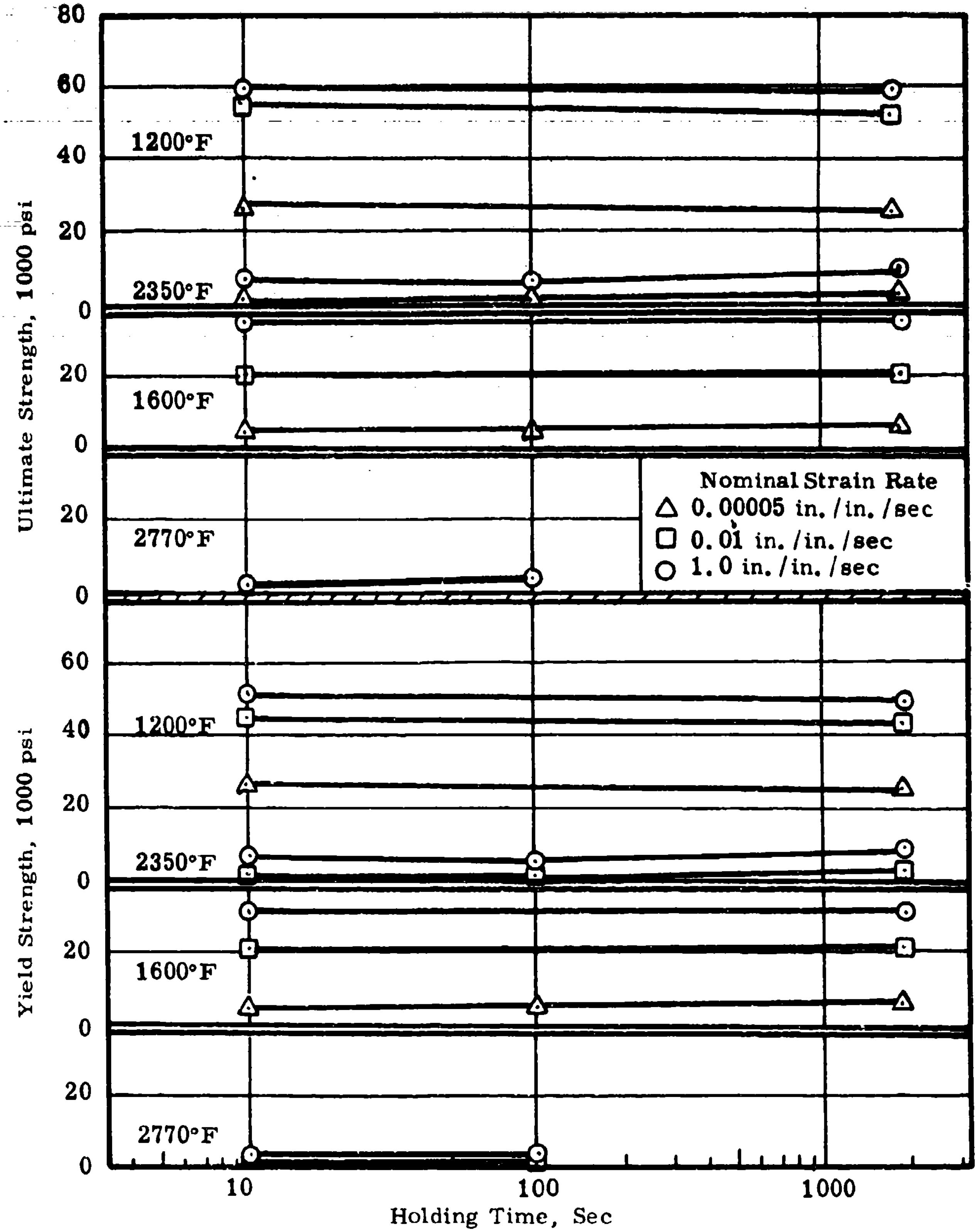

Figure 34. Effect of holding time on the 0.2%-offset yield strength and ultimate tensile strength of annealed A110-AT Titanium alloy sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

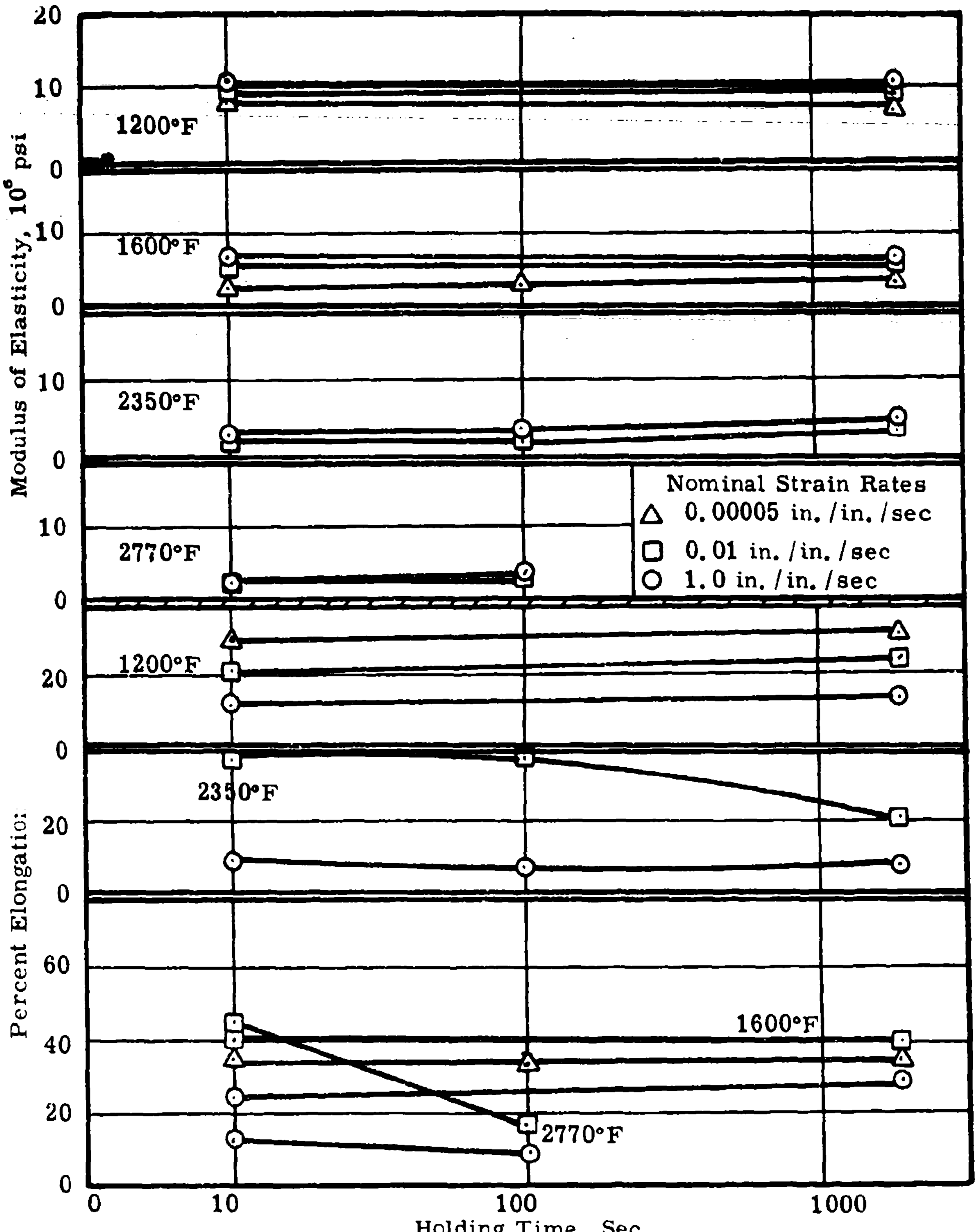

Figure 35. Effect of holding time on the percent elongation and modulus of elasticity of annealed A110-AT Titanium alloy sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

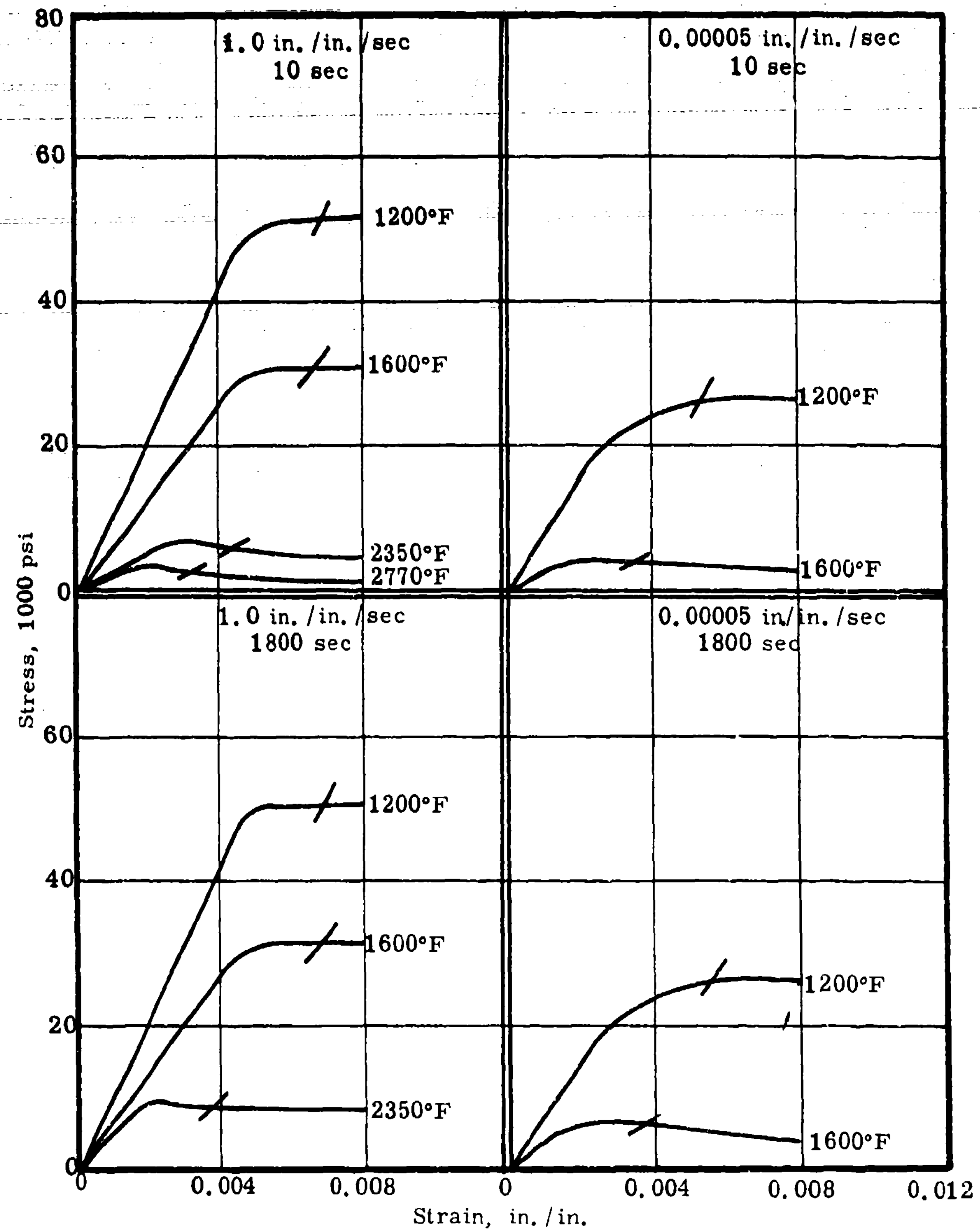

Figure 36. Stress-strain curves for annealed A110-AT Titanium-alloy sheet at different temperatures, strain rates, and holding times. Specimens were heated to test temperature within 10 sec.

Temp, °F	Strain Rate, In./In./Sec	Holding Time, Sec
1200	1.0	10
1200	0.00005	1800
1600	1.0	10
1600	0.00005	1800
2350	1.0	10
2350	1.0	1800
2770	1.0	10
2770	1.0	100

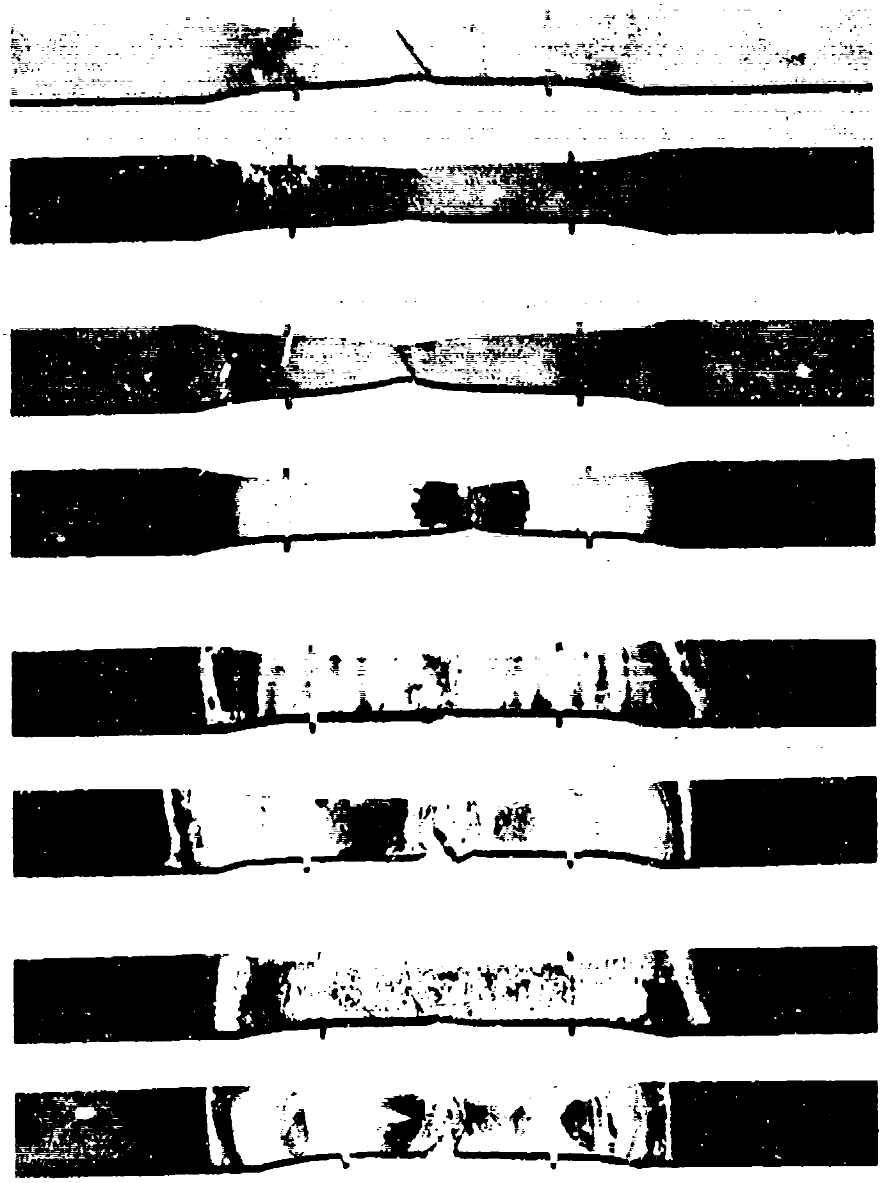

Figure 37. Surface condition of annealed A110-AT Titanium alloy sheet after high-temperature testing.

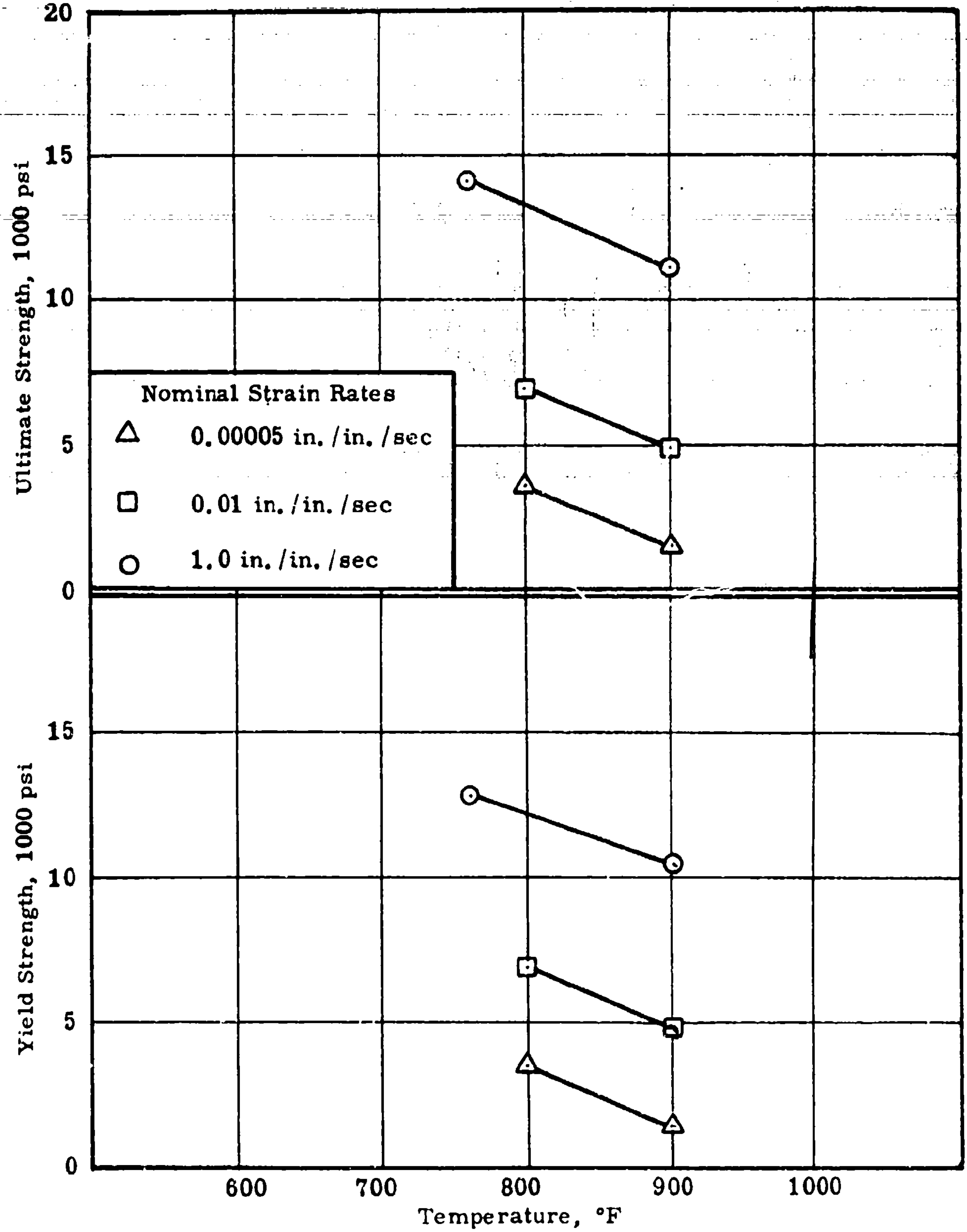

Figure 38. Effect of temperature, after 1800-sec holding time, on the 0.2%-offset yield strength and ultimate tensile strength of Alclad 2024-T3 Aluminum alloy sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

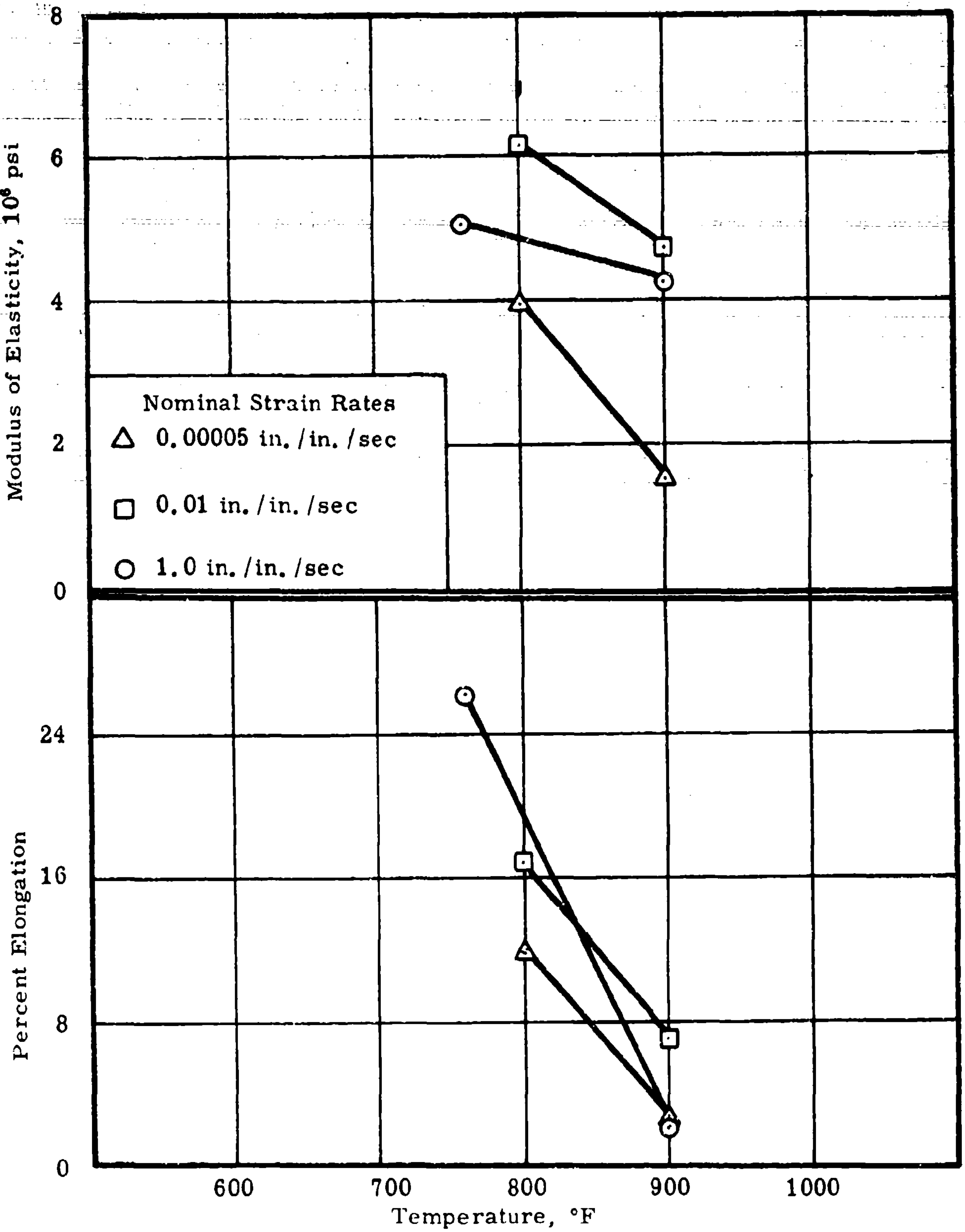

Figure 39. Effect of temperature, after 1800-sec holding time, on the percent elongation and modulus of elasticity of Alclad 2024-T3 Aluminum alloy sheet at different strain rates. Specimens were heated to test temperature within 10 sec.

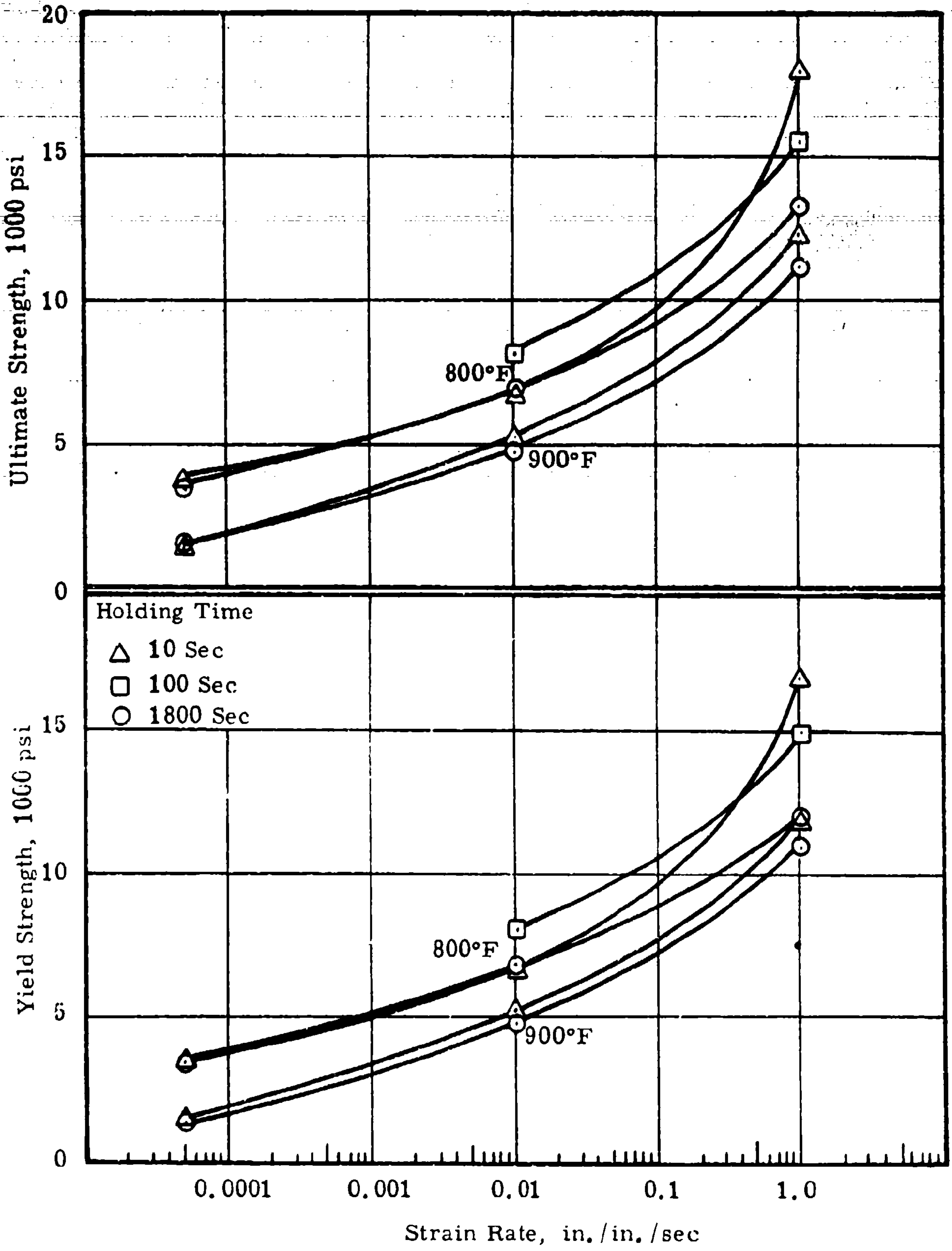

Figure 40. Effect of strain rate on the 0.2%-offset yield strength and ultimate tensile strength of Alclad 2024-T3 Aluminum alloy sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

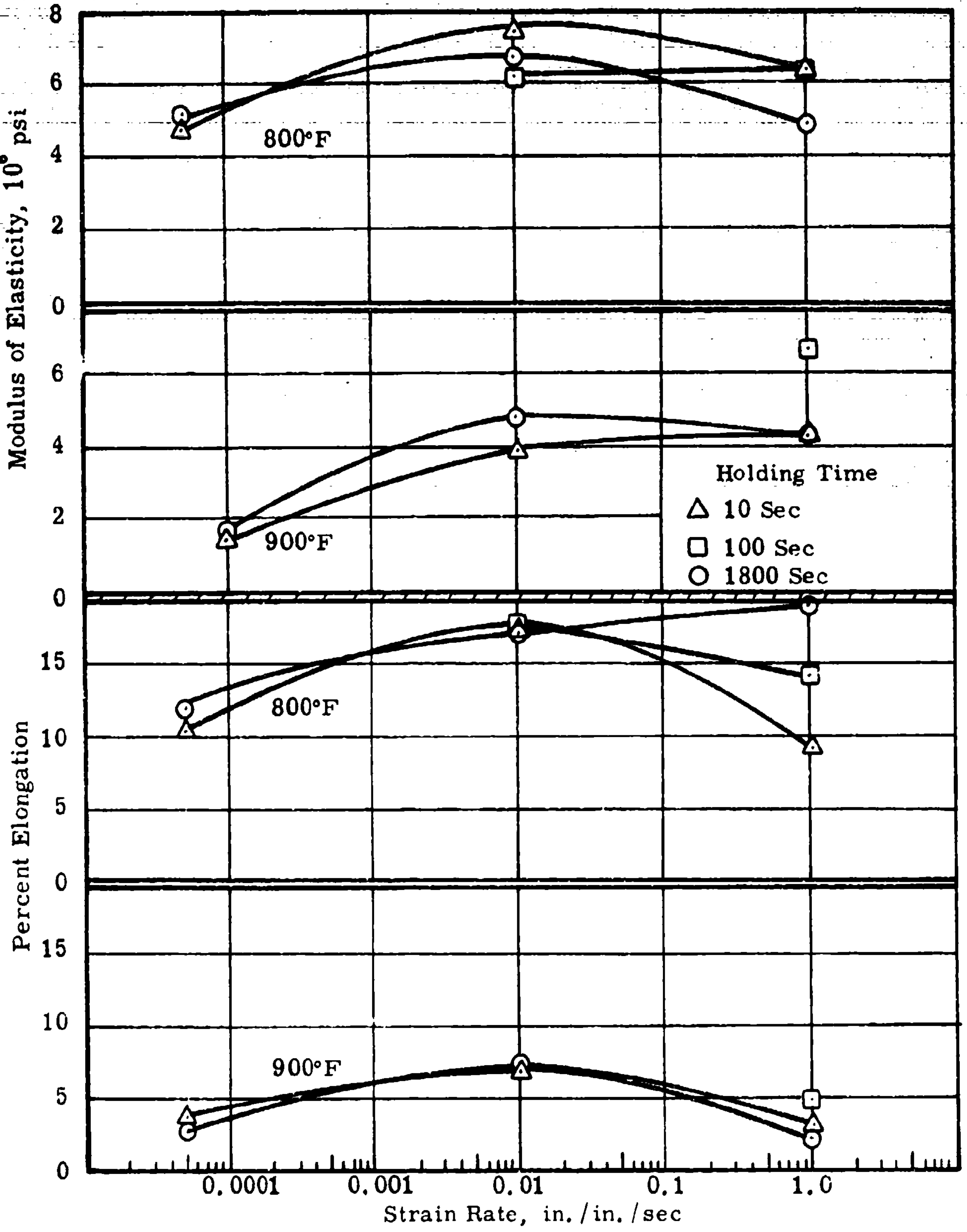

Figure 41. Effect of strain rate on the percent elongation and modulus of elasticity of Alclad 2024-T3 Aluminum alloy sheet at different temperatures and holding times. Specimens were heated to test temperature within 10 sec.

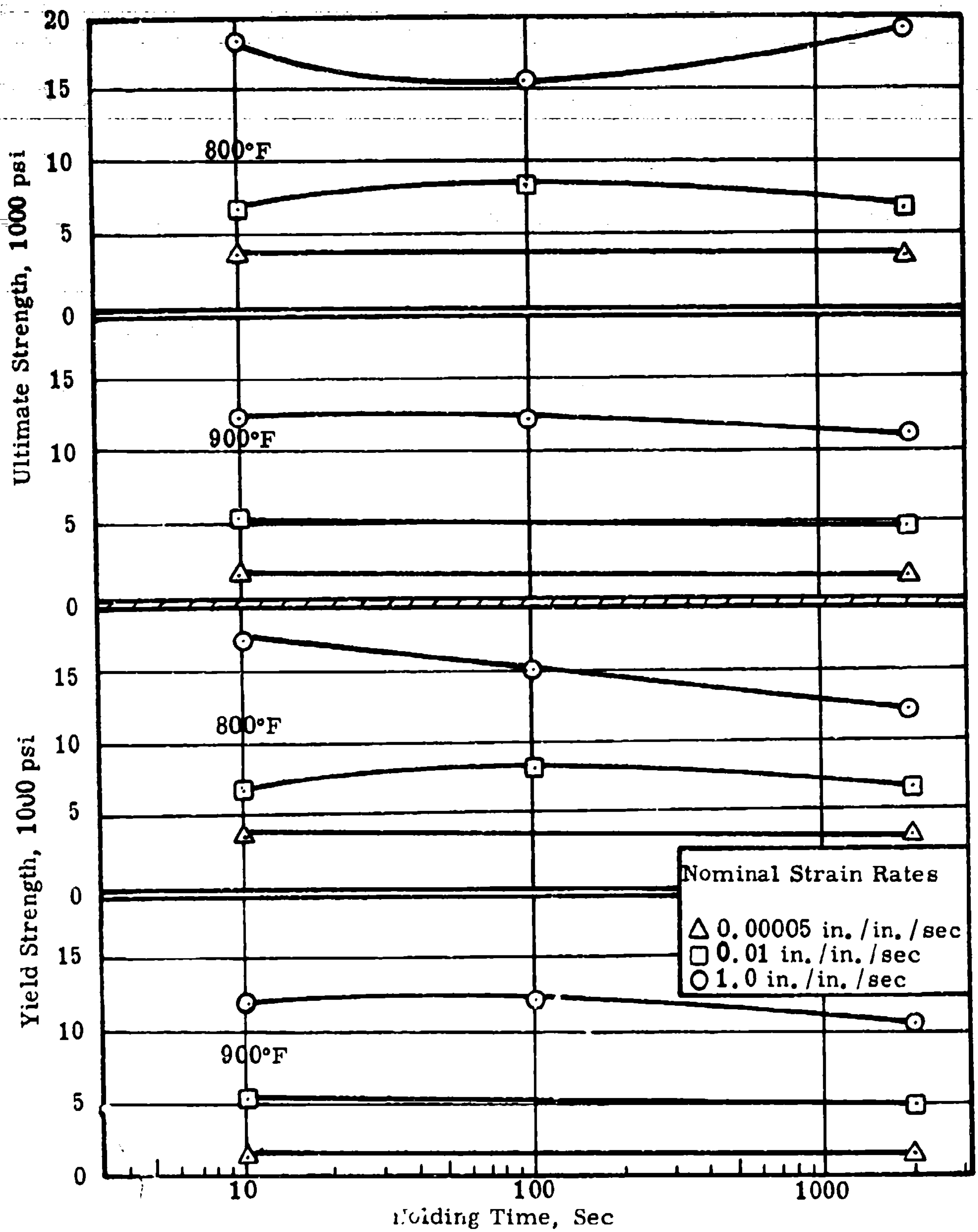

Figure 42. Effect of holding time on the 0.2%-offset yield strength and ultimate tensile strength of Alclad 2024-T3 Aluminum alloy sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

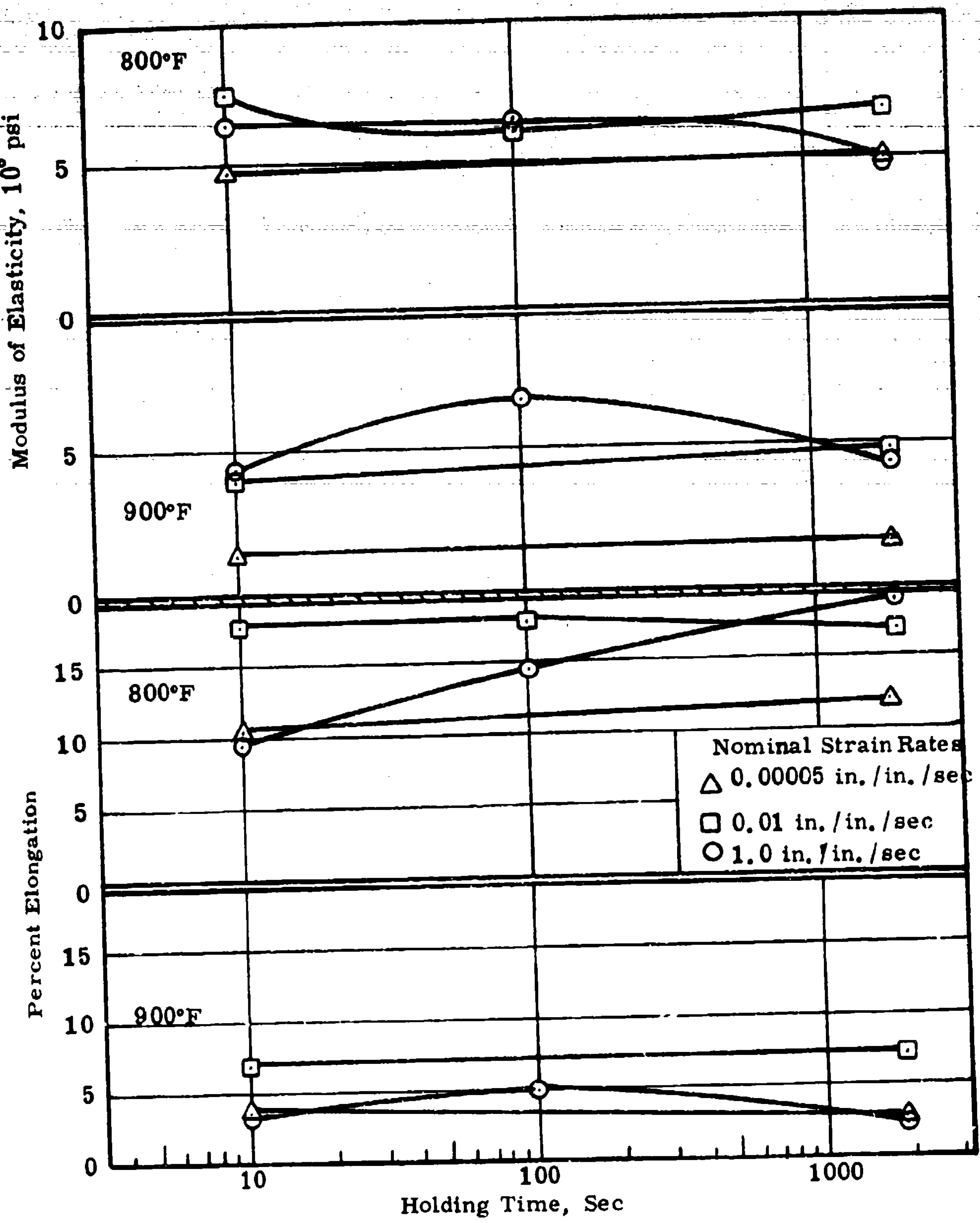

Figure 43. Effect of holding time on the percent elongation and modulus of elasticity of Alclad 2024-T3 Aluminum alloy sheet at different temperatures and strain rates. Specimens were heated to test temperature within 10 sec.

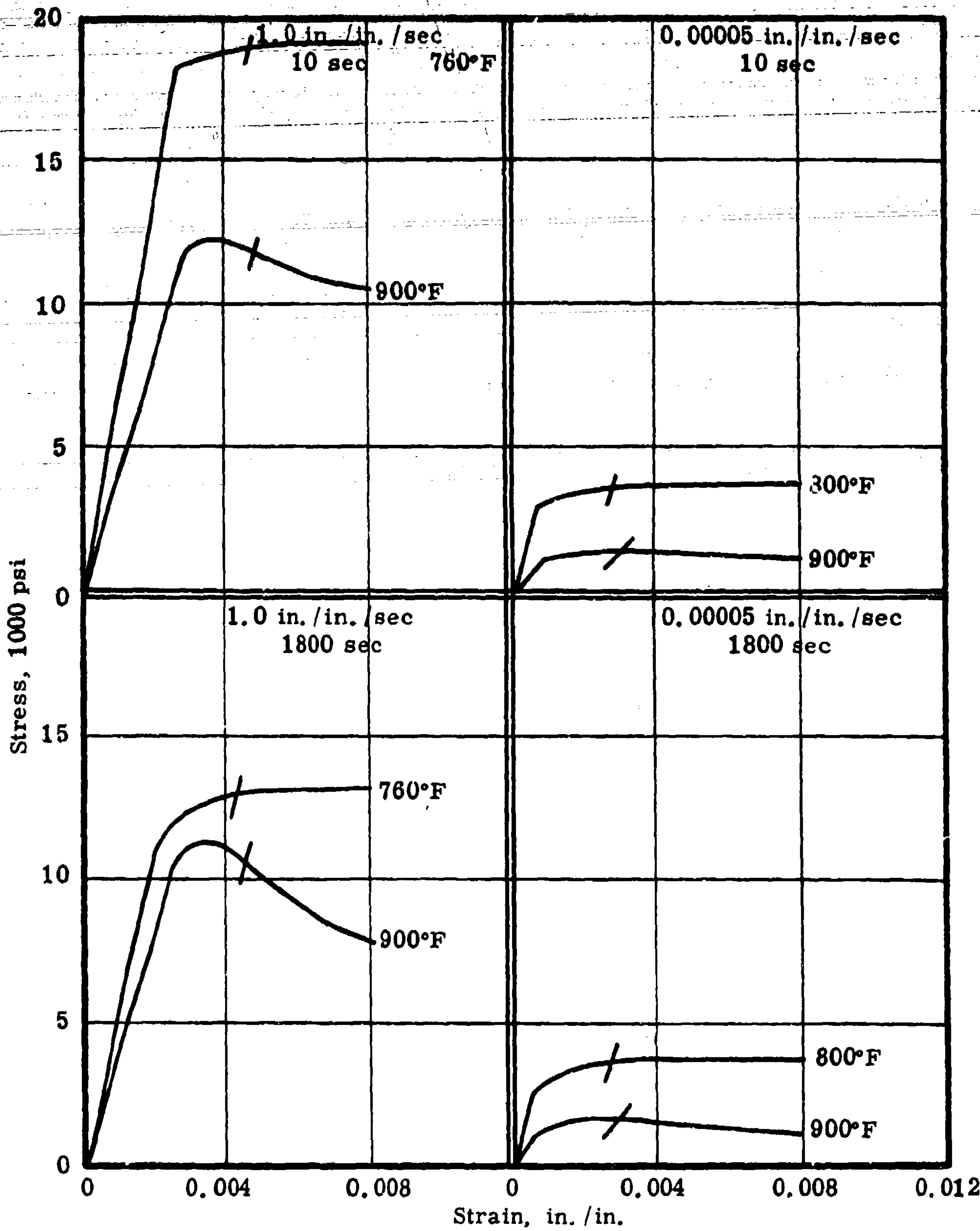

Figure 44. Stress-strain curves for Alclad 2024-T3 Aluminum alloy sheet at different temperatures, strain rates, and holding times. Specimens were heated to test temperature within 10 sec.

Temp, °F	Strain Rate, In./In./Sec	Holding Time, Sec
800	1.0	10
800	0.00005	1800
900	1.0	10
900	0.00005	1800

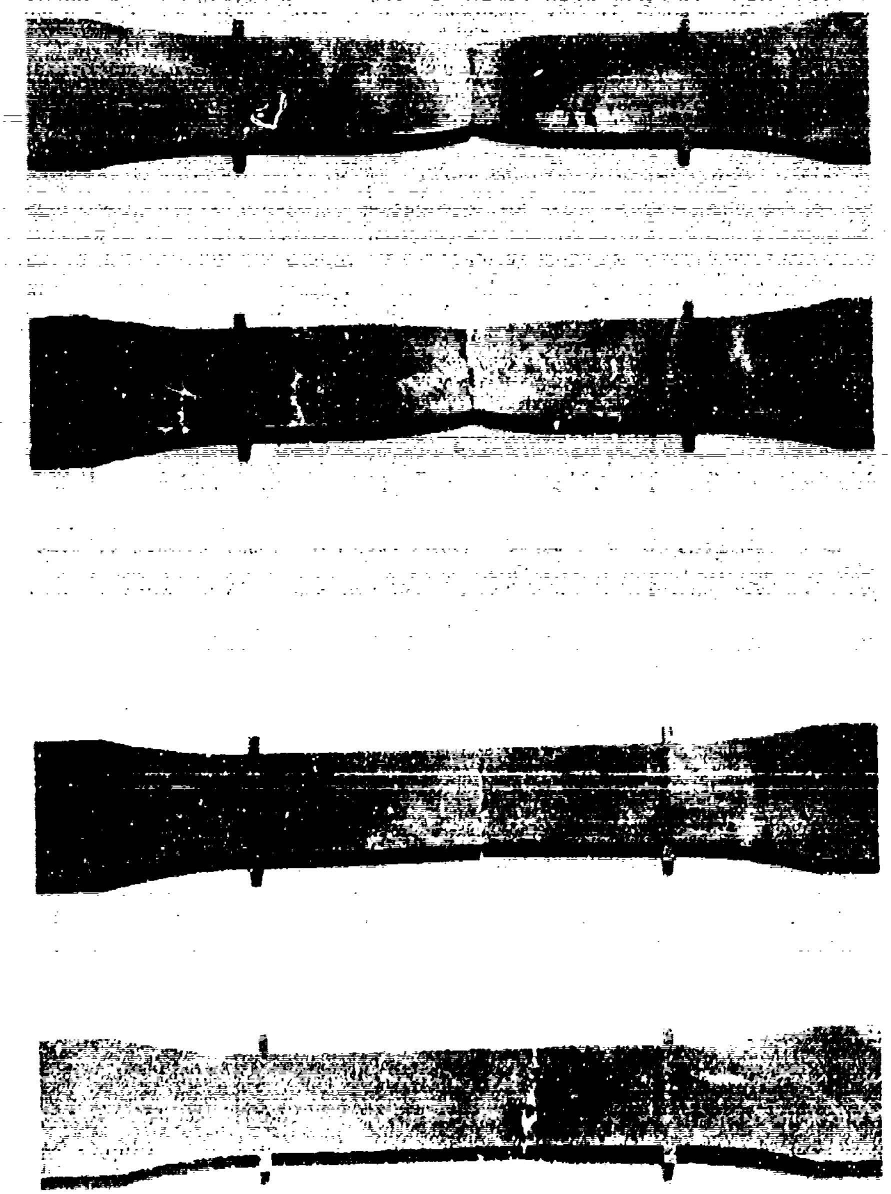

Figure 45. Surface condition of Alclad 2024-T3 Aluminum alloy sheet after high-temperature testing.

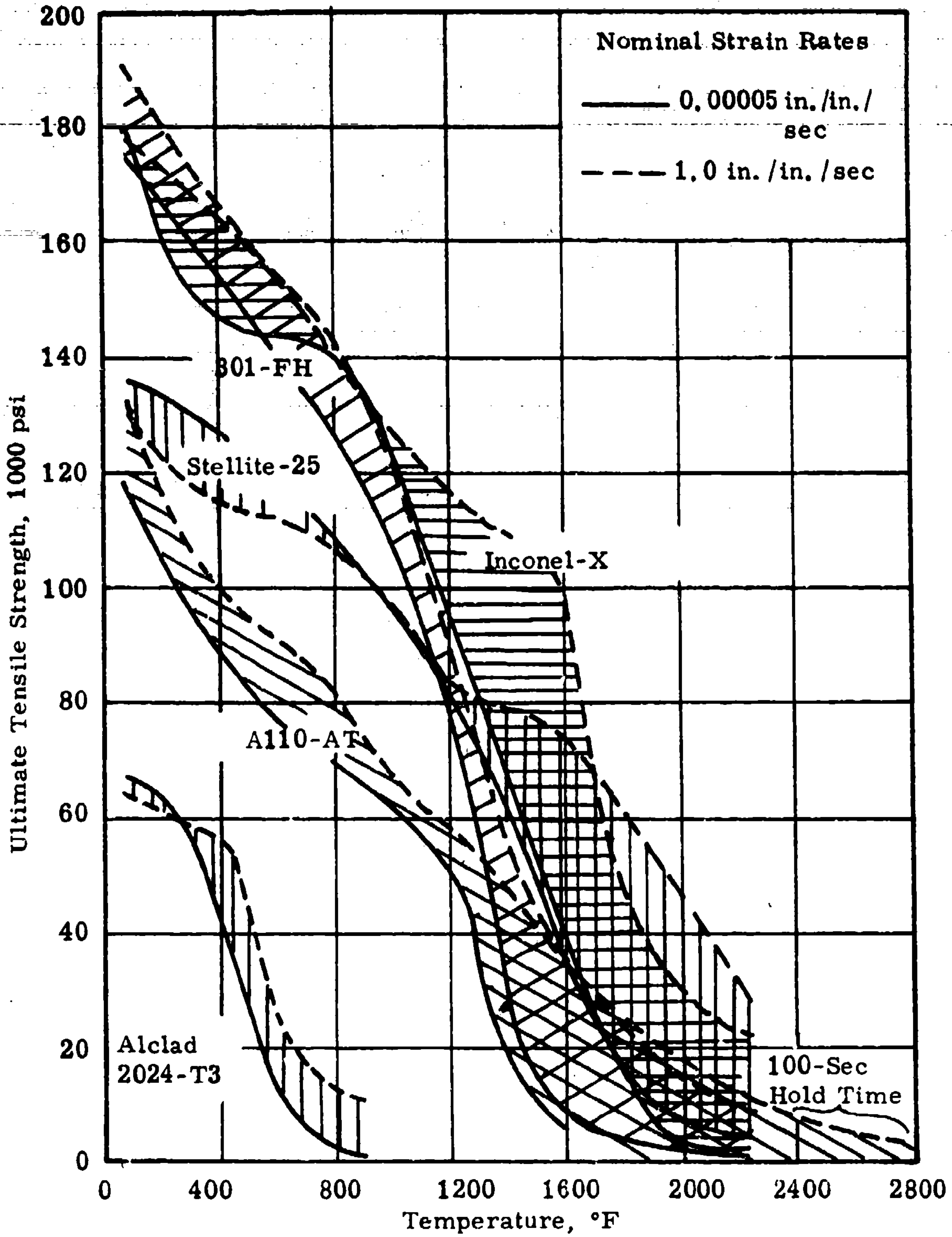

Figure 46. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the ultimate tensile strength of test metals over a range of strain rates from 0.00005 to 1.0 in./in./sec.

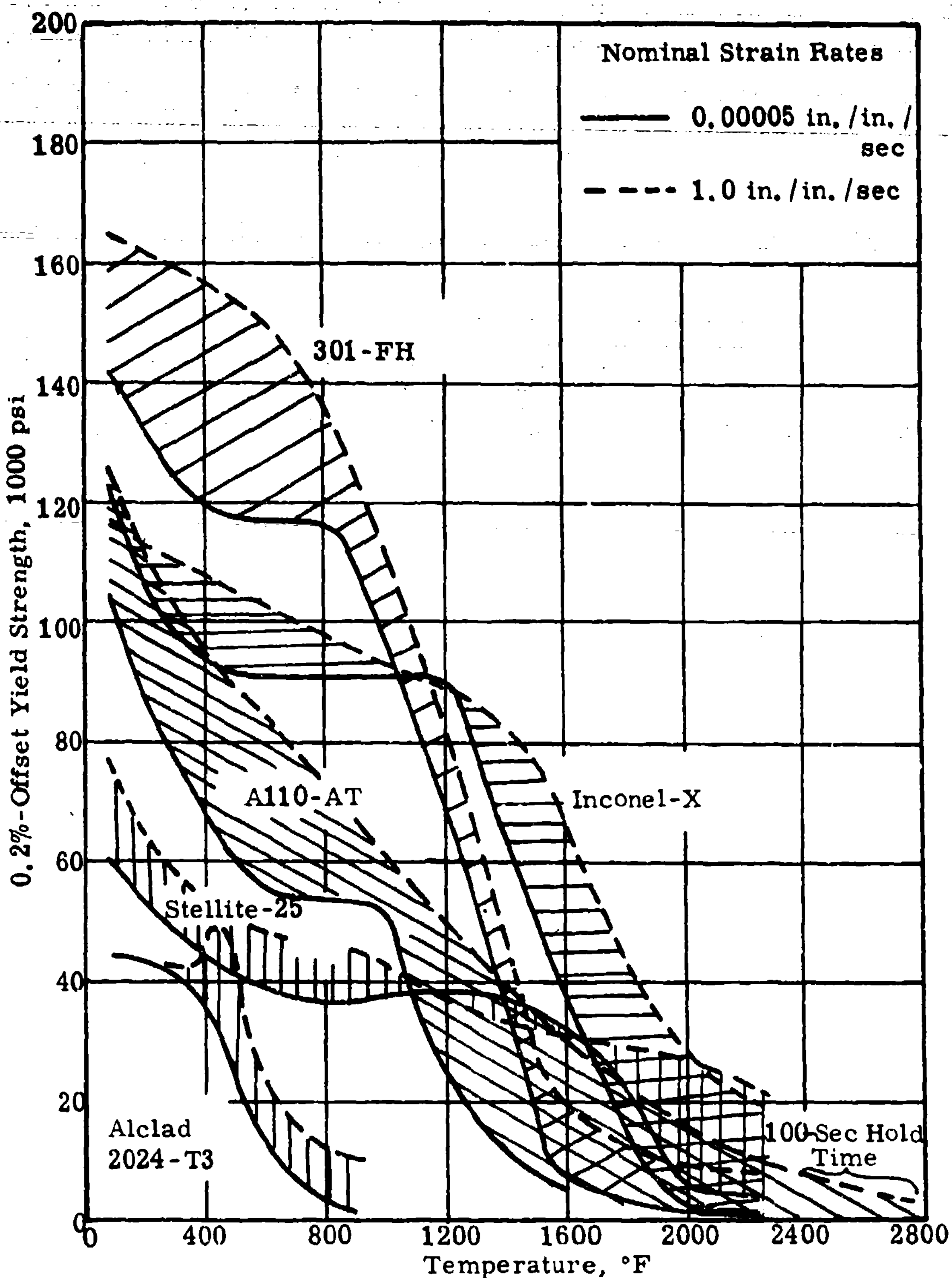

Figure 47. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the 0.2%-offset yield strength of test metals over a range of strain rates from 0.00005 to 1.0 in./in./sec.

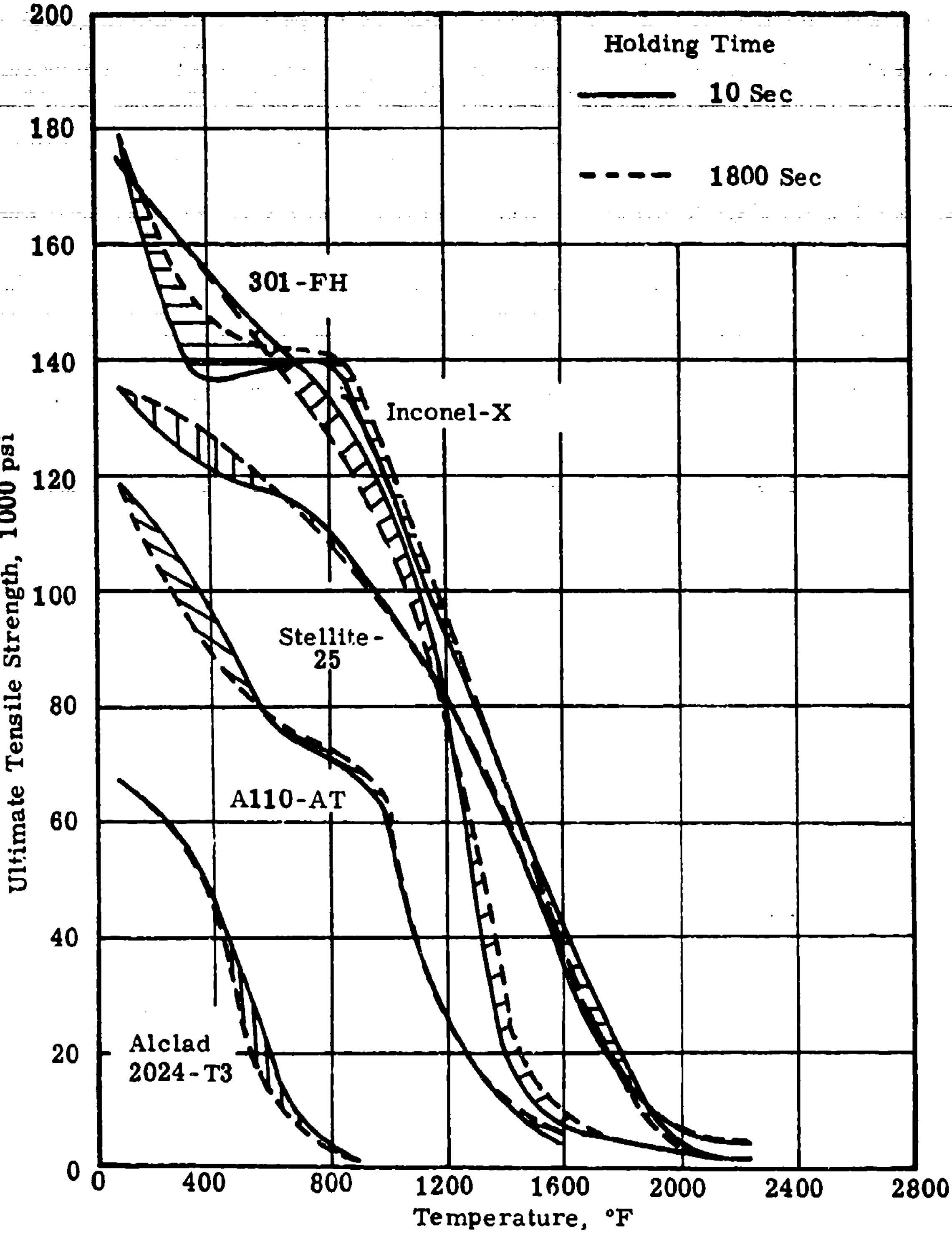

Figure 48. Effect of temperature, after 10-sec heating time and two different holding times, on the ultimate tensile strength of test metals at a strain rate of 0.00005 in./in./sec.

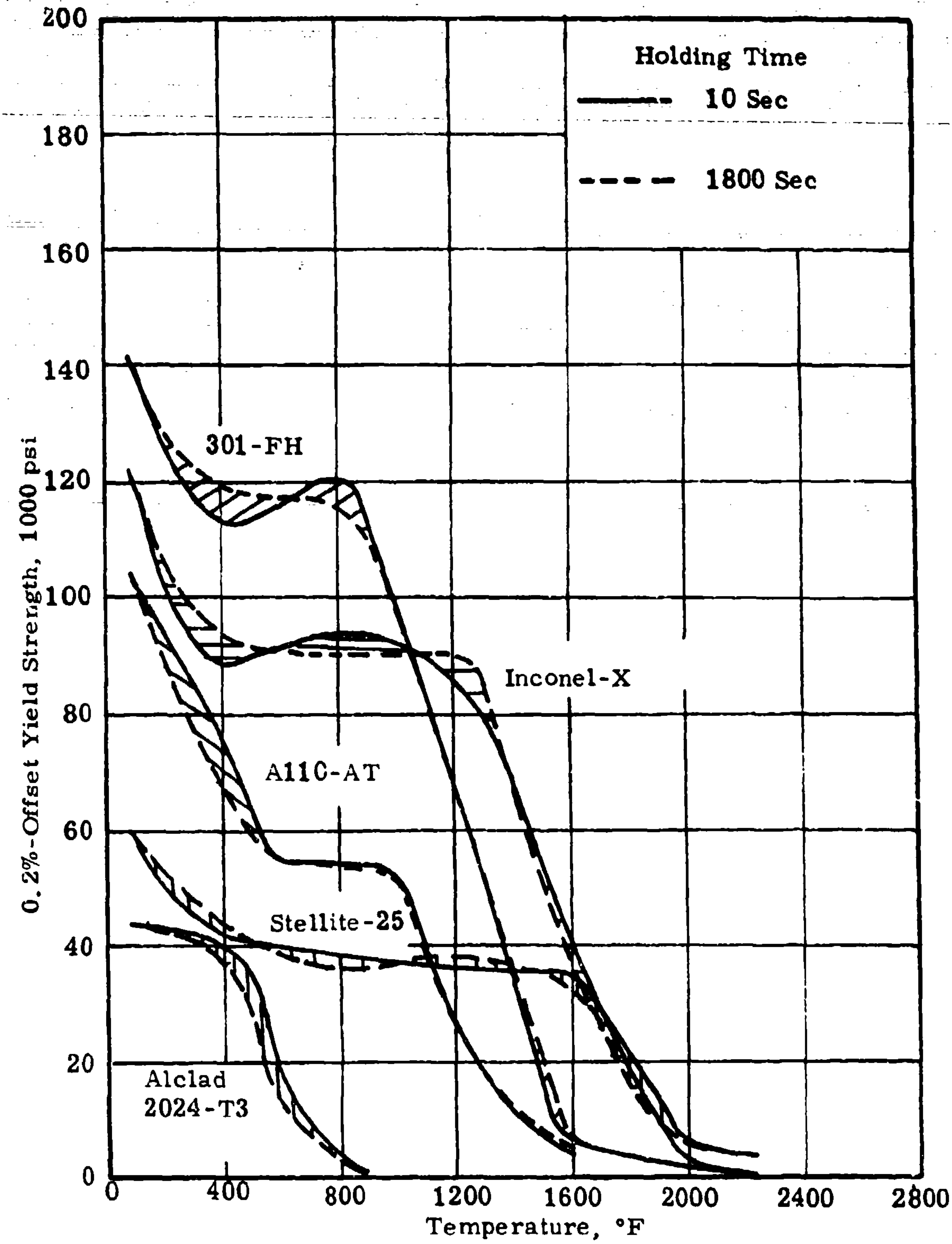

Figure 49. Effect of temperature, after 10-sec heating time and two different holding times, on the 0.2%-offset yield strength of test metals at a strain rate of 0.00005 in./in./sec.

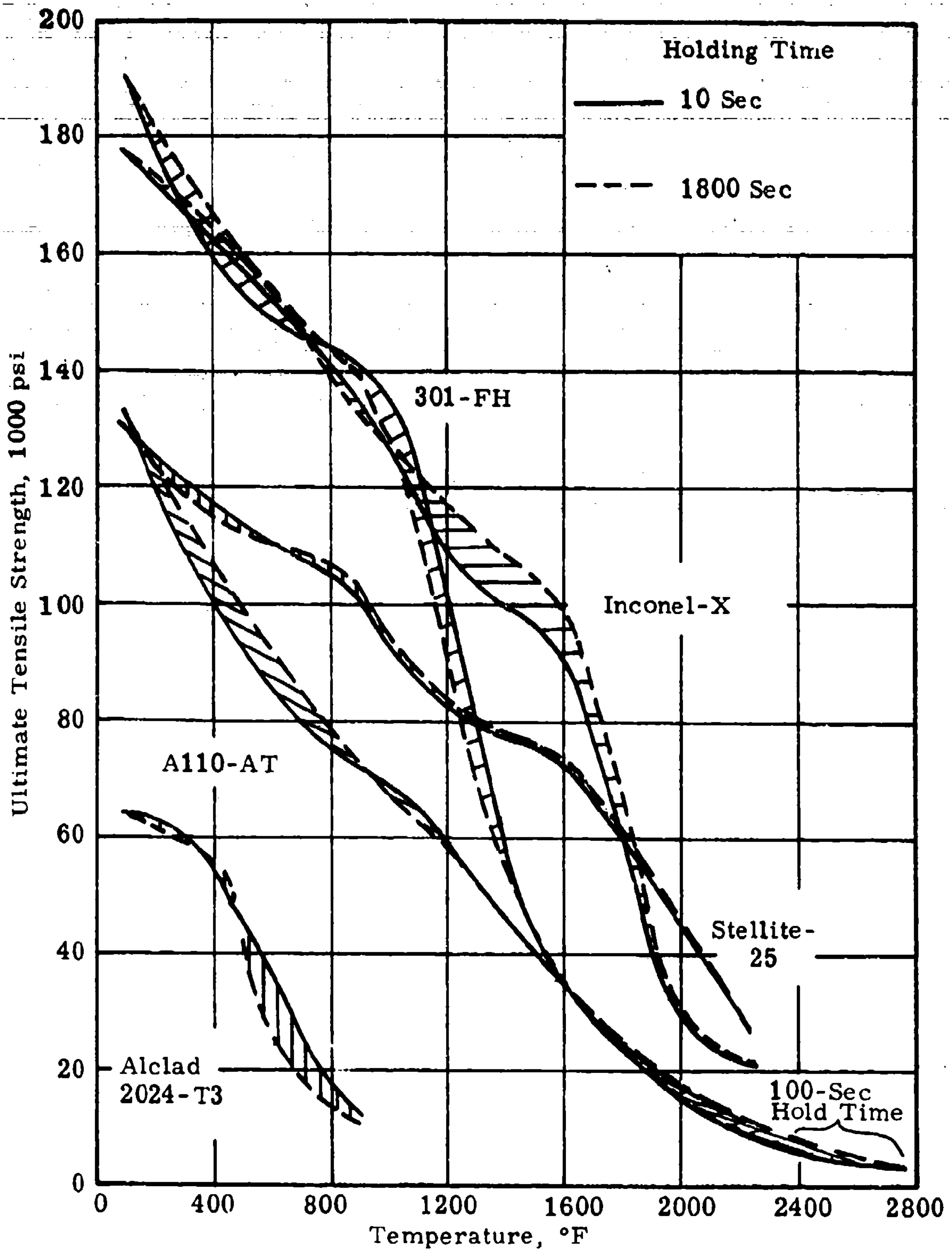

Figure 50. Effect of temperature, after 10-sec heating time and two different holding times, on the ultimate tensile strength of test metals at a strain rate of 1.0 in./in./sec.

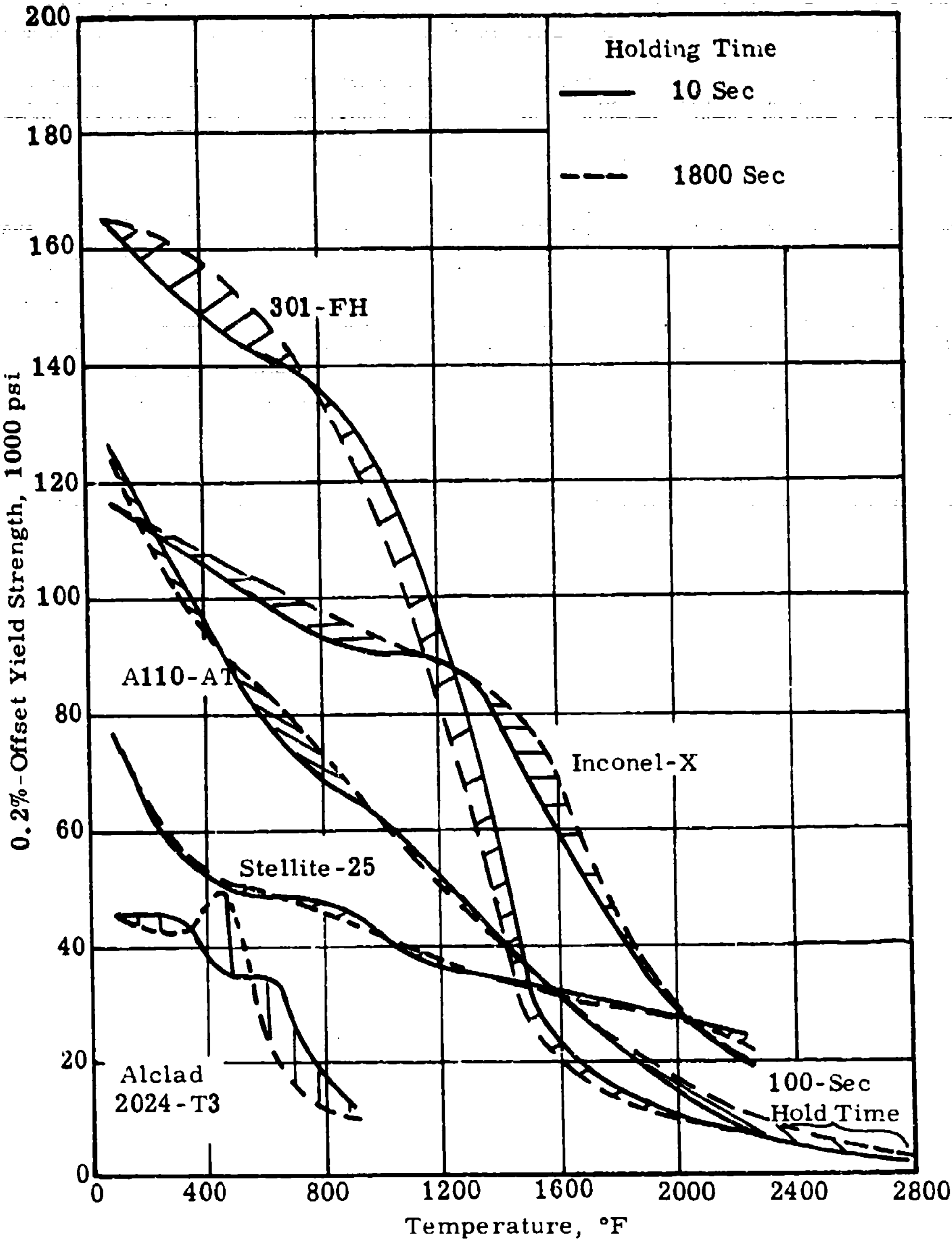

Figure 51. Effect of temperature, after 10-sec heating time and two different holding times, on the 0.2%-offset yield strength of test metals at a strain rate of 1.0 in./in./sec.

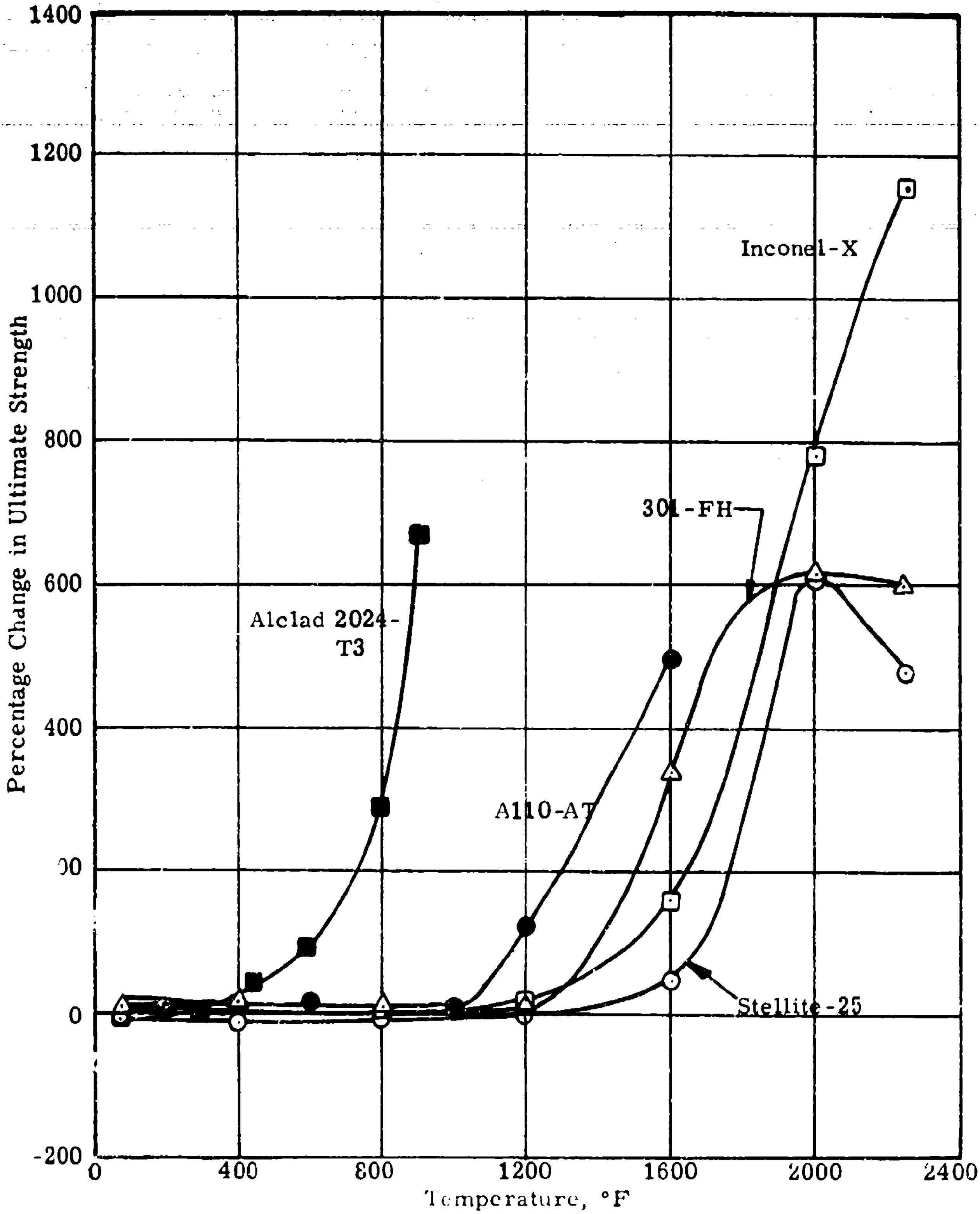

Figure 52. Effect of temperature on the percentage change in ultimate tensile strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec.

Table III

Tensile Properties of Annealed Stellite-25 Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit	0.2%-Offset Yld. Str.	Ult. Str.	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
			1000 psi					
1600	10	0.000045	22.1	37.7	39.7	20.9	13.5	840
1600	10	0.000057	22.8	34.4	34.9	18.3	13.5	
1600	10	0.000055	21.7	32.2	34.9	16.1	13.0	
Av.			22.2	34.8	36.5	18.4	13.3	
1600	10	0.0083	31.0	33.4	59.3	22.2	26.0	
1600	10	0.0097	30.4	33.2	64.2	20.6	24.5	10
Av.			30.7	33.3	61.7	21.4	25.3	
1600	10	0.97	24.6	33.2	74.3	23.0	43.5	
1600	10	0.90	27.3	31.5	71.8	17.3	42.0	
1600	10	1.02	26.5	32.0	72.2	18.8	35.0	
Av.			26.1	32.2	72.8	19.7	40.2	0.23
1600	1800	0.000040	18.5	33.7	35.0	23.7	11.5	720
1600	1800	0.000041	20.1	33.1	35.3	20.4	13.0	660
1600	1800	0.000050[1]	22.2	31.7	35.0	20.8	14.0	
Av.			20.3	32.8	35.1	21.6	12.8	
1600	1800	0.0105	27.4	30.8	58.5	21.0	27.0	
1600	1800	0.0090	30.6	34.6	64.1	20.1	29.0	
Av.			28.5	32.7	61.3	20.6	28.0	11
1600	1800	1.00	28.4	30.3	72.5	17.1	47.5	
1600	1800	1.09	29.0	30.2	74.0	17.6	46.5	
1600	1800	1.02	27.9	31.8	74.4	18.8	50.0	
Av.			28.4	30.8	73.6	17.8	48.0	0.26
2000	10	0.000050[1]	2.88	5.38	5.89	7.3	9.0	
2000	10	0.000050[1]	4.02	6.08	6.37	7.9	9.0	
2000	10	0.000074	3.17	7.01	7.05	6.3	3.0	45
Av.			3.36	6.16	6.44	7.2	7.0	
2000	10	0.0126	16.7	21.4	21.8	14.5	21.0	1.3
2000	10	0.0098	16.1	22.9	23.6	14.1	21.5	1.3
Av.			16.4	22.2	22.7	14.3	21.3	

Table III (Cont'd.)

Tensile Properties of Annealed Stellite-25 Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
2000	10	1.09	26.1	27.1	45.5	14.7	27.0	
2000	10	0.85	26.3	28.7	45.6	14.3	35.0	
2000	10	0.96	22.0	26.0	44.2	15.2	34.0	
Av.			24.8	27.3	45.1	14.7	32.0	0.09
2000	1800	0.000058	3.98	6.14	6.36	12.8	10.0	80
2000	1800	0.000050[1]	3.24	5.61	6.20	5.2	11.5	
2000	1800	0.000067	3.76	6.60	6.78	7.7	10.5	60
Av.			3.66	6.12	6.45	8.6	10.7	
2000	1800	0.0076	15.4	24.2	24.4	17.5	17.5	1.7
2000	1800	0.0090	15.8	24.2	24.3	18.9	--	
Av.			15.6	24.2	24.4	18.2	17.5	
2000	1800	0.94	24.3	27.5	48.5	19.4	31.5	
2000	1800	0.80	20.3	27.5	47.0	17.9	32.5	
2000	1800	0.99	24.2	26.0	41.6	14.4	35.5	
Av.			22.9	27.0	45.7	17.2	33.2	0.09
2250	10	0.000060	2.32	4.21	4.55	8.3	8.5	
2250	10	0.000052	3.10	4.17	4.60	8.1	8.0	
2250	10	0.000056	2.74	4.12	4.55	4.9	7.0	161
Av.			2.72	4.17	4.57	7.1	7.8	
2250	10	0.0100	8.94	12.2	12.2	11.8	18.0	
2250	10	0.0111	7.10	10.7	10.8	11.3	19.0	1.5
Av.			8.02	11.5	11.5	11.6	18.5	
2250	10	1.16	22.3	23.0	25.3	19.1	42.0	0.01
2250	10	0.91	22.5	24.4	26.3	17.2	31.0	0.01
2250	10	1.32	20.1	25.3	28.1	----[2]	41.5	0.01
Av.			21.6	24.2	26.6	18.2	38.2	
2250	100	0.0125	10.6	14.6	14.9	11.0	21.0	0.75
2250	100	0.0105	8.65	12.4	12.4	12.2	11.5	1.0
Av.			9.63	13.5	13.7	11.6	16.3	

Table III (Cont'd.)

Tensile Properties of Annealed Stellite-25 Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
2250	1800	0.000031	3.95	5.00	5.18	6.1	9.0	
2250	1800	0.000056	2.45	3.88	4.40	10.6	9.0	157
2250	1800	0.000053	2.88	3.71	4.26	5.8	9.0	180
Av.			3.09	4.20	4.61	7.5	9.0	
2250	1800	0.0088	11.2	14.6	14.6	14.4	19.0	0.33
2250	1800	0.0105	10.9	16.4	16.4	14.7	20.5	0.36
Av.			11.1	15.5	15.5	14.6	19.8	
2250	1800	1.16	19.8	21.1	25.8	----[2]	30.5	0.01
2250	1800	0.90	18.0	19.6	26.8	20.1	30.0	0.01
2250	1800	1.40	22.5	24.6	27.7	16.9	27.0	0.01
Av.			20.1	21.8	26.8	18.5	29.2	

1. Nominal strain rate; timing signal illegible.
2. Stress-strain curve defective in elastic region.

Table IV

Tensile Properties of Heat-Treated[1] Inconel-X Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
1600	10	0.000047	32.7	42.6	42.6	14.0	7.0	100
1600	10	0.000048	29.0	39.5	39.5	14.4	7.0	80
1600	10	0.000052	31.0	42.2	43.7	17.4	7.0	70
Av.			30.9	41.4	41.9	15.3	7.0	
1600	10	0.0086	42.8	52.2	57.4	17.1	6.0	3.0
1600	10	0.0088	39.2	51.0	55.6	17.3	5.5	1.3
Av.			41.0	51.6	56.5	17.2	5.8	
1600	10	0.93	53.8	57.8	87.5	15.8	9.0	0.02
1600	10	0.86	55.8	60.6	90.0	21.3	12.5	
1600	10	0.88	54.1	60.0	94.0	19.6	13.5	
Av.			54.6	59.5	90.5	18.9	11.7	0.08
1600	100	0.000070	26.9	42.5	42.5	17.7	7.0	80
1600	100	0.000073	29.7	43.2	43.7	17.0	5.5	60
Av.			28.3	42.9	43.1	17.4	6.3	
1600	100	0.0084	29.1	54.1	60.5	18.4	5.5	2.0
1600	100	0.0095	37.7	49.1	52.8	16.6	10.0	1.5
Av.			33.4	51.6	57.7	17.5	7.8	
1600	100	1.0[2]	64.6	70.0	98.8	20.9	9.0	
1600	100	1.0[2]	63.0	69.1	93.8	21.7	9.5	
Av.			63.8	69.6	96.3	21.3	9.3	0.07
1600	1800	0.000026	22.2	35.0	35.0	16.0	7.5	120
1600	1800	0.000038	22.9	37.6	38.4	18.6	6.5	110
1600	1800	0.000044	24.2	39.0	39.4	19.1	5.0	100
Av.			23.1	37.2	37.6	17.9	6.3	
1600	1800	0.0083	37.9	61.7	65.6	18.0	4.5	1.0
1600	1800	0.0086	36.0	62.7	66.8	18.3	4.5	2.0
Av.			37.0	62.2	66.2	18.2	4.5	
1600	1800	0.86	60.4	63.5	91.8	23.4	7.5	
1600	1800	0.79	56.2	70.4	102.4	18.7	8.5	
1600	1800	1.03	42.7	69.0	103.5	20.0	8.5	
Av.			56.4	67.6	99.2	20.7	8.2	0.05

Table IV (Cont'd.)

Tensile Properties of Heat-Treated[1] Inconel-X Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
2000	10	0.000052	2.17	2.89	3.20	8.0	31.5	
2000	10	0.000059	2.53	3.27	3.40	8.0	31.5	
2000	10	0.000059	2.46	3.45	3.70	5.5	24.0	
Av.			2.39	3.20	3.43	7.2	29.0	780
2000	10	0.0147	8.39	9.80	10.0	8.5	33.0	5.0
2000	10	0.0078	7.13	8.65	10.3	9.8	31.5	5.0
Av.			7.76	9.23	10.2	9.2	32.3	
2000	10	0.62	27.0	29.0	29.0	8.0	60.3	0.009
2000	10	0.51	25.5	27.6	27.6	15.3	74.0	0.010
2000	10	0.94	27.6	29.6	30.4	13.0	69.0	0.007
Av.			26.7	28.7	29.0	12.1	67.8	
2000	100	0.0170	7.81	10.2	10.5	10.7	33.0	
2000	100	0.0099	9.33	11.1	11.3	11.6	39.0	0.30
Av.			8.57	10.7	10.9	11.2	36.0	
2000	1800	0.000059	2.74	3.16	3.40	7.2	29.5	
2000	1800	0.000054	2.94	3.62	3.70	6.6	----	
2000	1800	0.000065	1.98	3.00	3.16	6.9	25.5	
Av.			2.55	3.26	3.42	6.9	27.5	840
2000	1800	0.0147	10.7	12.0	12.2	10.1	34.0	0.32
2000	1800	0.0128	10.2	11.8	11.9	9.5	29.0	0.32
Av.			10.5	11.9	12.1	9.8	32.0	
2000	1800	1.34	21.9	28.4	30.8	17.0	48.0	0.007
2000	1800	0.95	24.9	27.0	28.8	24.3	61.5	0.006
2000	1800	1.22	27.0	29.7	31.0	10.9	58.5	0.005
Av.			24.6	28.4	30.2	17.4	58.0	
2250	10	0.000120	1.33	1.53	2.29	0.64	20.0	600
2250	10	0.000064	1.23	1.39	1.94	0.85	20.0	
2250	10	0.000050[2]	1.17	1.45	2.00	1.14	19.5	
Av.			1.24	1.46	2.08	0.88	19.8	

Table IV (Cont'd.)

Tensile Properties of Heat-Treated[1] Inconel-X Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
2250	10	0.0089	5.93	6.04	7.04	11.0	27.5	4.0
2250	10	0.0090	6.34	6.67	7.27	9.4	30.0	5.0
Av.			6.14	6.36	7.16	10.2	28.8	
2250	10	1.34	20.5	19.3	20.5	14.1	66.0	0.004
2250	10	1.35	21.5	21.5	23.3	8.1	63.0	0.004
2250	10	1.02	20.1	18.8	20.1	11.3	78.0	0.004
Av.			20.7	19.9	21.3	11.2	69.0	
2250	100	0.0126	4.98	6.10	6.52	10.9	22.0	
2250	100	0.0124	6.03	7.13	7.41	11.5	30.0	4.0
Av.			5.51	6.62	6.97	11.2	26.0	
2250	1800	0.000076	1.19	1.52	2.29	2.60	23.0	
2250	1800	0.000078	0.59	0.89	1.03	0.65	----	1080
Av.			0.89	1.21	1.66	1.63	23.0	
2250	1800	0.0149	7.30	7.96	8.34	9.8	30.5	4.2
2250	1800	0.0132	6.28	7.14	7.46	10.0	29.0	
Av.			6.79	7.55	7.90	9.9	29.8	
2250	1800	1.24	19.8	18.3	20.2	9.9	22.5	0.004
2250	1800	1.09	21.3	21.4	22.0	11.5	50.5	0.004
2250	1800	1.42	19.4	19.5	22.0	13.4	50.0	0.004
Av.			20.2	19.7	21.4	11.6	41.0	

1. Aged at 1300°F for 20 hours and air cooled.
2. Nominal strain rate; timing signal illegible.

Table V

Tensile Properties of Full-Hard 301 Stainless Steel Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit	0.2%-Offset Yld. Str.	Ult. Str.	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
			1000 psi					
1600	10	0.000044	1.15	5.92	7.57	6.0	21.0	
1600	10	0.000050[1]	5.44	7.02	8.36	6.0	26.0	
1600	10	0.000061	3.53	6.41	7.71	6.0	22.5	600
Av.			3.37	6.45	7.88	6.0	23.2	
1600	10	0.0105	12.1	17.7	23.8	10.7	29.0	6.0
1600	10	0.0102	11.6	17.0	22.8	12.2	32.5	6.0
Av.			11.9	17.4	23.3	11.5	30.8	
1600	10	1.01	16.6	20.2	34.2	13.0	26.0	
1600	10	0.78	17.1	21.2	35.9	18.0	27.5	
1600	10	0.94	18.9	21.5	36.7	15.3	25.5	
Av.			17.5	21.0	35.6	15.4	26.3	0.10
1600	1800	0.000064	2.34	7.19	7.70	10.3	24.0	
1600	1800	0.000044	5.54	8.15	8.80	6.4	23.0	
1600	1800	0.000067	2.56	6.38	7.59	5.9	25.0	600
Av.			3.48	7.24	8.03	7.5	24.0	
1600	1800	0.0107	9.87	16.5	23.5	15.7	36.0	9.0
1600	1800	0.0119	11.6	17.3	24.3	15.6	38.0	8.0
Av.			10.7	16.9	23.9	15.7	37.0	
1600	1800	1.02	17.6	18.5	33.8	15.1	32.0	
1600	1800	1.07	16.4	19.2	34.5	15.6	31.5	
1600	1800	1.17	17.5	20.9	38.0	17.5	32.0	0.08
Av.			17.2	19.5	35.4	16.1	31.8	
2000	10	0.000058	1.60	2.26	2.63	2.4	16.0	
2000	10	0.000057	1.77	2.21	2.67	2.1	18.5	
2000	10	0.000056	1.67	2.12	2.50	2.8	18.5	
Av.			1.68	2.20	2.60	2.4	17.7	1020
2000	10	0.0165	4.75	5.51	8.05	6.2	42.0	8.0
2000	10	0.0180	4.62	5.21	7.98	7.0	35.0	9.0
Av.			4.69	5.36	8.02	6.6	38.5	

Table V (Cont'd.)

Tensile Properties of Full-Hard 301 Stainless Steel Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
2000	10	1.82	10.5	11.7	18.4	8.6	42.5	
2000	10	1.16	8.6	9.3	15.9	9.2	57.0	
2000	10	1.0[1]	7.5	11.2	16.3	7.3	67.0	
Av.			8.9	10.7	16.9	8.4	55.5	0.09
2000	100	0.000041	1.63	2.31	2.76	3.3	20.0	540
2000	100	0.000057	1.35	2.04	2.43	2.4	21.0	600
Av.			1.49	2.18	2.60	2.9	20.5	
2000	100	1.0[1]	7.8	9.7	18.6	18.1	60.5	
2000	100	1.0[1]	7.6	9.9	18.4	15.3	47.0	
Av.			7.7	9.8	18.5	16.7	53.8	0.08
2000	1800	0.000045	1.61	1.97	2.25	2.4	20.5	
2000	1800	0.000046	1.55	1.87	2.14	4.7	17.0	133
2000	1800	0.000045	1.06	1.71	1.87	3.7	20.0	128
Av.			1.41	1.85	2.09	3.6	19.2	
2000	1800	0.0150	5.02	5.92	8.40	7.8	34.0	7.0
2000	1800	0.0113	4.03	5.50	7.60	7.2	34.0	9.0
Av.			4.53	5.71	8.00	7.5	34.0	
2000	1800	1.0[1]	9.4	9.4	14.5	10.3	65.0	
2000	1800	1.0[1]	8.6	9.2	13.4	9.7	51.0	
2000	1800	1.52	9.7	9.9	17.2	7.1	55.0	
Av.			9.2	9.5	15.0	9.0	57.0	0.09
2250	10	0.000068	0.770	1.08	1.43	1.2	13.0	
2250	10	0.000052	0.743	0.925	0.978	0.95	18.0	160
2250	10	0.000045	0.729	0.982	1.10	1.3	12.5	166
Av.			0.747	0.996	1.17	1.2	14.5	
2250	10	0.0223	3.64	3.72	5.42	7.2	38.0	
2250	10	0.0128	3.12	3.57	5.04	9.6	33.5	2.8
Av.			3.38	3.65	5.23	8.4	35.8	

Table V (Cont'd.)

Tensile Properties of Full-Hard 301 Stainless Steel Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
2250	10	1.0[1]	4.76	5.83	11.3	7.5	66.5	
2250	10	1.0[1]	5.02	6.50	10.1	4.2	70.0	
2250	10	1.0[1]	5.06	6.61	9.1	4.9	70.5	
Av.			4.95	6.31	10.2	5.5	69.0	0.078
2250	100	0.000039	0.620	0.740	0.910	0.54	17.0	360
2250	100	0.000044	0.670	0.990	1.08	1.3	16.0	300
Av.			0.645	0.865	0.995	0.92	16.5	
2250	100	1.0[1]	6.00	7.82	13.2	15.3	33.0	
2250	100	1.0[1]	5.40	6.37	11.5	11.5	25.5	
Av.			5.70	7.10	12.4	13.4	29.3	0.084
2250	1800	0.000060	0.570	0.830	1.40	0.65	13.0	
2250	1800	0.000053	0.680	0.890	1.05	0.92	11.0	183
2250	1800	0.000046	0.700	0.940	1.04	1.1	18.0	168
Av.			0.650	0.887	1.16	0.89	14.0	
2250	1800	0.0114	2.42	3.53	4.47	11.7	20.5	
2250	1800	0.0100	3.10	3.53	4.00	9.8	10.0	
Av.			2.76	3.53	4.24	10.8	15.3	1.5
2250	1800	1.0[1]	7.50	7.67	8.18	4.5	36.0	0.010
2250	1800	1.0[1]	4.62	5.65	7.53	6.6	28.0	0.010
2250	1800	1.0[1]	8.35	8.35	9.35	4.7	30.0	0.007
Av.			6.82	7.22	8.35	5.3	31.3	

1. Nominal strain rate; timing signal illegible.

Table VI

Tensile Properties of Annealed A110-AT Titanium Alloy Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
1200	10	0.000070	17.1	27.4	28.4	7.4	24.0	
1200	10	0.000042	16.5	26.4	26.7	8.9	31.5	100
1200	10	0.000046	16.0	26.1	26.5	7.6	32.5	92
Av.			16.5	26.6	27.2	8.0	29.3	
1200	10	0.0210	30.6	46.0	55.8	10.2	19.0	1.3
1200	10	0.0180	26.9	43.8	54.8	9.0	21.0	1.5
1200	10	0.0140	29.8	45.5	55.3	9.4	21.0	1.9
Av.			29.1	45.1	55.3	9.5	20.0	
1200	10	0.96	49.6	53.1	60.6	10.9	10.5	
1200	10	0.97	52.3	53.8	60.2	10.3	11.5	
1200	10	0.41	41.4	48.6	58.5	9.9	12.5	
Av.			47.8	51.8	59.8	10.4	11.5	0.04
1200	1800	0.000052	17.4	24.8	25.4	7.5	32.0	100
1200	1800	0.000055	17.9	27.0	27.5	6.8	26.0	100
1200	1800	0.000052	17.0	24.8	25.0	6.8	36.0	92
Av.			17.4	25.5	26.0	7.0	31.3	
1200	1800	0.0140	33.6	44.6	54.5	9.8	23.0	2.0
1200	1800	0.0120	26.3	43.5	53.2	9.0	22.0	2.0
1200	1800	0.0130	28.0	41.3	49.8	8.5	26.5	2.3
Av.			29.3	43.1	52.5	9.1	23.8	
1200	1800	0.95	46.9	47.6	56.0	9.7	13.0	
1200	1800	1.04	48.9	52.1	61.0	11.0	12.5	
1200	1800	0.99	50.0	50.4	58.9	10.3	14.0	
Av.			48.6	50.0	58.6	10.3	13.2	0.03
1600	10	0.000071	3.63	4.28	4.67	2.8	35.5	99
1600	10	0.000055	3.12	4.22	4.22	2.6	34.0	55
1600	10	0.000059	2.96	4.14	4.14	2.5	34.0	60
Av.			3.24	4.21	4.34	2.6	34.5	
1600	10	0.0140	15.2	22.3	22.8	6.7	41.0	0.50
1600	10	0.0160	16.9	20.5	20.5	5.5	38.0	0.45
1600	10	0.0120	13.0	17.5	18.2	4.9	41.5	0.40
Av.			15.0	20.1	20.5	5.7	40.2	

Table VI (Cont'd.)

Tensile Properties of Annealed A110-AT Titanium Alloy Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit	0.2%-Offset Yld. Str.	Ult. Str.	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
			1000 psi					
1600	10	1.33	30.2	32.0	34.4	6.2	28.0	0.014
1600	10	1.11	22.0	29.1	33.9	6.8	13.2	0.019
1600	10	1.22	28.7	32.3	34.4	6.1	30.5	0.016
Av.			27.0	31.1	34.2	6.4	24.0	
1600	100	0.000065	4.04	5.14	5.14	2.8	33.5	78
1600	100	0.000072	2.86	4.15	4.15	2.7	34.0	
1600	100	0.000048	4.00	4.65	4.65	2.7	34.0	68
Av.			3.63	4.65	4.65	2.7	33.8	
1600	1800	0.000055	4.50	5.92	6.02	3.3	34.5	72
1600	1800	0.000050	4.35	5.65	5.65	3.3	35.0	55
1600	1800	0.000050[1]	3.79	5.75	5.75	3.1	34.0	
Av.			4.21	5.77	5.81	3.2	34.5	
1600	1800	0.0170	15.3	19.8	19.8	6.0	42.0	0.40
1600	1800	0.0150	15.4	20.3	20.3	5.6	39.0	0.45
1600	1800	0.0130	14.4	20.2	20.2	5.5	37.5	0.45
Av.			15.0	20.1	20.1	5.7	39.5	
1600	1800	0.56	27.0	32.0	37.2	7.1	20.0	
1600	1800	1.17	29.5	31.7	34.3	7.1	27.5	
1600	1800	1.16	26.4	29.0	32.8	6.0	36.5	
Av.			27.6	30.9	34.8	6.3	28.0	0.06
2350	10	0.0085	0.92	1.16	1.16	1.8	39.5	0.35
2350	10	0.0084	0.48	1.51	1.51	1.5	38.0	0.50
2350	10	0.0200	1.20	1.43	1.47	1.4	32.0	
Av.			0.87	1.36	1.38	1.6	36.5	
2350	10	1.52	7.06	6.10	7.44	2.6	7.0	0.003
2350	10	1.0[1]	5.28	5.95	6.05	2.3	10.0	0.01
Av.			6.17	6.03	6.75	2.5	8.5	
2350	100	0.0083	0.88	1.28	1.29	1.9	37.5	0.25
2350	100	0.0089	1.26	1.32	1.34	1.2	35.0	0.30
Av.			1.07	1.30	1.32	1.6	36.3	

Table VI (Cont'd.)

Tensile Properties of Annealed A110-AT Titanium Alloy Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult, Sec
2350	100	1.35	6.11	5.07	6.11	3.4	5.0	0.004
2350	100	1.0[1]	5.13	4.22	5.70	3.2	8.0	0.006
Av.			5.62	4.65	5.91	3.3	6.5	
2350	1800	0.0148	2.16	2.25	2.29	3.2	21.0	
2350	1800	0.0087	2.40	2.71	2.73	---[2]	19.0	0.25
Av.			2.28	2.48	2.51	3.2	20.0	
2350	1800	0.71	8.85	7.65	8.92	6.4	10.0	0.004
2350	1800	1.0[1]	8.62	8.44	8.62	3.3	5.0	0.004
Av.			8.78	8.04	8.77	4.9	7.5	
2770	10	0.0088	1.24	1.27	1.33	2.0	54.0	0.25
2770	10	0.0085	1.11	1.32	1.33	2.2	34.0	0.30
Av.			1.18	1.30	1.33	2.1	44.0	
2770	10	0.80	2.75	2.78	3.85	2.6	12.5	0.005
2770	10	1.0[1]	3.19	3.37	3.43	2.1	9.0	0.005
2770	10	1.0[1]	1.64	2.05	2.07	1.5	17.0	0.006
Av.			2.53	2.73	3.12	2.1	12.8	
2770	100	0.0083	1.18	1.51	1.53	3.1	17.0	0.50
2770	100	0.0100	1.56	1.72	1.98	2.6	----	0.45
Av.			1.37	1.62	1.74	2.9	17.0	
2770	100	1.0[1]	3.27	3.36	3.43	3.3	10.5	0.005
2770	100	1.0[1]	3.02	3.21	3.71	3.6	6.5	0.004
Av.			3.15	3.29	3.57	3.5	8.5	

1. Nominal strain rate; timing signal illegible.
2. Stress-strain curve defective in elastic region.

Table VII

Tensile Properties of Alclad 2024-T3[1] Aluminum Alloy Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult., Sec
800	10	0.000060	3.01	3.72	3.72	5.1	10.5	52
800	10	0.000061	2.98	3.72	3.78	4.7	12.0	
800	10	0.000052	2.75	3.66	3.92	4.4	9.0	60
Av.			2.91	3.70	3.81	4.8	10.5	
800	10	0.0148	4.90	5.88	5.88	5.6	17.0	0.2
800	10	0.0111	5.90	8.29	8.32	6.3	19.0	0.3
800	10	0.0130	2.95	6.29	6.29	10.5	17.5	0.3
Av.			4.58	6.82	6.83	7.5	17.8	
760	10	0.54	18.1	18.2	20.2	---[3]	11.5	0.013
760	10	0.86	18.9	21.1	21.6	7.8	12.0	0.012
760	10	0.92	17.8	17.9	19.6	6.7	12.0	0.012
Av.			18.3	19.1	20.5	7.2	11.8	
800	100	0.0126	5.20	7.95	7.95	6.0	17.5	1.0
800	100	0.0114	6.00	8.54	8.59	6.3	18.0	0.4
Av.			5.60	8.25	8.27	6.2	17.8	
760	100	1.31	15.5	16.5	17.2	6.4	17.0	0.012
760	100	0.96	14.7	15.6	16.8	6.0	19.0	0.012
Av.			15.1	16.1	17.0	6.2	18.0	
800	1800	0.000034	2.28	3.48	3.50	4.4	12.0	60
800	1800	0.000041	2.44	3.59	3.59	5.5	12.0	50
800	1800	0.000041	2.48	3.65	3.71	5.2	12.0	60
Av.			2.40	3.57	3.60	5.1	12.0	
800	1800	0.0112	4.09	6.77	6.84	7.0	22.0	1.2
800	1800	0.0118	5.10	7.10	7.14	6.3	12.0	
Av.			4.60	6.94	6.99	6.7	17.0	
760	1800	1.02	10.9	12.5	13.7	---[3]	26.5	0.013
760	1800	1.10	10.6	13.4	14.7	4.8	27.5	0.012
760	1800	1.07	11.5	12.7	14.1	5.3	25.0	0.010
Av.			11.0	12.9	14.2	5.1	26.3	

Table VII (Cont'd.)

Tensile Properties of Alclad 2024-T3[1] Aluminum Alloy Sheet at Different Temperatures, Holding Times, and Strain Rates

All Specimens Heated to Test Temperature Within 10 Sec

Temp, °F	Time at Temp, Sec	Strain Rate, In./In./Sec	Prop. Limit (1000 psi)	0.2%-Offset Yld. Str. (1000 psi)	Ult. Str. (1000 psi)	Mod. Elast., 10^6 psi	Elong., %	Time to Ult, Sec
900	10	0.000058	1.04	1.35	1.35	1.5	2.0	56
900	10	0.000066	1.22	1.67	1.67	1.4	4.5	67
900	10	0.000055	1.31	1.74	1.74	1.5	5.0	70
Av.			1.19	1.59	1.59	1.5	3.8	
900	10	0.0105	4.18	5.23	5.23	3.9	7.0	0.4
900	10	0.0135	3.83	5.17	5.17	3.9	7.0	0.4
900	10	0.0147	4.33	5.60	5.60	4.0	7.0	0.4
Av.			4.11	5.33	5.33	3.9	7.0	
900	10	1.85	11.0	11.3	12.1	3.7	2.0	0.006
900	10	1.21	12.1	12.0	12.2	3.8	4.0	0.006
900	10	1.06	12.7	12.6	12.9	5.5	4.0	0.006
Av.			11.9	11.9	12.4	4.3	3.3	
900	100	1.30	12.0	12.2	12.6	6.7	5.0	0.005
900	100	1.32	11.3	12.0	12.0	6.6	5.0	0.006
Av.			11.7	12.1	12.3	6.7	5.0	
900	1800	0.000076	1.30	1.70	1.75	1.7	3.5	94
900	1800	0.000066	1.10	1.61	1.65	1.7	3.0	84
900	1800	0.000030	0.60	1.12	1.13	1.5	2.0	80
Av.			1.00	1.48	1.51	1.6	2.8	
900	1800	0.0150	3.25	4.78	4.78	4.2	7.5	0.4
900	1800	0.0130	3.39	5.02	5.02	5.4	7.0	0.4
Av.			3.32	4.90	4.90	4.8	7.3	
900	1800	1.44	10.9	10.7	11.6	4.2	2.5	0.006
900	1800	1.02	10.3	10.4	10.8	5.0	2.5	0.005
900	1800	1.0[2]	10.4	10.3	11.2	3.7	1.5	0.005
Av.			10.5	10.5	11.2	4.3	2.2	

1. Quenched.
2. Nominal strain rate; timing signal illegible.
3. Stress-strain curve defective in elastic region.