NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3727

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SUMMARY

The relationships between conditions of hot-working and properties at high temperatures and the influence of the hot-working on response to heat treatment were investigated for an alloy containing nominally 20 percent chromium, 20 percent nickel, 20 percent cobalt, 3 percent molybdenum, 2 percent tungsten, and 1 percent columbium. Comercially produced bar stock was solution treated at 2,200° F to minimize prior history effects and then rolled at temperatures of 2,200°, 2,100°, 2,000°, 1,800°, and 1,600° F. Working was carried out at constant temperature and with incremental decreases in temperature simulating a falling temperature during hot-working. In addition, a few special repeated cyclic conditions involving a small reduction at a high temperature followed by a small reduction at a low temperature were used to study the possibility of inducing very low strengths by the extensive precipitation accompanying such procedures. Most of the rolling was done in open passes with a few check tests being made with closed passes. Reductions up to 40 percent were used, with some conditions carried to as high as 65 percent. Heat treatments at both 2,050° and 2,200° F subsequent to working were used to study the influence on response to heat treatment.

The evaluation of the effects of rolling was based on rupture tests at 1,200° and 1,500° F, on creep rates during the rupture tests, and on creep rates for stresses of 25,000 psi at 1,200° F and 8,000 psi at 1,500° F. Hardness, microstructures, and lattice-parameter measurements were used to obtain data explaining the metallurgical factors responsible for the observed effects on properties at high temperatures.

The results explain many of the observed variations in properties for the hot-worked condition. Limited isothermal deformations increase strength. Larger reductions either do not increase strength or cause a decrease. Thus, high-production processes, giving large reductions at essentially constant temperature, lead to low or medium strength in the hot-worked condition. Working over a falling-temperature range with finishing temperatures of 1,800° F or higher can give very high strengths at 1,200° F, equal to those usually obtained only by hot-cold-work. Repeated reduction with low reheat temperatures leads to very low

strengths. Hardness does not correlate with strengths because hardness can continue to increase while strengths fall off for more than optimum reduction. Ductility in the rupture tests at 1,500° F was very sensitive to amount of reduction. Very uniform response to heat treatment was obtained, suggesting that variable response when it occurs may be mainly due to unidentified heat-to-heat differences.

The variations in strength in the hot-worked condition appear to be due to working having both a strengthening and a weakening effect on the structure of the alloy. Strengthening apparently was mainly due to strain-hardening. Recrystallization when it occurred had a weakening effect. It suggests that weakening in the absence of recrystallization is due either to the same structural changes from rolling which induce recrystallization at the higher temperatures or to a recovery process similar to recrystallization, possibly the formation of substructures in the grains. Working over a falling-temperature range allows more strengthening of the type effective at 1,200° F for a given reduction.

Considerable precipitation occurs during working from 1,600° to 2,000° F, particularly at 1,800° F. This appears to be detrimental to long-time strength at 1,200° F but to have little effect at 1,500° F because of extensive further precipitation during testing at 1,500° F. Temperature of working has a substantial effect on properties at 1,200° F, apparently because of the effects of the precipitation reaction. It also had considerable influence on ductility in the rupture test at 1,500° F.

There were a number of striking relations between conditions of working and properties at high temperatures. For working at constant temperature, maximum rupture strengths at 1,200° F were obtained for 15-percent reduction. This was probably true for temperatures from room temperature to 2,100° F. In addition, if it were not for the influence of the high-temperature precipitation reaction, the strengths would apparently be nearly constant. Constant maximum rupture strengths were obtained at 1,500° F for isothermal working from 1,600° to 2,200° F, but the optimum reductions were not constant. Maximum creep resistance was generally associated with smaller reductions than was maximum rupture strength.

Lattice parameters varied markedly with conditions of working and with cooling rate for reasons which are not understood. Grain size in itself did not appear to be a controlling factor.

Because of the limitations of the experimental conditions there are a number of limitations to the generality of the results.

INTRODUCTION

The investigation covered by this report consisted in studying by controlled experiments the principles governing the influence of hot-working conditions on the high-temperature properties of one type of heat-resistant alloy in the hot-worked condition and the influence of such hot-working conditions on response to subsequent final heat treatments. The study applies mainly to those complex austenitic heat-resistant alloys dependent on solution treatment or hot-cold-work for properties at high temperatures and not on strong age-hardening reactions.

The composition of the particular alloy used was nominally 0.15 percent carbon, 20 percent chromium, 20 percent nickel, 20 percent cobalt, 3 percent molybdenum, 2 percent tungsten, 1 percent columbium, and the balance iron. Working was carried out at several constant temperatures to define the influence of amount of reduction at a given temperature. Specific reductions at specific temperatures over a range of decreasing temperatures were used to study the influence of working over the usual falling-temperature range. Additional limited studies were made to establish the effects of possible heating and working schedules involving reheats to temperatures below and in the resolution range with reductions at low temperatures where extensive precipitation occurs. In addition, samples were given typical final solution, solution and aging, and solution and hot-cold-working treatments for the purpose of studying the effects of prior working on response to heat treatment.

At least two general factors influence the properties of individual alloys of the type investigated at high temperatures. First, various final treatments may be used to obtain specific properties. These can range in wrought products from the hot-worked condition with no subsequent treatment through so-called stress-relieving, solution treatments at various temperatures with or without subsequent aging treatments and, for the type of alloy considered, possibly cold-work or hot-cold-working operations after the other treatments. The other general factor leading to variability in properties arises from the variation in properties with specific final treatments. Recognized possible sources of the latter type of variation include the influence of conditions of hot-working on the response to final treatments, variations in chemical composition, and unidentified heat-to-heat differences.

Properties in the hot-worked condition are considered to be difficult to control. Practical limitations in the reproducibility of conditions of working as well as lack of information regarding the influence of the conditions of working are involved. It is known that both very high and very low strengths are observed in hot-worked products not subjected to further treatment as well as intermediate values of strength.

No completely reliable means of predicting the level of properties was available. Certainly microstructure or hardness and other normal short-time mechanical-property tests do not reliably predict creep and rupture values. No information was available regarding the influence of amount and temperature of reduction on properties. Likewise, there was no good information on the degree of influence of the hot-working conditions on response to the usual final treatments as reflected in the property ranges for a specific final treatment.

Extensive previous studies had been carried out for the National Advisory Committee for Aeronautics on the same alloy as that used for the present investigation to establish the influence of various types of treatment on the properties at high temperatures. The primary objective of these studies had been to determine the basic fundamental causes for variation in properties at high temperatures. It had been found that the creep and rupture strengths were primarily functions of the degree of solution of odd-sized alloying atoms in solid solution and the degree of strain-hardening present from working the metal. So far as could be ascertained, precipitation reduced creep strength as measured by secondary creep rates only by removal of odd-sized atoms from solution. Increases in rupture strength from precipitation appeared to be due mainly to increased deformation before fracture occurred and some reduction in creep rates during primary creep. These latter effects increased rupture strength only at relatively short times for rupture (high stress levels) where their influence predominated over lowered secondary creep resistance. Strain-hardening increased creep and rupture strengths up to the point where recovery effects occurred during testing because of excessive cold-work for structural stability.

A major objective of the present investigation was to explain the observed variation in properties at high temperatures due to working conditions at high temperatures in terms of fundamental concepts. Detailed microstructural studies were carried out to define the structural effects of hot-working. Hardness was used as a measure of strain-hardening effects. X-ray diffraction studies were instituted with the expectation of being able to study the degree of solution of odd-sized atoms from the alloying elements.

The research was conducted by the Engineering Research Institute of the University of Michigan under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics as part of an investigation of the fundamental metallurgy of heat-resistant alloys of the types used in propulsion systems for aircraft.

EXPERIMENTAL PROCEDURES

Although there are numerous methods for hot-working metals and alloys, such as rolling, forging, extruding, and pressing, this investigation was limited to rolling. By rolling, it was relatively easy to control working variables such as temperature and amount of deformation with reproducible rates of deformation. Bar stock was selected for the experimental material as the best compromise between convenience for manipulation and minimizing temperature variation during working. This investigation was restricted to two of the most important variables, rolling temperature and amount of reduction. The rate of compression during rolling was kept as nearly constant as possible by keeping the roll speed, roll diameter, and initial cross-sectional area of the stock constant.

In this report the term "hot-working" refers to all working carried out in the temperature range usually associated with the hot-working of complex, heat-resistant alloys, irrespective of whether or not recrystallization occurs. Technically, the term "hot-working" should refer only to working at or above the simultaneous recrystallization temperatures. In commercial practice hot-working is often carried out over a falling-temperature range. Although the starting temperature may be well above the minimum temperature required for recrystallization, the finishing temperatures can be so low that no recrystallization takes place during the latter stages of working. In such cases, despite some recovery or stress relief, the metal is partially strain-hardened or cold-worked.

The research program was organized as follows:

(1) Stock was isothermally rolled varying amounts at temperatures ranging above and below the minimum temperature of recrystallization during rolling.

(2) Stock was nonisothermally rolled over controlled temperature ranges to provide a basis for determining how decreasing temperatures during hot-working influenced the high-temperature strengths.

(3) Stock was cyclicly rolled over three temperature ranges to determine the influence of extensive precipitation during working to very low temperature on the properties at elevated temperatures.

(4) Heat treatment was carried out after selected conditions of rolling to determine if the influence of hot-working was reflected in the response to heat treatment.

(5) Rupture and creep tests, hardness measurements, microstructural examinations, and lattice-parameter measurements were made after the various hot-working operations to obtain information for studying the mechanism by which hot-working affects high-temperature properties.

Material

The material used in this investigation was 7/8-inch bar stock from a commercial heat of an alloy having the following chemical analysis:

Chemical composition, percent

C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	N	Fe
0.13	1.63	0.42	21.22	19.00	19.70	2.90	2.61	0.84	0.13	Bal.

The bar stock was produced from a 13-inch billet. The commercial processing details are given in the appendix.

The same lot of bar stock had been utilized in other fundamental studies on the same type of heat-resistant alloys at the University of Michigan (refs. 1 to 3). It was expected that the data from these prior studies, concerned with the influence of heat treatment and cold-working on high-temperature strength, would simplify arriving at general principles.

All stock was solution treated for 1 hour at 2,200° F and then water quenched before rolling to minimize the effects of the prior working.

Rolling

After the solution treatment at 2,200° F the bar stock was rolled at temperatures of 2,200°, 2,100°, 2,000°, 1,800°, and 1,600° F. The conditions of hot-rolling carried out are summarized in figure 1. Most of the specimens were rolled in open passes on a two-high, single-pass, nonreversible mill with 5-inch rolls. Both rolls were power driven and revolved at a speed of 70 rpm. No lubricant was used on the rolling surface.

For rolling temperatures of 1,800° F and above, an automatically controlled gas-fired furnace holding temperatures to within ±5° F was used. An automatically controlled electric muffle furnace was used for temperatures below 1,800° F.

Cooling curves from the various rolling temperatures showed the maximum temperature drop during rolling to be 50° F. Because such temperature changes vary for any particular hot-working operation, it was decided to heat to a slightly higher temperature than the desired temperature so that the results could be expressed in terms of the average actual metal temperature. Consequently, the stock was heated to 25° F above the rolling temperature. A holding time of 1/2 hour before rolling established thermal equilibrium between the furnace and bars. The initial bar lengths were chosen to give a final length after rolling of 12 inches. All reductions were based on the original cross-sectional area.

The rolling procedure for making reductions up to 15 percent at 1,600° F and up to 25 percent from 1,800° to 2,200° F was to pass the bar through the rolls twice for a given roll setting, turning the bar 90° between passes. Reductions of 25 percent at 1,600° and 40 percent at 1,800° F and above could not be made in a single roll setting because of the limitations of the rolling mill. Consequently, for these reductions the stock was first rolled 10 percent at 1,600° F or 15 percent at 1,800° F and above, reheated for 5 minutes, and then reduced an additional 15 percent at 1,600° F or 25 percent at 1,800° F and above. A 40-percent reduction at 1,600° F required successive reductions of 10, 15, and 15 percent with two 5-minute reheats. A reduction of 65 percent required successive reductions of 15, 15, 15, 10, and 10 percent with four reheats. All bars were air cooled after the final reductions.

Rather approximate procedures, in comparison with actual practice, where temperatures probably fall continuously during working, were used to simulate working on a falling-temperature range. These were dictated by the need to know as exactly as possible the actual temperatures and amounts of reduction. Rolling over a temperature range involved the following procedure: For rolling first at 2,200° F and then finishing at 2,000° F, the bars were rolled initially 15 percent at 2,200° F; replaced in the furnace, which cooled in 6 minutes for rolling at 2,000° F; and then reduced an additional 25 percent. Two furnaces were used for rolling first at 2,200°, 2,000°, or 1,800° F and then reducing again at 1,800° or 1,600° F. The bars for these series were first heated to the initial rolling temperature in the established manner, rolled, and then immediately placed in the second furnace which was maintained at the desired lower rolling temperature, cooled to that temperature in the furnace, and given the second reduction. One series of bars was rolled 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F, giving a total reduction of 40 percent. For this series the gas-fired furnace was used for cooling between 2,200° and 2,000° F and the electric furnace was used for temperatures of 1,800° and 1,600° F.

In these experiments involving one or more reductions at successively lower temperatures, a dummy bar with a thermocouple inserted into the center along the longitudinal axis was used to determine when the stock was at the proper rolling temperature. Measurements with the dummy bar indicated that a period of 6 minutes was sufficient to reach the desired temperature for all temperature intervals.

An unusual and complex series of reductions was carried out to check the effect of precipitation during rolling on the high-temperature strength of the alloy. One group of bars in this series was rolled as follows: Heated to 1,800° F, held 1/2 hour, rolled 5 percent, cooled to 1,500° F, rolled 5 percent, held 2 hours, and then reheated to 1,800° F, with the cycle repeated three more times to give a total of 40-percent reduction. The two other groups of bars in this series were rolled in the same way except that the rolling temperatures were 2,000° and 1,500° F and 2,200° and 1,500° F, respectively.

In order to check the uniformity of working over the cross-sectional area, hardness surveys were made across the transverse sections of selected bars rolled between 5 and 25 percent. Vickers hardness tests (50-kilogram load) were used for these surveys. Likewise, six bars from each of three rolling conditions were checked for hardness to see if there were any pronounced variations in the hardness of similarly rolled bars. No variations were found in either case.

In the open-pass rolling the roll speed, roll surface, and initial size of the stock were kept the same throughout the investigation. This was done in order to keep variations in the compression rate nearly the same. However, by varying the amount of reduction, the compression rate during rolling was also varied. Although variations in compression rate have little effect on strain-hardening during cold-working, they do have an effect during hot-rolling.

A small amount of closed-pass rolling was done to study the relative influence of a change in the mode of deformation during rolling. That is, rolling in closed passes eliminated the lateral spread which occurred during open-pass rolling.

The closed-pass work was done on a large reversing mill recently installed at the University of Michigan and equipped with rolls $9\frac{1}{2}$ inches in diameter and 27 inches long. The roll speed used was 30 rpm. Reductions of 15 and 25 percent at 1,800° and 2,000° F and of 65 percent at 1,800° F were made in closed passes. The rolling procedure was the same as that described above for open-pass rolling with the exception that the stock was passed through the rolls only once for the 15- or 25-percent reductions. The 65-percent reduction at 1,800° F was made using a series of 7/8-, 3/4-, 5/8-, and 1/2-inch-square passes. These square passes were separated from one another by oval passes. Six reheats were required.

Prior to rolling 15 or 25 percent in a closed pass, the bars were machined to an initial size such that, after they were put through the 3/4-inch pass, the desired reduction was obtained.

The actual reductions after rolling for both open and closed passes in no instance differed by more than 2 percent from the desired reductions.

Rupture and Creep Tests

Both rupture and creep tests were used to evaluate the experimental variables. Testing temperatures of 1,200° and 1,500° F were used to cover the temperature range in which the type of alloy is widely used.

The effect of all rolling conditions on rupture and creep strength in the hot-worked condition was determined. Stress-rupture tests were of sufficient duration to establish the rupture strengths for 100 and 1,000 hours. The creep tests of 1000-hour duration were conducted at 1,200° F under 25,000-psi stress and at 1,500° F under 8,000-psi stress. Creep data were also established for the rupture tests. Minimum creep rates were used to evaluate the effects of variables on creep resistance.

Conventional beam-loaded units were used for both creep and rupture tests. The test specimens machined from the bar stock were 0.250 inch in diameter with a 1-inch gage length. Accurate measurements were made on all specimens prior to testing. Time-elongation data were taken during the rupture tests by a method in which movement of the beam was related to the extension of the specimen. Modified Martens-type extensometers with a sensitivity of ±0.00002 inch were used to obtain time-elongation data for the creep tests. Reynolds, Freeman, and White (ref. 4) found that there was good agreement between creep rates from the two types of deformation measurements. The creep and rupture units were equipped with automatically controlled electric resistance furnaces. Temperature variations along the gage length of the specimens were held to less than 3° F. The loading practice followed was to bring both specimen and furnace up to within 100° F of the testing temperature overnight. In the morning the unit was brought up to temperature and then loaded.

Several check creep tests were run during this investigation, as noted in the tabulations of the experimental data, and the corresponding creep rates checked within ±0.00003 percent per hour.

Hardness

Hardness was intended to be used as a measure of strain-hardening during hot-working. It is recognized that certain variations in hardness resulted from precipitation. However, for any given rolling temperature the change in hardness with amount of reduction was primarily a function of the strain-hardening.

Hardness measurements were made at the center of transverse sections cut from all specimens after rolling. A Brinell hardness machine with a 10-millimeter ball and a 3,000-kilogram load was used.

Lattice Parameters

The intent was to use lattice-parameter variations as a measure of the extent to which odd-sized atoms from the alloying elements remained in solution after rolling.

A minimum of 0.03 inch was removed from the surface of samples in an electrolytic polisher in order to insure a surface free of preparation strains. An electrolyte consisting of one-third concentrated hydrochloric acid and two-thirds glycerin was used. The parameter measurements were made using a high-precision symmetrical focusing camera. Cohen's method (ref. 5) was used to compensate for uniform shrinkage of film and camera radii errors. Several check tests were run and the reproducibility was determined to be within 0.0005 angstrom unit.

For the most part, the measurements were made on surfaces transverse to the rolling direction. However, several measurements were also made on surfaces either parallel to or at 45° to the rolling direction to check for possible orientation effects.

Microstructural Studies

Sections parallel to the rolling axis were cut from all bars after rolling and prepared for metallographic examination. All specimens were electrolytically etched in 10 percent chromic acid solution.

In addition to the examination of the structures of the variously rolled bars, extensive studies were made on completed creep specimens.

RESULTS

The results of the experimental studies are presented separately for isothermal rolling, rolling and falling temperatures, special cyclic conditions of rolling, and response to heat treatment. The influence of conditions of rolling was evaluated through determination of rupture and creep properties at 1,200° and 1,500° F, hardness values, microstructures, and lattice parameters. All testing was carried out on hot-worked material except for that involving the influence of working conditions on response to heat treatment.

Attention is directed to the fact that in each case the hot-working was carried out starting with 7/8-inch-square bar stock that had been heated 1 hour at 2,200° F and water quenched. The stock had been commercially produced from a large arc furnace ingot.

Isothermal Rolling

The data reported in this section are for the as-rolled condition for rolling at constant temperature. Tables I through IV and figures 2 through 19 present the rupture and creep data. Hardness data are included in table V and figure 20. Typical microstructures are shown by figures 21 through 27. Lattice-parameter data are in table VI and are illustrated by figures 28 through 32.

Rupture properties at 1,200° F.- The influence of amount of reduction and temperature of rolling on the rupture properties at 1,200° F was as follows:

(1) A reduction of approximately 15 percent resulted in maximum rupture strength for both 100 and 1,000 hours for rolling temperatures of 1,600° to 2,100° F (see figs. 2(a) through 6(a)). Reductions between 0 and 40 percent at 2,200° F had no significant influence on the rupture strengths (fig. 2(a)).

(2) The influence of temperature of reduction on rupture strengths is summarized by figure 7(a). The maximum strengths at 15-percent reduction increased as the rolling temperature was reduced from 2,200° to 2,000° F. Lowering the rolling temperature to 1,800° and 1,600° F increased the strength for 100 hours slightly more but resulted in a decrease in 1,000-hour strength. The loss in strength by larger reductions was nearly constant at each temperature so that the curves for 40-percent reduction (fig. 7(a)) were nearly parallel to the 15-percent-reduction curves. The only exception was for 1,000 hours at 1,600° F where strength continued to increase slightly.

(3) Simply heating to the rolling temperatures had little effect on rupture strength, except for a significant lowering of strength for 2,100° F, as is shown by the 0-percent-reduction curve of figure 7(a). Rolling increased rupture strength above that resulting from simply heating alone to the rolling temperature in all cases except for 2,200° F.

Certainly reductions larger than 65 percent at the other rolling temperatures would be required to reduce strength below that for material heated for 1/2 hour without reduction.

(4) The maximum rupture strengths after reduction were from 7,000 to 10,000 psi higher than those for specimens heated without reduction at 2,100° to 1,600° F. The range in 100-hour strengths was from 42,000 to 57,000 psi, with one lower value of 38,500 psi resulting from heating at 2,100° F without reduction. The corresponding range for 1,000-hour strengths was 37,000 to 47,000 psi, again with a low value of 33,000 psi for heating to 2,100° F.

(5) No significant difference between rupture strengths for material rolled in open and closed passes was found for a limited number of samples rolled at 1,800° and 2,000° F. (See tables II and IV and figs 4(a) and 5(a).)

(6) Increasing reductions at 2,200° and 2,100° F increased elongations for fracture in 100 and 1,000 hours from as low as 5 percent to as high as 18 percent (figs. 9 and 10). Rolling to increased reductions at 2,000° and 1,800° F first lowered and then increased elongations (figs. 11 and 12). The increase at larger reductions was not observed in stock rolled at 1,600° F (fig. 13). It should be noted that simply heating to these latter three temperatures increased elongations relative to those of the stock originally solution treated at 2,200° F. Minimum elongations in both 100 and 1,000 hours were in the order of 5 percent for all conditions of rolling.

The rupture-test elongations for material rolled in closed passes at 1,800° and 2,000° F agreed perfectly with those for open passes, except for higher elongation after a 25-percent reduction at 2,000° F for the closed-pass material. (Cf. tables II and IV.)

Creep properties at 1,200° F.- The relations between minimum creep rate at 1,200° F for stresses of 50,000 and 25,000 psi and percent reduction at the rolling temperatures, as presented in table II and figures 15 and 16, show that:

(1) Increasing amounts of reduction first increased creep resistance (reduced minimum creep rates) to a maximum for a limited amount of reduction. Creep resistance then fell off for larger reductions.

(2) The amount of reduction giving maximum creep resistance (fig. 19(a)) varied with both the rolling temperature and the testing stress. For a stress of 50,000 psi this reduction was 15 percent, except at 2,200° and 1,800° F. For the lower stress of 25,000 psi, the reduction ranged from 5 to 15 percent with the largest reduction being required at 2,000° and 2,100° F. The influence of reduction on creep

resistance under 50,000-psi stress was similar to its influence on the rupture strengths, except for the higher reductions at 1,800° F. Except for rolling at 2,000° to 2,200° F, less reduction was required for maximum creep resistance under 25,000-psi stress.

(3) Rolling at 1,600°, 1,800°, and 2,000° F gave similar but definitely higher creep resistance for 25,000-psi stress (fig. 16) than did rolling at 2,100° and 2,200° F. Creep resistance, however, fell off considerably with increased reductions past those giving maximum resistance for all temperatures of rolling. At the higher stress of 50,000 psi (fig. 15), the decrease in creep resistance past the maximum was much less after rolling at the three lower temperatures than for 2,100° and 2,200° F. The material rolled at 2,000° F, however, was considerably weaker than the materials rolled at 1,600° and 1,800° F.

(4) The creep resistance after rolling in closed passes (tables II and IV), with the exception of the somewhat low strength of the stock rolled 65 percent at 1,800° F, agreed well with the creep resistance of bars rolled corresponding amounts in open passes.

(5) The creep resistance of stock heated from 1,600° to 2,100° F for 1/2 hour without rolling (figs. 15 and 16) was lower for both 50,000- and 25-000-psi stress than the creep resistance of the material heated to 2,200° F for 1/2 hour. Heating to 1,800° F lowered creep resistance the most.

(6) Isothermal reductions from 5 to 25 percent at 1,800° and 1,600° F and from 5 to 15 percent at 2,000° F eliminated first-stage creep during the 1,000-hour creep tests under 25,000-psi stress. Larger reductions resulted in the reappearance of the first-stage component. Creep tests on all the specimens rolled at 2,100° F had a first-stage component. There was no first-stage component during the 1,000-hour creep tests involving specimens previously reduced 5 to 15 percent at 2,200° F. However, reductions in excess of 15 percent at 2,200° F did result in a first-stage creep component.

Rupture properties at 1,500° F.- The major features of the data for rupture properties at 1,500° F can be summarized as follows:

(1) A specific reduction gave the highest rupture strength at 1,500° F for each rolling temperature (figs. 2(b) through 6(b)). These reductions were the same for both 100 and 1,000 hours (fig. 8) and continually increased as the rolling temperature was lowered from 2,200° to 1,600° F. There was no appreciable difference in the maximum strength (fig. 7(b)) with rolling temperature at either 100 or 1,000 hours.

(2) Although there were no variations with rolling temperature in the maximum rupture strengths, there were pronounced differences at each

temperature between the maximum strength and the strengths produced by both larger and smaller reductions (see fig. 7(b)). The largest variation in strength for open-pass rolling resulted from rolling at 1,800° F where the maximum and minimum 100-hour strengths were 21,500 and 14,000 psi, respectively. Corresponding values for 1,000 hours were 16,000 and 7,500 psi. The lowest values obtained were for a closed-pass reduction of 65 percent at 1,800° F which yielded values of 10,500 and 5,700 psi, respectively, for 100 and 1,000 hours.

(3) Many conditions of working resulted in lower strength than did heating to the working temperature without reduction (fig. 7(b)) or solution treatment at 2,200° F. This is in contrast with the data for 1,200° F where improved strength resulted for all reductions considered.

(4) Heating to the rolling temperature without reduction had little effect on strength at 1,500° F, as is shown by the curves for 0-percent reduction in figure 7(b). An exception was the low 1,000-hour strength after heating at 1,800° F.

(5) The rupture strengths after rolling in closed passes (tables II and IV and figs. 4(b) and 5(b)) agreed well with those for open passes for reductions of 15 and 25 percent at 1,800° F and 15 percent at 2,000° F. A reduction in closed passes of 25 percent at 2,000° F gave somewhat higher strengths and of 65 percent at 1,800° F gave somewhat lower strengths than those for the corresponding reductions in open passes.

(6) Conditions of rolling had very pronounced effects on elongation in the rupture tests at 1,500° F (figs. 9 through 13). The elongations at 100 hours varied between 4 and 60 percent and those at 1,000 hours, from 5 to 41 percent. The relations involved were:

(a) The elongation decreased with increasing amounts of reduction to minimum values and then tended to increase with further reduction.

(b) The differences in elongation for heating with no reduction and the reduction giving minimum elongation (fig. 14) became very large at temperatures below 2,200° F. Pronounced increases in elongation resulting from simply heating the stock originally solution treated at 2,200° F were removed by subsequent working. The effect was much greater at 100 hours than at 1,000 hours. For instance, heating to 1,800° F resulted in an elongation at 100 hours of 57 percent, whereas the same material reduced 40 percent at 1,800° F had an elongation of only 4 percent. At 1,000 hours the corresponding values were 25 and 5 percent.

(c) Reductions for minimum elongation at each rolling temperature (fig. 14) ranged from 15 to 40 percent at 100 hours and were 15 percent at all temperatures for 1,000 hours. Actually, rather low values were associated with reductions of 15 to 40 percent at all rolling temperatures.

(d) There are reductions at all temperatures which give rather low elongations and less or more reduction resulted in increased elongation. Reference to figures 9 through 13 shows that high elongation is particularly associated with large reductions at 2,100° and 2,200° F. The increase with large reductions was much less at the lower temperatures.

(e) The limited data for closed-pass rolling (table IV) indicate the same general influence of hot-working on elongation in the rupture tests. The differences resulting from open- and closed-pass rolling were no greater than the degree of scatter which might be expected where ductility varies so rapidly with conditions.

Creep properties at 1,500° F.- The variations in creep data at 1,500° F can be summarized as follows:

(1) There was an optimum reduction (figs. 17 and 18) at each rolling temperature resulting in the highest creep resistance at 1,500° F. This optimum reduction increased slightly as the rolling temperature was lowered (fig. 19(b)) and was generally somewhat less for the tests at 8,000 psi than for those at 15,000 psi.

(2) The loss in creep resistance for reductions greater than those producing the maximum was generally quite rapid, particularly at 8,000 psi. These larger reductions generally resulted in considerably lower creep resistance than that for material simply heated without reduction. There was some indication that for very large reductions the creep resistance approached a minimum.

(3) The creep resistance of stock rolled 15 and 25 percent at 1,800° or 2,000° F in closed passes (table IV) agreed well with the creep resistance of the bars rolled corresponding amounts in open passes (table II). However, the creep resistance at 8,000 psi of stock rolled 65 percent at 1,800° F in closed passes was low.

(4) The minimum creep rates for an initial stress of 15,000 psi ranged from 0.002 to 0.13 percent per hour as the result of varying the rolling temperatures from 2,200° to 1,600° F and the percent reduction from 0 to 65 percent. Over the same ranges of rolling temperatures and reductions the minimum creep rates for an initial stress of 8,000 psi varied from 0.00003 to 0.024 percent per hour.

(5) The creep resistance at 1,500° F of the stock heated at 1,600° to 2,100° F for 1/2 hour without rolling was lower for both 15,000- and 8,000-psi stress than that of the bar stock heated to 2,200° F for

1/2 hour. Heating, as well as reduction, affected the creep resistance with the maximum effect at 1,800° F.

(6) Reductions from 0 to 40 percent at 1,800° and 1,600° F slightly decreased the first-stage component of creep in the 1000-hour creep tests under a stress of 8,000 psi in comparison with that of the original stock. The reduction of 65 percent at 1,800° F resulted in both a substantial increase in the first-stage component and the appearance of a third-stage component. Reductions at 2,200° to 2,000° F did not decrease first-stage creep.

Hardness.- Brinnel hardness measurements were made after all conditions of rolling and the results are tabulated in table V. Figure 20 presents the relationship between Brinell hardness and amount of isothermal reduction in open passes at rolling temperatures ranging between 1,600° and 2,200° F. The essential features of the hardness data can be summarized as follows:

(1) Hardness started to increase with percent reduction at all temperatures. However, there was a rapid drop in hardness after the reduction reached 7 percent at 2,200° and 10 percent at 2,100° F. Little further increase was obtained for more than 15-percent reduction at 2,000° F. All reductions at 1,800° and 1,600° F increased hardness, the amount of increase decreasing with increased reduction. When the bars were reduced at 2,200° and 2,100° F, minimum hardness was obtained for reductions of 12 to 15 percent followed by a slight increase and again a decrease for more reduction.

(2) The Brinell hardness of the bars rolled 15 or 25 percent in closed passes at either 2,000° or 1,800° F agreed well with that of the corresponding bars rolled in open passes. The hardness of the bar rolled 65 percent in closed passes at 1,800° F was substantially lower than that of the corresponding bar rolled in open passes.

(3) The overall levels of the various hardness curves in figure 20 were influenced by the heating temperature alone, as evidenced by the increases in the hardness of stock simply heated to the rolling temperatures and cooled without rolling.

Influence of rolling conditions on microstructures.- Typical microstructures of the bars given various reductions at 1,600°, 1,800°, 2,000°, and 2,200° F are shown in figures 21 through 24, respectively. The changes in microstructure during rolling can be summarized as follows:

(1) Recrystallization occurred during rolling at 2,200°, 2,100°, and 2,000° F depending on the amount of reduction. Recrystallization

was not observed during open-pass rolling at 1,800° or 1,600° F. It did occur during the 65-percent reduction in closed passes at 1,800° F.

(2) The observed conditions of recrystallization were as follows:

(a) At 2,200° F: Started at 5- to 7-percent reduction; essentially complete at 15-percent reduction; continued refinement of grain size with further reduction

(b) At 2,100° F: Started at 10-percent reduction; essentially complete at 15-percent reduction; continued refinement with further reduction

(c) At 2,000° F: Started at 15-percent reduction; required a reduction of 65 percent for complete recrystallization

It will be noted that the discontinuities in the hardness curves of figure 20 correspond with the observed recrystallization characteristics.

(3) A finely dispersed precipitate formed in the matrix when the alloy was previously solution treated at 2,200° F and then heated to 1,800° or 2,000° F for 1/2 hour. Increasing the amount of reduction of these temperatures appeared to increase the amount of precipitation in the matrix. Previous to this investigation it was not known that this alloy was subject to precipitation in the matrix between 1,800° and 2,000° F. Even rolling at 2,200° F appeared to cause a dispersed precipitate to form in grain boundaries.

(4) A matrix precipitate did not form in the bar stock during the 1/2-hour heat at 1,600° F, although a grain-boundary precipitate did form. Moreover, there was no visible evidence of any general precipitation in the matrix during rolling at 1,600° F.

Microstructures after creep testing.- Metallographic examination was made of the creep specimens after testing for 1,000 hours in order to obtain information on the structural stability of the stock in the as-rolled condition during testing at 1,200° and 1,500° F. Figures 25 and 26 show microstructures of bar stock rolled at 1,600° and 2,200° F, respectively, and tested at 1,200° F. Figure 27 shows typical structures after testing at 1,500° F. The structural changes during creep testing are summarized as follows:

(1) Structural changes during testing at 1,200° F were largely dependent on the initial as-rolled condition of the bar stock. Extensive precipitation took place in the matrix during testing provided precipitation had occurred during rolling. The precipitation was much less after rolling at 2,200° or 2,100° F where little precipitation occurred during rolling. Rolling at 1,600° F, however, apparently

resulted in nucleation of precipitates during testing, inasmuch as extensive precipitation occurred even though only grain-boundary precipitation was evident after rolling. The structure, after testing, of the material rolled at 1,800° and 2,000° F was similar to that of the material rolled at 1,600° F. In cases where matrix precipitation did occur during testing at 1,200° F, it appeared to increase with increasing amounts of rolling.

(2) The structural changes which occurred during creep testing at 1,500° F appeared to be largely independent of the initial conditions of the microstructure. That is, extensive precipitation and agglomeration occurred in all bars during testing and all structures were remarkably similar after testing.

Lattice-parameter measurements.- Lattice-parameter measurements are tabulated in table VI. Although measurements were possible over the complete range of reductions at temperatures of 2,000° F and above, determinations could be made for only the 0-, 5-, 10-, and 40-percent reductions at 1,800° F. The diffraction lines were too diffuse for all other reductions at 1,800° F and for all reductions at 1,600° F. Check measurements were made in some cases and these are also given in table VI. Most determinations were carried out on surfaces transverse to the direction of rolling with some check measurements being made on surfaces at other angles to the rolling direction.

The influence of amount and temperature of reduction on lattice parameters (figs. 28, 29, and 30) was fairly complex. Successive minimum and maximum values appeared as the amount of reduction was increased. The amount of reduction required to produce these effects increased as the rolling temperature was reduced.

A measurement made on stock reduced 35 percent at 2,000° F without reheating is plotted on the curve (fig. 28) intermediate between the values for reductions of 25 and 40 percent. This indicated that the reheating for the 40-percent reduction was not the cause of the rapid increase in parameter when the reduction was increased from 25 to 40 percent. This conclusion is further substantiated by a similar behavior at 2,100° and 2,200° F within the reduction range where reheats were not used.

The agreement between measurements made transverse to the rolling with the check determinations at other angles (fig. 28) indicates that any orientation effects were small.

During the course of the investigation it was established that cooling rate had a pronounced effect (figs. 31 and 32) on the measured lattice parameter. Air-cooling resulted in larger parameters than did water-quenching. Limited data for a range of cooling rates from 2,025° F show that intermediate cooling rates resulted in larger parameters. That is, air-cooling resulted in larger values than did either very slow or very rapid cooling (fig. 32). The temperatures used for these studies were the same as those for heating for rolling, 25° F above the nominal rolling temperature. The use of the cooling rate at 1,200° F for preparing figure 32 was simply a matter of convenience for measurements of the rates. This defined cooling-rate effects somewhat better than would a description of the method of cooling alone.

Rolling With Falling Temperatures

Specimens were prepared by nonisothermal rolling over controlled temperature ranges to obtain data to investigate how the decreasing temperatures during hot-working influenced high-temperature strengths. Experiments were confined to combinations of reductions totaling 40 percent. The initial rolling temperatures varied from 1,800° to 2,200° F.

<u>Rupture properties at 1,200° F</u>.- Rolling first at 2,200° or 2,000° F and then at 2,000°, 1,800°, or 1,600° F for a total reduction of 40 percent (tables VII and VIII) had the following effects on the rupture properties at 1,200° F:

(1) Very high strengths resulted from reduction at 2,200° or 2,000° F and then at 1,800° or 1,600° F. The strengths were considerably higher (fig. 33(a)) than those obtained by isothermal reductions of either 15 or 40 percent at 1,600° or 1,800° F.

(2) A reduction of 25 percent at 2,200° F followed by 15 percent at 2,000° F resulted in lower strength than did isothermal reductions of either 15 or 40 percent at 2,000° F (fig. 33(a)).

(3) Elongations (table VIII) were as high as or higher than those for comparative isothermally rolled materials. A reduction of 10 percent at all four temperatures gave both high strength and very high elongation.

<u>Creep properties at 1,200° F</u>.- The creep data at 1,200° F (table VIII) were similar to the rupture data in that finishing at 1,600° or 1,800° F gave high creep resistance, while finishing at 2,000° F gave comparatively low resistance (see fig. 34). The advantage of rolling first at 2,200° or 2,000° and finally at 1,600° or 1,800° F over isothermally rolling the bars was not so outstanding as it was in the rupture tests.

<u>Rupture properties at 1,500° F</u>.- Rupture strengths at 1,500° F (table VIII) increased as finishing temperature decreased (fig. 33(b)).

The strengths were, in general, higher than those resulting from reductions of 40 percent at constant temperature. They were, however, well below the maximum strengths associated with smaller isothermal reductions. The strengths were also less than those for isothermal reductions of 15 percent where these were less than the maximum values.

The rolling over a falling-temperature range, therefore, avoided part of the loss in strength associated with large reductions in constant-temperature rolling. The conditions used did not, however, produce higher strengths than those for specific constant-temperature reductions at 1,600° or 1,800° F, as was observed at 1,200° F. The relatively high strengths for reductions of 10 percent at each temperature of rolling suggest that a schedule of small reductions as temperature decreases might be beneficial to strength.

Rolling over a falling-temperature range did not markedly improve elongation in the rupture tests over that of isothermally rolled stock (tables II and VIII) except for the schedule of 10-percent reduction at each temperature. The material finished at 2,000° F may have been improved also. In all other cases, the elongations were similar to those of comparative isothermally rolled stock.

Creep properties at 1,500° F.- The creep resistance at 1,500° F (table VIII) increased as the finishing temperature was lowered (fig. 35). The values mostly ranged between those for isothermal rolling to reductions of 15 and 40 percent. Certain sequences gave strengths similar to those for the most creep resistant isothermal conditions, while the strengths of the material rolled 25 percent at 2,200° F followed by 15 percent more reduction at the lower temperatures tended to be similar to those of the material isothermally rolled 40 percent.

Hardness.- All of the conditions of rolling except one developed high as-rolled Brinell hardness values in the range of 272 to 283 (table V). The one exception was the material rolled between 2,200° and 2,000° F which had a Brinell hardness of 221. Except for this latter condition, the hardness values approached those obtained by isothermal reductions of 40 percent at the finishing temperature rather than those obtained isothermally with the actual final reductions.

Microstructures.- Examination of the structures after rolling (fig. 36) and after subsequent creep testing (fig. 37) gave the following results:

(1) Rolling at 2,200° F, before rolling at lower temperatures, reduced grain size by recrystallization. For this reason the grain sizes of the material subsequently rolled at 1,600° and 1,800° F were

finer than those of the material isothermally rolled at these temperatures. (Cf. fig. 36 with figs. 21 and 22.) The material rolled first at 2,200° and then at 2,000° F was very fine grained, indicating that recrystallization continued at the lower temperature. Rolling first at 2,000° F and then at 1,600° F resulted in a duplexed grain structure because recrystallization was incomplete during the reduction at 2,000° F.

(2) Samples rolled initially at 2,200° F and then at lower temperatures did not have the general matrix precipitation observed in samples isothermally rolled at 1,800° and 2,000° F. The precipitate was, however, present in material rolled initially at 1,800° or 2,000° F and finally at 1,600° F.

(3) After creep testing at 1,200° F (fig. 37) the structures showed little precipitation during testing for material initially rolled at 2,200° and finished at 1,600° or 1,800° F. In all other conditions the structures underwent considerable precipitation at 1,200° F. Structures of all samples tested at 1,500° F showed the same extensive precipitation and agglomeration described for the isothermally rolled stock. The only differences noted were the changes in grain size.

Special Cyclic Conditions of Rolling

Samples were prepared by cyclic reductions of 5 percent at 1,500° F and at three higher temperatures of 1,800°, 2,000°, and 2,200° F. Repeated reductions at the upper and lower temperature were used until a total reduction of 40 percent was obtained.

These cyclic reductions were investigated to study the possibility of producing abnormally low as-rolled strength by using conditions leading to extensive precipitation and agglomeration of precipitates. These conditions were approximated with a top temperature of 1,800° F. Top temperatures of 2,000° and 2,200° F were selected as being in and above the solution temperature range for the alloy. One of the main reasons for this work was the absence of abnormally low strengths for the isothermally and nonisothermally rolled materials. Such low strengths are sometimes observed in practice and the possibility of extensive precipitation by use of low working temperatures was explored as an explanation.

<u>Rupture and creep properties at 1,200° F.</u>- Cyclic rolling between 1,500° and 1,800° F resulted in lower rupture strength and higher elongation at 1,200° F than did rolling at upper temperatures of 2,000° or 2,200° F. (See tables IX and X and fig. 38(a).)

The material rolled between 1,500° and 1,800° F had strengths similar to those for the material simply heated to 1,800° F without reduction and considerably below any of those for the material rolled isothermally or with falling temperatures. (Cf. data in table X with tables II, IV, and VIII.) On the other hand, rolling 5 percent first at 1,500° and then at 2,000° and 2,200° F produced strengths much higher than those obtained under any condition of isothermal rolling at 2,000° or 2,200° F and approaching those obtained by 25-percent reduction at 2,000° or 2,200° F followed by 15-percent reduction at 1,800° or 1,600° F.

The cyclic rolling resulted in substantially higher elongations than were obtained by other conditions of rolling except the 10-percent reduction at 2,200°, 2,000°, 1,800°, and 1,600° F. (Cf. data in table X with tables II, IV, and VIII.)

Creep resistance was also much lower for the material cyclically rolled at 1,500° and 1,800° F than for the material rolled at upper temperatures of 2,000° or 2,200° F. (See table X and fig. 39.) The creep rates were actually faster than those for any other condition of rolling except large reductions at 2,200° F. (Cf. data in table X with tables II, IV, or VIII.) On the other hand, the creep resistance of the material rolled between 1,500° and 2,000° or 2,200° F was as high as that obtained under any other conditions of rolling.

Rupture and creep properties at 1,500° F.- The rupture strengths at 1,500° F were very low for the material rolled at 1,500° and 1,800° F, whereas raising the upper temperature to 2,000° and 2,200° F resulted in considerably higher values. (See tables IX and X and fig. 38(b).) As at 1,200° F, the strengths resulting from rolling at 1,500° and 1,800° F were low in comparison with those resulting from isothermal rolling or rolling over a falling-temperature range. In fact, only material reduced 65 percent at 1,800° F had as low strength. (Cf. data in table X with tables II, IV, and VIII.) Likewise, the strengths resulting from rolling at 1,500° and 2,000° or 2,200° F were nearly as high as the highest produced by the other conditions of rolling.

Elongations were quite good at 100 hours. The material rolled at 1,500° and 2,000° F had very low elongation at 1,000 hours.

The conditions of cyclic rolling influenced creep resistance in the same way as they did rupture strength. (See tables IX and X and fig. 39.) Rolling at 1,500° and 1,800° F resulted in very low creep resistance; again, only 65-percent reduction at 1,800° F caused as low strength. (Cf. data in table X with tables II, IV, and VIII.) The other two conditions of cyclic rolling gave strengths on the high side of the range found in the investigation.

Hardness.- There was very little difference in hardness (table V) for the three conditions of cyclic rolling. The values were 253 for the material rolled at 1,500° and 1,800° F and 248 for the material rolled at upper temperatures of 2,000° or 2,200° F.

Microstructures.- As expected, the cycling between 1,500° and 1,800° F resulted in extensive precipitation and agglomeration in the microstructures (fig. 40). When the upper temperatures were 2,000° or 2,200° F, there was little evidence of this. There was little difference in grain size as the result of the three conditions of cyclic rolling. Apparently, the grain refinement obtained at the higher temperatures with equivalent single total reductions was avoided. Likewise, the material rolled between 1,500° and 1,800° F did not show so much distortion as did the material rolled 40 percent at 1,800° F.

Response to Heat Treatment

A study was made of the degree to which the conditions of hot-working influenced the properties after four heat treaments within the temperature range commonly used in heat-treating the alloy.

Solution treated at 2,200° F and water quenched.- The rupture strengths and creep resistance for material solution treated at 2,200° F and water quenched were remarkably uniform after a wide range in hot-rolling conditions. (See tables XI and XII and fig. 41.) All of the rolling conditions studied did not substantially alter the response to the heat treatment.

The individual curves of stress versus rupture time gave the following ranges in rupture strength:

Temp., °F	Rupture strength, psi, in -	
	100 hr	1,000 hr
1,200	42,000 to 45,000	37,000 to 40,000
1,500	17,500 to 18,500	[a]13,000 to 14,000

[a]Only two conditions tested to 1,000 hr.

The minor nature of this variation is shown by figure 41 where all the individual tests plotted well on single curves of stress versus rupture time. Moreover, the rupture strengths agreed with the values for the original stock solution treated at 2,200° F without any rolling. Elongations, however, were considerably higher than those obtained for the original stock.

The limited creep data showed little variation and were similar to the data for the original stock.

Solution treated at 2,200° F, 1 hour, water quenched, and aged at 1,400° F for 24 hours.- The data obtained (tables XIII and XIV) for a number of conditions of hot-working showed no significant variation in rupture strength or creep resistance for material solution treated at 2,200° F for 1 hour, water quenched, and aged at 1,400° F for 24 hours. The small range in rupture strengths disappeared when all the actual data points were plotted on one curve in figure 42.

Solution treated at 2,050° F, 2 hours, and water quenched.- A temperature of 2050° F was used for an extensive series of tests on the basis that this intermediate temperature might show more influence of the rolling conditions on response to heat treatment as reflected in creep and rupture properties. The specimens were solution treated at this temperature for 2 hours and then water quenched. While the data (tables XV and XVI) again show little variation as a result of different conditions of rolling, there was somewhat more than was observed after treatment at 2,200° F. The following ranges in rupture strength were indicated by the individual curves of stress versus rupture time:

Temp., °F	Rupture strength, psi, in -	
	100 hr	1,000 hr
1,200	43,000 to 48,500	38,000 to 42,000
1,500	16,000 to 18,500	12,000 to 13,500

The actual variation represented is illustrated by figure 43 where all the test points plot very nearly on one curve of stress versus rupture time.

No systematic relationship between hot-rolling conditions and the variation in strengths was found.

Solution treated at 2,050° F, 2 hours, water quenched, and hot-cold-worked 15 percent at 1,200° F.- The three conditions of cyclic rolling, representing extremes in as-rolled rupture and creep strength, were solution treated at 2,050° F for 2 hours followed by water quenching and then a 15-percent reduction by rolling at 1,200° F. The resultant hot-cold-worked materials had practically no variation in strength or ductility. (See tables XVII and XVIII and fig. 44.) Moreover, the strengths were the same as those which had previously been obtained for this same treatment (ref. 1).

DISCUSSION

Application of the results of this investigation explains many of the variations in high-temperature properties of the alloy studied and those of similar metallurgical characteristics studied in the hot-worked condition. The metallurgical mechanism responsible cannot be accounted for in terms of solid solution, internal strain from cold-work, precipitation effects, or structural stability. Apparently, some other factor involving the plastic deformation of the metal during working is involved. The absence of an appreciable influence of prior working on response to heat treatment was unexpected. Apparently, if heat-treating conditions are adequate for completion of metallurgical reactions, the properties will be relatively independent of prior history and the major source of variation arises from heat-to-heat differences.

Control of Properties in Hot-Worked Condition

There were two outstanding results from the studies of the properties at 1,200° and 1,500° F in the hot-worked condition:

(1) As the amount of reduction under isothermal conditions was increased, strengths increased up to an optimum reduction. Further reductions either did not continue to increase strength or resulted in a falloff in strength.

(2) Successive reductions over a decreasing temperature range produced higher strengths at 1,200° F than were obtained during working at constant temperature. At 1,500° F, the strengths were only slightly higher than those obtained by equivalent total isothermal reductions.

These two features of the data can be applied in a general way to account for some of the variations in strength commonly observed for the hot-worked condition:

(1) Medium to low strengths would be expected from large reductions at nearly constant temperature. This seems to be characteristic of the properties of the alloys from high-production processes involving rapid and extensive reductions at relatively high working temperatures.

(2) On the other hand, experimentally produced materials frequently have abnormally high strength in the hot-worked condition. This probably arises from production conditions where the metal is given successive small reductions as the temperature decreases. Almost all alloys of the type considered have shown record high strengths in the hot-worked condition. A sequence of hot-working of this type is almost

certainly responsible. The experiments carried out in this investigation were not so complete as would be desirable. It appears, however, that the working schedule must meet the following requirements:

(a) The reductions must all either be below the amounts causing recrystallization or, if recrystallization occurs at the higher temperatures, be carried down to temperatures where recrystallization ceases.

(b) Probably many small reductions at small temperature intervals are most effective.

The falling-temperature - small-reduction principle appears to have considerable importance for high strength at 1,200° F. Strengths equal to or in excess of those normally obtained only by hot-cold-work in the range of 1,200° to 1,400° F can be produced with finishing temperatures in excess of 1,800° F. For example:

Working conditions	Rupture properties at 1,200° F			
	100 hr		1,000 hr	
	Strength, psi	Elongation, percent	Strength, psi	Elongation, percent
Reduced 25 percent at 2,200° F plus 15 percent at 1,800° F	61,000	5	48,000	6
Reduced 10 percent at 2,200°, 2,000°, 1,800°, and 1,600° F	60,000	20	48,000	18
Solution treated at 2,050° F, 2 hr, water quenched, and reduced 15 percent at 1,200° F	56,000	4	50,000	4
Solution treated at 2,200° F, 1 hr, water quenched, and reduced 15 percent at 1,200° F	54,000	1	52,000	5

Apparently, many small reductions at frequent temperature intervals are the key to high ductility in rupture tests in combination with high strength.

In addition to the major generalities of the results, there were a number of additional important features of the data of a somewhat more detailed nature relating to properties in the hot-worked condition after isothermal working:

(1) Maximum rupture strength at 1,200° F was obtained by 15-percent reduction at any temperature. There was little effect from increasing the reduction beyond 15 percent (fig. 45), except for a loss in strength for working at 2,100° F.

(2) The temperature of working had a considerable influence on the level of rupture strength at 1,200° F (figs. 7 and 45). Relatively high rupture strengths, in excess of 50,000 and 40,000 psi for 100 and 1,000 hours, required working below 2,100° F.

(3) The hot-worked condition generally yielded rupture strengths at 1,200° F higher than can be obtained by heat treatment alone. Only exposure to 2,100° F and large reductions at 2,100° F gave lower strengths (fig. 45). In most cases, heat treatment reduced rupture strength at 1,200° F.

(4) The control of rupture strengths at 1,500° F for the hot-worked condition is mostly dependent on the degree of reduction (figs 7 and 46) and only slightly dependent on the temperature of working. Specific reductions dependent on the temperature of working (fig. 8) are required for maximum strength with large reductions being detrimental. It is noteworthy that a reduction of 7 percent at 2,200° F yielded as high a rupture strength at 1,500° F as could be obtained by any other conditions of working investigated. Lowering the temperature of working (fig. 46) generally resulted in less falloff in the rupture strength at 1,500° F for more than optimum reductions.

(5) It appears that high elongation and reduction of area in rupture tests at 1,200° F were dependent on large reductions from 1,800° to 2,000° F. (See figs. 9 through 14.) High-temperature working with recrystallization also increased ductility.

(6) Elongation and reduction of area in rupture tests at 1,500° F were very sensitive to degree of reduction. (See figs. 9 through 14.) Heating to the working temperatures alone greatly increased their values for 100 hours. However, they could be reduced to very low values by increasing amounts of reduction. High values are obtained only when working is carried out at essentially constant temperature if the temperatures are in excess of 2,000° F or if the reductions are very small.

(7) Creep resistance in low-stress tests is apparently more sensitive to degree of reduction than is rupture strength. (Cf. figs. 16 and 18 with figs. 45 and 46.) At 1,200° F, a good deal of the sensitivity to temperatures of working observed in rupture tests is retained (fig. 16). Low strengths are particularly to be expected for large

reductions above 2,000° F. At 1,500° F, the creep resistance was more sensitive to degree of reduction (fig. 18) with an indication that large reductions below 2,000° F might be particularly damaging.

(8) The reduction for maximum creep resistance under low stresses is less than that for maximum rupture strength (fig. 19).

(9) Repeated small reductions to low temperatures with reheats to below 2,000° F can lead to very low strengths. Apparently, this is the source of low strength in sheet when low reheat temperatures are used to reduce scaling and help preserve a good surface. For the alloy studied, reheat temperatures of 2,000° to 2,200° F for 1/2 hour were adequate to give relatively high strengths.

(10) Recrystallization during working without further working at a lower temperature leads to low hardness and low strength.

(11) The alloy studied was subject to extensive precipitation during working in the temperature range of 1,600° to 2,000° F. Apparently, this is a major source of the excess constituents so frequently observed in the microstructure of alloys of this type. It apparently can lead to low long-time rupture strengths at 1,200° F and probably is related to other strength effects.

Mechanisms of Strengthening and Weakening by Hot-Working

The results of this investigation mainly provide a basis for hypothesis to explain the observed influences of hot-working conditions on the creep-rupture properties of the alloy. Apparently, both strengthening and weakening occur during working, as evidenced by the increases and then decreases in strength as the amount of reduction was increased. The relative effects vary with stress and temperature of testing. It appears that strain-hardening is a major factor involved in strengthening, although this is probably an incomplete simplification. The suggestion is made that weakening mainly arises from a recovery type of process during working, exhibiting itself as recrystallization during working at the higher temperatures. When recrystallization does not actually occur, the damage arises from the same structural alterations as those which induce recrystallization to occur at higher temperatures. In addition, there are other effects from the precipitation during working at 1,600° to 2,000° F, and during testing.

Strengthening during working.- The correlations of hardness to rupture and creep strength (figs. 47 through 50) show that there were reasonably close relationships between hardness and rupture strengths at 1,200° F. When the stress was reduced to 25,000 psi at 1,200° F, the resulting creep rates did not correlate so well. The strengths at 1,500° F were little influenced by hardness. It is recognized that hardness is an imperfect indicator of strain-hardening. The correlation at 1,200° F for high-stress - rupture tests, however, seems fairly good evidence that, when creep is largely a slip process under relatively low temperature rapid creep conditions, strain-hardening is a major controlling factor. As the creep rate is reduced and the test temperature increased so that the creep process becomes more what can be somewhat loosely termed "viscous" in nature, strain-hardening becomes less effective and the correlation breaks down.

Weakening during working.- The appearance of recrystallization seems definitely to limit strengthening from working. The evidence at 1,200° F for rupture strength is not entirely clear on this point. Maximum rupture strength upon working at 2,100° F occurred for 15-percent reduction, whereas recrystallization started at 10 percent and was reasonably complete at 15 percent. It will be noted, however, that this was the only case where rupture strengths fell off with further reduction (fig. 45) and it may be necessary to obtain complete recrystallization before weakening occurs. Strengths did not increase with reduction at 2,200° F, presumably because of continuous recrystallization. Continuous recrystallization during working first at 2,200° and then at 2,000° F was also accompanied by low strength. The appearance of recrystallization during closed-pass rolling to a reduction of 65 percent at 1,800° F did not result in much reduction of rupture strength at 1,200° F, probably because it was incomplete.

Recrystallization is a recovery process from lattice strain. It appears first in the grain boundaries. Larger reductions result in its initiation within grains. The suggestion is therefore made that the same structural alterations which lead to recrystallization also lower resistance to creep as it becomes more a function of grain-boundary conditions (lower creep rates and higher temperatures) and probably accumulate damage within the crystals. Because actual recrystallization apparently causes damage, it may well be that some sort of similar process such as subgrain formation occurs in the absence of recrystallization. The damage component seems to be accumulative because rupture strengths at 1,500° F and low-stress creep resistance at both 1,200° and 1,500° F are increasingly reduced as reductions are increased past the optimum. Secondly, it appears at smaller reductions as the creep stress is reduced and the test temperature increased (fig. 19), as would be expected from the theory.

In fact, because of the analogy of the increasing damage from increasing reduction as creep becomes more viscous in nature, there is reason to suspect that a major source of damage may be the nonslip or viscous flow so long identified with rapid plastic deformation by experimenters. Certainly plastic deformation is nonhomogeneous in polycrystalline aggregates and gives evidence of both slip and nonslip processes.

Detailed experimental results related to mechanism.- The optimum reduction for maximum rupture strength at 1,200° F was constant at 15 percent. This suggests that the damage component begins to predominate at this reduction regardless of the temperature of working. There is, in fact, considerable reason to believe that 15-percent reduction gives near-optimum strength for temperatures of reduction as low as 1,000° F when stock is initially solution treated at 2,200° F (ref. 1). Apparently, the hardness can continue to increase with further reduction in the absence of recrystallization, but the rupture strength does not. This results in the strengths no longer correlating with hardness (figs. 47(a) and 47(b)) when the material is worked at 1,800° and 1,600° F and probably at lower temperatures. In reference 2, it was shown that correlation with internal strain broke down for creep resistance at 1,200° F under 50,000-psi stress when a reduction of 40 percent was used at 76° F. It now seems, however, that this breakdown was due to excessive deformation rather than to recovery during testing as originally proposed.

To account for the observed behavior, it seems necessary to postulate that only strain-hardening accumulated with reductions up to 15 percent at any temperature is effective before the damage component prevents further strengthening from increasing strain-hardening. It would certainly be easier to explain this if subgrain formation controlled rupture strength and was largely dependent on degree of reduction and independent of temperature of working. This explanation would seem to require a rupture strength independent of the temperature of working. Actually, this is not far from the facts. In figure 51 rupture data for reductions of 15 percent down to 1,000° F have been added to those from this investigation for material initially solution treated at 2,200° F. There is remarkably little variation in strength for reductions between 1,000° and 2,000° F and this can be accounted for in terms of the precipitation reaction between 1,600° and 2,000° F.

The maximum rupture strengths at 1,500° F were constant (fig. 8) regardless of the temperature of reduction. Again, the data suggest that a recrystallization type of subgrain mechanism controls. In this case, however, it is necessary to have the amount of reduction to obtain the optimum structure decrease with increasing temperature of working. If this is not the case, then there must be a complex interrelationship between cold-work, recrystallization, precipitation during working, precipitation and agglomeration during testing, and the mechanisms of creep and rupture leading to uniformity of rupture strength.

Precipitation during hot-working.- The rupture data were replotted (fig. 52) in terms of change in rupture strength for varying reductions. This gave quite uniform changes in strength for a given reduction at 1,200° F which were independent of the temperature of reduction except at 2,200° F. There was little change at 1,500° F where strengths originally had been mainly a function only of degree of reduction.

The sensitivity of rupture strength at 1,200° F to temperature of reduction was therefore mainly due to effects of heating to the working temperature. In particular, the low strength of material worked at 2,100° F seems to be due to exposure to that temperature and not the effect of reduction. The results of reduction at the other temperatures were also brought closer together. The only suggested explanation involves some influence on the precipitation which is only microscopically evident after working at lower temperatures. The low strength after working at 2,200° F seems to be due to the fact that continuous recrystallization prevented strengthening either through the restriction of strain-hardening or the development of unfavorable grain structures.

The drop in maximum rupture strengths for 1,000 hours at 1,200° F from working at 1,600° to 2,000° F (fig. 51) seems related to the precipitation during hot-working. This precipitate also induced extensive further precipitation during testing at 1,200° F. Both effects would be expected to have little effect on short-time rupture strength but would be expected to lower long-time strength (ref. 3).

The precipitation effects could account for the falloff in strength at 1,200° F for the observed hardness after working at 1,600° and 1,800° F (figs. 47(a) and 47(b)). Previous work (ref. 3) had shown that during aging hardness can increase but strength decrease. The evidence, however, seems more in favor of the main influence being the changes in structure as controlled by working. This seems to be supported by the lack of evidence of a precipitation effect on low-stress creep where precipitation would be expected to be more influential in reducing strength than it is in rupture tests.

Precipitation seemed to have little effect at 1,500° F. It is presumed that this was due to the fact that precipitation and agglomeration during testing were so rapid and extensive that prior precipitation had little influence on properties.

In view of the improvement in the relation between rupture strength at 1,200° F and amount of reduction resulting from the use of changes in rupture strength, the data were replotted using changes in hardness rather than actual hardness. This considerably widened the scatter over that shown by figures 48 through 50. It was concluded that actual hardness was a better measure of strength than changes in hardness.

The changes in hardness due to heating to the working temperature (fig. 20) were apparently related to the strengths.

Ductility in rupture tests.- The data suggest that the same mechanism which leads to weakening in most cases leads to increased elongation and reduction of area in the rupture tests. This seems to be particularly true for recrystallization. There are details in the ductility relationships which do not appear to fit into this mechanism. However, the factors which control amount of deformation before fracture are not understood and the deviations are therefore difficult to explain.

The most difficult factors to explain are the pronounced increases in elongation at 1,500° F for 100 hours resulting from simply heating to the working temperatures (fig. 14) and the pronounced decreases with increasing reduction at both 100 and 1,000 hours. These results strongly suggest some influence from the precipitation reaction. The reductions for maximum strength seem to bear little, if any, relation to the reductions for minimum elongation. There must be some complex effects of working which change the initiation of cracking and fracture. Apparently, when the recovery processes during working become sufficiently extensive, ductility is restored.

Hot-working with decreasing temperature.- The major change introduced by working on a falling-temperature range was an apparent increase in the amount of hardening from working first at 2,200° and then at 1,800° or 1,600° F. Not only was the hardness higher than would have been anticipated from isothermal data, but the rupture strengths at 1,200° F were accordingly higher (figs. 47(a) and 47(b)). The hardness values after working at 2,000° or 1,800° and then at 1,600° F were near to the incremental additive effects estimated from isothermal data at the two temperatures. The same was true for reductions of 10 percent at 2,200°, 2,000°, 1,800°, and 1,600° F. The material worked first at 2,200° and then at 2,000° F had low hardness because of continuous recrystallization at both temperatures. The rupture strengths at 1,200° F of material worked at 2,000° and 1,600° F and those given the reductions of 10 percent were also high and in accord with their hardness. Thus, the procedure also allowed the development of high strength and high hardness with large total reduction. This was not quite so true for working first at 1,800° and then at 1,600° F. The continuously recrystallized material from working at 2,200° and 2,000° F had strength in accord with its hardness.

All of these factors point to an increase in the low-temperature strengthening mechanism during working without an increase in the weakening effect. The cause is not clear from the data. The material worked first at 2,200° F may have been simply made more susceptible to strain-hardening for a given reduction at lower temperatures. Reduction of grain size with a corresponding increase in the grain-boundary area to be moved to obtain a given degree of damage could be involved. The suppression of precipitation during working at 1,800° and 1,600° F may have been involved. The high strengths of the material worked without recrystallization suggest that a stable structure was developed by the high-temperature working which could be given further limited reductions at lower temperatures without increasing the damage.

The improvement in strength for low-stress creep (fig. 48(b)) was less than that for rupture strength, as would be expected. The strengths at 1,500° F were generally more nearly in accord with those obtained by a total reduction of 40 percent (figs. 33, 35, 49, and 50) than with those obtained by any additive effect of strengthening without increasing damage. Apparently, insofar as strength at 1,500° F is concerned, the weakening component involved in the amount of reduction was not inhibited nearly so much as that for 1,200° F by working on a falling-temperature range.

Cyclic heating and working.- When the samples were prepared by heating and working repeatedly at 1,500° F and at 1,800°, 2,000°, or 2,200° F, there was opportunity for a number of complicated reactions to occur. Precipitation and agglomeration were extensive when the top temperature was 1,800° F. Presumably, extensive precipitation took place particularly at 1,800° F. When the top temperature was 2,000° F, the opportunity for precipitation at the top temperatures was reduced. Presumably, there was no precipitation at 2,200° F and the opportunity for nearly complete solution of precipitates formed at 1,500° F. Likewise, the opportunity for recovery from prior working was present during the 1/2-hour heating periods at the upper temperature.

If it is assumed that the 1/2 hour at 2,200° F give the opportunity for nearly complete solution and recovery from prior working, then the properties ought to be close to those arising from reductions of 5 percent at 2,200° F plus 5 percent at 1,500° F. Data are not available for working at 1,500° F. However, estimates based on available data from this investigation and reference 1 indicate that the hardness and properties are close to those which might be anticipated on this basis. Moreover, they are generally in accord with the hardness correlations of figures 47 through 50. The same is true for an upper temperature of 2,000° F.

The material worked between 1,800° and 1,500° F, however, had both low strength and low hardness. Moreover, the properties were low on the basis of the hardness correlations (figs. 47 through 50). It is presumed that the combination of extensive precipitation and agglomeration during working at 1,800° and 1,500° F combined with recovery effects at 1,800° F and the damage of extensive reduction at low tempertures all contributed to low strength.

The recovery from the damage of extensive deformation when 2,000° or 2,200° F was the top temperature would seem to be the major factor.

Effects of Reheating During Working

The role of reheats was given very little attention in this investigation. The indications were, although it was not proven, that the brief 5-minute reheats used had little influence on the accumulative effects of continued reduction by isothermal hot-working with reheats. On the other hand, solution treatments of 2 hours at 2,050° or of 1 hour at 2,200° F apparently erased prior history effects. The assumption, therefore, is that, in practice, reheats will have effects in between these extremes depending on the time and temperature. Sufficiently long times and high temperatures for the metallurgical reactions to attain completion will introduce materials with uniform initial properties and structures. On the other hand, too short times and low temperatures to permit stabilization of the structure will introduce materials with varied initial properties and structures on which additional working will be superimposed. This would presumably alter the degree-of-reduction effects as set forth in this investigation.

The material cyclically rolled between 1,800° and 1,500° F (table X) gave every indication that 1/2 hour at 1,800° F was not removing prior history effects. On the other hand, the materials cyclically rolled between 2,000° or 2,200° F and 1,500° F had properties fairly close to those which might be anticipated for solution-treated material reduced 5 percent at those temperatures and then given a 5-percent reduction at 1,500° F. Thus, the 1/2 hour at the higher temperatures may have quite effectively eliminated any influence from the prior cycle.

Response to Heat Treatment

The results from this investigation indicate that response to heat treatment is virtually independent of prior working conditions for heat-treating temperatures in the range of 2,050° to 2,200° F. That is, quite uniform response at either 2,050° or 2,200° F was obtained, although the properties were different after each treatment. These data are proof that the damage component from working is not permanent and can be removed by heat treatment.

This leaves a question as to the cause of the variations in properties observed in practice for specific treatments. The suggestion is that they are due to unidentified heat-to-heat variations. Before this suggestion is accepted, however, checks should be made for cases where actual differences are observed to make sure that there are not conditions of working in practice which can introduce variable response.

Treatment at 2,200° F was found to eliminate differences observed between two heats during a previous investigation (refs. 1 and 6). One heat tended to have substantially higher strengths at 1,200° F when the material was heat treated at 2,050° F and then hot-cold-worked. This is reflected in figure 51 for heat 30276. More extensive data in reference 6 showed that the material from heat 30276 had substantially lower strength at the higher temperatures and longer time periods when it was initially treated below 2,200° F. Moreover, there were extensive structural changes which did not occur in heat A-1726, the material used for the present investigation. There is no clear evidence as to whether the difference between the heats was due to differences in prior history or to heat-to-heat differences. Since a treatment at 2,200° F seemed to eliminate the difference between the two heats, the tendency is to suspect prior history as the major factor. This, however, has not been established. The available comparative data are presented in table XIX and, with the exception noted, show remarkable agreement considering the possible variations in treatment and testing. It will be noted that, insofar as heat A-1726 is concerned, the original stock heat treated only at 2,050° F had similar properties to those of the material initially treated at 2,200° F and then rerolled before heat treatment at 2,050° F in this investigation.

Heat treatment would be expected to dissolve precipitates and allow their diffusion for chemical uniformity. In addition, recovery from straining effects would be expected either by recrystallization or by annealing without recrystallization. From the results obtained in this investigation, it appears that 2 hours at 2,050° F is a somewhat marginal condition for these reactions to take place. The variations were somewhat more than seems attributable to testing variables. This fact together with the variations in strength for the same treatment observed in references 1 and 6 between heats leads to some question as to the completeness of the metallurgical reactions in 2 hours at 2,050° F after all conditions of working.

The absence of any apparent effects from reheating during isothermal working indicates that response to heat treatment is sensitive to time at temperature during heat treatment. Evidently, the 5-minute reheats were too brief to allow much change when the working was being carried out at or close to the reheat temperature. On the other hand, the 1/2-hour periods at the upper temperatures of 2,000° and 2,200° F during cyclic working apparently were very effective, whereas the treatment at 1,800° F was not. It is apparent that as the temperature and time of heat treatment are increased prior history variations will have less effect on the response to treatment. Apparently, complete independence from all such effects requires treatment at higher temperatures than 2,050° F for 2 hours, whereas there are conditions which can be eliminated by 1/2 hour at temperatures as low as 2,000° F.

There are working conditions which lead to abnormal grain growth. It is recognized that under these conditions the response to heat treatment will not be independent of prior history regardless of treatment condition.

It should be noted that the elongations in rupture tests were more variable than the strengths. In particular, higher elongations at 1,200° F were obtained after a 2,200° F solution treatment than were obtained from the original stock.

General Observations

The relationships between hardness and properties in figures 47 through 50 clearly demonstrate the reasons for the inadequacy of hardness for predicting properties at high temperatures. Large reductions at essentially constant temperature or repeated reductions with reheats to low temperatures too short in duration to allow recovery and solution lead to low strength in relation to the hardness. Furthermore, if a heat treatment is used which does not effectively remove effects of prior history (or allows unidentified heat-to-heat differences to exert an effect), there will be abnormal variations in the relationship between hardness and strength. For instance, the material from heat 30276 (refs. 1 and 6) had high rupture strength at 1,200° F in relation to its hardness (fig. 51) and low strength at 1,500° F (table XIX) in comparison with the material used for the present investigation.

No direct relationship between grain size and properties was observed. Recrystallization during working was frequently accompanied by low strength. It is doubtful, however, that grain size in itself was nearly so much a factor as were strain-hardening, recovery effects, and possible structural alterations or precipitation effects accompanying the deformation.

The high-temperature precipitation accompanying exposure to or working in the temperature range of 1,600° to 2,000° F had not previously been observed. It certainly is the source of the extensive precipitates frequently observed in hot-worked products. There is good evidence that this precipitate is detrimental to longer time strengths at 1,200° F and that its effect was a maximum from working at 1,800° F. Precipitation during working was also accompanied by increased precipitation during testing at 1,200° F. This as well as the original precipitation during working could have contributed to the decreased long-time strength. Most of the data suggested that the very extensive precipitation and agglomeration during testing at 1,500° F overshadowed any effects from prior precipitation. It must, however, be admitted that there were certain cases where a modification of precipitation effects by working would have been a convenient way to explain the results at 1,500° F.

This was particularly true for the relatively high strengths at 1,500° F of the materials worked at 1,600° F and the large reductions possible at 1,600° F without much loss in strength.

The reasons for or the significance of the sensitivity of the lattice parameters to cooling rate are not understood. Likewise, their variation with temperature and degree of reduction is not clear. There does not appear to be an obvious reason for the observed effect of cooling rate. The variation in parameters with conditions of working does not seem to be explainable on the basis of ordinary solution and precipitation of odd-sized atoms or in terms of the influence of the working on the crystal structure of the grains. Lattice-parameter variations were, however, so large that they do raise a question as to the presence of unidentified metallurgical reactions which could be having more effect on properties than now seems evident. Certainly the results could not be used to estimate solubility of alloying elements as was originally intended.

The observation that diffraction lines were too diffuse for accurate parameter measurements after all reductions at 1,600° F and after intermediate reductions at 1,800° F suggests that the degree of reduction must not be the same at all temperatures. The sharpening of the lines for large reductions supports a recovery-type mechanism for weakening in the absence of visible recrystallization. Certainly there were corresponding hardness levels at 1,600° F where lattice parameters could be measured for equivalent hardness values after working at the higher temperatures. This seems to be additional evidence that the plastic-flow mechanism during working could be understood better.

Limitations of Results

The use of experimental material which had been drastically reduced by hot-working is the most serious limitation on the generality of the results. The possible undetected influence of unknown prior history effects cannot be ruled out. So far as could be determined, the 2,200° F treatment was effective in minimizing any influence from prior history. Certainly, it could be expected that, even with a 2,200° F treatment, prior working which did not eliminate cast structures would influence the response to working.

In practical hot-working such high-temperature treatments as that at 2,200° F may not be applied as part of the normal practice. This could lead to retention of the effects of prior working and to different properties than would be predicted from the results of this investigation. It would seem that the heating for working must effectively eliminate prior history effects if the properties are to be predictable. The study of the response to heat treatment suggests that this would be the case for temperatures as low as 2,050° F. However, there are cases where the same properties were not obtained between heats (refs. 1 and 6) with a 2,050° F treatment. It must be concluded that heating for working to temperatures of 2,050° F and below may result in variable response to hot-work. Experience with the alloy has not, however, as yet disclosed cases where a 2,200° F treatment did not give quite reproducible properties.

Although the limitations introduced by the method and conditions of working are uncertain, the general principles should remain the same. It is difficult, however, to foresee the effects of more rapid and larger reductions during rolling, the difference between rolling and hammer-forging, the influence of constraint of dies, and so forth. The surprisingly little difference between open- and closed-pass rolling suggests that such factors may be minor. Only when closed-pass rolling induced recrystallization for a 65-percent reduction, whereas it was absent during open-pass rolling, was the difference significant.

The conditions of working on a falling-temperature range investigated were extremely limited. It now appears that this would be a fertile field for further experimentation to cover more ranges of reductions and temperatures of reduction. It is suspected that still higher strengths than those observed at both 1,200° and 1,500° F would be developed as well as more conditions leading to low strength. Furthermore, the mechanism involved ought to be clearer. Also, there is reason to suspect that working rapidly enough to cause an increase in temperature might be very damaging to strengths.

In this investigation, reasonably uniform working throughout the cross sections was obtained. In actual practice, there may be considerable variation in the metal movement within a given cross section. This should lead to variable properties across the section in the hot-worked condition. The properties at each individual point should, however, be in accordance with the degree of metal movement as indicated by this investigation. Also, all tests in this investigation were carried out on samples taken from the bars in the direction of rolling. There may or may not be significant differences in properties for bars in other directions in relation to the direction of working.

It is believed that the general principles observed apply to all alloys of the same general metallurgical type. This would include practically all of the high-temperature alloys, except those dependent on the age-hardening derived from aluminum plus titanium. The amounts and temperatures of reduction for increases or decreases in strength would be expected to vary depending on relative strain-hardening and recovery characteristics during working, as well as on individual structural stability characteristics during testing.

The observations recorded in the section "Results" regarding the influence of working conditions on the extent and duration of the various stages of creep were not extensively evaluated. They could have pronounced effects on the time to attain limited amounts of creep and thereby be as important as the other properties more extensively examined.

CONCLUSIONS

A study was made to determine the influence of various hot-working conditions on the high-temperature properties of a heat-resistant alloy and the effects of the hot-working on response to subsequent heat treatment. Many of the variations in properties at high temperatures in the hot-worked condition for alloys of the type investigated can be predicted from the results. Medium to low strengths will result from high rate of production processes where large reductions are made at nearly constant high temperatures. Very high strengths at 1,200° F and relatively high strengths at 1,500° F are characteristic of gradual reductions over a decreasing temperature range, probably being responsible for the common high strengths of experimental materials. Strengths equal to those characteristic of hot-cold-working at 1,200° F can be obtained by such procedures with finishing temperatures as high as 1,800° F. Repeated working with abnormally low reheat temperatures is one cause of very low strengths.

These general explanations of characteristic properties for hot-worked products are based on the following summarized results:

1. Strengths increased to maximum values and then remained constant or decreased as the amount of reduction at constant temperature was increased. Optimum reductions generally were no more than 15 percent and for long-time creep resistance, were less. Strengths at 1,200° F were sensitive to the temperature of hot-working, tending to decrease as temperature increased. Strengths at 1,500° F were relatively insensitive to temperature of working. Both were dependent on the degree of reduction.

2. Working over a decreasing-temperature range induced higher strengths at 1,200° F than can be obtained by working at a constant temperature. Strengths at 1,500° F were not improved very much in relation to isothermal reductions of the same degree. Low strengths were obtained only when recrystallization continued at all temperatures of working.

3. Repeated working between 1,800° and 1,500° F yielded very low strengths, while upper temperatures of 2,000° and 2,200° F gave quite high strengths.

The data clearly show that hardness is not a reliable indicator of strength mainly because hardness can continue to increase while strengths are ralling off with more than optimum reduction.

Ductility in the rupture tests, particularly at 1,500° F, decreased and then increased with the amount of reduction and very low values were avoided only for the larger reductions above 2,000° F.

The metallurgical causes for the observed variations in strength and ductility were not definitely established. The data suggest that:

1. Strain-hardening is a major source of strengthening, although other factors are involved.

2. Recovery effects due to recrystallization or, when the working temperature was too low for recrystallization, to the same factors which induce recrystallization appeared to limit strengthening and cause decreasing strength with increasing reduction past the optimum amounts.

3. There were aspects of the falloff in strength for more than optimum reduction which suggested the development of subgrain structures as a mechanism. The decrease in the amount of reduction for reduced strength and the accumulative damage effects for low-stress creep suggest that weakening involves a recovery process in the grain-boundary regions, as suggested by the fact that recrystallization started first in such areas.

4. Rupture strengths at 1,200° F did not fall off much with more than the optimum reduction of 15 percent, suggesting that the damage component of working had less influence on the resistance to the more uniform crystalline slip processes of creep at relatively low temperatures and high stresses than on the more viscous creep processes at low stresses and/or higher temperatures.

5. An extensive precipitation reaction at 1,600° to 2,000° F appeared to reduce long-time rupture strength at 1,200° F. This heretofore unrecognized precipitation reaction also induced extensive precipitation during testing at 1,200° F. Apparently, it had little effect at 1,500° F because of the extensive precipitation for all conditions during testing at that temperature.

6. Apparently, some effect of the precipitation reaction was involved in the sensitivity of strength at 1,200° F to the temperature of working. This also appeared to be the case for ductility in rupture tests at 1,500° F.

7. The results, in conjunction with data from other investigations, suggest that maximum rupture strength at 1,200° F for working at constant temperature occurs at a reduction of 15 percent regardless of the temperature of working from room temperature to 2,100° F. Secondly, there is reason to believe that, if the precipitation at 1,600° to 2,000° F did not influence strength, the maximum strengths would be nearly constant. Maximum rupture strengths at 1,500° F were independent of temperature of working from 1,600° to 2,200° F but did not occur at constant reduction.

8. Working over a falling-temperature range permitted an increase in the amount of hardening and strengthening at 1,200° F for a given degree of reduction at the finishing temperature when recrystallization occurred at the higher working temperatures. If reductions were kept small at all temperatures so that recrystallization did not occur, the strengthening at 1,200° F, from limited reduction, appeared to become additive. The weakening component appeared to remain constant as a function of degree of reduction.

Very uniform responses to heat treatment were observed in this investigation regardless of the conditions of hot-working. It appeared that the temperature 2,050° F was marginal, with no apparent effect at 2,200° F. Brief reheats during isothermal working to maintain temperature did not appear to induce any changes. A reheat of 1/2 hour at 2,000° F after limited reduction at both 2,000° and 1,500° F appeared to eliminate the effects of prior working. This suggests that reheats range in their effectiveness depending on whether the temperature and time at temperature are sufficient for the metallurgical reactions to reach completion.

An unexplained high degree of sensitivity of lattice parameters to conditions of hot-working and to cooling rate was observed.

There are a number of limitations to the results imposed by the limitations of the experimental investigation. The experimental material was extensively hot-worked and then solution treated at 2,200° F prior to working for this investigation. Rather few data for working over a falling-temperature range were obtained. Little study of reheat effects was done. The limitation of the test material to one alloy also raises a question as to the generality of the results. Because hot-working was limited to rolling, further proof of the validity of expressing the results in terms of amount of reduction would be desirable even though there was little difference between the results for open- and closed-pass rolling.

University of Michigan,
Ann Arbor, Mich., May 20, 1955.

APPENDIX

PROCESSING OF LOW-CARBON N-155 7/8-INCH BROKEN-CORNER SQUARE BAR STOCK FROM HEAT A-1726[a]

An ingot was hammer cogged and then rolled to bar stock under the following conditions:

(1) Hammer cogged to 13-inch-square bilet
Furnace temperature, 2,210° to 2,220° F
Three heats - Starting temperature on die, 2,050° to 2,070° F
Finish temperature on die, 1,830° to 1,870° F

(2) Hammer cogged to $10\frac{3}{4}$-inch-square billet
Furnace temperature, 2,200° to 2,220° F
Three heats - Starting temperature on die, 2,050° to 2,070° F
Finish temperature on die, 1,790° to 1,800° F

(3) Hammer cogged to 7-inch-square billet
Furnace temperature, 2,200° to 2,220° F
Three heats - Starting temperature on die, 2,050° to 2,070° F
Finish temperature on die, 1,790° to 1,890° F

Billets ground to remove surface defects

(4) Hammer cogged to 4-inch-square billet
Furnace temperature, 2,190° to 2,210° F
Three heats - Starting temperature on die, 2,040° to 2,060° F
Finish temperature on die, 1,680° to 1,880° F

Billets ground to remove surface defects

(5) Hammer cogged to 2-inch-square billet
Furnace temperature, 2,180° to 2,210° F
Three heats - Starting temperature on die, 2,050° to 2,065° F
Finish temperature on die, 1,730° to 1,870° F

Billets ground to remove surface defects

(6) Rolled from 2-inch-square billet to 7/8-inch broken-corner square bar - one heat
Furnace temperature, 2,100° to 2,110° F
Bar temperature start of rolling, 2,050° to 2,060° F
Bar temperature finish of rolling, 1,910° F

[a]Reported by the manufacturer.

(7) Bars are numbered 1 through 56; bar 1 represents the extreme bottom of ingot and bar 56, the extreme top position

All billets were kept in number sequence throughout all processing, so that ingot position of any bar can be determined by its number

(8) All bars were cooled on the bed and no anneal or stress relief was applied after rolling

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TABLE I

RUPTURE AND CREEP TEST RESULTS AT 1,200° AND 1,500° F FOR BAR STOCK ROLLED ISOTHERMALLY BETWEEN 1,600° AND 2,200° F IN OPEN PASSES

[Time for creep tests is duration of test and not rupture time]

Reduction, percent	Tested at 1,200° F					Tested at 1,500° F				
	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr
Rolled at 1,600° F										
0	52,000	29	11	15	--------	18,000	85	49	38	-------
	45,000	179	8	12	0.022	16,000	322	54	56	0.085
	41,000	377	8	10	.012	15,000	324	62	56	.02
	25,000	(1,002)	(Creep test)		.00036	8,000	(996)	(Creep test)		.00015
5	55,000	28	5	8	--------	22,000	37	27	26	0.2
	48,000	113	5	10	.15	18,000	211	50	42	.02
	40,000	598	7	--	.0035	16,000	474	31	42	.0075
	25,000	(1,054)	(Creep test)		.000035	8,000	(995)	(Creep test)		.00007
10	55,000	54	3	8	.015	23,000	75	32	26	.4
	43,000	503	2	8	.003	19,000	221	27	25	.009
	25,000	(1,007)	(Creep test)		.000048	15,000	1,246	20	31	.0024
15	55,000	134	5	4	.01	23,000	76	14	22	--------
	50,000	272	5	3	.045	20,000	187	14	27	.013
	48,000	664	5	7	.0015	18,000	449	11	20	.0085
	25,000	(1,099)	(Creep test)		.0001	16,000	684	6	8	.003
	25,000	(996)	(Creep test)		.0001	8,000	(994)	(Creep test)		.00003
25	58,000	72	3	4	--------	25,000	62	4	4	--------
	50,000	172	3	6	.005	20,000	259	14	7	.043
	43,000	990	5	--	.00076	17,000	768	6	11	.004
	25,000	(1,053)	(Creep test)		.00012	8,000	(992)	(Creep test)		.00006
40	55,000	100	4	4	.013	21,000	88	13	11	--------
	45,000	390	4	4	.005	18,000	251	7	6	.0075
	25,000	(1,007)	(Creep test)		.00012	16,000	423	8	4	.0028
	------	-------	--	--	--------	8,000	(1,135)	(Creep test)		.00022
	------	-------	--	--	--------	8,000	(960)	(Creep test)		.00019
Rolled at 1,800° F										
0	50,000	44	10	9	0.1	21,000	33	48	44	--------
	40,000	352	8	8	.0095	16,000	205	61	56	0.15
	37,000	1,499	27	23	.006	11,000	975	26	22	.005
	25,000	(997)	(Creep test)		.0007	8,000	(1,052)	(Creep test)		.00029
5	50,000	90	10	10	.054	20,000	47	59	31	.15
	48,000	137	10	6	.03	16,000	343	54	48	.013
	38,500	881	9	14	.0055	14,500	979	23	40	.003
	25,000	(1,008)	(Creep test)		.000095	8,000	(994)	(Creep test)		.000035
10	50,000	118	8	8	.019	22,000	38	42	47	.28
	42,000	331	8	9	.007	17,000	343	19	27	.009
	38,000	895	19	13	.0024	15,000	>1,076	(Turned off)		.0025
	25,000	(1,000)	(Creep test)		.00004	8,000	(1,006)	(Creep test)		.0004
15	55,000	76	5	6	.055	23,000	62	37	40	.22
	50,000	205	6	8	.021	20,000	185	31	36	.038
	48,000	268	8	10	.017	18,000	378	11	18	.0095
	45,000	893	13	14	.0045	16,000	>989	(Turned off)		.0025
	25,000	(1,186)	(Creep test)		.00006	------	-------	--	--	--------
	25,000	(1,008)	(Creep test)		.00006	------	-------	--	--	--------
25	50,000	90	4	2	-------	25,000	29	19	23	.21
	48,000	253	4	6	.008	23,000	61	10	9	.075
	47,000	136	4	3	.0052	21,000	115	8	13	.018
	45,000	534	7	6	.0044	19,000	230	12	9	.0055
	25,000	(1,030)	(Creep test)		.000088	16,000	470	5	4	.0035
	------	-------	--	--	--------	8,000	(1,063)	(Creep test)		.0001
40	54,000	83	6	6	.04	20,000	78	4	4	.04
	50,000	233	7	9	.0075	16,000	323	5	5	.009
	47,000	415	9	7	.0047	13,000	382	5	2	.004
	44,000	532	5	6	.0044	12,000	626	7	4	.003
	25,000	(1,006)	(Creep test)		.0002	8,000	(1,033)	(Creep test)		.00045
65	55,000	41	20	22	.2	18,000	37	30	7	--------
	45,000	325	19	22	.02	11,000	254	18	15	.018
	40,000	762	23	20	.008	8,000	730	20	5	.0028
	25,000	(1,005)	(Creep test)		.00026	------	-------	--	--	--------

TABLE I.- Continued

RUPTURE AND CREEP TEST RESULTS AT 1,200° AND 1,500° F FOR BAR STOCK ROLLED ISOTHERMALLY BETWEEN 1,600° AND 2,200° F IN OPEN PASSES

Reduction, percent	Tested at 1,200° F					Tested at 1,500° F				
	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr
Rolled at 2,000° F										
0	52,000	20	11	10	0.12	20,000	41	63	32	0.6
	42,000	308	9	12	.016	16,000	243	35	49	.045
	39,000	836	14	13	.008	13,000	1,171	32	39	.0035
	25,000	(1,002)	(Creep test)		.00065	8,000	(1,006)	(Creep test)		.00012
5	48,000	19	5	13	--------	20,000	37	38	42	.14
	43,000	310	9	11	.012	17,000	477	20	29	.01
	40,000	384	6	11	.005	15,000	1,014	19	28	.0035
	25,000	(1,009)	(Creep test)		.00007	8,000	(996)	(Creep test)		.000045
10	50,000	40	5	9	--------	22,000	52	25	23	.15
	45,000	171	5	7	.016	19,000	341	10	16	.011
	42,000	600	11	--	.006	17,000	754	9	10	.006
	25,000	(1,149)	(Creep test)		.00005	8,000	(1,003)	(Creep test)		.00006
15	55,000	66	6	6	.07	24,000	62	25	35	.2
	52,000	151	6	8	.023	20,000	176	11	11	.019
	50,000	719	12	13	.0074	16,000	629	3	3	.0043
	45,000	949	16	23	.0049	13,000	>1,457	(Turned off)		.00035
	25,000	(1,197)	(Creep test)		.00004	8,000	(1,154)	(Creep test)		.00065
	25,000	(1,000)	(Creep test)		.00005	------	-------			--------
25	52,000	86	9	10	.082	21,000	61	15	19	.1
	50,000	185	10	12	.026	18,000	180	10	13	--------
	48,000	348	14	16	.02	16,500	287	5	5	.0056
	45,000	967	11	20	.0045	15,000	420	2	4	.004
	25,000	(1,001)	(Creep test)		.0001	12,500	816	6	6	.0023
	------	-------	--	--	--------	8,000	(1,025)	(Creep test)		.00013
40	52,000	69	21	13	--------	18,000	62	28	24	--------
	50,000	183	15	15	.03	16,000	197	7	9	.016
	44,000	1,786	19	19	.026	12,500	341	11	12	.0085
	25,000	(1,008)	(Creep test)		.00033	10,000	816	9	8	.0016
	------	-------	--	--	--------	8,000	(989)	(Creep test)		.00055
65	50,000	311	28	24	.02	18,000	62	23	28	--------
	25,000	(1,038)	(Creep test)		.00013	15,000	252	19	24	.15
	------	-------	--	--	--------	12,500	600	13	11	.0043
	------	-------	--	--	--------	8,000	(1,002)	(Creep test)		.00036
Rolled at 2,100° F										
0	45,000	24	11	12	--------	18,000	74	40	43	--------
	38,000	106	5	12	0.01	15,000	403	43	48	0.015
	32,000	>1,122	>5 (Turned off)		.0023	8,000	(1,003)	(Creep test)		.0001
	25,000	(1,038)	(Creep test)		.0006	------	-------	--	--	--------
5	45,000	45	6	12	.014	20,000	86	43	38	.14
	40,000	210	--	10	.0026	17,000	378	27	36	.011
	37,000	1,095	12	11	.0028	15,000	766	20	23	.0026
	25,000	(999)	(Creep test)		.00021	8,000	(1,247)	(Creep test)		.00006
10	45,000	86	11	15	.019	22,000	86	28	42	--------
	43,000	378	12	10	.01	20,000	132	45	39	.045
	40,000	840	11	--	.0046	19,000	250	18	25	--------
	25,000	(1,005)	(Creep test)		.00015	8,000	(1,163)	(Creep test)		.00008
$12\frac{1}{2}$	45,000	67	(Broke in threads)		--------	23,000	48	23	32	--------
	43,000	180	8	3	.0076	20,000	194	17	23	.015
	40,000	959	15	15	.0036	18,000	340	12	22	.005
	25,000	(994)	(Creep test)		.00014	17,000	656	10	16	.0028
	------	-------	--	--	--------	8,000	(1,146)	(Creep test)		.000046
15	50,000	60	14	9	.025	20,000	64	20	26	.09
	45,000	270	15	10	.011	16,000	727	6	7	.0038
	------	-------	--	--	--------	8,000	(1,003)	(Creep test)		.00015
25	25,000	(1,007)	(Creep test)		.00052	20,000	41	39	42	--------
	------	-------	--	--	--------	15,000	302	13	20	.025
	------	-------	--	--	--------	8,000	(1,145)	(Creep test)		.00014
40	49,000	10	8	--	--------	18,000	64	44	43	--------
	45,000	109	11	11	.065	15,000	114	52	48	.035
	40,000	394	18	18	.021	10,000	648	29	35	.0044
	38,000	1,032	19	15	.014	8,000	(1,150)	(Creep test)		.0007
	25,000	(1,000)	(Creep test)		.00095	------	-------	--	--	--------

TABLE I.- Concluded

RUPTURE AND CREEP TEST RESULTS AT 1,200° AND 1,500° F FOR BAR STOCK ROLLED ISOTHERMALLY

BETWEEN 1,600° AND 2,200° F IN OPEN PASSES

Reduction, percent	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, hr
	Rolled at 2,200° F									
0	50,000	38	9	12	0.04	19,000	84	16	25	0.12
	45,000	111	4	15	.011	17,000	196	27	18	.027
	40,000	238	6	12	.0052	14,000	1,417	25	23	.0035
	35,000	>1,800	--	--	.002	8,000	(1,000)	(Creep test)		.00005
	25,000	(998)	(Creep test)		.00022	------	-------	--	--	--------
3	------	-------	--	--	--------	20,000	61	35	30	--------
	------	-------	--	--	--------	16,000	552	41	36	.011
	------	-------	--	--	--------	8,000	(1,007)	(Creep test)		.000048
5	45,000	36	12	18	--------	22,000	78	29	30	--------
	40,000	305	5	11	.0031	20,000	137	22	17	.019
	38,000	1,101	6	6	.00035	19,000	181	19	22	.012
	25,000	(983)	(Creep test)		.00016	17,000	434	15	19	.0035
	------	-------	--	--	--------	8,000	(992)	(Creep test)		.00006
7	50,000	37	8	12	--------	22,000	66	28	29	--------
	40,000	366	7	5	.004	20,000	164	21	39	.025
	25,000	-------	(Creep test)		.00018	18,000	454	15	24	.012
	------	-------	--	--	--------	8,000	(998)	(Creep test)		.00008
10	50,000	16	11	19	--------	21,000	99	21	28	.016
	42,000	98	7	9	.0052	18,000	392	19	28	.008
	35,000	>1,816	(Turned off)		.0017	16,500	981	12	16	.005
	25,000	(1,008)	(Creep test)		.0002	8,000	(1,134)	(Creep test)		.00011
12	45,000	46	7	14	--------	20,000	77	23	47	.11
	40,000	238	7	12	.005	17,000	664	12	16	--------
	37,000	1,172	8	13	.0029	8,000	(993)	(Creep test)		.0001
15	48,000	12	10	5	--------	19,000	45	19	18	--------
	45,000	110	8	8	.015	17,000	174	32	44	.07
	40,000	158	8	6	.0045	16,000	227	45	43	.075
	35,000	>1,314	>8(Turned off)		.0027	13,000	>1,143	(Turned off)		.0032
	25,000	(1,174)	(Creep test)		.00038	8,000	(1,007)	(Creep test)		.000125
18	45,000	34	7	11	--------	18,000	63	25	49	--------
	40,000	336	7	6	.007	16,000	206	20	37	--------
	38,000	816	19	11	.0058	15,000	512	17	30	--------
	25,000	(1,010)	(Creep test)		.0004	8,000	(1,016)	(Creep test)		.00012
20	------	-------	--	--	--------	17,000	248	23	36	--------
	25,000	(1,008)	(Creep test)		.0005	8,000	(1,140)	(Creep test)		.00014
25	48,000	50	9	10	.028	18,000	84	56	50	.26
	45,000	94	6	10	.022	15,500	252	35	41	.045
	40,000	365	7	10	.0074	14,000	633	48	39	.03
	35,000	1,340	5	4	.0027	8,000	(1,200)	(Creep test)		.00072
	25,000	(1,679)	(Creep test)		.00055	7,000	(938)	(Creep test)		.00013
40	45,000	47	9	11	.07	18,000	86	44	41	.16
	42,000	241	10	12	.022	15,000	255	44	40	.05
	40,000	881	14	15	.0092	12,500	518	40	40	.022
	25,000	(1,000)	(Creep test)		.00064	8,000	(1,136)	(Creep test)		.00098
	25,000	(1,003)	(Creep test)		.00065	8,000	(1,068)	(Creep test)		.00088
65	------	-------	--	--	--------	17,000	128	49	34	--------
	------	-------	--	--	--------	15,000	278	41	45	.032
	------	-------	--	--	--------	12,000	1,137	20	32	.007
	------	-------	--	--	--------	8,000	(1,009)	(Creep test)		.0004

TABLE II

SUMMARY OF RUPTURE AND CREEP PROPERTIES AT 1,200° AND 1,500° F FOR BAR STOCK ROLLED ISOTHERMALLY BETWEEN 1,600° AND 2,200° F IN OPEN PASSES

Reduction, percent	Tested at 1,200° F						Tested at 1,500° F					
	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr		Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
	100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi	100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
Rolled at 1,600° F												
0	47,500	[a]37,500	9	[a]7	4,500 × 10^{-5}	35 × 10^{-5}	17,000	[a]14,500	49	---	4,500 × 10^{-5}	15 × 10^{-5}
5	48,000	38,500	5	8	2,000	3.5	19,500	[a]14,500	37	[a]25	500	7
10	50,000	40,000	3	3	1,000	4.8	21,500	15,500	30	20	250	8
15	57,000	43,000	5	5	450	10	22,500	15,500	14	6	200	3
25	55,500	43,000	3	5	500	12	23,000	16,500	5	6	200	6
40	55,000	[a]44,000	4	[a]4	800	12	20,500	[a]14,500	12	[a]8	750	22
Rolled at 1,800° F												
0	46,000	37,000	10	20	10,000	70	17,500	11,000	57	26	8,500	29
5	49,000	38,000	10	9	5,500	9.5	18,500	13,500	55	23	800	3.5
10	50,000	37,500	8	20	2,200	4	19,500	15,500	40	15	250	4
15	53,000	45,000	6	15	1,700	6	21,500	16,000	35	5	150	------------
25	50,000	44,000	4	9	1,000	9	21,000	[a]14,500	10	[a]5	200	8
40	52,000	43,000	6	5	750	20	18,500	11,000	4	7	1,000	45
65	50,000	40,000	20	23	800	26	14,000	7,500	25	20	13,000	280
Rolled at 2,000° F												
0	45,500	38,000	10	14	9,000	65	18,000	13,000	60	32	2,000	12
5	45,000	[a]39,000	6	[a]8	6,000	7	19,000	15,500	35	19	350	4.5
10	47,000	40,000	5	12	2,800	5	21,000	16,500	20	9	350	9
15	53,500	47,000	6	16	2,000	4	22,000	14,500	17	5	300	6.5
25	51,500	45,000	9	11	3,000	10	19,500	12,000	12	6	400	13
40	51,000	45,000	20	19	3,500	33	16,500	10,000	17	9	1,200	55
65	------	------	--	---	2,000	12	17,000	11,000	22	15	1,400	36
Rolled at 2,100° F												
0	38,500	33,000	5	--	7,000	60	17,500	[a]13,500	40	[a]35	1,500	10
5	43,000	37,000	6	12	4,000	21	19,500	15,500	35	20	500	6
10	44,500	39,500	11	11	3,500	15	21,000	[a]16,000	30	[a]15	500	8
12	45,000	40,000	9	15	3,000	14	21,000	15,500	22	10	300	------------
15	48,000	[a]41,000	13	[a]15	2,300	-----------	19,000	15,500	20	6	600	15
25	------	-------	--	---	------------	55	17,500	[a]13,000	25	[a]10	------------	13
40	44,000	38,000	11	17	12,000	95	16,000	9,000	50	25	3,500	70
Rolled at 2,200° F												
0	45,000	37,500	5	7	3,300	22	18,500	14,500	18	25	800	5
3	------	-------	--	---	------	-----------	19,000	15,000	35	41	600	4.8
5	42,500	38,000	8	6	1,700	16	20,500	[a]15,500	25	[a]13	250	6
7	44,000	[a]36,500	8	---	------	-----------	21,000	[a]17,000	24	[a]12	300	8
10	42,000	37,000	7	5	2,000	20	21,000	16,500	21	12	350	11
12	42,500	37,500	7	8	------	-----------	19,500	16,000	23	10	1,000	10
15	43,000	38,000	9	12	2,500	38	17,500	14,000	19	10	2,000	12.5
18	42,500	38,000	7	19	2,800	40	17,000	14,000	24	15	------------	12
20	------	-------	--	---	------	50	18,000	-------	--	---	------------	14
25	44,000	38,000	6	6	4,000	55	17,500	13,000	40	30	4,500	7
40	43,500	39,500	9	15	40,000	65	17,500	11,500	44	32	7,000	94
65	------	-------	--	---	------	-----------	17,500	12,500	50	35	3,800	40

[a]Extrapolated.

TABLE III

RUPTURE AND CREEP TESTS RESULTS AT 1,200° AND 1,500° F FOR BAR STOCK ROLLED ISOTHERMALLY AT 1,800° OR 2,000° F IN CLOSED PASSES

[Time for creep tests is duration of test and not rupture time]

Reduction, percent	Tested at 1,200° F					Tested at 1,500° F				
	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr
Rolled at 1,800° F										
15	55,000	61	6	8	0.05	23,000	38	36	29	0.040
	50,000	151	4	6	.016	20,000	226	17	12	.012
	25,000	(1,025)	(Creep test)		.00004	18,000	354	13	20	.007
	------	--------	--	--	--------	8,000	(1,001)	(Creep test)		.00003
25	50,000	51	4	6	.012	24,000	22	4	6	.02
	48,000	141	7	4	.0053	21,000	158	19	25	.009
	45,000	464	10	6	--------	17,000	423	5	8	.005
	25,000	(1,030)	(Creep test)		.00006	8,000	(1,001)	(Creep test)		.00005
65 (using square and oval passes)	52,000	24	23	33	.02	14,000	31	36	41	-------
	45,000	238	17	32	.032	8,000	238	--	--	.024
	40,000	467	22	28	.011	6,000	806	38	31	.0065
	25,000	(999)	(Creep test)		.00045	------	-------	--	--	-------
Rolled at 2,000° F										
15	52,000	60	6	7	--------	20,000	172	5	6	0.03
	48,000	302	10	10	0.02	18,000	248	4	4	.008
	25,000	(1,030)	(Creep test)		.000045	16,000	725	9	6	.007
	------	-------	--	--	--------	8,000	(1,005)	(Creep test)		.00006
25	55,000	54	15	10	.022	23,000	76	9	10	.022
	50,000	342	15	14	.027	20,000	194	5	9	.008
	48,000	738	14	12	.011	16,000	642	5	2	.002
	25,000	(1,001)	(Creep test)		.000075	8,000	(1,005)	(Creep test)		.00008

TABLE IV

SUMMARY OF RUPTURE AND CREEP PROPERTIES AT 1,200° AND 1,500° F FOR BAR STOCK ROLLED ISOTHERMALLY AT 1,800° F OR 2,000° F IN CLOSED PASSES

Reduction, percent	Tested at 1,200° F						Tested at 1,500° F					
	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		*Minimum creep rate*, percent/hr		Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
	100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi	100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
Rolled at 1,800° F												
15	53,000	[a]45,000	5	---	$1{,}600 \times 10^{-5}$	4×10^{-5}	21,500	[a]16,000	25	--	200×10^{-5}	3×10^{-5}
25	49,500	[a]44,000	4	---	1,200	6	21,000	[a]14,500	12	[a]5	300	5
65 (using square and oval passes)	48,000	[a]39,000	20	[a]22	13,000	45	10,500	5,700	36	38	8,000	2,400
Rolled at 2,000° F												
15	52,000	[a]46,000	6	---	3,000	4.5	22,000	15,000	5	9	400	6
25	53,000	46,000	15	13	2,700	7.5	21,000	14,500	8	5	280	8

[a]Extrapolated.

TABLE V

BRINELL HARDNESS OF AS-ROLLED BAR STOCK

(a) Isothermal rolling

Rolling temperature °F	Hardness for reduction, percent, of -											
	0	3	5	7	10	12	15	18	20	25	40	65
Open passes												
1,600	214	---	221	---	239	---	255	---	---	270	292	---
1,800	202	---	226	---	237	---	247	---	---	259	276	284
2,000	202	---	215	---	229	---	240	---	---	245	240	251
2,100	195	---	213	218	221	203	211	---	---	214	210	---
2,200	184	197	208	209	206	200	185	191	194	198	202	194
Closed passes												
1,800	---	---	---	---	---	---	243	---	---	263	---	251
2,000	---	---	---	---	---	---	238	---	---	249	---	---

(b) Nonisothermal rolling

Rolling conditions	Brinell hardness
25 percent at 2,200° F plus 15 percent at 2,000° F	221
25 percent at 2,200° F plus 15 percent at 1,800° F	272
15 percent at 2,200° F plus 25 percent at 1,800° F	273
25 percent at 2,200° F plus 15 percent at 1,600° F	278
10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F	274
25 percent at 2,000° F plus 15 percent at 1,600° F	283
25 percent at 1,800° F plus 15 percent at 1,600° F	283
Heat to 1,800° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 1,800° F. Repeat cycle 3 more times.	253
Heat to 2,000° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle 3 more times.	248
Heat to 2,200° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,200° F. Repeat cycle 3 more times.	248

TABLE VI

VARIATIONS IN LATTICE PARAMETER

[Unless specified otherwise, specimens were air cooled and measurements were made on surfaces transverse to rolling direction]

(a) Influence of amount and temperature of reduction

Reduction, percent	Lattice parameter, A
Rolled at 1,600° F	
0	3.5874
Rolled at 1,800° F	
0	3.5890
0	3.5886
5	3.5877
10	3.5869
40	3.5891
40	3.5887
Rolled at 2,000° F	
0	3.5889
0	3.5889
5	3.5878
10	3.5870
15	3.5866
18	3.5869
[a]18	3.5867
[b]18	3.5871
25	3.5868
31	3.5870
35	3.5893
[b]35	3.5890
40	3.5906
40	3.5895
65	3.5900
Rolled at 2,100° F	
0	3.5894
3	3.5864
5	3.5863
5	3.5865
7	3.5870
9	3.5879
11	3.5887
12	3.5880
12	3.5883
15	3.5892
25	3.5890
40	3.5880

[a]45° to rolling direction.
[b]90° to rolling direction.

TABLE VI.- Concluded

VARIATIONS IN LATTICE PARAMETER

(a) Influence of amount and temperature of reduction - Concluded

Reduction, percent	Lattice parameter, A
Rolled at 2,200° F	
0	3.5900
3	3.5884
3	3.5878
$5\frac{1}{2}$	3.5860
$5\frac{1}{2}$	3.5866
6	3.5862
6	3.5871
7	3.5881
7	3.5881
11	3.5890
11	3.5891
15	3.5880
15	3.5875
20	3.5880
25	3.5888
40	3.5901
40	3.5895

(b) Influence of cooling rate from reheat temperature

[Specimens heated to indicated temperature, 1/2 hour, and water quenched]

Reheat temperature, °F	Lattice parameter, A
1,625	3.5837
1,825	3.5844
2,025	3.5847
2,225	3.5883

(c) Influence of cooling rate from 2,025° F

[Specimens heated to 2,025° F, 1/2 hour, and cooled as indicated]

Method of cooling	Lattice parameter, A
Oil quenched	3.5848
Cooled in vermiculite	3.5854
Furnace cooled	3.5834

TABLE VII

RUPTURE AND CREEP RESULTS AT 1,200° F AND 1,500° F FOR BAR STOCK ROLLED

OVER CONTROLLED TEMPERATURE RANGES

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Tested at 1,200° F					Tested at 1,500° F				
	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr
Rolled 25 percent at 2,200° F plus 15 percent at 2,000° F	50,000	60	(Piece missing)		0.094	20,000	58	52	33	0.36
	47,000	78	10	6	.055	16,000	143	22	36	.054
	42,000	230	8	9	.017	12,000	751	21	21	.0005
	38,000	1,377	24	18	.0055	------	-------	--	--	--------
	25,000	(1,124)	(Creep test)		.00058	------	-------	--	--	--------
Rolled 25 percent at 2,200° F plus 15 percent at 1,800° F	60,000	155	5	5	.017	20,000	90	8	6	.058
	55,000	273	5	6	.014	16,000	350	11	11	.01
	50,000	724	6	9	.0025	8,280	(736)	(Creep test)		.00035
	25,000	(1,175)	(Creep test)		.00005	8,000	(1,079)	(Creep test)		.000185
Rolled 15 percent at 2,200° F plus 25 percent at 1,800° F	60,000	91	5	8	.05	19,000	151	5	5	--------
	55,000	277	8	9	.011	16,000	514	4	8	--------
	50,000	420	4	9	.003	14,000	542	7	5	.006
	47,000	1,410	8	9	.0025	12,500	867	7	6	.0015
	45,000	1,866	5	7	.0018	8,000	(1,146)	(Creep test)		.00024
	25,000	(1,008)	(Creep test)		.000024	------	-------	--	--	--------
Rolled 25 percent at 2,200° F plus 15 percent at 1,600° F	60,000	121	3	2	--------	23,000	7	19	14	.12
	55,000	318	3	11	.0076	19,000	179	12	9	.018
	25,000	(1,068)	(Creep test)		.000047	14,000	659	5	5	.005
Rolled 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F	60,000	106	20	22	.019	23,000	112	27	14	.038
	50,000	736	25	16	.0015	20,000	231	7	7	.017
	48,000	1,091	18	27	.0026	16,000	914	6	5	.0019
	25,000	(1,155)	(Creep test)		.00006	8,000	(1,075)	(Creep test)		.000035
	25,000	(1,146)	(Creep test)		.00008	------	-------	--	--	--------
Rolled 25 percent at 2,200° F plus 15 percent at 1,600° F	60,000	101	10	14	--------	21,000	73	3	4	--------
	53,000	391	19	19	.0061	18,000	315	9	3	.0058
	25,000	(1,178)	(Creep test)		.000075	16,000	416	7	2	--------
	------	-------	--	--	--------	8,000	(994)	(Creep test)		.0001
Rolled 25 percent at 1,800° F plus 15 percent at 1,600° F	60,000	40	5	9	--------	20,000	113	5	9	.04
	50,000	343	4	5	.0041	17,000	310	2	6	.012
	25,000	(1,004)	(Creep test)		.00005	8,000	(994)	(Creep test)		.00004

TABLE VIII

SUMMARY OF RUPTURE AND CREEP PROPERTIES AT 1,200° AND 1,500° F FOR BAR STOCK ROLLED OVER CONTROLLED TEMPERATURE RANGES

Rolling conditions	Tested at 1,200° F						Tested at 1,500° F					
	Rupture strengths psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr		Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
	100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi	100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
Rolled 25 percent at 2,200° F plus 15 percent at 2,000° F	47,000	39,000	10	20	$9,200 \times 10^{-5}$	58×10^{-5}	17,500	11,500	30	20	$3,500 \times 10^{-5}$	-----------
Rolled 25 percent at 2,200° F plus 15 percent at 1,800° F	61,000	48,000	5	6	550	5	19,500	[a]13,500	15	--	1,000	18.5×10^{-5}
Rolled 15 percent at 2,200° F plus 25 percent at 1,800° F	60,000	48,000	5	8	400	2.4	20,000	13,000	5	5	600	24
Rolled 25 percent at 2,200° F plus 15 percent at 1,600° F	61,000	[a]49,500	3	[a]3	600	4.7	21,500	13,500	19	5	700	-----------
Rolled 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F	60,000	48,000	20	18	550	6	23,500	16,000	28	16	230	5
Rolled 25 percent at 2,000° F plus 15 percent at 1,600° F	60,000	[a]49,000	10	--	450	7.5	20,500	[a]15,000	3	[a]5	240	10
Rolled 25 percent at 1,800° F plus 15 percent at 1,600° F	55,000	[a]46,000	5	--	410	5	20,000	[a]14,000	5	--	600	4

[a]Extrapolated.

TABLE IX

RUPTURE AND CREEP TEST RESULTS AT 1,200° AND 1,500° F FOR CYCLICALLY ROLLED BAR STOCK

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Tested at 1,200° F					Tested at 1,500° F				
	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr
Heat to 1,800° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 1,800° F. Repeat cycle 4 times.	50,000	64	44	38	0.24	20,000	26	29	35	-------
	45,000	157	33	40	.11	17,000	29	28	26	-------
	37,000	540	30	40	.011	8,000	479	10	10	0.0115
	25,000	(1,086)	(Creep test)		.00073	------	-------	--	--	-------
Heat to 2,000° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle 4 times.	55,000	108	18	18	0.1	22,000	62	16	26	0.11
	50,000	396	13	17	.015	18,000	271	10	9	.0078
	45,000	797	16	22	.0056	15,000	784	3	2	.0025
	25,000	(1,080)	(Creep test)		.000078	8,000	(870)	(Creep test)		.00018
Heat to 2,200° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,200° F. Repeat cycle 4 times.	55,000	187	16	22	0.045	22,000	62	28	37	0.053
	50,000	258	11	16	.016	18,000	324	22	27	.0098
	45,000	712	19	19	.011	15,000	1,028	14	12	.0084
	25,000	(1,087)	(Creep test)		.000056	8,000	(1,151)	(Creep test)		.00007

TABLE X

SUMMARY OF RUPTURE AND CREEP PROPERTIES AT 1,200° AND 1,500° F FOR CYCLICALLY ROLLED BAR STOCK

Rolling conditions	Tested at 1,200° F						Tested at 1,500° F					
	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr		Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
	100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi	100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
Heat to 1,800° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 1,800° F. Repeat cycle 4 times.	47,000	34,500	40	30	$24,000 \times 10^{-5}$	730×10^{-5}	12,800	6,500	20	10	----------	$1,150 \times 10^{-5}$
Heat to 2,000° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle 4 times.	55,500	44,000	18	15	1,500	7.8	20,000	14,500	12	5	250×10^{-5}	18
Heat to 2,200° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle 4 times.	57,500	44,000	20	20	2,000	5.6	21,000	15,000	25	14	440	7

TABLE XI

RUPTURE AND CREEP TEST RESULTS AT 1,200° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED

AT 2,200° F, 1 HOUR, AND WATER QUENCHED

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi
15 percent at 1,800° F	50,000	17	11	16	-------	45,000	40,000	8	12	------------	---------
	45,000	89	8	15	-------	------	-------	--	--	------------	---------
	40,000	1,062	12	16	-------	------	-------	--	--	------------	---------
25 percent at 1,800° F	48,000	41	12	14	-------	45,500	39,000	12	10	------------	---------
	40,000	792	10	10	0.005	------	-------	--	--	------------	---------
65 percent at 1,800° F	45,000	82	13	8	-------	------	-------	--	--	------------	---------
	42,000	133	10	12	.0052	42,000	37,000	10	6	$1,400 \times 10^{-5}$	38×10^{-5}
	37,000	936	6	10	.0035	------	-------	--	--	------------	---------
	25,000	(1,003)	(Creep test)		.00038	------	-------	--	--	------------	---------
15 percent at 2,000° F	45,000	86	12	10	0.07	44,500	38,500	12	5	------------	34
	40,000	534	7	8	-------						
	25,000	(1,046)	(Creep test)		.00034						
65 percent at 2,000° F	45,000	47	(Broke in threads)		-------	------	-------	--	--	------------	35
	25,000	(1,001)	(Creep test)		.00035						
15 percent at 2,200° F	45,000	29	11	18	-------	43,000	[a]38,500	10	[a]6	------------	---------
	40,000	439	6	7	-------						
25 percent at 2,200° F	45,000	81	9	18	0.015	44,000	-------	9	--	------------	---------
	40,000	266	7	11	-------						

[a]Extrapolated.

TABLE XII

RUPTURE AND CREEP TEST RESULTS AT 1,500° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED

AT 2,200° F, 1 HOUR, AND WATER QUENCHED

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
15 percent at 1,600° F	18,000	158	48	52	0.11	18,500	-------	48	---	------------	---
15 percent at 1,800° F	18,000	108	41	29	-----	18,000	-------	41	---	------------	---
65 percent at 1,800° F	18,000	127	51	52	0.13	18,500	13,000	50	30	------------	---
	14,000	637	29	36	-----						
15 percent at 2,000° F	18,000	134	51	50	-----	18,500	-------	--	---	------------	---
65 percent at 2,000° F	18,000	85	51	49	0.250	17,500	[a]14,000	50	[a]45	$1,700 \times 10^{-5}$	---
	15,000	460	55	56	.017						
15 percent at 2,200° F	18,000	86	47	53	-----	17,500	-------	50	---	------------	---

[a]Extrapolated.

TABLE XIII

RUPTURE AND CREEP TEST RESULTS AT 1,200° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED AT 2,200° F, 1 HOUR, WATER QUENCHED, AND AGED AT 1,400° F FOR 24 HOURS

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi
25 percent at 1,800° F	49,000	62	12	11	0.075	47,000	39,000	10	10	9,000 × 10^-5	35 × 10^-5
	45,000	194	11	12	.032						
	40,000	841	11	13	.0076						
	25,000	(1,036)	(Creep test)		.00035						
40 percent at 1,800° F	47,000	116	13	15	.075	47,000	40,000	12	15	6,000	43
	45,000	238	7	12	.027						
	41,000	646	21	21	.012						
	25,000	(986)	(Creep test)		.00043						
25 percent at 2,000° F	49,000	62	19	13	0.16	47,000	[a]41,000	20	[a]10	7,000	---------
	45,000	268	12	13	.36						
	42,000	470	12	14	.017						
40 percent at 2,000° F	48,000	145	13	12	.044	49,000	39,000	15	10	6,000	---------
	45,000	226	11	12	-------						
	41,000	605	10	12	.01						
25 percent at 2,200° F	50,000	61	11	10	0.085	48,000	[a]38,000	11	[a]8	8,500	36
	47,000	148	11	9	-------						
	40,000	425	8	9	.007						
	25,000	(1,007)	(Creep test)		.00036						
40 percent at 2,200° F	50,000	87	--	--	-------	49,000	38,000	10	14	8,500	---------
	45,000	195	8	11	.035						
	40,000	580	14	14	.016						
15 percent at 2,200° F plus 25 percent at 1,800° F	48,000	112	9	14	0.057	48,000	40,000	10	15	5,000	42
	45,000	163	11	13	.038						
	40,000	1,168	20	20	.0052						
	25,000	(1,657)	(Creep test)		.00042						

[a]Extrapolated.

TABLE XIV

RUPTURE AND CREEP TEST RESULTS AT 1,500° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED AT 2,200° F, 1 HOUR, WATER QUENCHED, AND AGED AT 1,400° F FOR 24 HOURS

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
25 percent at 1,800° F	18,000	110	29	33	0.065	18,000	12,500	30	12	$1,400 \times 10^{-5}$	10×10^{-5}
	15,000	336	25	27	.016						
	12,000	1,254	12	9	.0012						
	8,000	(1,118)	(Creep test)		.0001						
	7,000	(986)	(Creep test)		.00003						
40 percent at 1,800° F	18,500	53	22	23	.220	17,000	[a]13,500	23	[a]25	2,200	---------
	16,000	241	24	28	.033						
	14,500	449	26	28	.013						
25 percent at 2,000° F	18,000	132	22	26	0.064	18,500	12,500	25	15	2,000	---------
	16,000	250	19	22	.038						
	12,500	444	--	--	.0064						
	10,000	>1,526	(Turned off)		.0002						
40 percent at 2,000° F	19,000	72	34	29	-------	18,000	13,000	30	24	2,000	---------
	16,000	256	28	31	.028						
	13,000	987	24	30	.0075						
25 percent at 2,200° F	18,000	109	28	29	0.11	18,000	13,000	28	10	1,300	---------
	15,500	278	14	20	.018						
	14,000	549	12	17	.006						
40 percent at 2,200° F	18,000	100	30	27	.08	18,000	13,000	30	---	1,400	---------
	15,000	336	27	26	.014						
	13,000	>1,087	(Turned off)		.0034						
25 percent at 2,200° F plus 15 percent at 1,800° F	18,000	86	36	39	0.175	17,500	12,500	35	30	1,500	---------
	16,000	225	32	21	.04						
	13,000	857	30	19	.004						

[a]Extrapolated.

TABLE XV

RUPTURE AND CREEP TEST RESULTS AT 1,200° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED AT 2,050° F, 2 HOURS, AND WATER QUENCHED

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi
15 percent at 1,600° F	55,000	16	11	13	-------	44,500	38,000	11	11	2,800 × 10^-5	50 × 10^-5
	48,000	34	11	13	-------						
	35,000	>1,145	>10 (Turned off)		0.0033						
	25,000	(914)	(Creep test)		.0005						
15 percent at 1,800° F	50,000	42	8	16	-------	46,500	[a]39,000	10	[a]10	3,700	40
	42,000	389	10	15	0.012						
	25,000	(960)	(Creep test)		.0004						
25 percent at 1,800° F	50,000	49	10	13	.04	48,000	42,000	10	20	4,000	44
	43,000	614	23	16	.013						
	25,000	(1,170)	(Creep test)		.00044						
40 percent at 1,800° F	50,000	73	17	10	-------	48,500	[a]38,000	15	[a]10	------------	---------
	42,000	327	12	13	.0165						
65 percent at 1,800° F	50,000	27	9	12	-------	47,500	-------	10	---	------------	---------
	45,000	345	12	11	0.02						
15 percent at 2,000° F	50,000	11	7	7	-------	43,000	[a]38,000	--	---	------------	54
	40,000	329	---	--	0.016						
	25,000	(1,124)	(Creep test)		.00054						
25 percent at 2,000° F	50,000	14	5	18	-------	------	-------	--	---	------------	60
	47,000	26	9	18	-------						
	45,000	39	10	16	0.085						
	25,000	(1,011)	(Creep test)		.0006						
40 percent at 2,000° F	48,000	44	8	14	.11	------	-------	--	---	------------	---------

[a]Extrapolated.

TABLE XV.- Concluded

RUPTURE AND CREEP TEST RESULTS AT 1,200° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED AT 2,050° F, 2 HOURS, AND WATER QUENCHED

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi
15 percent at 2,200° F	50,000	40	10	15	-------	47,000	[a]40,500	10	[a]8	2,200 × 10⁻⁵	60 × 10⁻⁵
	43,000	428	8	6	0.01						
	25,000	(897)	(Creep test)		.0006						
25 percent at 2,200° F	50,000	18	10	23	-------	48,000	38,000	10	---	------------	64
	36,000	>817	(Turned off)		.0064						
	25,000	(1,277)	(Creep test)		.00064						
40 percent at 2,200° F	45,000	151	7	7	-------	46,000	-------	7	---	------------	---------
25 percent at 2,200° F plus 15 percent at 1,600° F	45,000	29	12	11	-------	43,000	[a]38,500	14	[a]20	7,500	53
	40,000	416	19	16	0.017						
	25,000	(1,155)	(Creep test)		.00053						
Rolled 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F	50,000	44	9	15	.08	48,000	40,000	12	---	8,000	49
	45,000	103	12	11	.040						
	40,000	>842	(Turned off)		.0062						
	25,000	(1,113)	(Creep test)		.00049						

[a]Extrapolated.

TABLE XVI

RUPTURE AND CREEP TEST RESULTS AT 1,500° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED AT 2,050° F, 2 HOURS, AND WATER QUENCHED

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction in area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
15 percent at 1,600° F	23,000	16	58	53	--------	18,000	[a]12,800	60	--	$3,200 \times 10^{-5}$	5×10^{-5}
	18,000	113	70	60	--------						
	15,000	354	35	51	0.027						
	14,000	391	43	36	.023						
	8,000	(914)	(Creep test)		.00005						
15 percent at 1,800° F	20,000	30	64	37	--------	17,500	[a]13,500	50	--	------------	6
	16,000	204	39	39	--------						
	8,000	(961)	(Creep test)								
25 percent at 1,800° F	20,000	60	61	57	0.320	17,500	[a]12,000	60	--	4,000	-----------
	14,000	429	44	49	--------	------					
40 percent at 1,800° F	16,000	186	57	56	.10	------	-------	--	--	------------	-----------
65 percent at 1,800° F	16,000	96	31	55	--------	------	-------	--	--	------------	-----------
15 percent at 2,000° F	20,000	34	57	54	0.560	17,000	12,500	50	35	3,500	6.5
	16,000	167	49	50	.042						
	12,000	1,460	32	40	.0064						
	8,000	[a](973)	(Creep test)		.000065						
25 percent at 2,000° F	20,000	34	35	32	--------	17,000	12,000	50	35	2,800	-----------
	16,000	217	58	54	.042						
	12,500	684	35	39	.0048						
40 percent at 2,000° F	18,000	58	66	61	.240	16,000	-------	50	--	5,000	-----------
	13,000	472	47	48	.016						

[a]Extrapolated.

TABLE XVI.- Concluded

RUPTURE AND CREEP TEST RESULTS AT 1,500° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED AT 2,050° F, 2 HOURS, AND WATER QUENCHED

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction in area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
15 percent at 2,200° F	20,000	35	67	58	-------	17,500	[a]13,000	55	[a]40	$4,000 \times 10^{-5}$	12×10^{-5}
	14,000	523	42	48	0.021						
	8,000	(1,176)	(Creep test)		.00021						
25 percent at 2,200° F	23,000	14	57	52	-------	18,500	-------	50	---	------------	---------
	18,000	155	64	57	.06						
40 percent at 2,200° F	15,000	270	53	53	-------	------	-------	--	---	------------	---------
25 percent at 2,200° F plus 15 percent at 1,600° F	20,000	31	41	49	-------	17,000	[a]13,000	44	---	4,200	10
	15,000	276	46	51	0.043						
	8,000	(987)	(Creep test)		.00015						
Rolled 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F	20,000	46	64	59	0.2	18,000	13,000	50	40	3,100	---------
	14,000	580	43	51	.019						

[a]Extrapolated.

TABLE XVII

RUPTURE AND CREEP TEST RESULTS AT 1,200° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED

AT 2,050° F, 2 HOURS, WATER QUENCHED, AND HOT-COLD-WORKED 15 PERCENT AT 1,200° F

[Time for creep tests is duration of test and not rupture time]

Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi
Heat to 1,800° F, 1/2 hr, roll 5 per-	60,000	36	2	1	0.048	57,000	51,500	4	4	70×10^{-5}	8×10^{-5}
cent, cool to 1,500° F, roll 5 per-	55,000	343	4	4	.0011						
cent, hold 2 hr, reheat to 1,800° F.	50,000	1,517	5	5	.0007						
Repeat cycle 3 more times.	25,000	(1,001)	(Creep test)		.00008						
Heat to 2,000° F, 1/2 hr, roll 5 per-	55,000	90	4	5	0.0055	55,000	49,000	4	-	56	4
cent, cool to 1,500° F, roll 5 per-	50,000	540	2	10	.0056						
cent, hold 2 hr, reheat to 2,000° F.	40,000	>1,025	(Turned off)		.0005						
Repeat cycle 3 more times.	25,000	(1,028)	(Creep test)		.00004						
Heat to 2,200° F, 1/2 hr, roll 5 per-	60,000	14	(Broke in threads)		--------	56,000	50,000	4	4	80	4.5
cent, cool to 1,500° F, roll 5 per-	55,000	207	2	3	0.004						
cent, hold 2 hr, reheat to 2,200° F.	50,000	954	4	5	.0008						
Repeat cycle 3 more times.	25,000	(1,050)	(Creep test)		.000045						

TABLE XVIII

RUPTURE AND CREEP TEST RESULTS AT 1,500° F FOR BAR STOCK ROLLED AS INDICATED AND THEN SOLUTION TREATED

AT 2,050° F, 2 HOURS, WATER QUENCHED, AND HOT-COLD-WORKED 15 PERCENT AT 1,200° F

[Time for creep tests is duration of test and not rupture time]

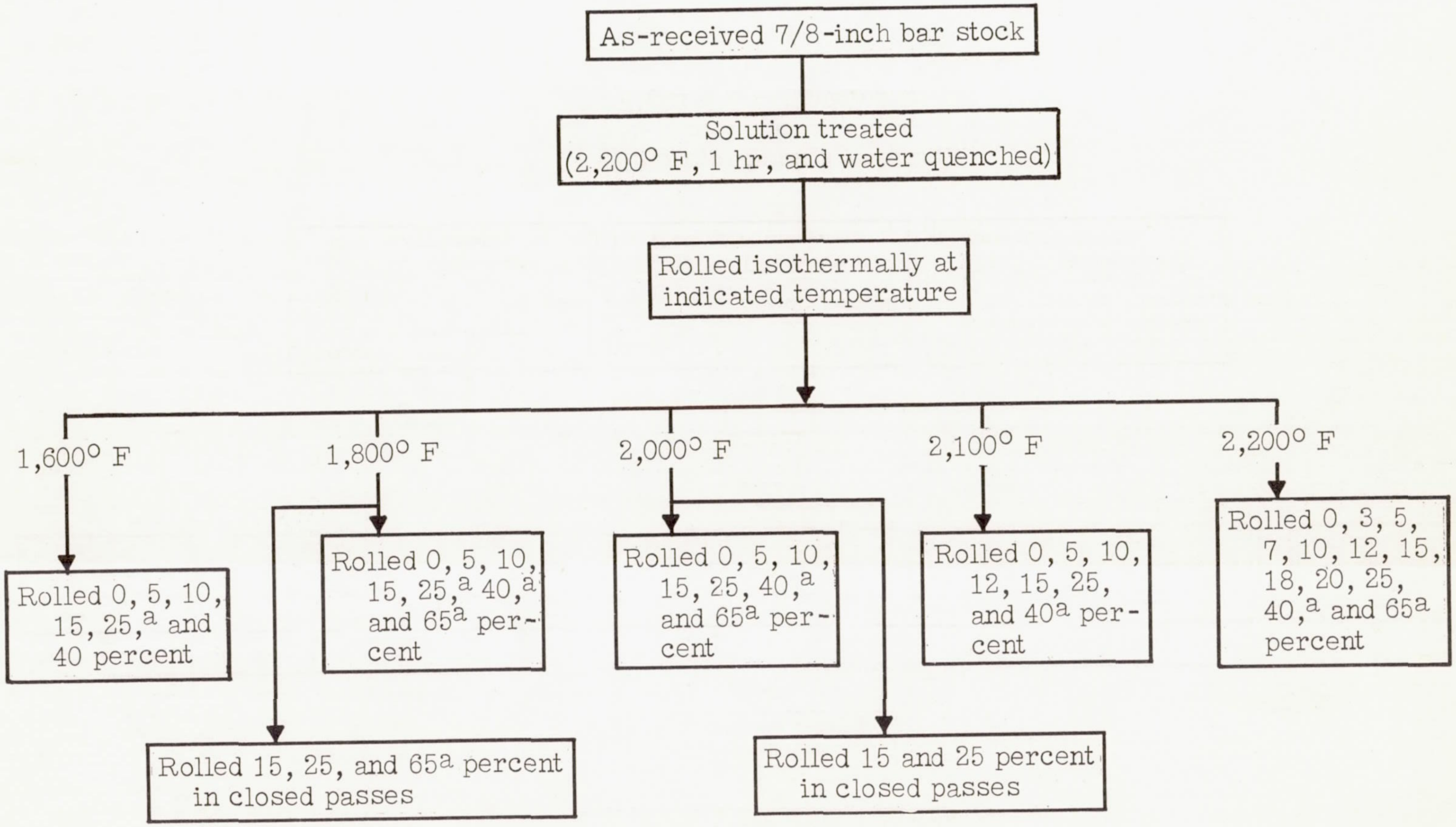
Rolling conditions	Initial stress, psi	Rupture time, hr	Rupture elongation, percent in 1 in.	Reduction of area, percent	Minimum creep rate, percent/hr	Rupture strengths, psi		Interpolated rupture elongation, percent in 1 in.		Minimum creep rate, percent/hr	
						100 hr	1,000 hr	100 hr	1,000 hr	15,000 psi	8,000 psi
Heat to 1,800° F, 1/2 hr, roll 5 per-	26,000	54	21	34	--------	23,500	16,000	20	10	100×10^{-5}	5×10^{-5}
cent, cool to 1,500° F, roll 5 per-	22,000	204	16	19	0.011						
cent, hold 2 hr, reheat to 1,800° F.	18,000	585	11	12	.005						
Repeat cycle 3 more times.	8,000	(1,125)	(Creep test)		.00005						
Heat to 2,000° F, 1/2 hr, roll 5 per-	26,000	50	16	30	0.150	24,000	18,000	10	7	100	7
cent, cool to 1,500° F, roll 5 per-	22,000	315	9	19	.0078						
cent, hold 2 hr, reheat to 2,000° F.	19,000	787	7	9	.0024						
Repeat cycle 3 more times.	8,000	(1,028)	(Creep test)		.00007						
Heat to 2,200° F, 1/2 hr, roll 5 per-	26,000	65	15	28	--------	24,000	17,500	12	10	70	4.4
cent, cool to 1,500° F, roll 5 per-	22,000	186	10	16	0.016						
cent, hold 2 hr, reheat to 2,200° F.	18,000	784	9	9	.0015						
Repeat cycle 3 more times.	8,000	(984)	(Creep test)		.000044						

TABLE XIX

COMPARATIVE DATA ON RESPONSE TO HEAT TREATMENT

Heat	Temp., °F	Rupture strengths, percent		Rupture elongation, percent		Secondary creep rate, percent/hr				Reference
						1,200° F		1,500° F		
		100 hr	1,000 hr	100 hr	1,000 hr	50,000 psi	25,000 psi	15,000 psi	8,000 psi	
2,050° F, 2 hr, and water quenched										
30276	1,200	45,500	39,000	10	20	--------	--------	--------	--------	1
A-1726	1,200	43,000 to 48,000	38,000 to 42,000	7 to 15	8 to 20	--------	--------	--------	--------	(a)
2,050° F, 2 hr, water quenched, and hot-cold-worked 15 percent at 1,200° F										
30276	1,200	62,000	53,500	1	5	0.0009	0.000015	--------	--------	1,6
A-1726	1,200	55,000	48,000	3	1.5	0.0007 to 0.001	0.00004 to 0.00007	--------	--------	6
A-1726	1,200	55,000 to 57,000	59,000 to 51,500	4	4	--------	--------	--------	--------	(a)
30276	1,500	22,000	12,500	16	12	--------	--------	--------	--------	6
A-1726	1,500	24,000	17,000	14	6	--------	--------	0.0008	--------	6
A-1726	1,500	23,500 to 24,000	16,000 to 18,000	10 to 20	7 to 10	--------	--------	0.0006 to 0.0008	--------	(a)
2,200° F, 1 hr, and water quenched										
30276	1,200	42,000	38,000	4	6	--------	--------	--------	--------	1,6
A-1726	1,200	42,000 to 45,000	37,000 to 40,000	8 to 12	6 to 12	--------	--------	--------	--------	(a)
30276	1,500	19,000	14,500	50	36	--------	--------	--------	--------	6
A-1726	1,500	17,500 to 18,500	13,000 to 14,000	41 to 50	35 to 45	--------	--------	--------	--------	(a)
2,200° F, 1 hr, water quenched, and aged 24 hr at 1,400° F										
30276	1,200	50,000	42,000	14	21	--------	--------	--------	--------	1,6
A-1726	1,200	47,000	42,000	10	10	0.09	0.00025	--------	--------	6
A-1726	1,200	47,000 to 49,000	38,000 to 40,000	10 to 20	8 to 15	0.05 to 0.09	0.00035 to 0.00043	--------	--------	(a)
30276	1,500	21,000	14,000	50	23	--------	--------	--------	--------	6
A-1726	1,500	21,000	14,500	35	33	--------	--------	0.004	0.000033	6
A-1726	1,500	17,500 to 18,000	12,500 to 13,500	23 to 35	10 to 30	--------	--------	0.013 to 0.022	.0001	(a)

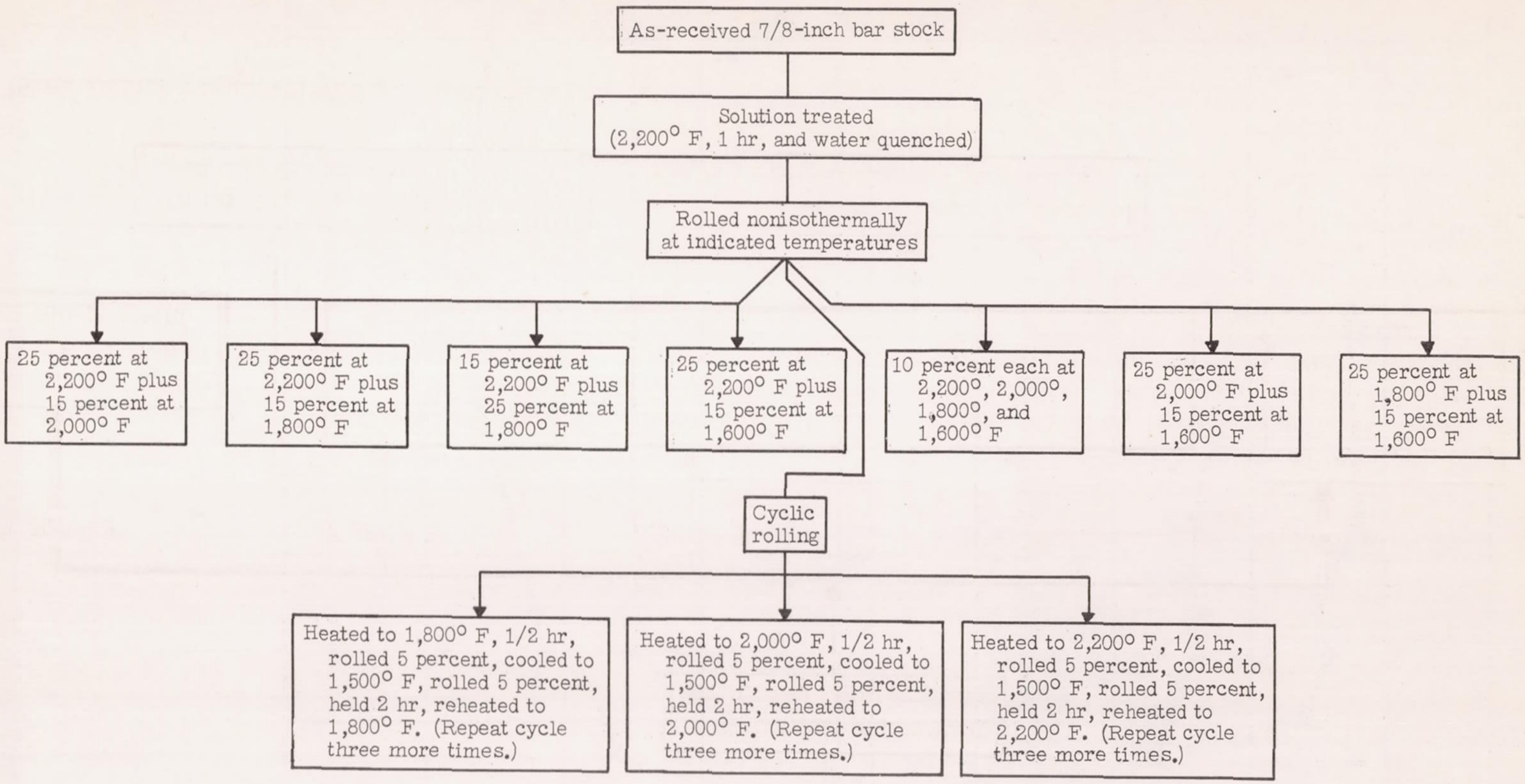
[a]Data from this report.



[a]Reductions required one or more reheats.

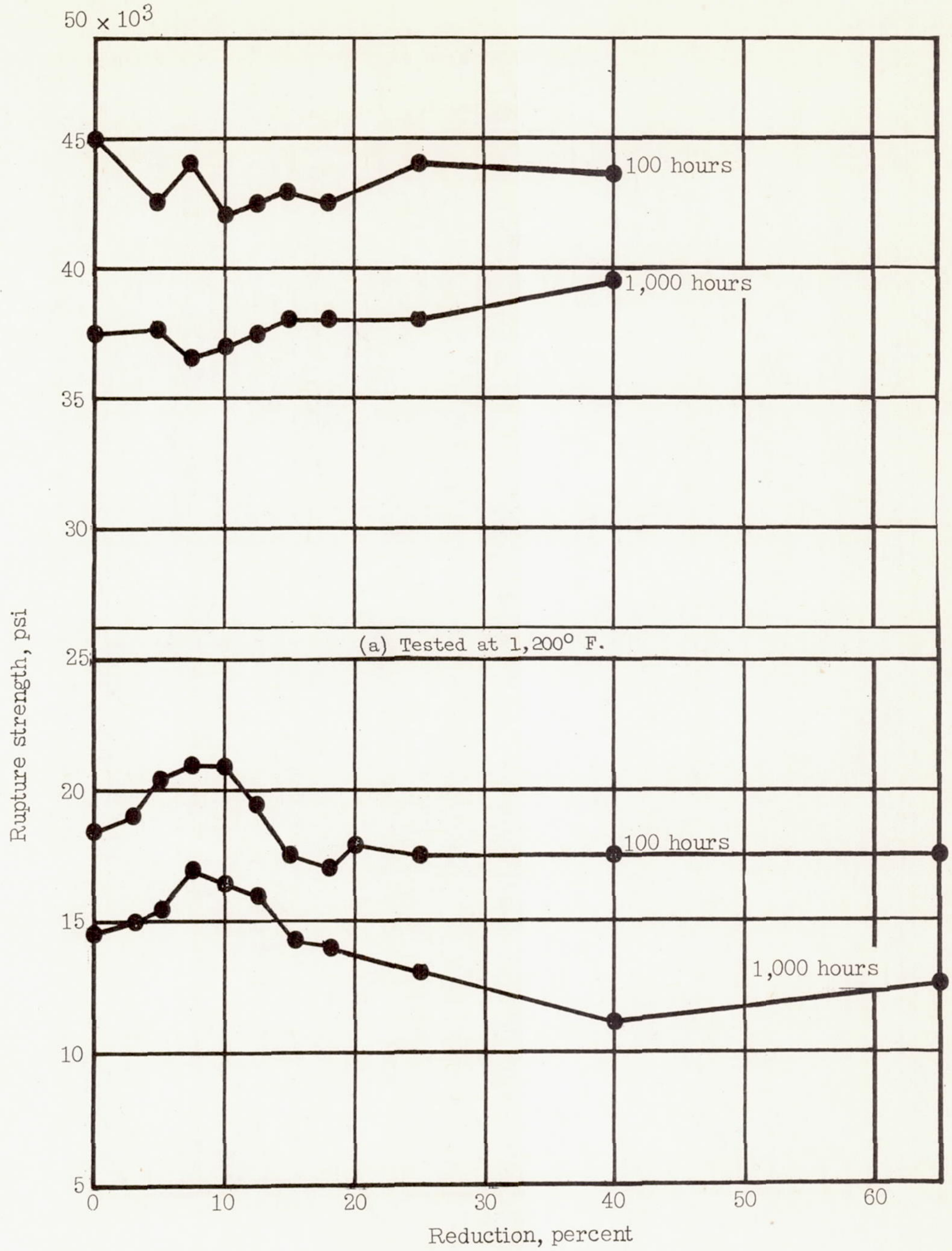
(a) Isothermal rolling.

Figure 1.- Flow sheet of rolling program. Reductions were made in open passes unless otherwise indicated



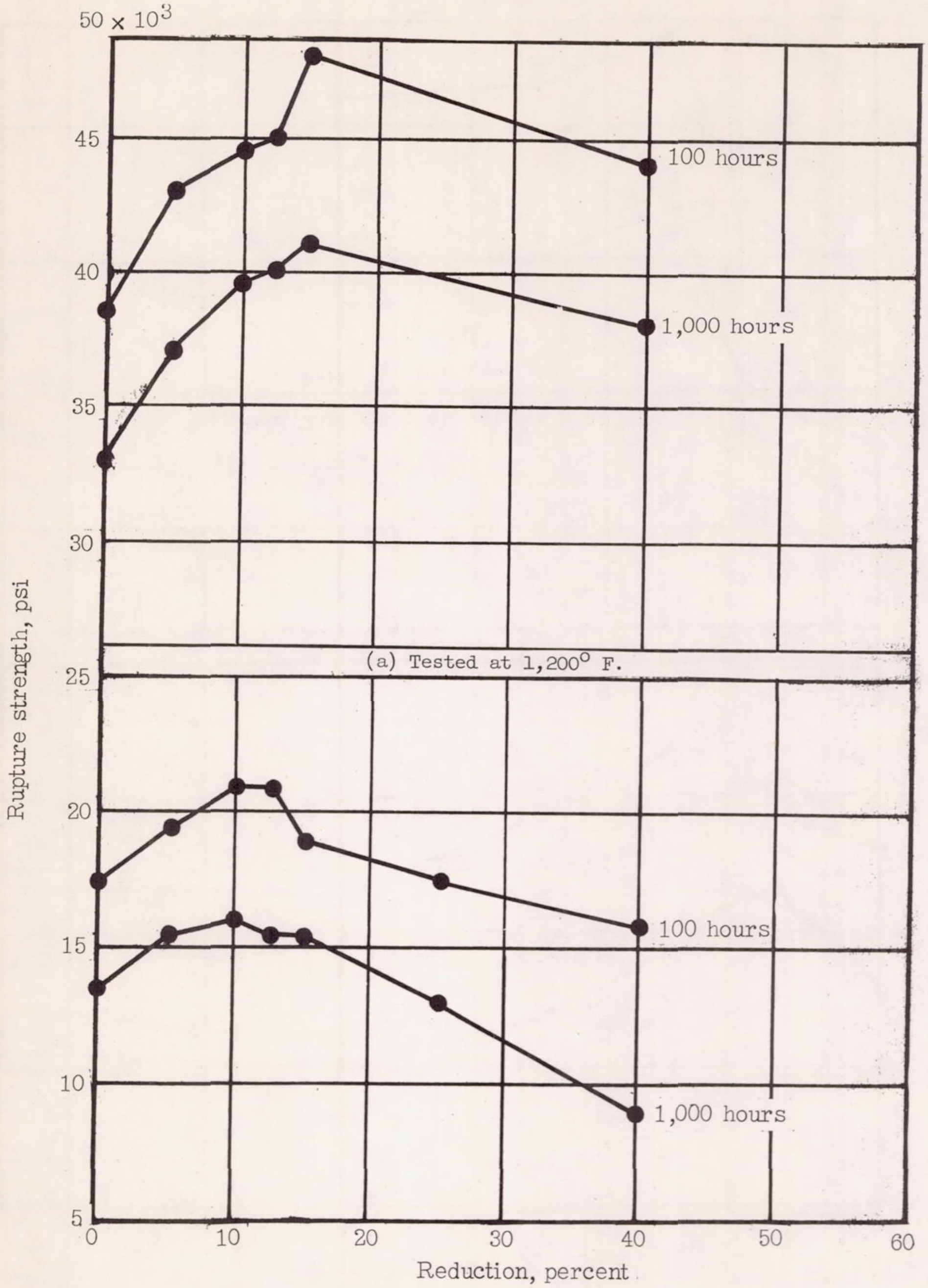
(b) Nonisothermal rolling.

Figure 1.- Concluded.



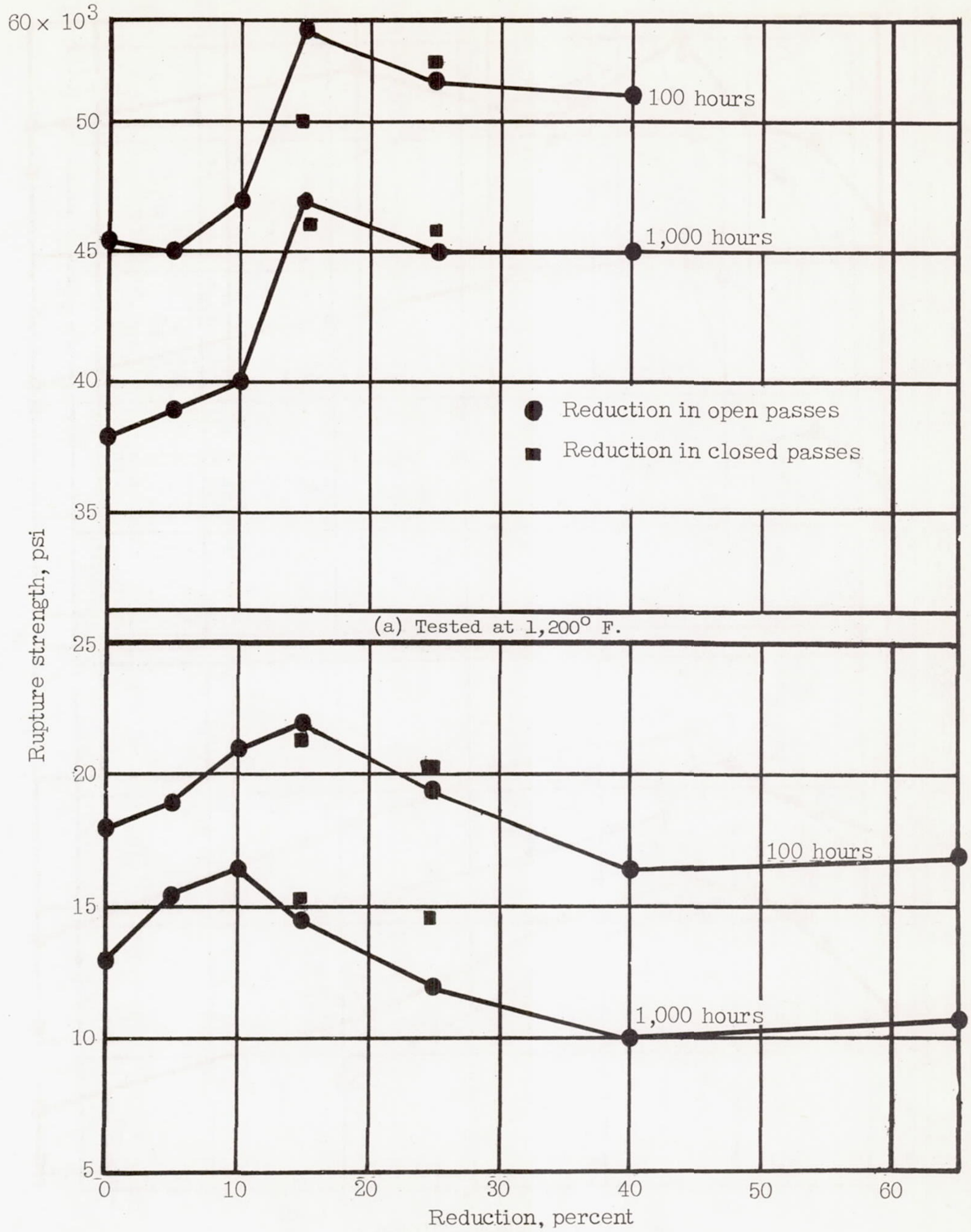
(b) Tested at 1,500° F.

Figure 2.- Influence of isothermal reductions at 2,200° F on as-rolled 100- and 1,000-hour rupture strengths at 1,200° and 1,500° F. Reductions larger than 25 percent required one or more reheats during rolling.



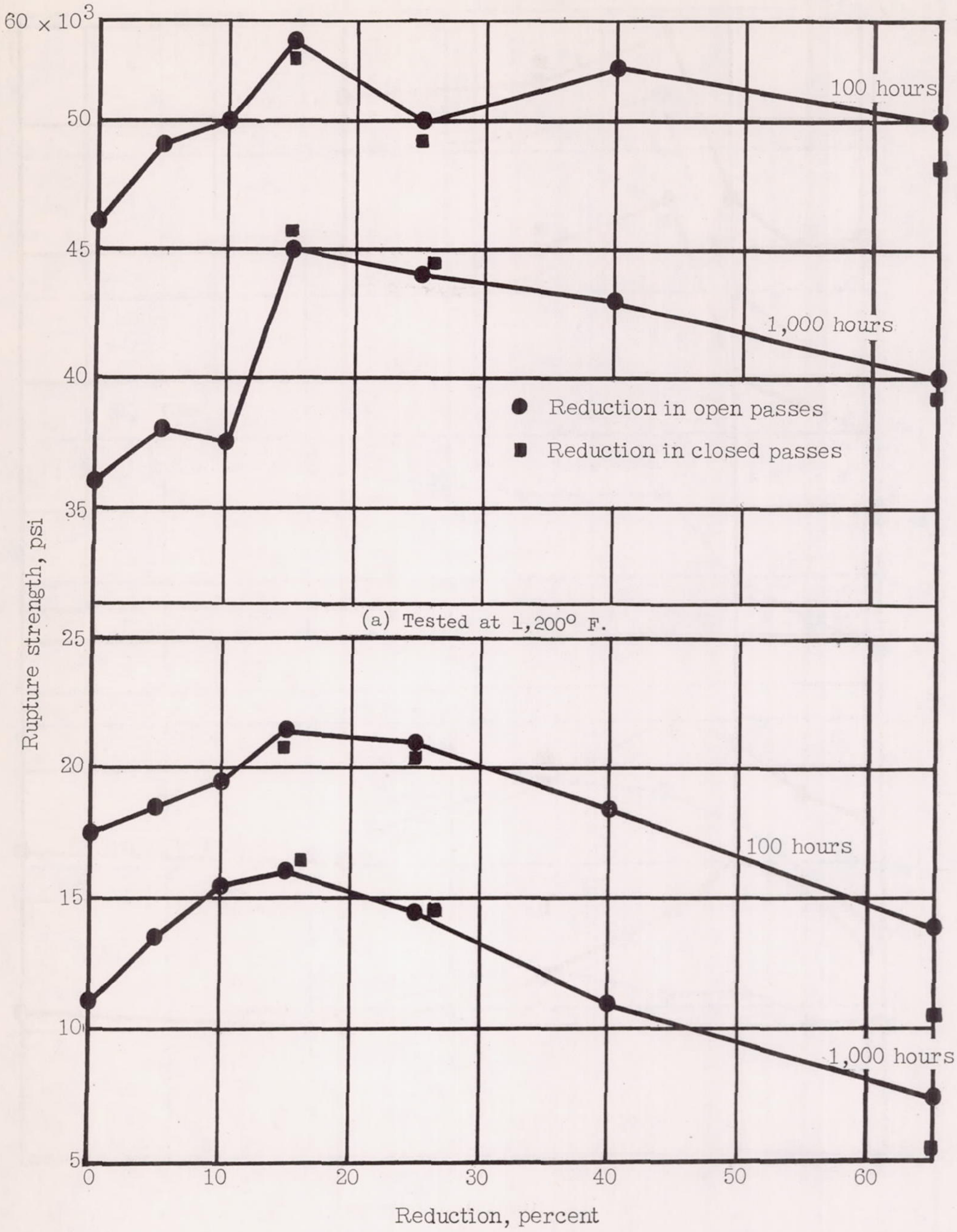
(b) Tested at 1,500° F.

Figure 3.- Influence of isothermal reductions at 2,100° F on as-rolled 100- and 1,000-hour rupture strengths at 1,200° and 1,500° F. Reduction of 40 percent required one reheat during rolling.



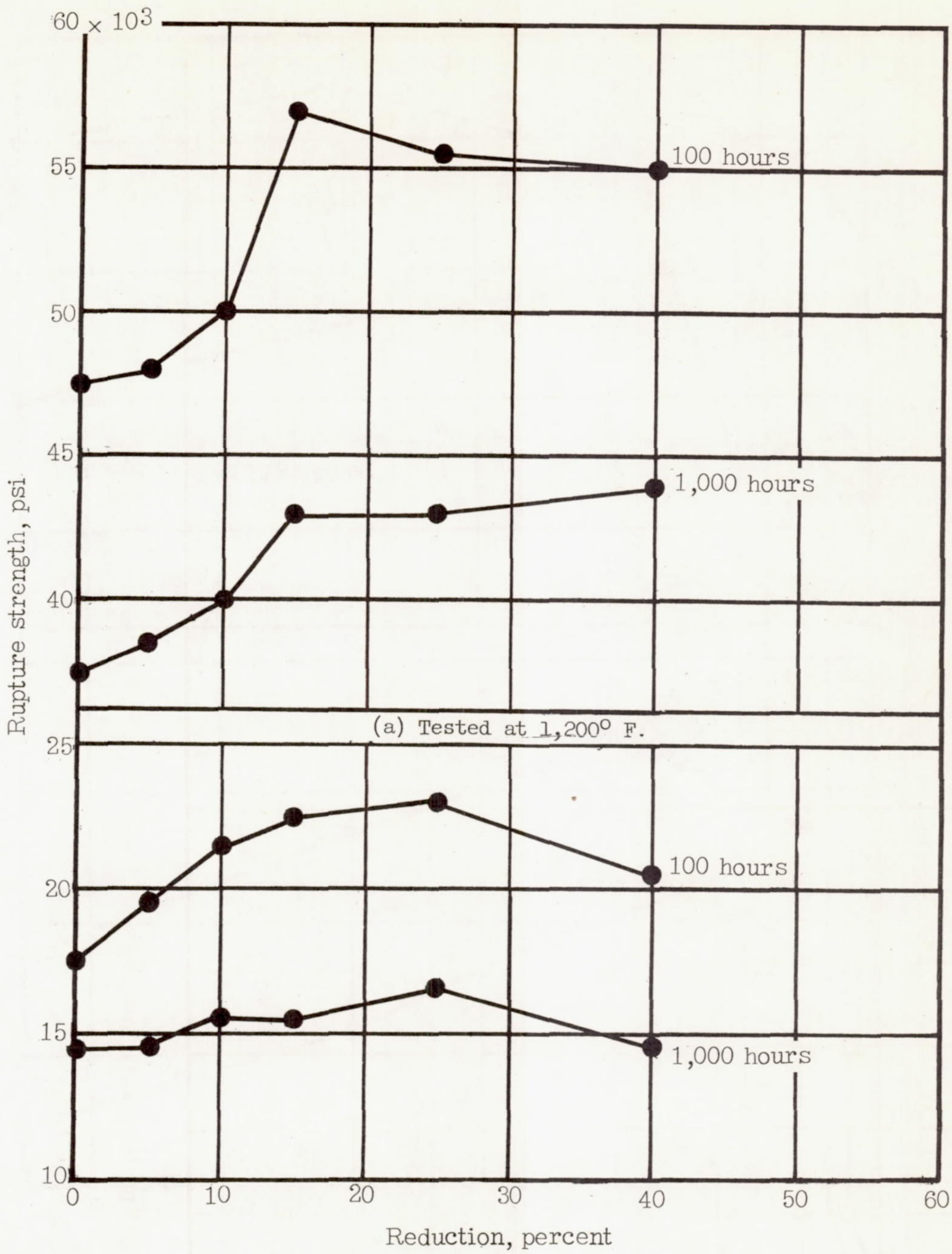
(b) Tested at 1,500° F.

Figure 4.- Influence of isothermal reductions at 2,000° F on as-rolled 100- and 1,000-hour rupture strengths at 1,200° and 1,500° F. Reductions larger than 25 percent required one or more reheats during rolling.



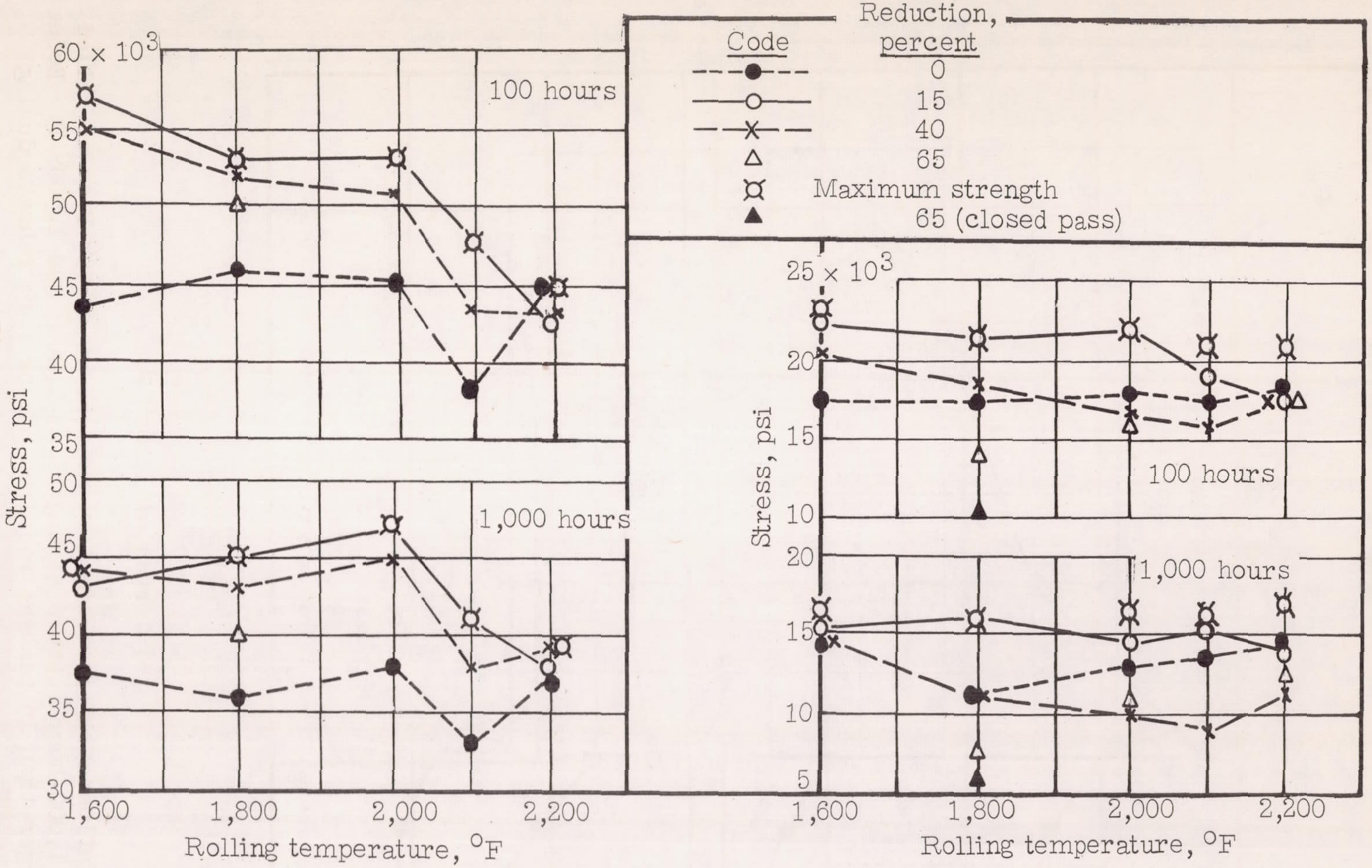
(b) Tested at 1,500° F.

Figure 5.- Influence of isothermal reductions at 1,800° F on as-rolled 100- and 1,000-hour rupture strengths at 1,200° and 1,500° F. Reductions larger than 25 percent required one or more reheats during rolling.



(b) Tested at 1,500° F.

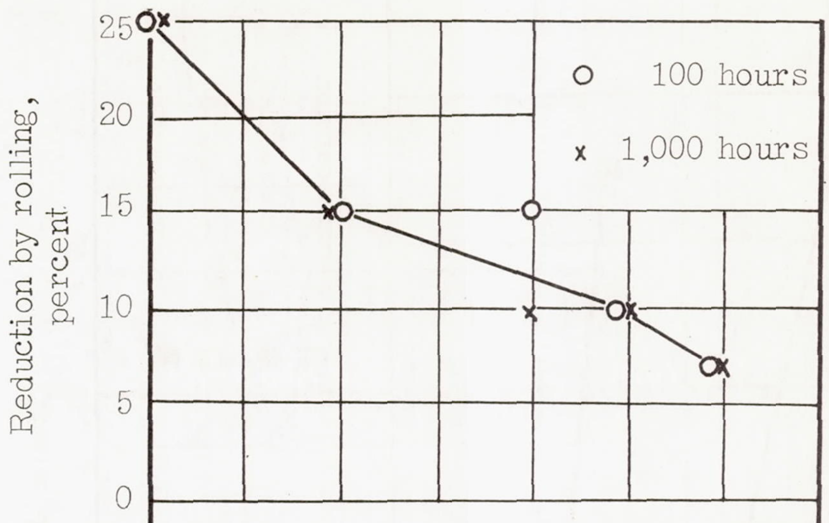
Figure 6.- Influence of isothermal reductions at 1,600° F on as-rolled 100- and 1,000-hour rupture strengths at 1,200° and 1,500° F. Reductions larger than 15 percent required one or more reheats during rolling.



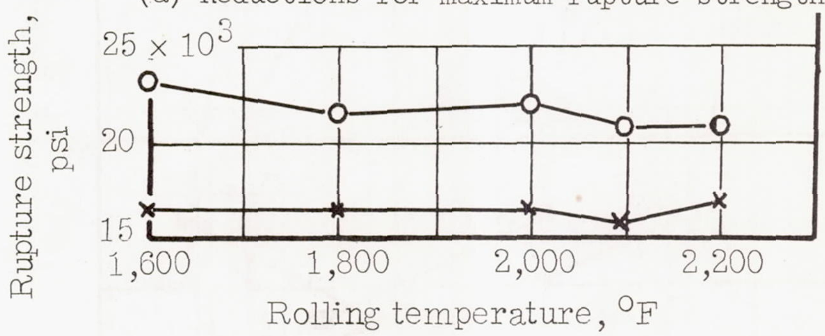
(a) Rupture strengths at 1,200° F.

(b) Rupture strengths at 1,500° F.

Figure 7.- Influence of temperature of hot-working on rupture strengths for 100 and 1,000 hours at 1,200° and 1,500° F.



(a) Reductions for maximum rupture strength.



(b) Maximum rupture strengths.

Figure 8.- Reduction by rolling for maximum rupture strength at 1,500° F.

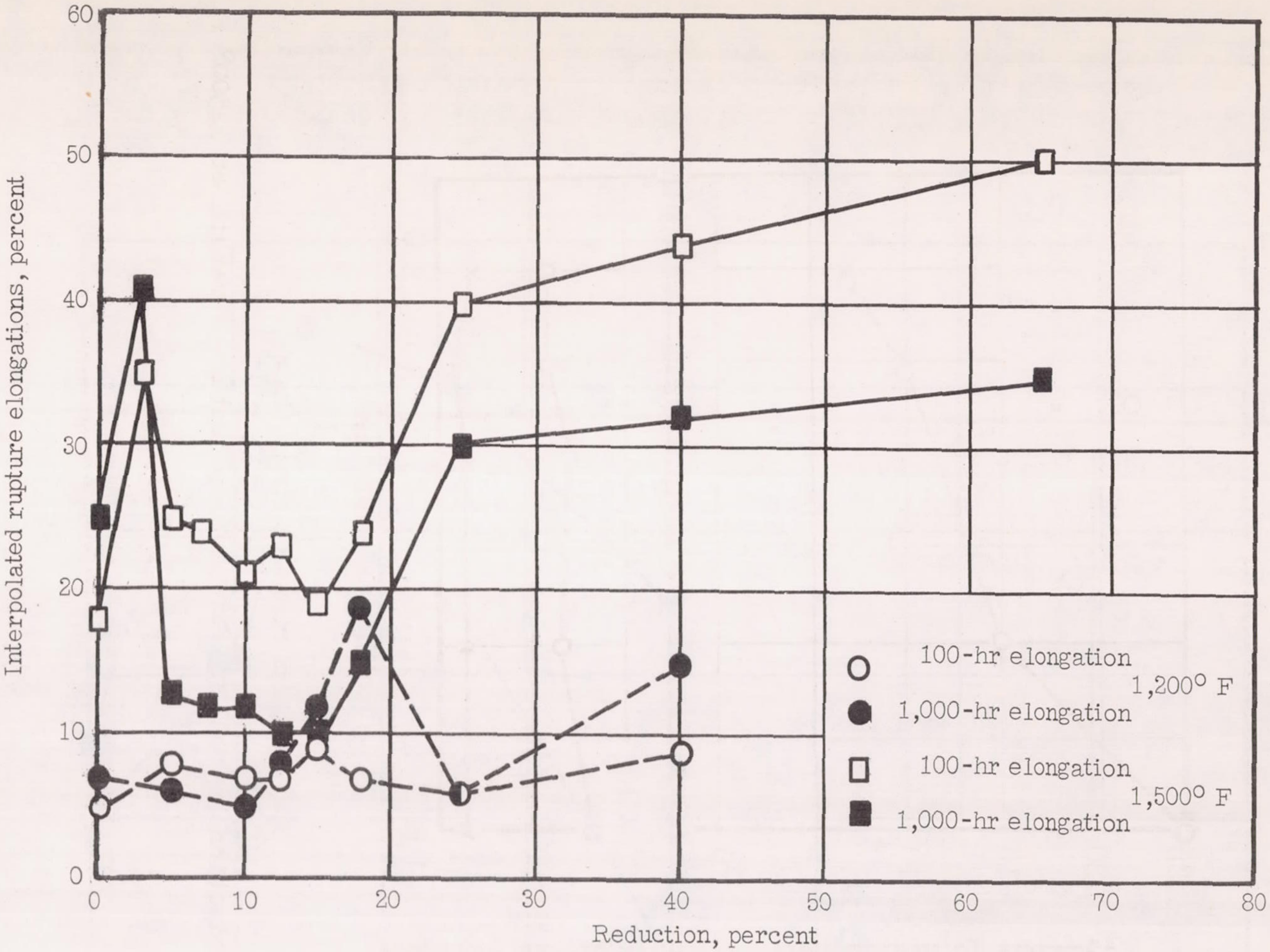


Figure 9.- Influence of isothermal reductions at 2,200° F on as-rolled 100- and 1,000-hour interpolated rupture elongations at 1,200° and 1,500° F. Reductions larger than 25 percent required one or more reheats during rolling.

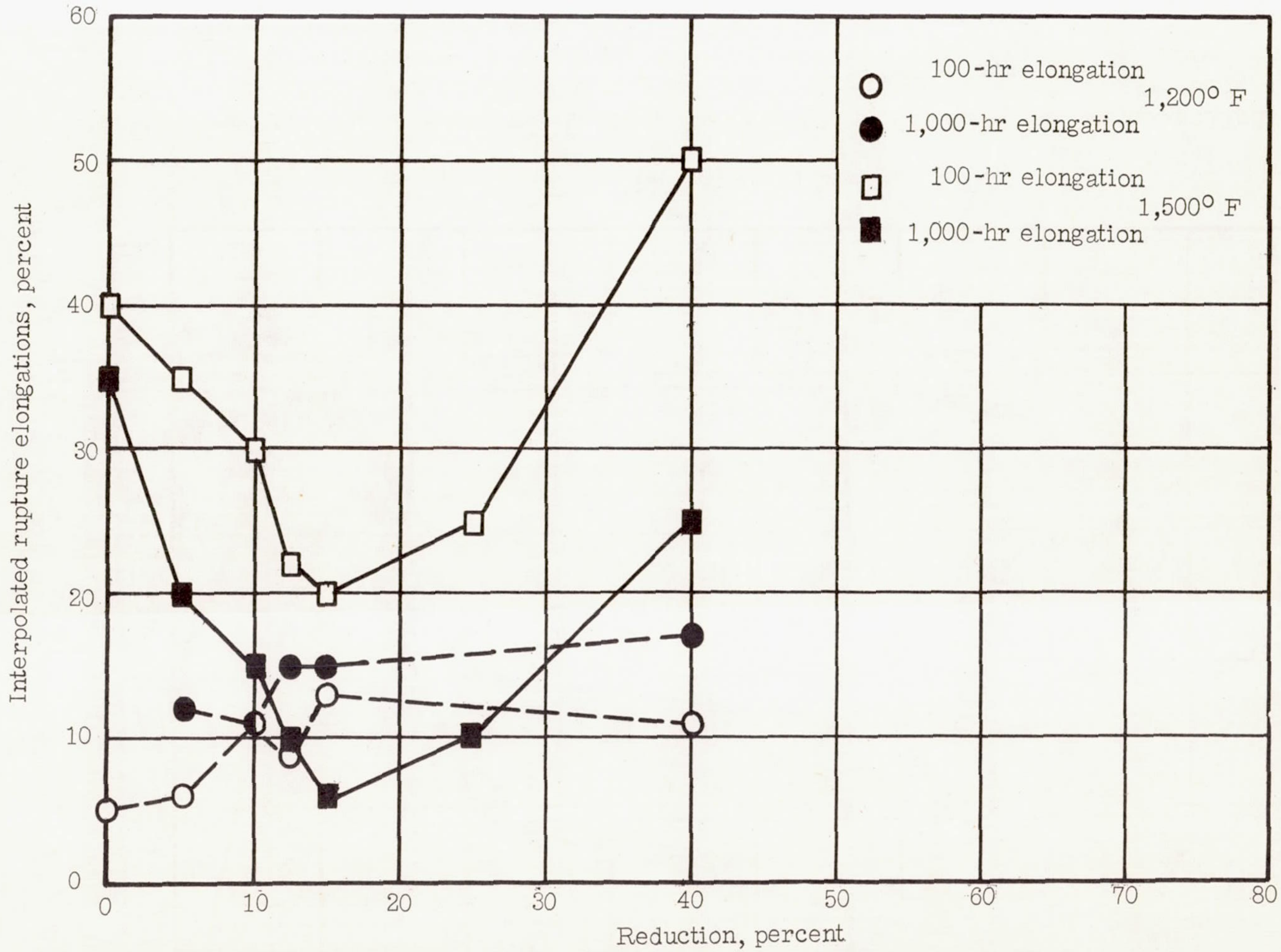


Figure 10.- Influence of isothermal reductions at 2,100° F on as-rolled 100- and 1,000-hour interpolated rupture elongations at 1,200° and 1,500° F. Reduction of 40 percent required one reheat during rolling.

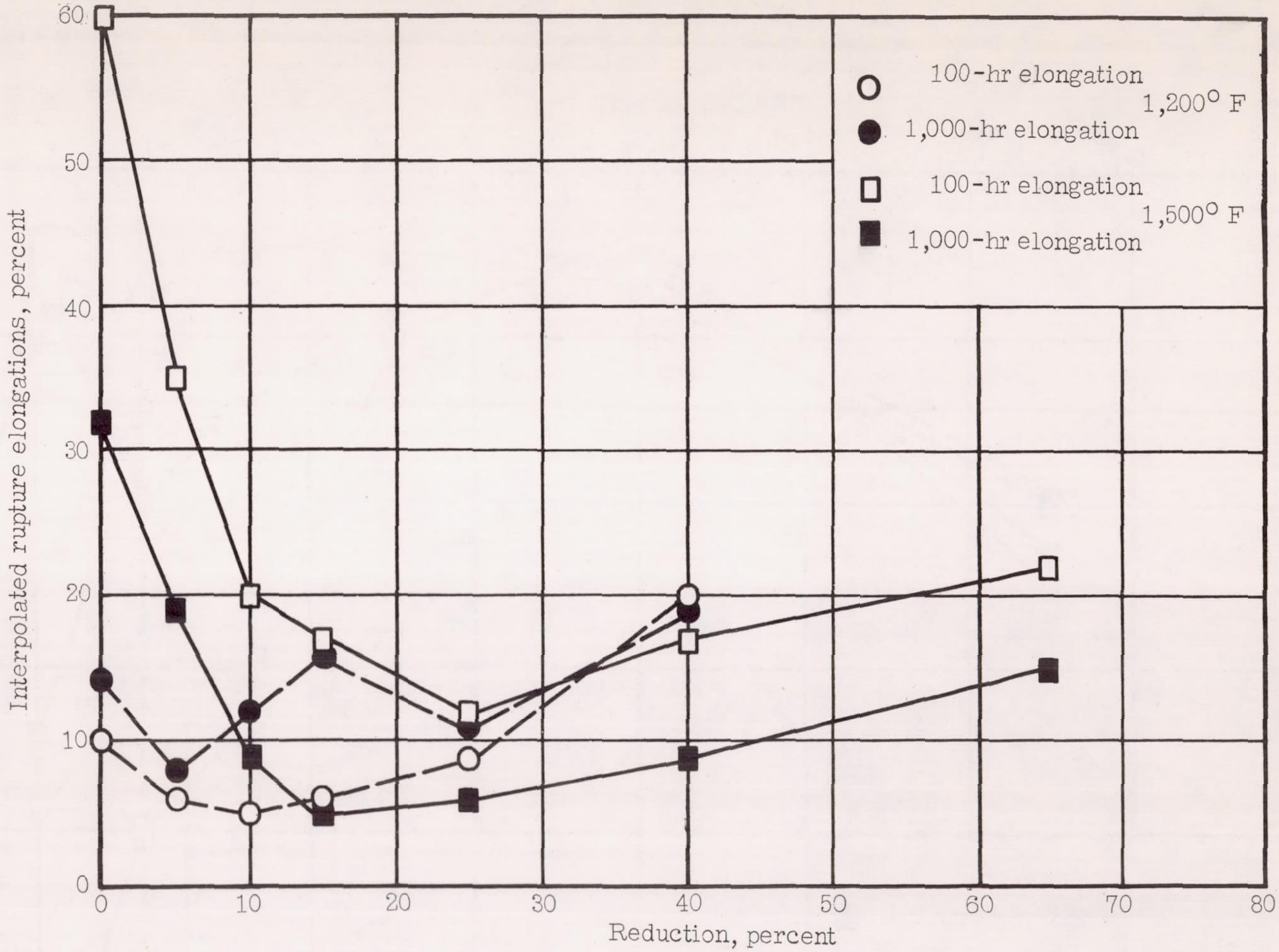


Figure 11.- Influence of isothermal reductions at 2,000° F on as-rolled 100- and 1,000-hour interpolated rupture elongations at 1,200° and 1,500° F. Reductions larger than 25 percent required one or more reheats during rolling.

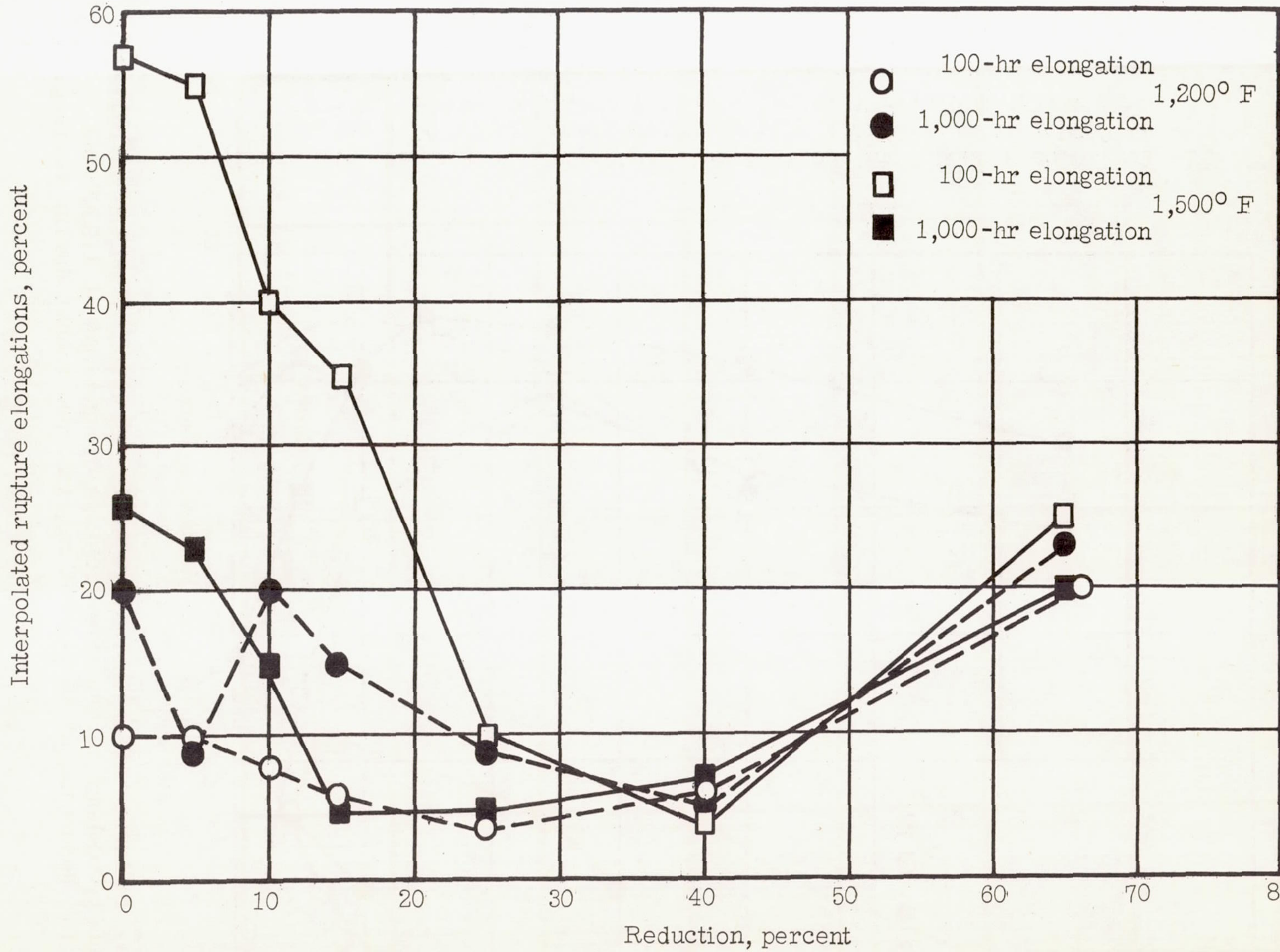


Figure 12.- Influence of isothermal reductions at 1,800° F on as-rolled 100- and 1,000-hour interpolated rupture elongations at 1,200° and 1,500° F. Reductions larger than 25 percent required one or more reheats during rolling.

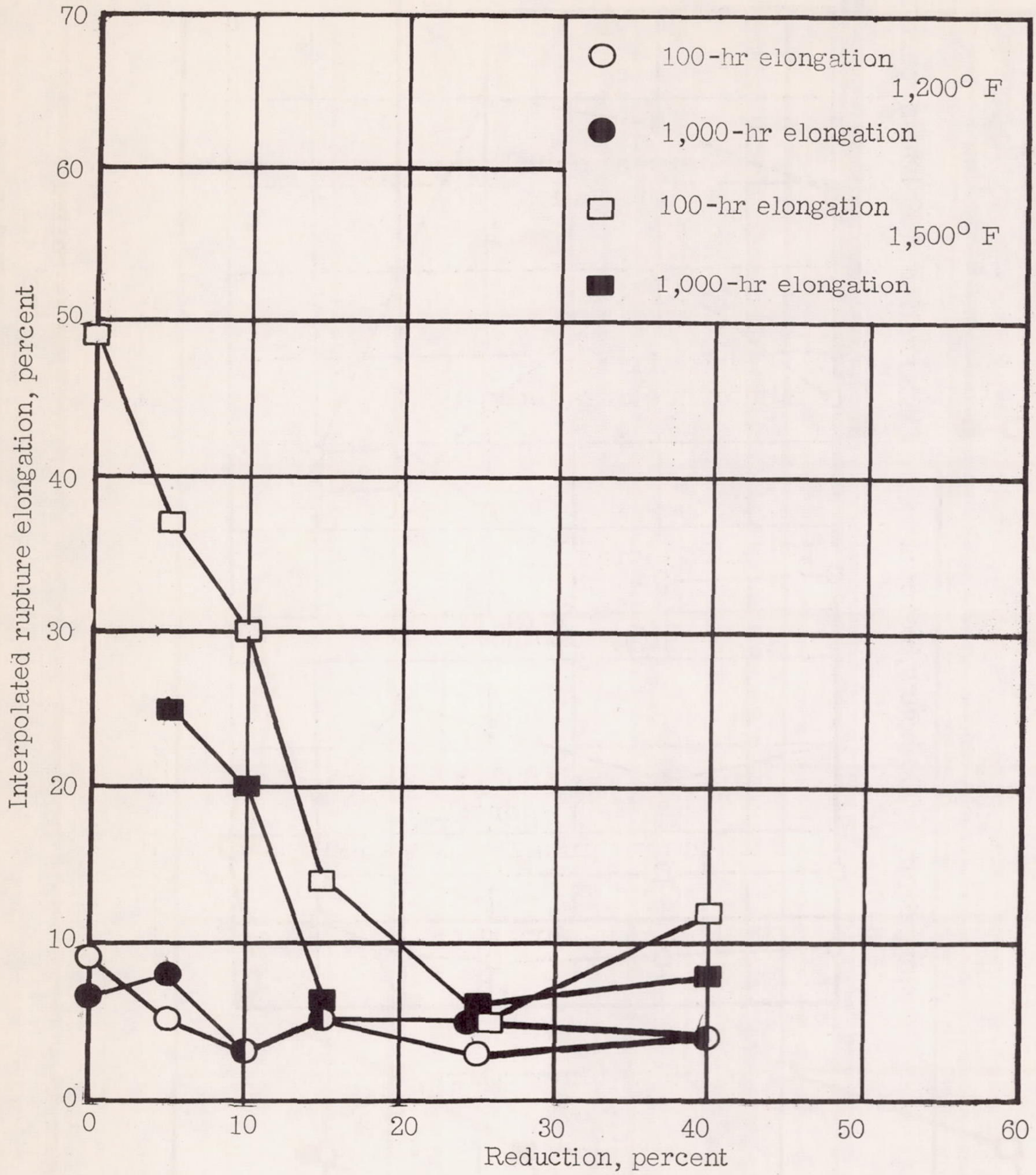
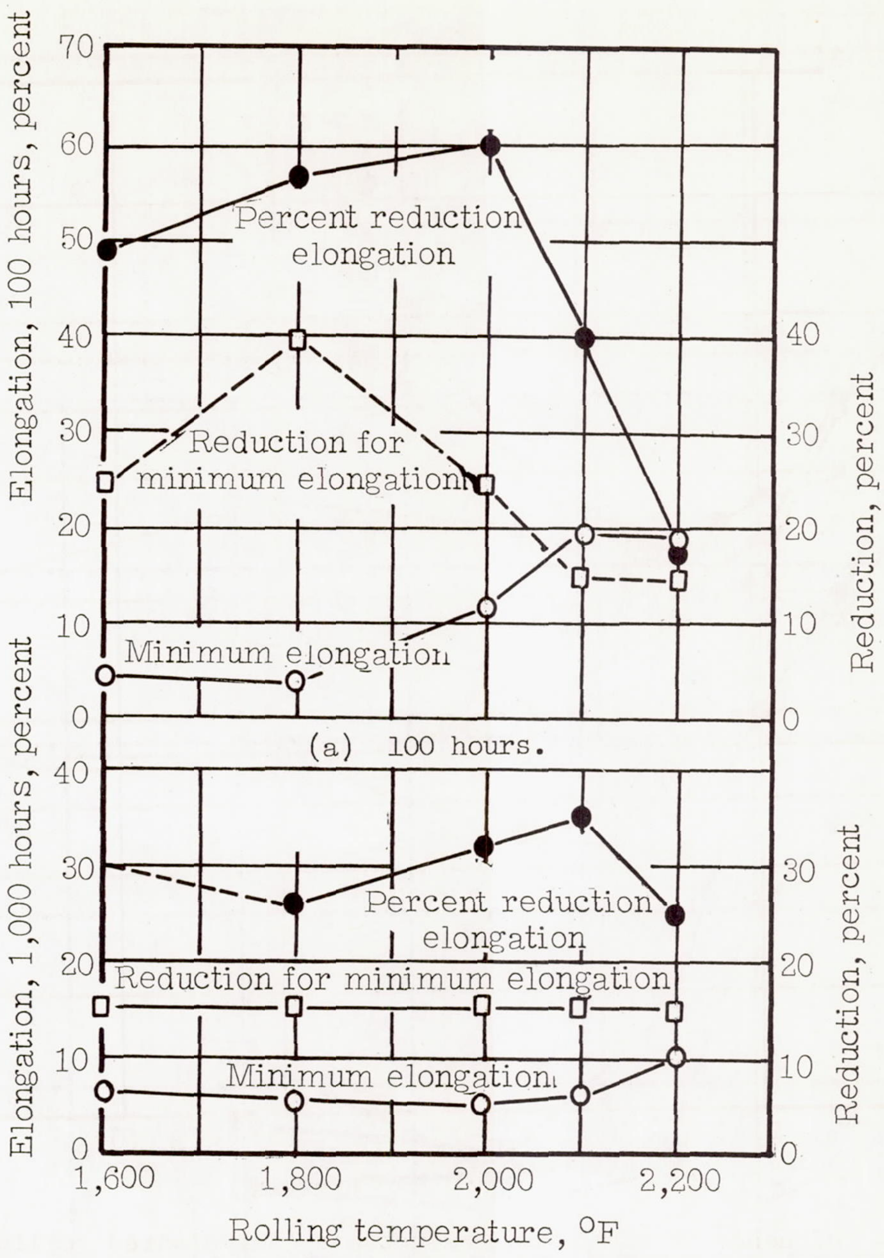


Figure 13.- Influence of isothermal reduction at 1,600° F on the as-rolled 100- and 1,000-hour interpolated rupture elongations at 1,200° and 1,500° F. Reduction of 40 percent required one reheat during rolling.



(b) 1,000 hours.

Figure 14.- Relationships between rolling temperature and elongation for rupture in 100 and 1,000 hours at 1,500° F for no reduction and for reduction giving minimum elongation.

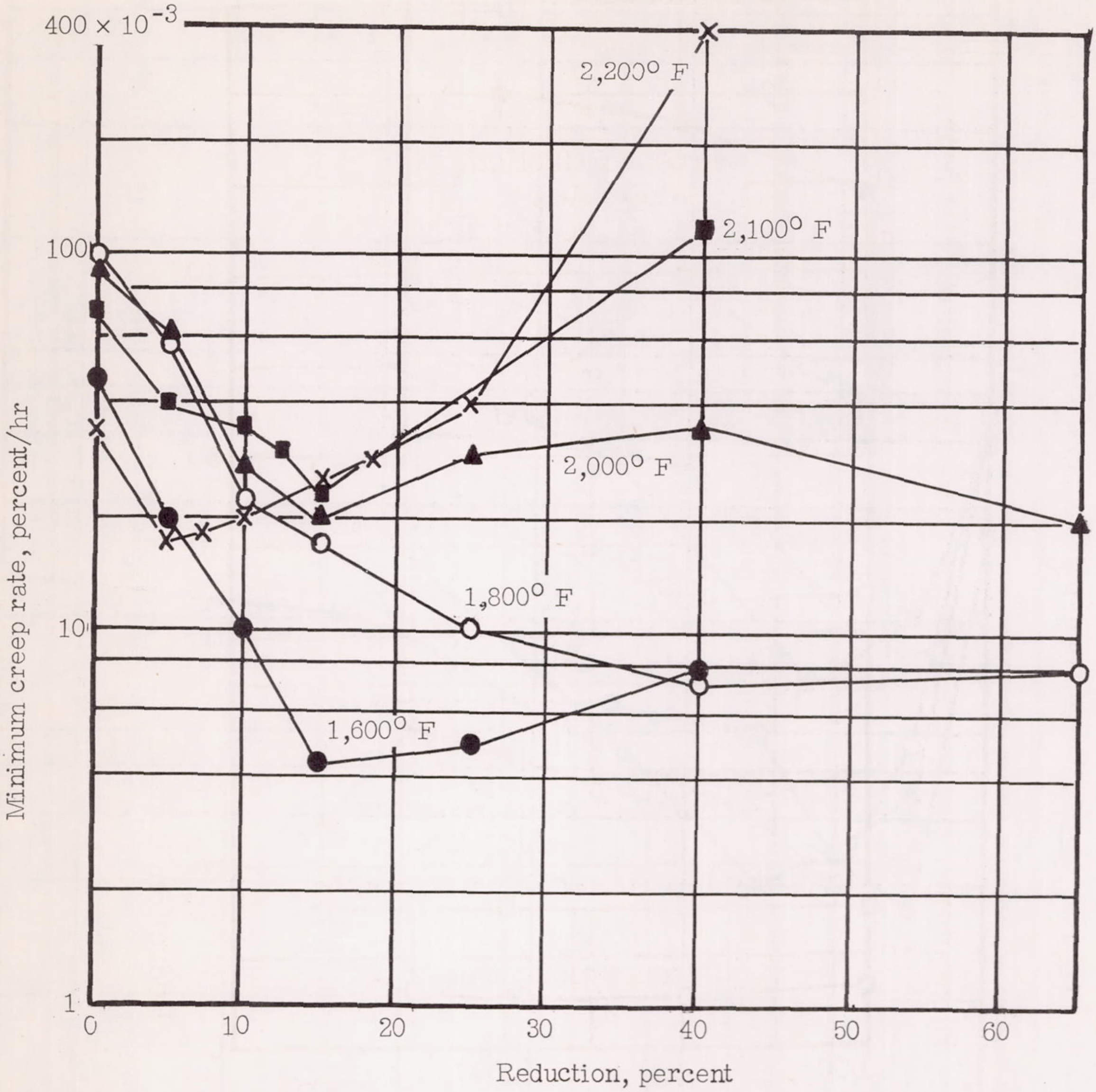


Figure 15.- Influence of isothermal reductions at indicated rolling temperature on as-rolled minimum creep rates for 50,000 psi at 1,200° F. Reductions larger than 15 percent at 1,600° F or larger than 25 percent at 1,800° F and above required one or more reheats during rolling.

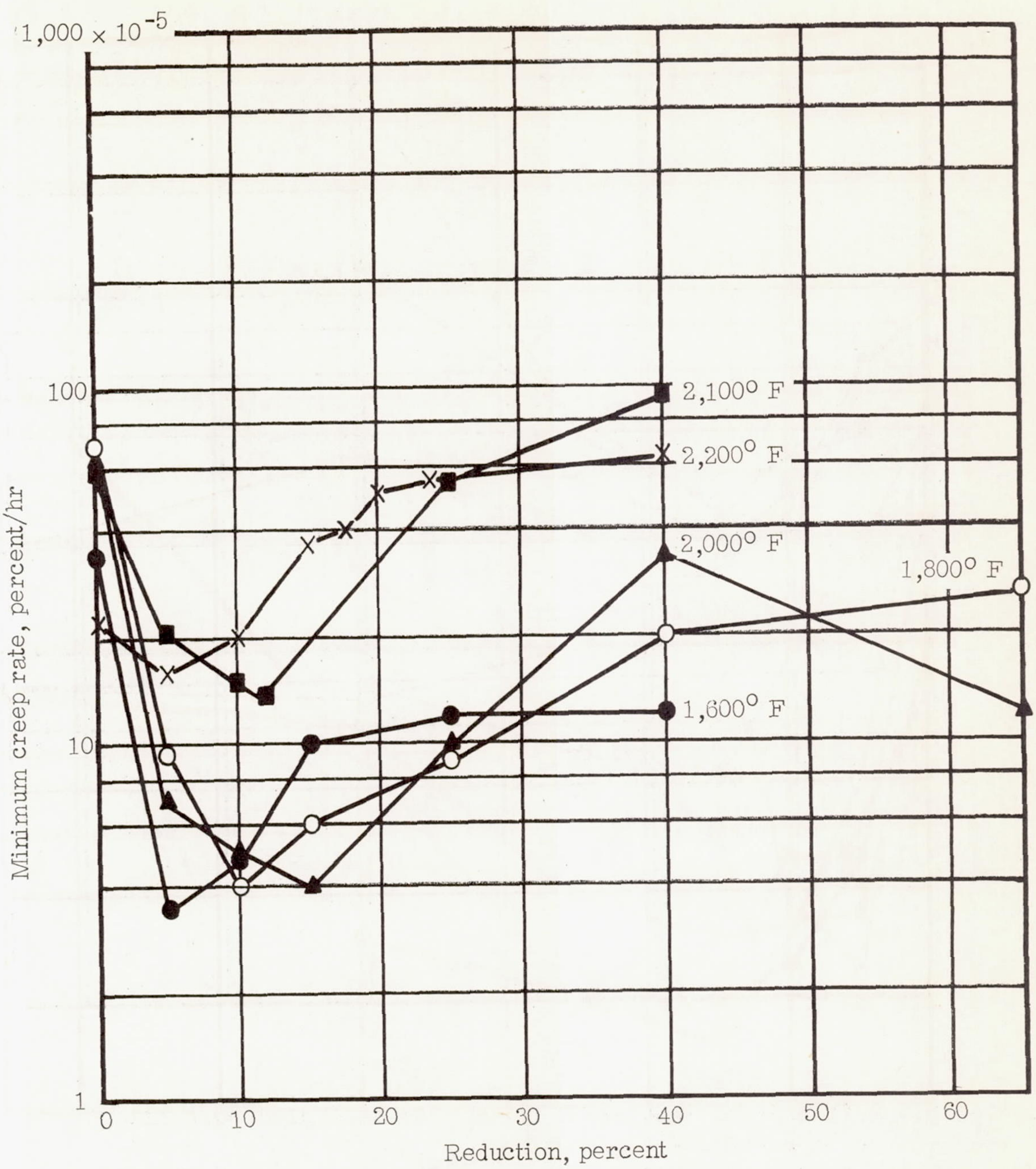


Figure 16.- Influence of isothermal reductions at indicated rolling temperature on as-rolled minimum creep rates in 1,000 hours for 25,000 psi at 1,200° F. Reductions larger than 15 percent at 1,600° F or larger than 25 percent at 1,800° F and above required one or more reheats during rolling.

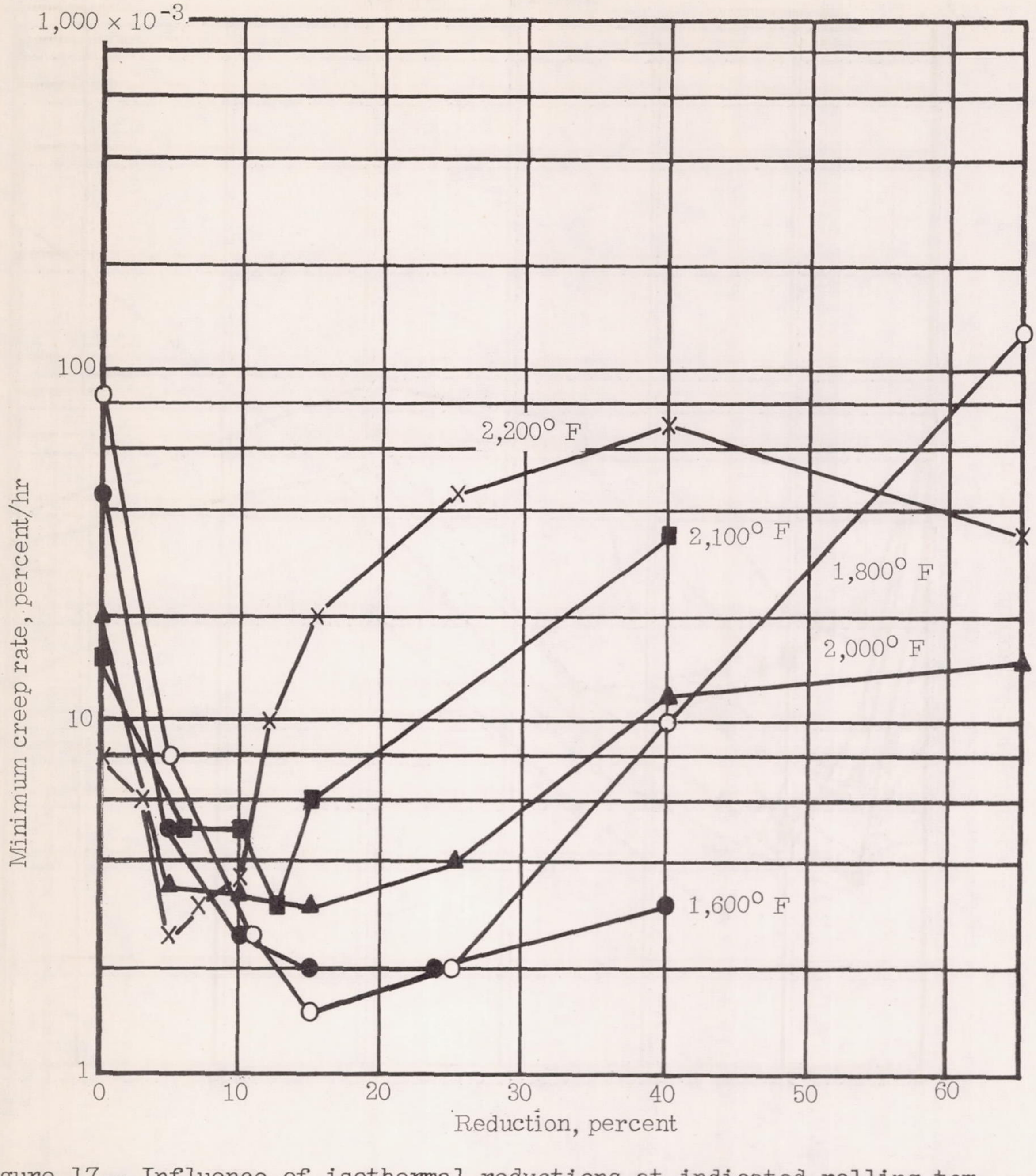


Figure 17.- Influence of isothermal reductions at indicated rolling temperatures on as-rolled minimum creep rate for 15,000 psi at 1,500° F. Reductions larger than 15 percent at 1,600° F or larger than 25 percent at 1,800° F and above required one or more reheats during rolling.

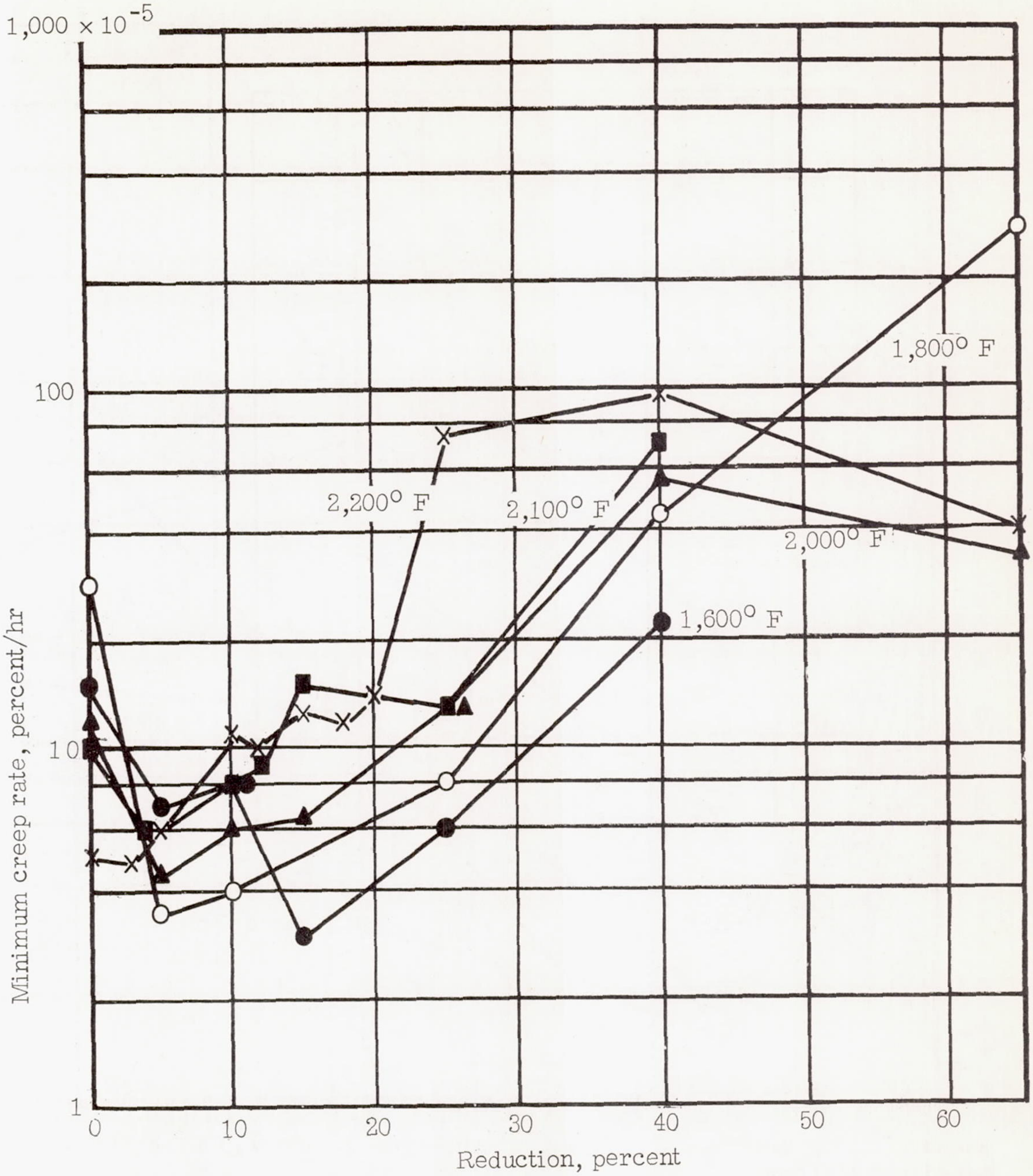
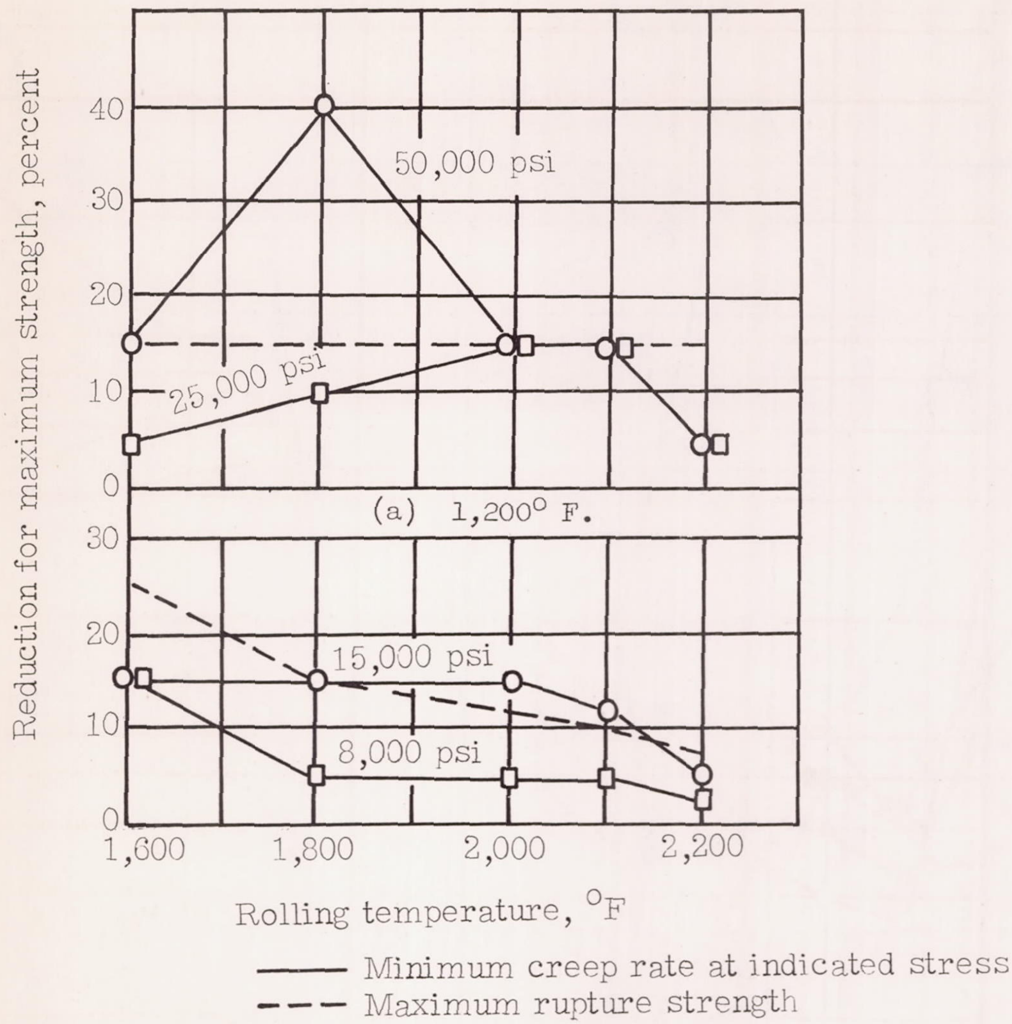


Figure 18.- Influence of isothermal reductions at indicated rolling temperatures on as-rolled minimum creep rate in 1,000 hours for 8,000 psi at 1,500° F. Reductions larger than 15 percent at 1,800° F and above required one or more reheats during rolling.



(b) 1,500° F.

Figure 19.- Influence of rolling temperature on percent reduction for maximum creep and rupture properties at 1,200° and 1,500° F for indicated conditions.

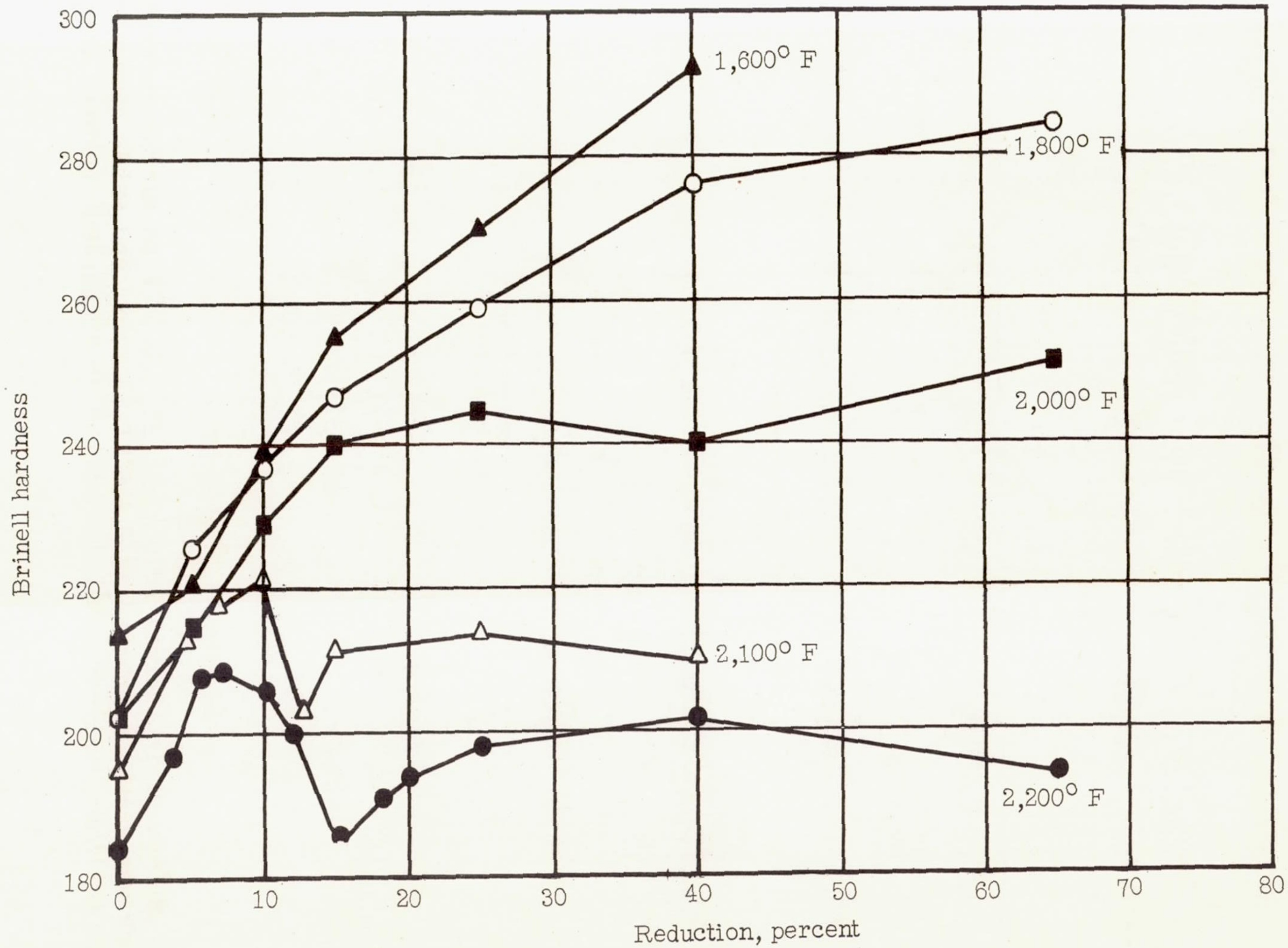
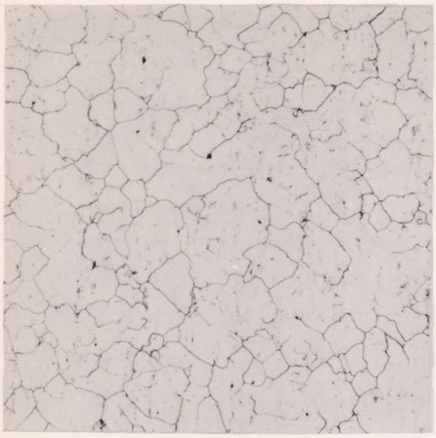


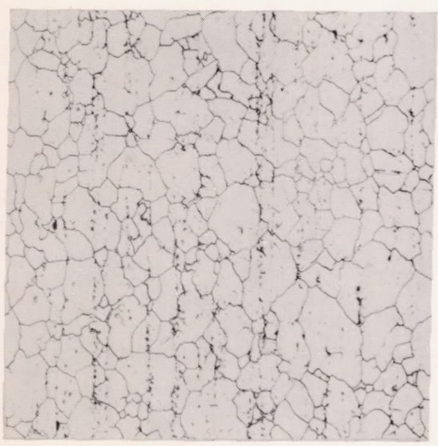
Figure 20.- Influence of isothermal reductions at 1,600°, 1,800°, 2,000°, 2,100°, or 2,200° F on as-rolled hardness. Reductions larger than 15 percent at 1,600° F or larger than 25 percent at 1,800° F and above required one or more reheats during rolling.



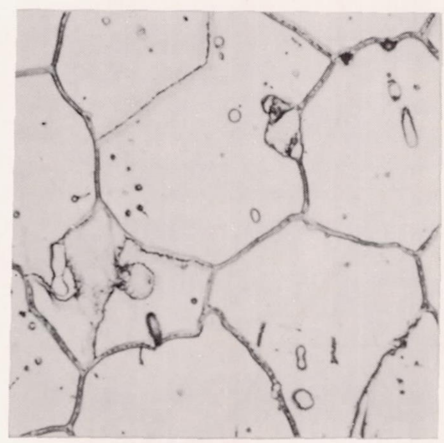
X100

X1000

(a) Rolled 0 percent.



X100



X1000

(b) Rolled 15 percent.

L-92488

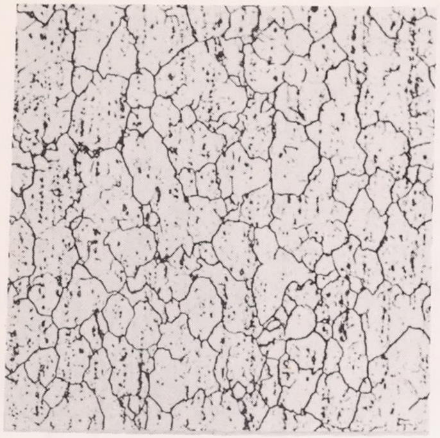
Figure 21.- Effect of isothermal reductions at 1,600° F on microstructures. Bar stock was solution treated at 2,200° F, 1 hour, and water quenched prior to rolling. (Electrolytically etched in 10 percent chromic acid.)

X100

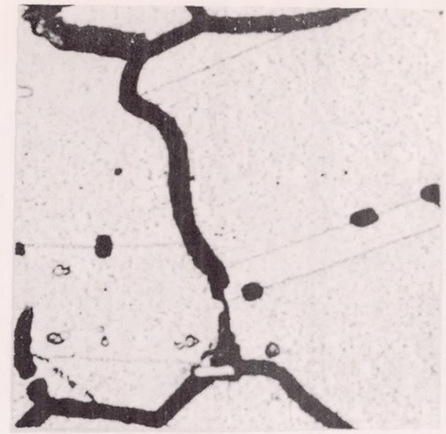
X1000

(c) Rolled 40 percent. L-92489

Figure 21.- Concluded.

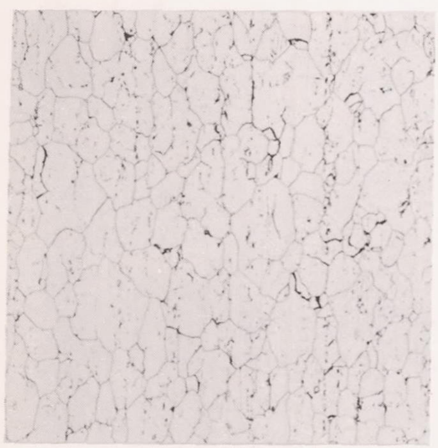


X100

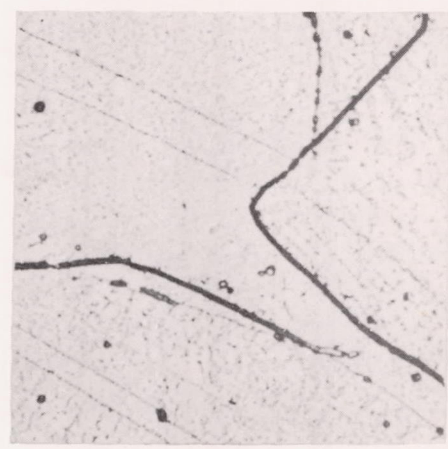


X1000

(a) Rolled 15 percent.



X100

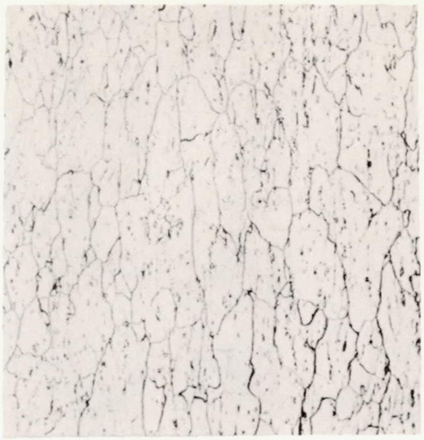


X1000

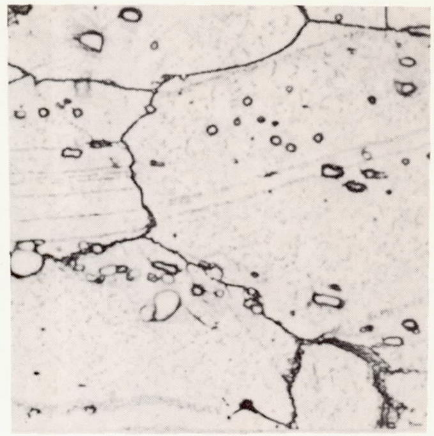
(b) Rolled 25 percent.

L-92490

Figure 22.- Effect of isothermal reductions at 1,800° F on microstructures. Bar stock was solution treated at 2,200° F, 1 hour, and water quenched prior to rolling. (Electrolytically etched in 10 percent chromic acid.)

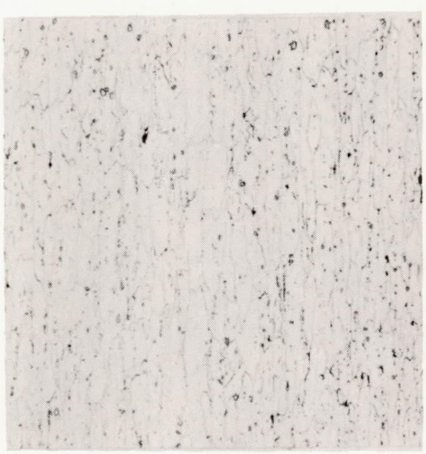


X100



X1000

(c) Rolled 40 percent.



X100

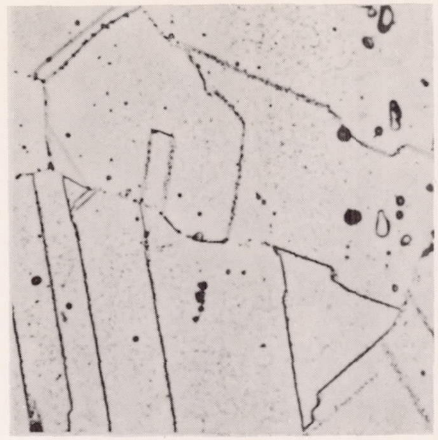
X1000

(d) Rolled 65 percent.

L-92491

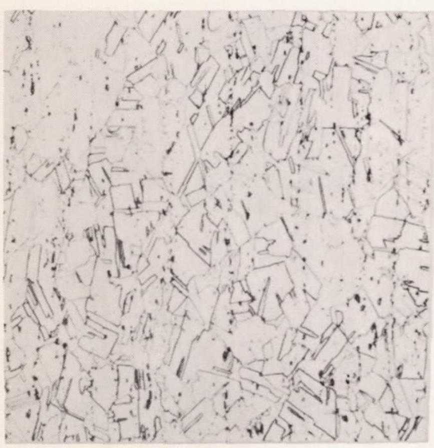
Figure 22.- Concluded.

X100

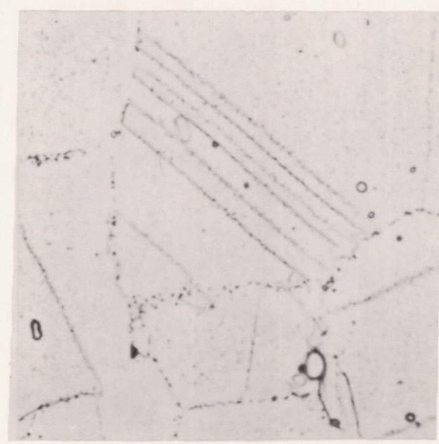


X1000

(a) Rolled 0 percent.



X100

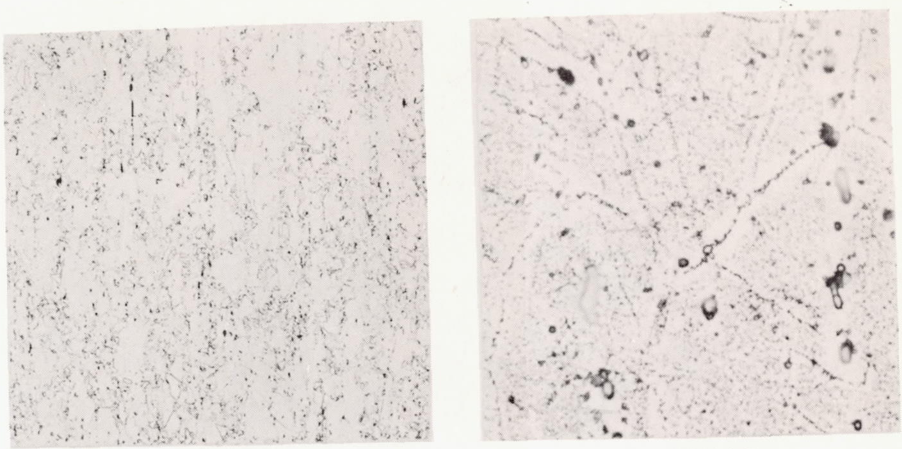


X1000

(b) Rolled 15 percent.

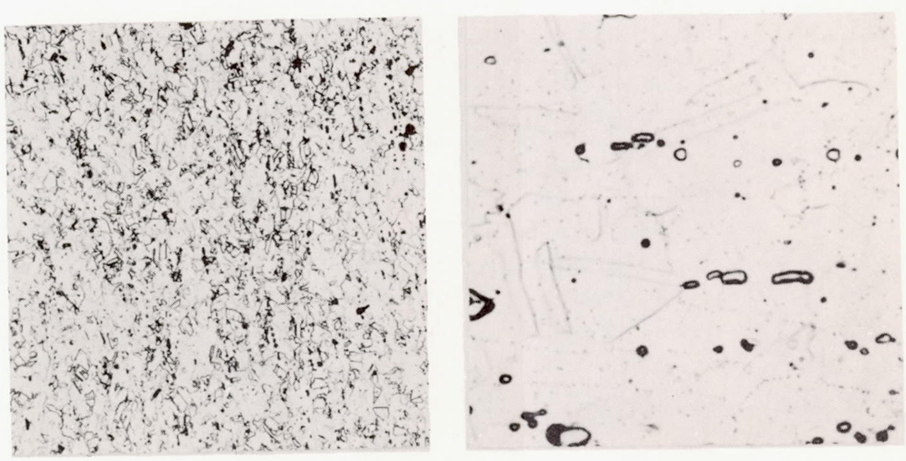
L-92492

Figure 23.- Effect of isothermal reductions at 2,000° F on microstructures. Bar stock was solution treated at 2,200° F, 1 hour, and water quenched prior to rolling. (Electrolytically etched in 10 percent chromic acid.)



X100 X1000

(c) Rolled 40 percent.

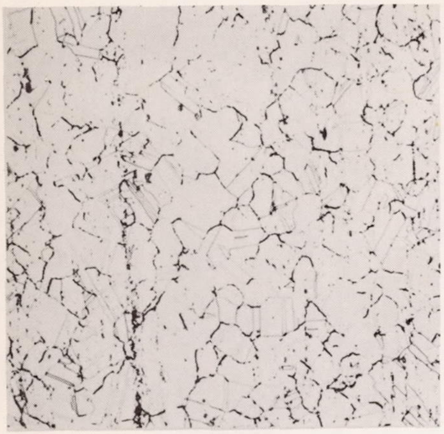


X100 X1000

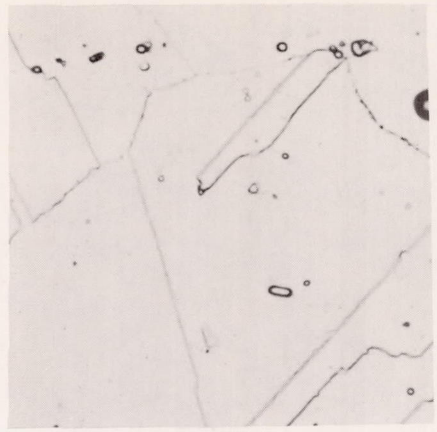
L-92493

(d) Rolled 65 percent.

Figure 23.- Concluded.



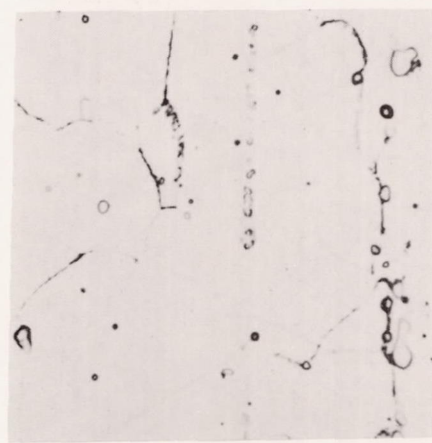
X100



X1000

(a) Rolled 5 percent.

X100

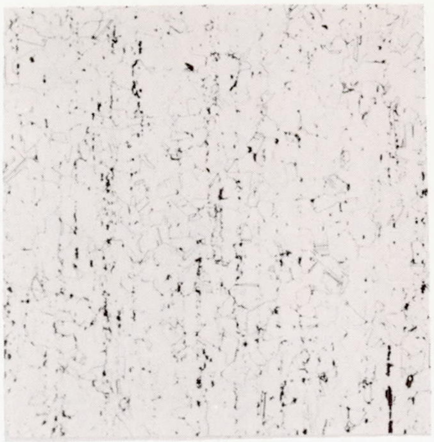


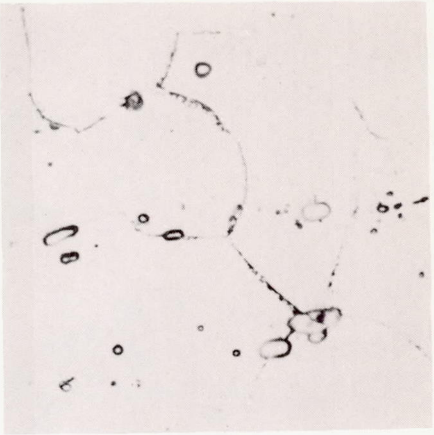
X1000

L-92494

(b) Rolled 10 percent.

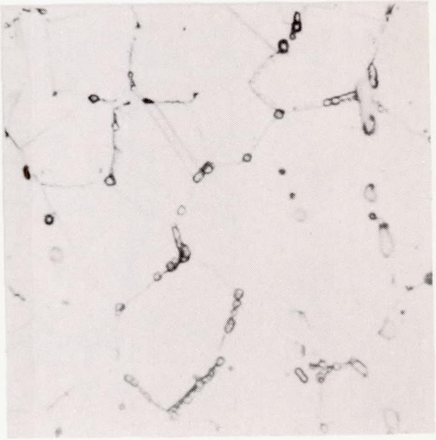
Figure 24.- Effect of isothermal reductions at 2,200° F on microstructures. Bar stock was solution treated at 2,200° F, 1 hour, and water quenched prior to rolling. (Electrolytically etched in 10 percent chromic acid.)





X100 X1000

(c) Rolled 15 percent.

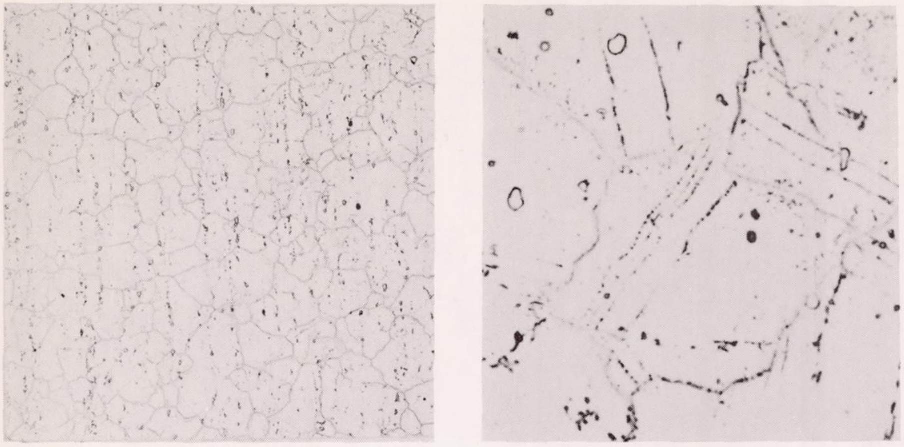


X100 X1000

(d) Rolled 40 percent.

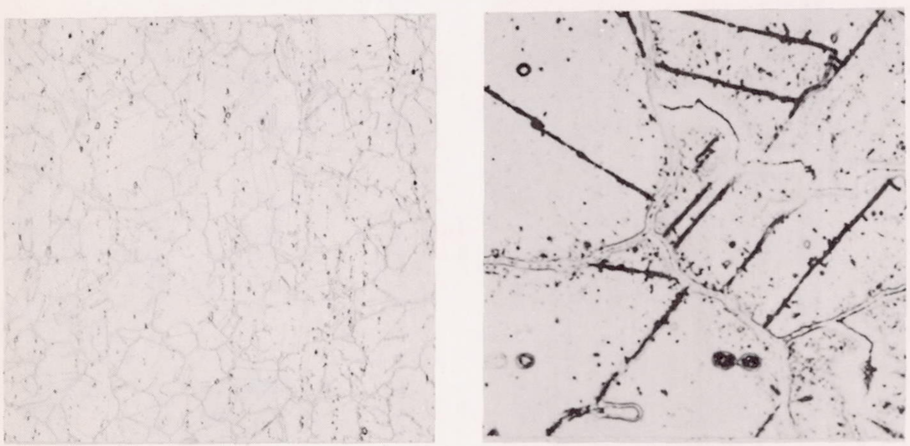
L-92495

Figure 24.- Concluded.



X100 X1000

(a) Rolled 0 percent.

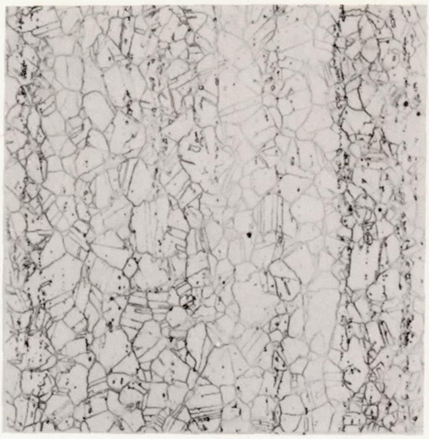


X100 X1000

(b) Rolled 10 percent.

L-92496

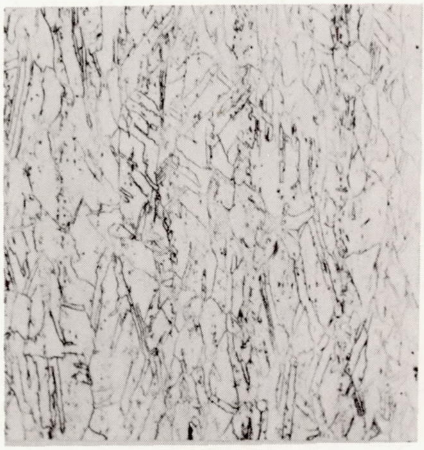
Figure 25.- Microstructures after creep testing for 1,000 hours at 1,200° F with stress of 25,000 psi. Prior to testing, bar stock was solution treated at 2,200° F, 1 hour, water quenched, and rolled at 1,600° F as indicated. (Electrolytically etched in 10 percent chromic acid.)



X100

X1000

(c) Rolled 15 percent.



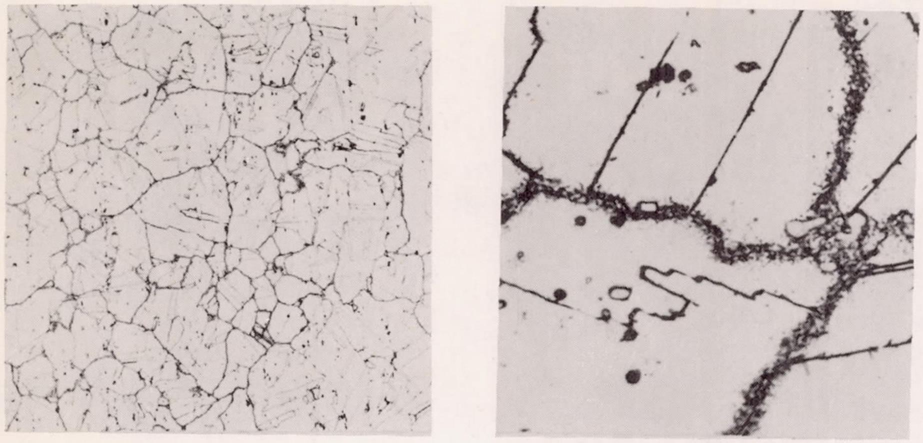
X100

X1000

(d) Rolled 40 percent.

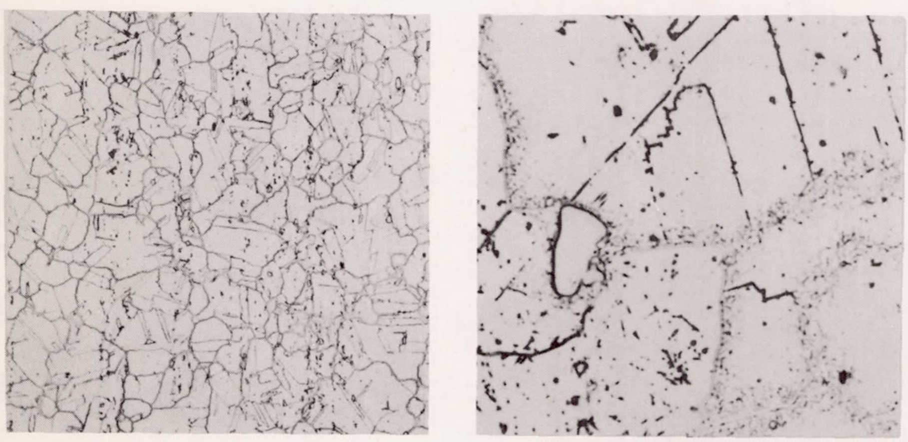
L-92497

Figure 25.- Concluded.



X100 X1000

(a) Rolled 5 percent.

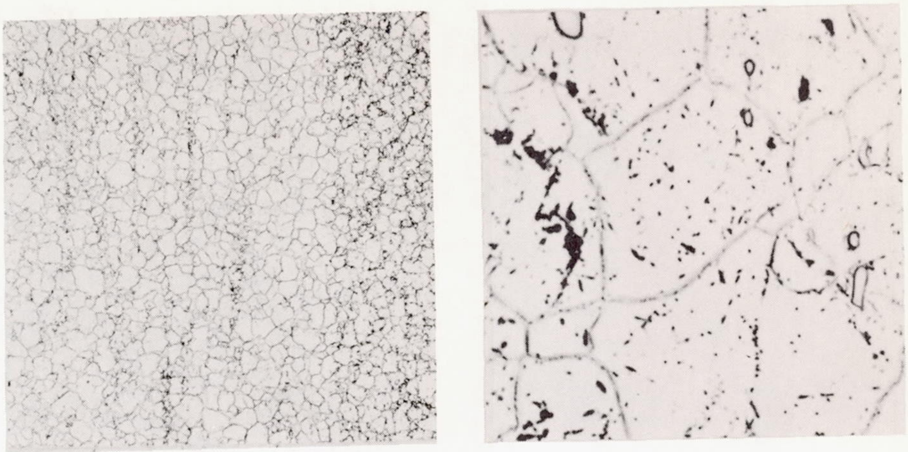


X100 X1000

L-92498

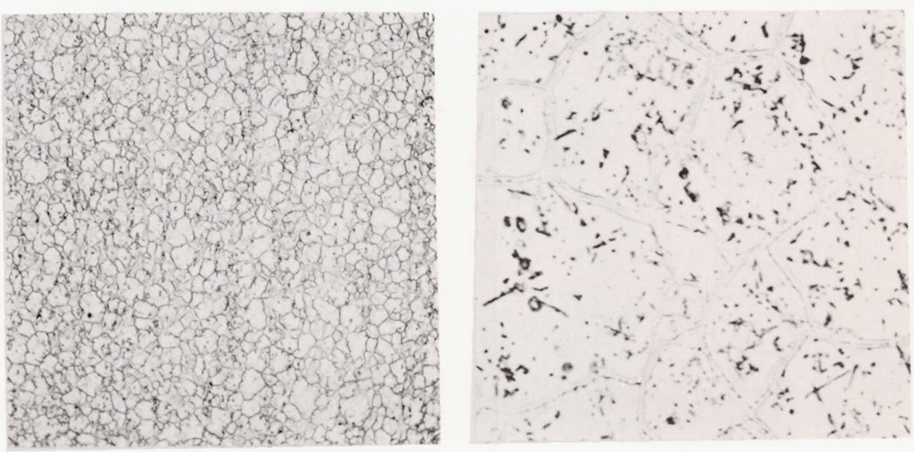
(b) Rolled 10 percent.

Figure 26.- Microstructures after creep testing for 1,000 hours at 1,200° F with stress of 25,000 psi. Prior to testing, bar stock was solution treated at 2,200° F, 1 hour, water quenched, and rolled at 2,200° F as indicated. (Electrolytically etched in 10 percent chromic acid.)



X100 X1000

(c) Rolled 15 percent.

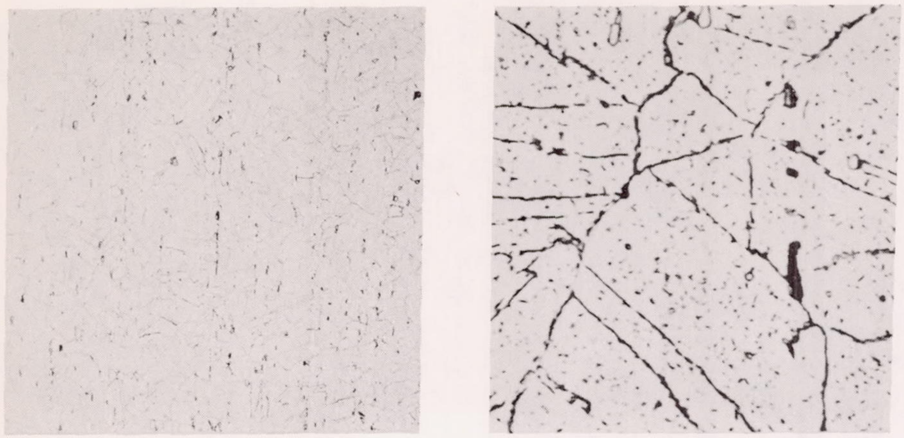


X100 X1000

(d) Rolled 40 percent.

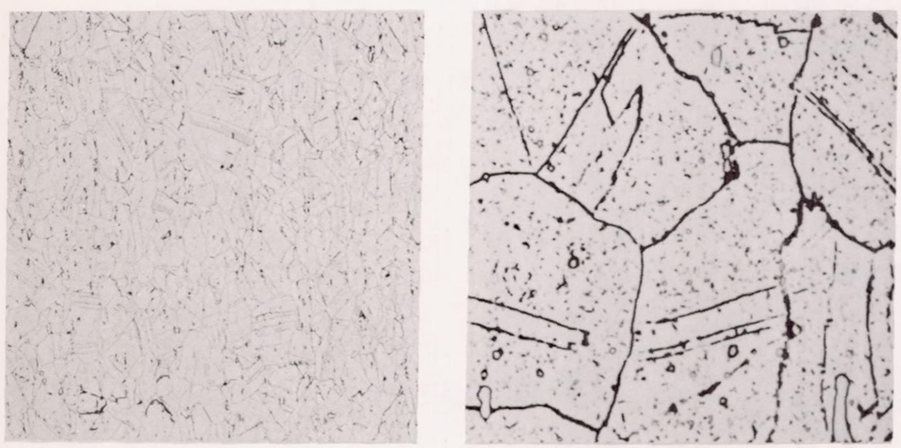
L-92499

Figure 26.- Concluded.



X100 X1000

(a) Rolled 10 percent at 1,600° F.

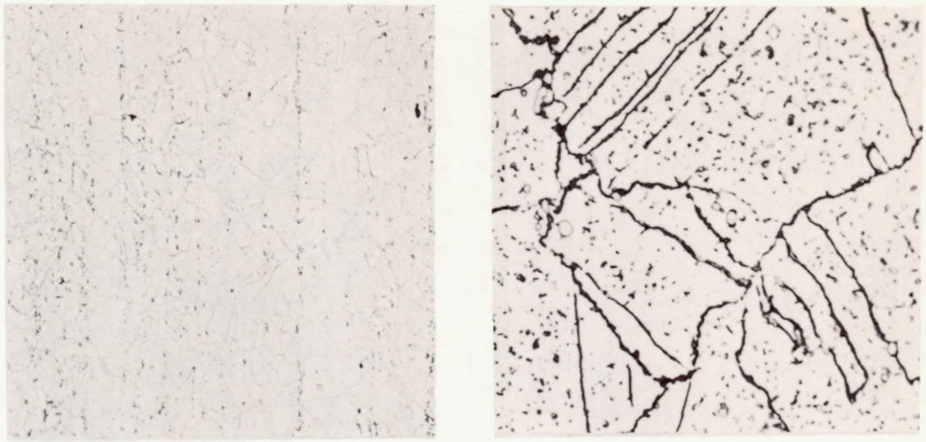


X100 X1000

(b) Rolled 25 percent at 1,800° F.

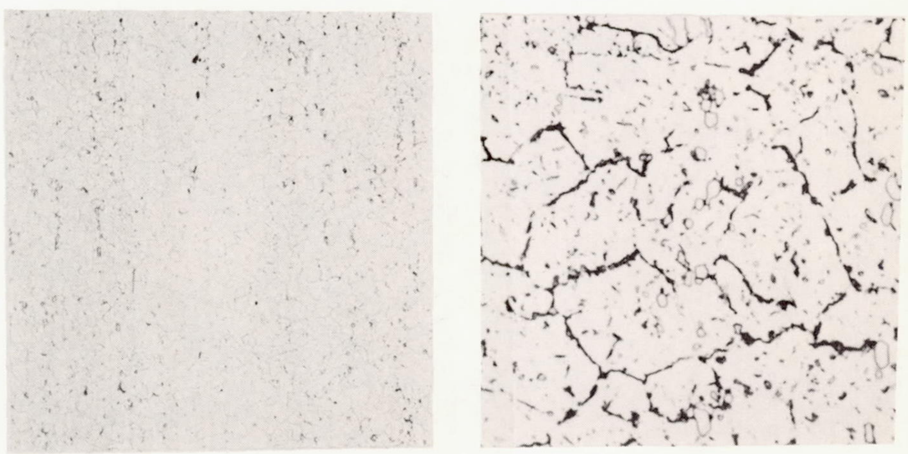
L-93491

Figure 27.- Typical microstructures after creep testing for 1,000 hours at 1,500° F with stress of 8,000 psi. Prior to testing, bar stock was solution treated at 2,200° F, 1 hour, water quenched, and rolled as indicated. (Electrolytically etched in 10 percent chromic acid.)



X100 X1000

(c) Rolled 15 percent at 2,000° F.



X100 X1000

L-93492

(d) Rolled 40 percent at 2,200° F.

Figure 27.- Concluded.

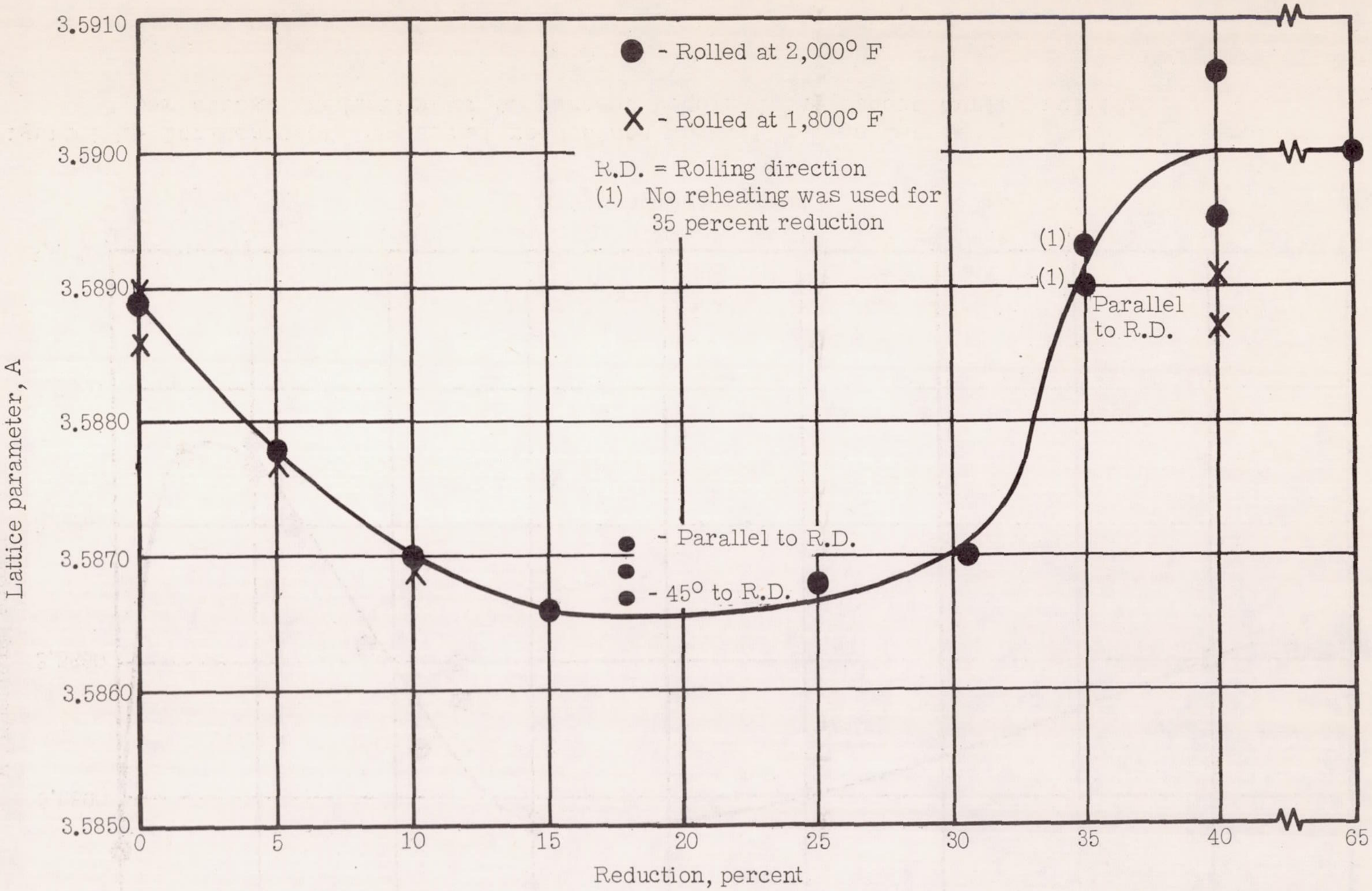


Figure 28.- Influence of isothermal reductions at 1,800° or 2,000° F on lattice parameter of as-rolled bar stock. Reductions larger than 25 percent required one or more reheats during rolling. All specimens are transverse to rolling direction unless indicated otherwise.

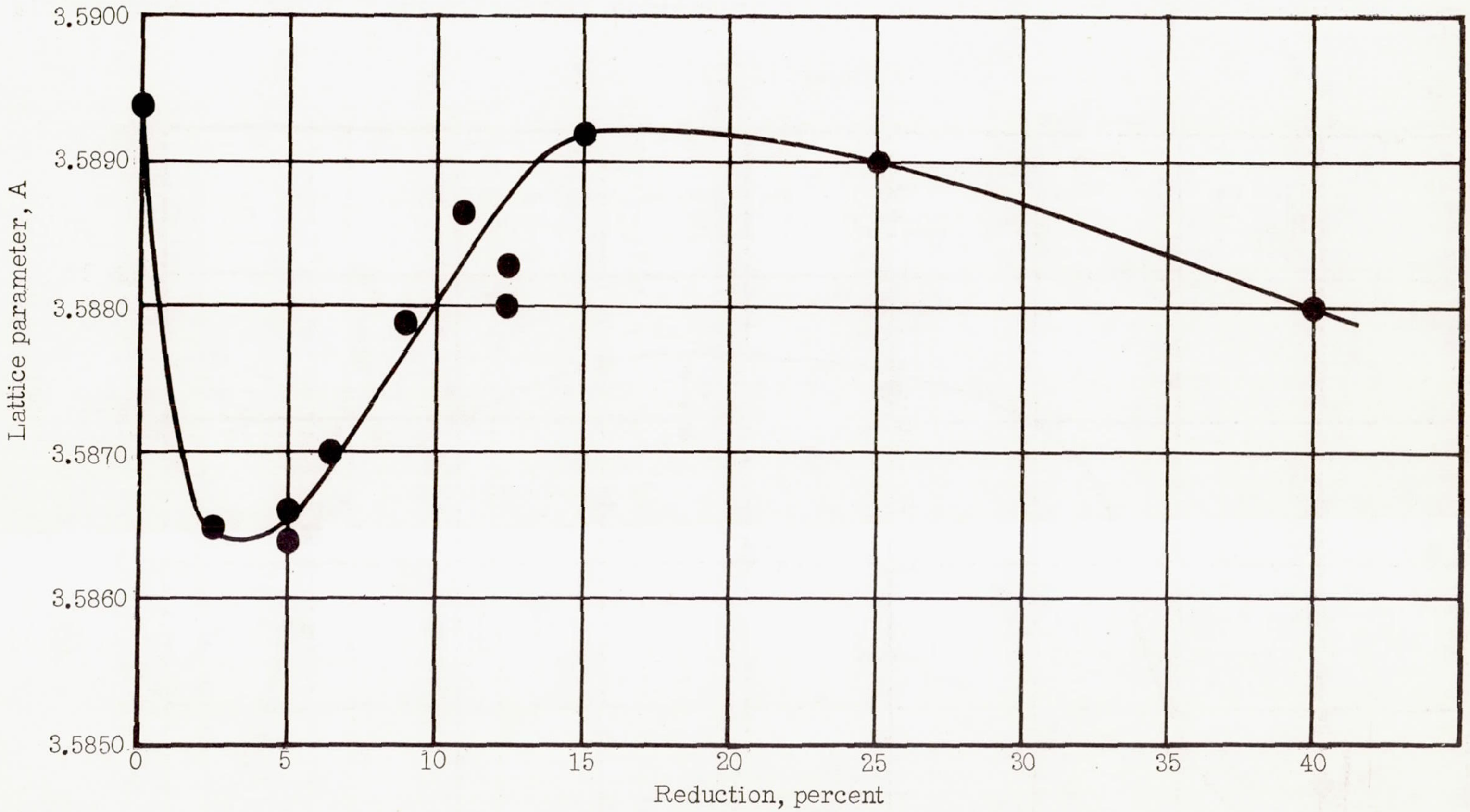


Figure 29.- Influence of isothermal reductions at 2,100° F on lattice parameter of as-rolled bar stock. Reduction of 40 percent required one reheat during rolling.

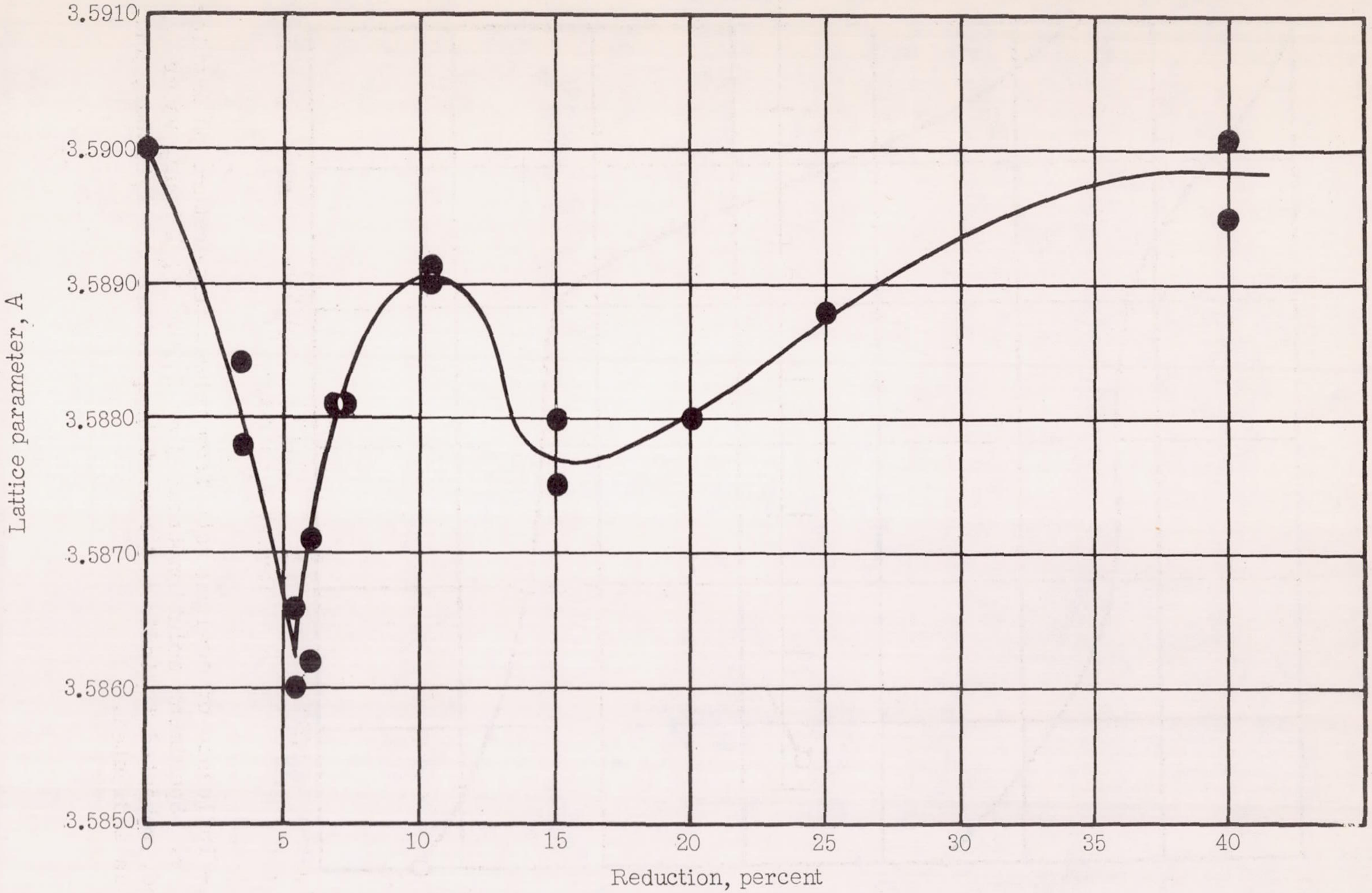


Figure 30.- Influence of isothermal reductions at 2,200° F on lattice parameter of as-rolled bar stock. Reduction of 40 percent required one reheat during rolling.

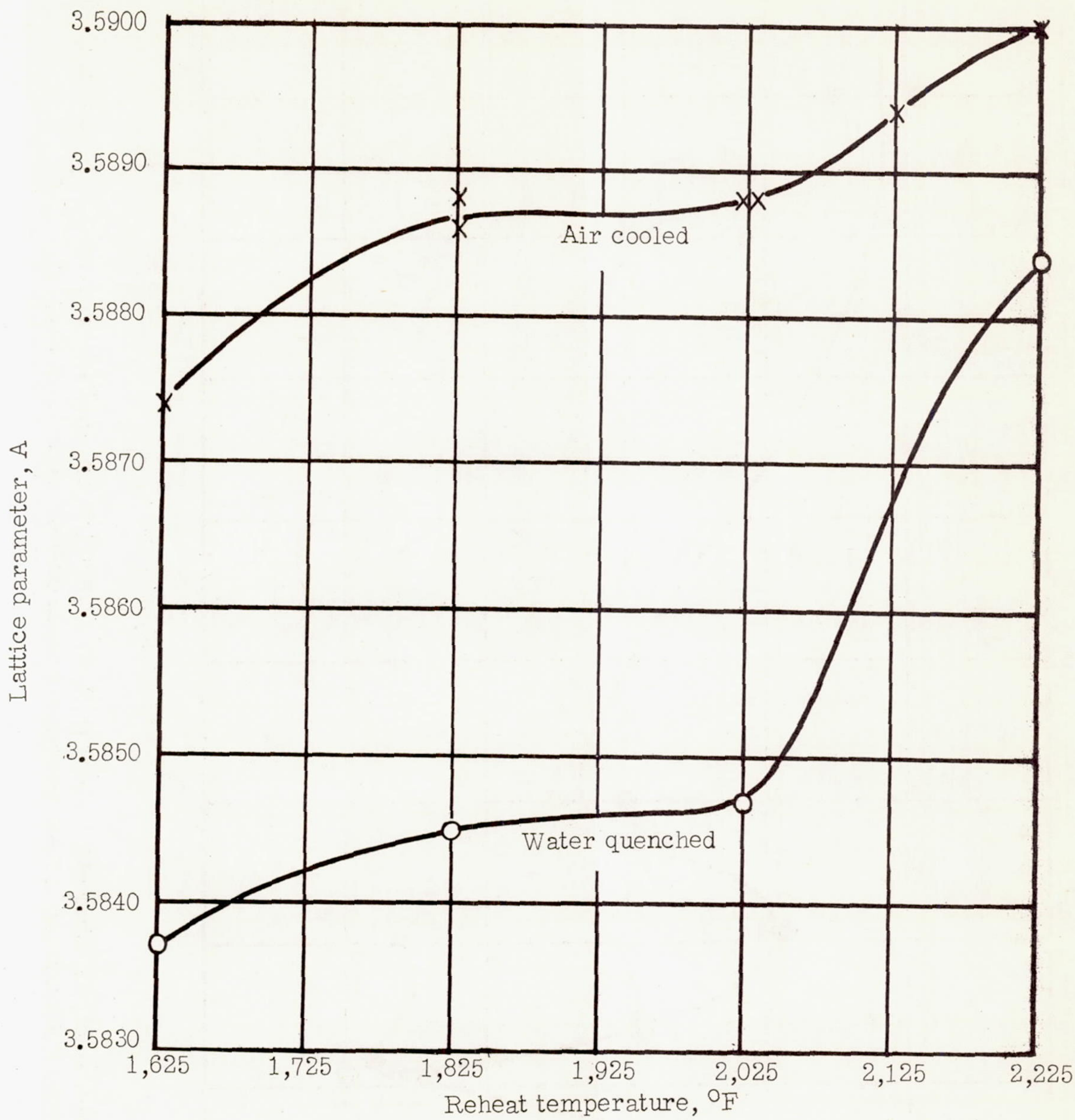


Figure 31.- Influence of cooling rate from reheat temperature on lattice parameter. Specimens solution treated at 2,200° F, 1 hour, water quenched, reheated to indicated reheat temperature for 1/2 hour, and cooled as indicated.

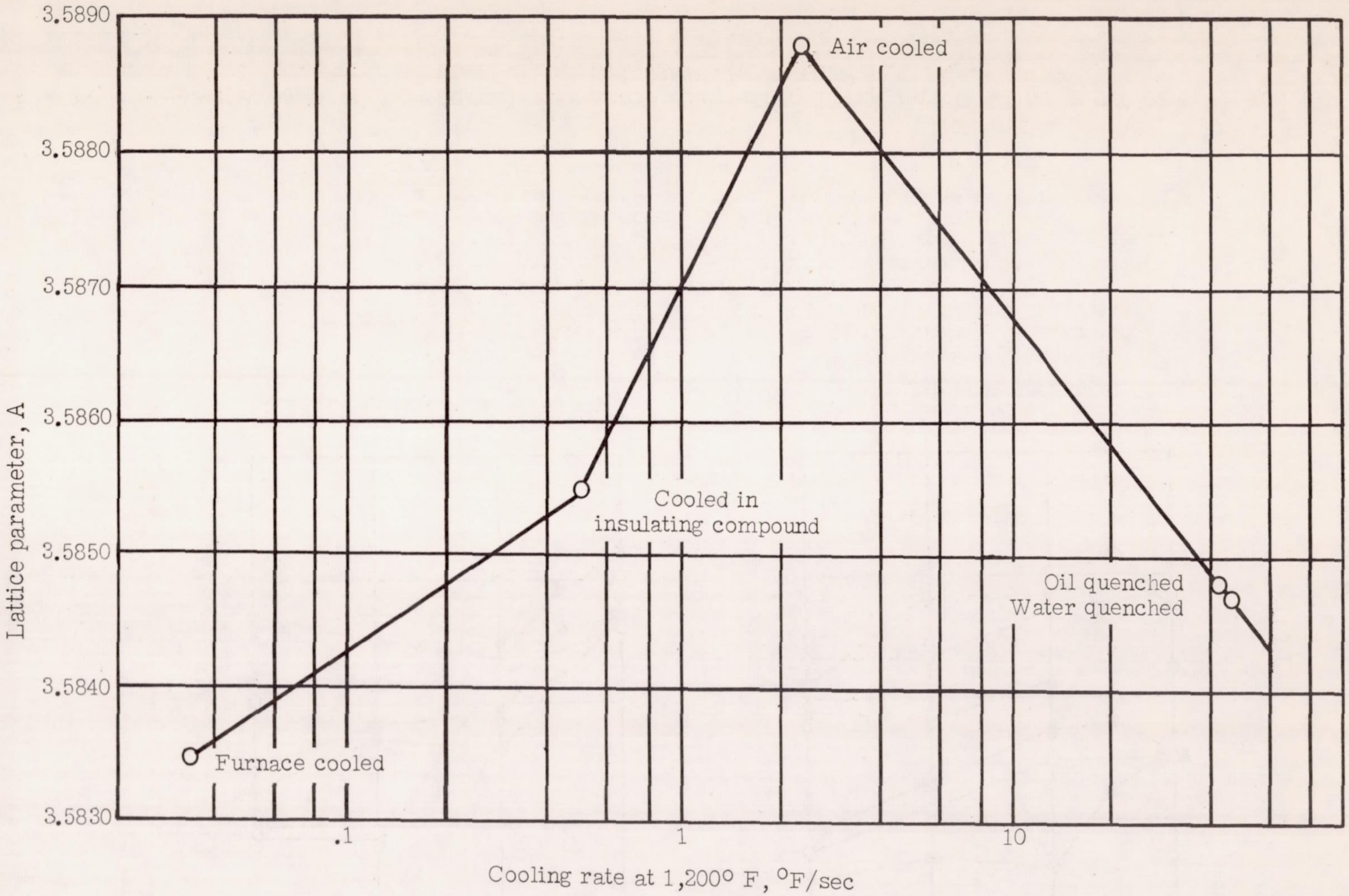
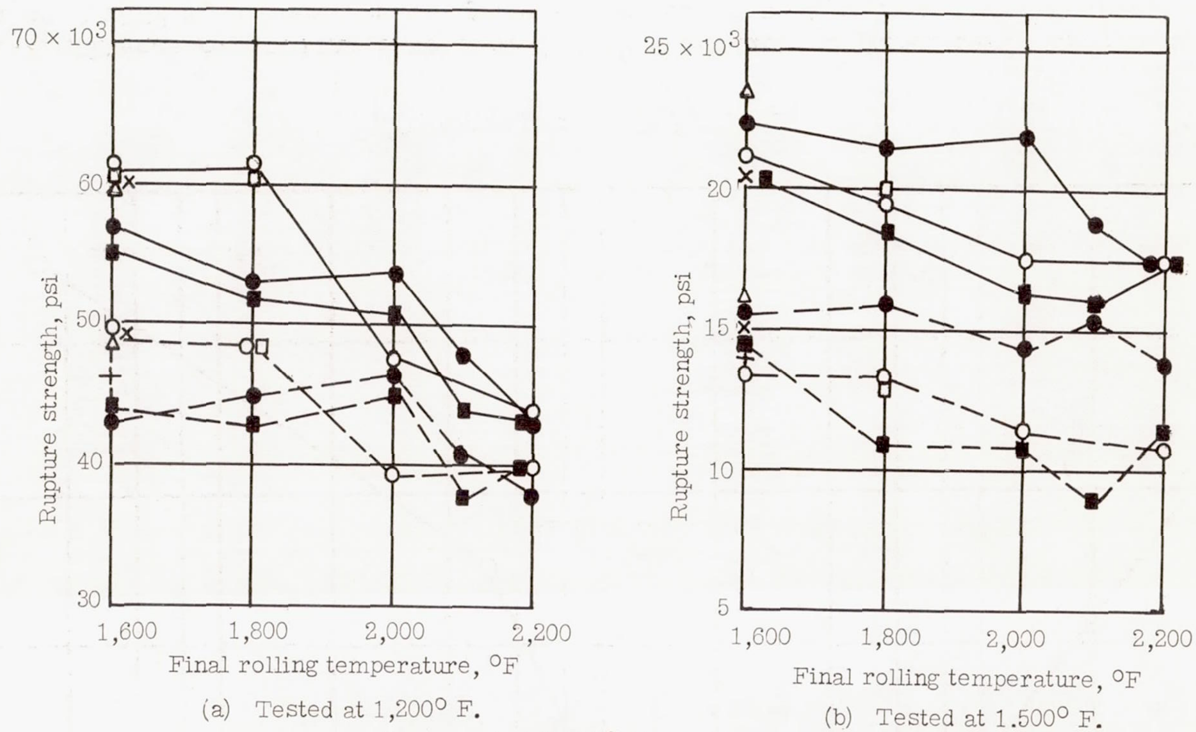
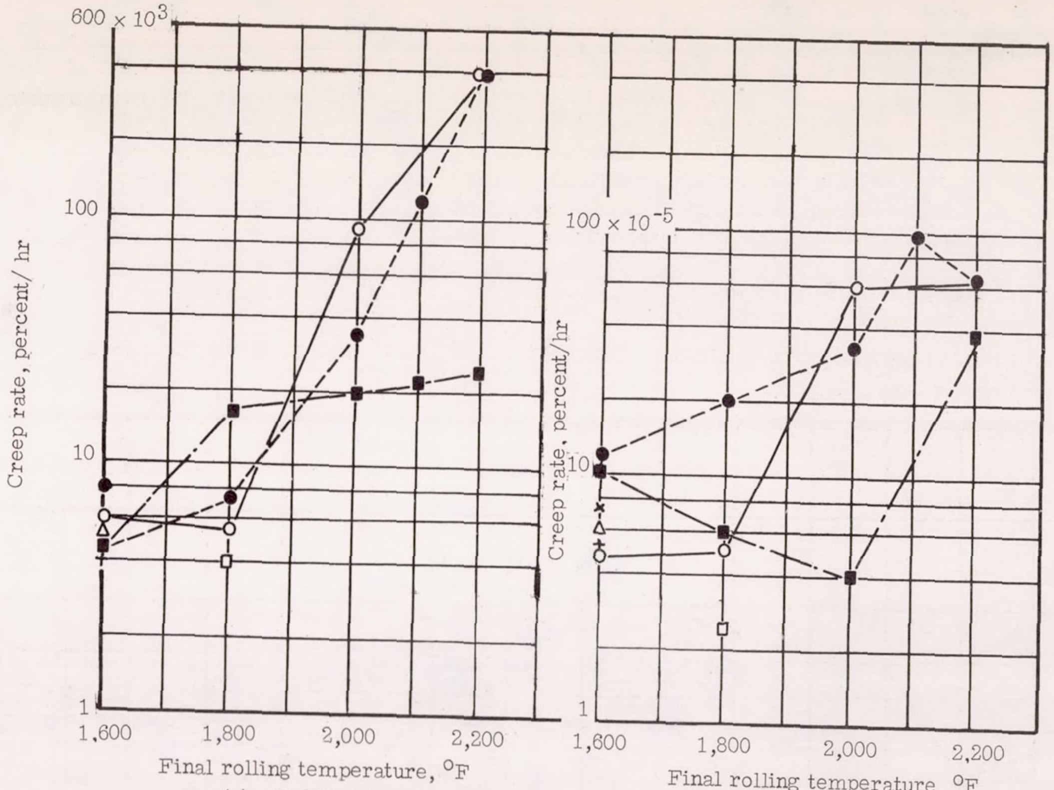


Figure 32.- Influence of cooling rate from 2,025° F on lattice parameter. Specimens solution treated at 2,200° F, 1 hour, water quenched, reheated to 2,025° F for 1/2 hour, and cooled as indicated.



○ - 25 percent at 2,200° F plus 15 percent at indicated temperature
□ - 15 percent at 2,200° F plus 25 percent at indicated temperature
△ - 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F
× - 25 percent at 2,000° F plus 15 percent at indicated temperature
\+ - 25 percent at 1,800° F plus 15 percent at indicated temperature
● - 15 percent isothermally at indicated temperature
■ - 40 percent isothermally at indicated temperature
——— - 100-hr rupture strength
— — - 1,000-hr rupture strength

Figure 33.- Comparison of isothermal and nonisothermal rolling on 100- and 1,000-hour rupture strengths at 1,200° and 1,500° F.

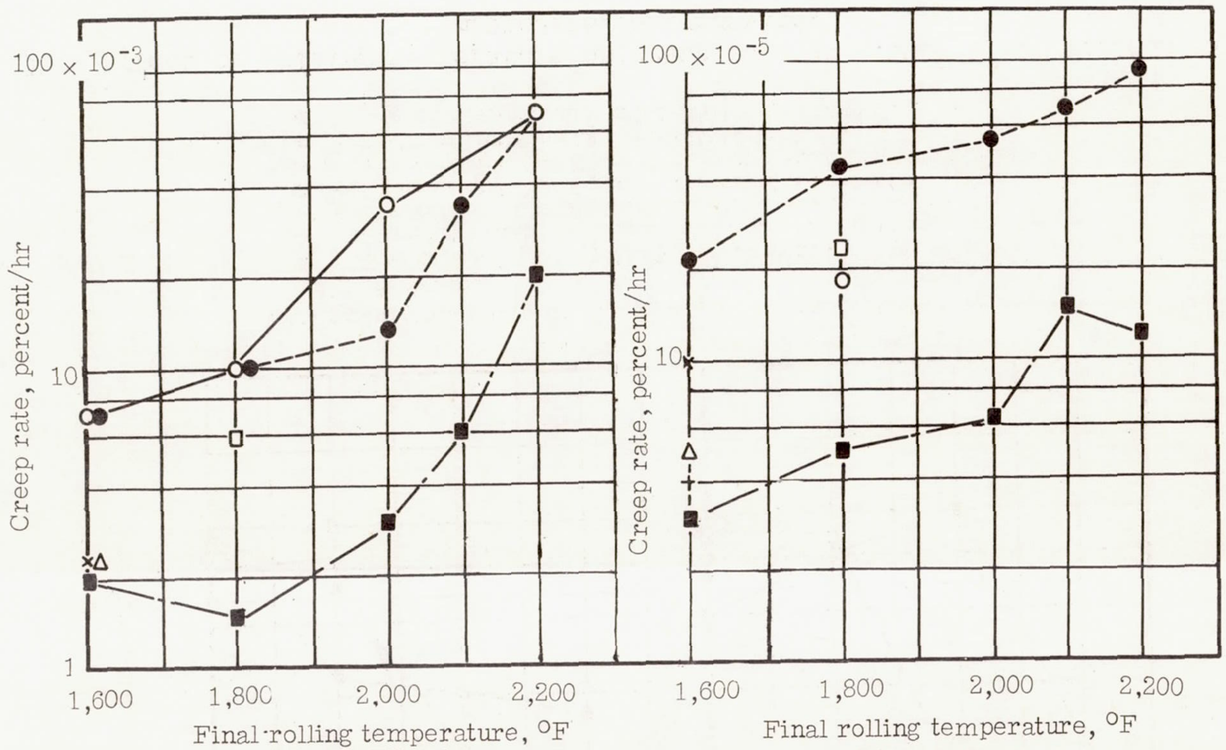


(a) 50,000 psi.

(b) 25,000 psi.

○ - 25 percent at 2,200° F plus 15 percent at indicated temperature
△ - 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F
+ - 25 percent at 1,800° F plus 15 percent at indicated temperature
□ - 15 percent at 2,200° F plus 25 percent at indicated temperature
× - 25 percent at 2,000° F plus 15 percent at indicated temperature
● - 40 percent isothermally at indicated temperature
■ - 15 percent isothermally at indicated temperature

Figure 34.- Effect of rolling temperature on creep rate at 1,200° F for various amounts and methods of deformation.

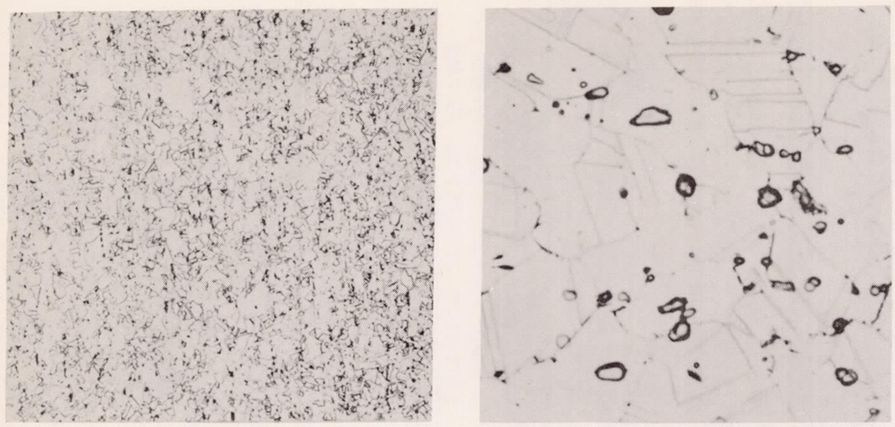


(a) 15,000 psi.

(b) 8,000 psi.

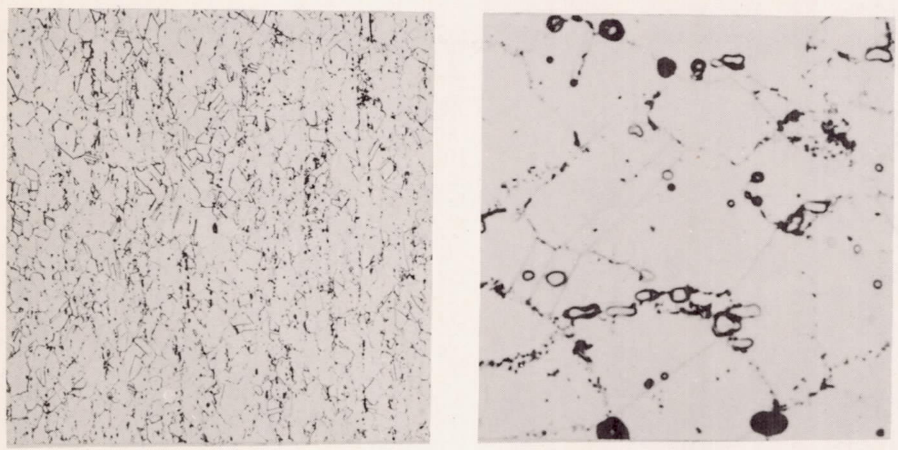
○ - 25 percent at 2,200° F plus 15 percent at indicated temperature
△ - 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F
+ - 25 percent at 1,800° F plus 15 percent at indicated temperature
□ - 15 percent at 2,200° F plus 25 percent at indicated temperature
× - 25 percent at 2,000° F plus 15 percent at indicated temperature
● - 40 percent isothermally at indicated temperature
■ - 15 percent isothermally at indicated temperature

Figure 35.- Effect of rolling temperature on creep rate at 1,500° F for various amounts and methods of deformation.



X100 X1000

(a) Rolled 25 percent at 2,200° F plus 15 percent at 2,000° F.

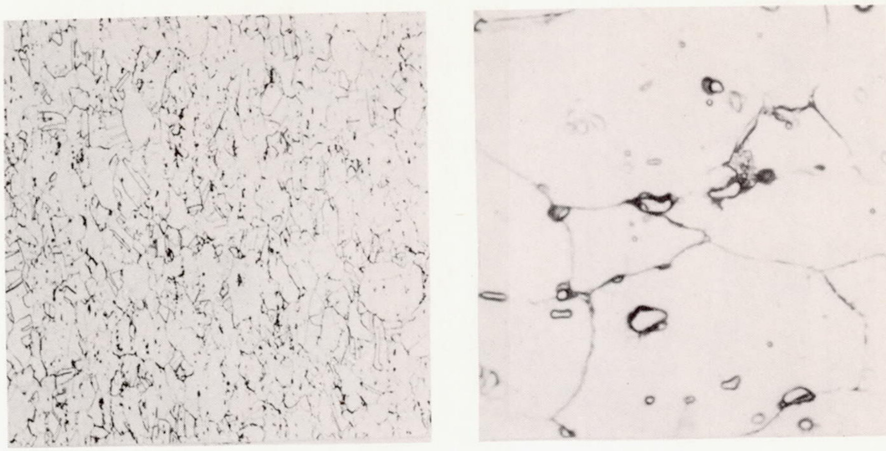


X100 X1000

L-93493

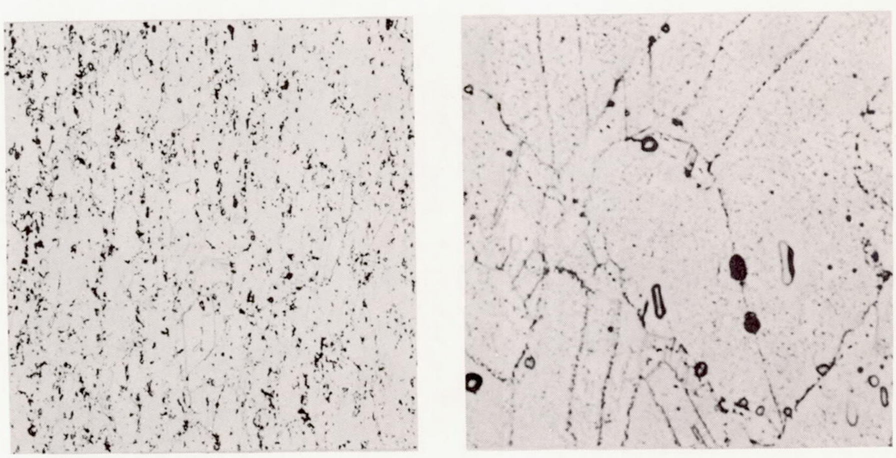
(b) Rolled 25 percent at 2,200° F plus 15 percent at 1,800° F.

Figure 36.- Effect of nonisothermal reductions on microstructures. Bar stock was solution treated, 1 hour, water quenched, and then rolled as indicated. (Electrolytically etched in 10 percent chromic acid.)



X100 X1000

(c) Rolled 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F.

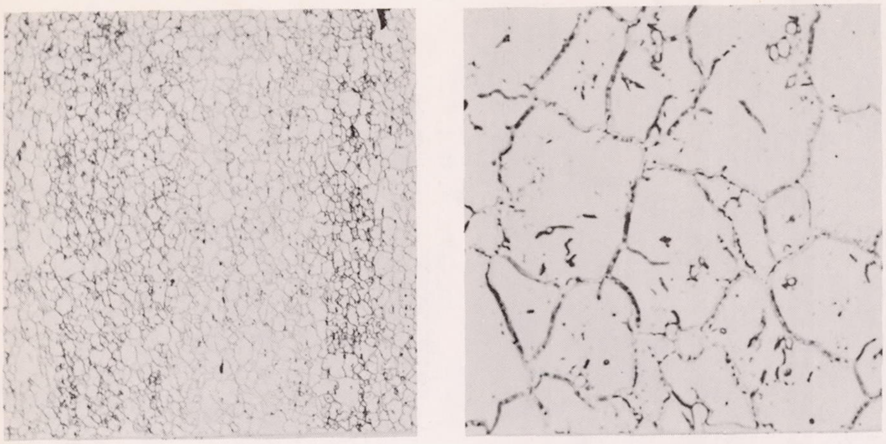


X100 X1000

L-93494

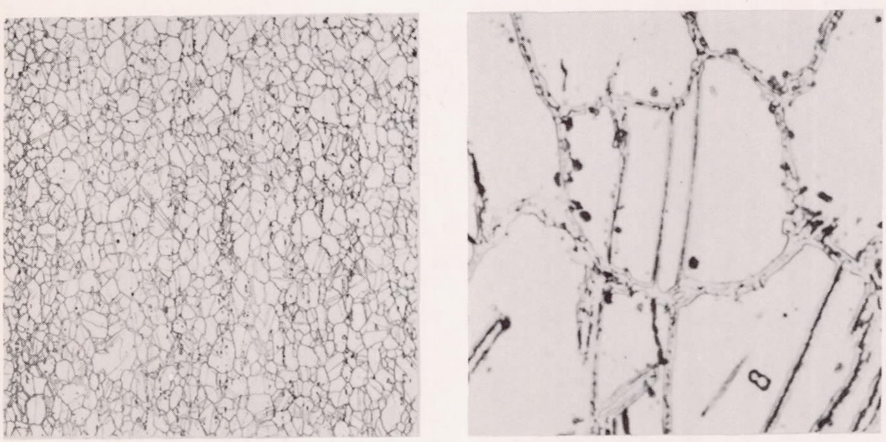
(d) Rolled 25 percent at 2,000° F plus 15 percent at 1,600° F.

Figure 36.- Concluded.



X100 X1000

(a) Rolled 25 percent at 2,200° F plus 15 percent at 2,000° F (1,125 hours).

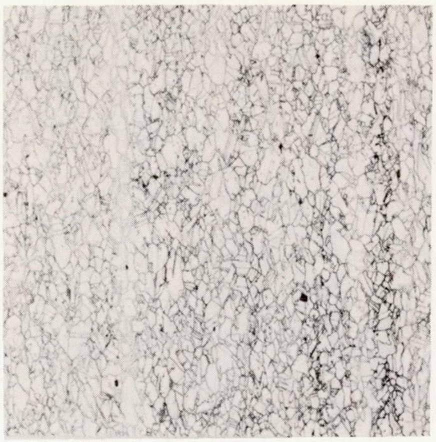


X100 X1000

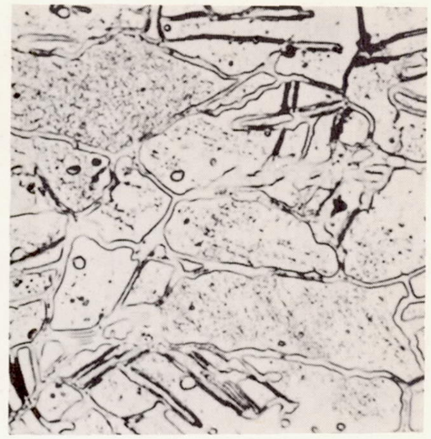
L-93495

(b) Rolled 25 percent at 2,200° F plus 15 percent at 1,800° F (1,175 hours).

Figure 37.- Microstructures after creep testing for 1,000 hours at 1,200° F with stress of 25,000 psi. Prior to testing, bar stock was solution treated at 2,200° F, 1 hour, water quenched, and rolled as indicated. (Electrolytically etched in 10 percent chromic acid.)

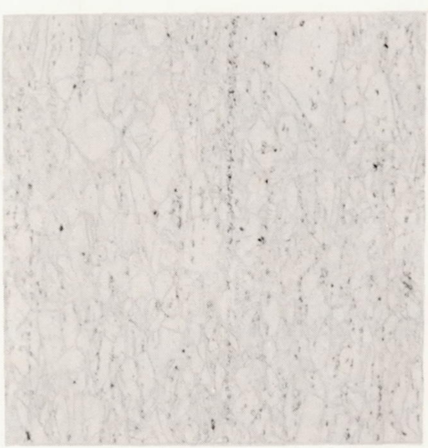


X100



X1000

(c) Rolled 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F (1,155 hours).



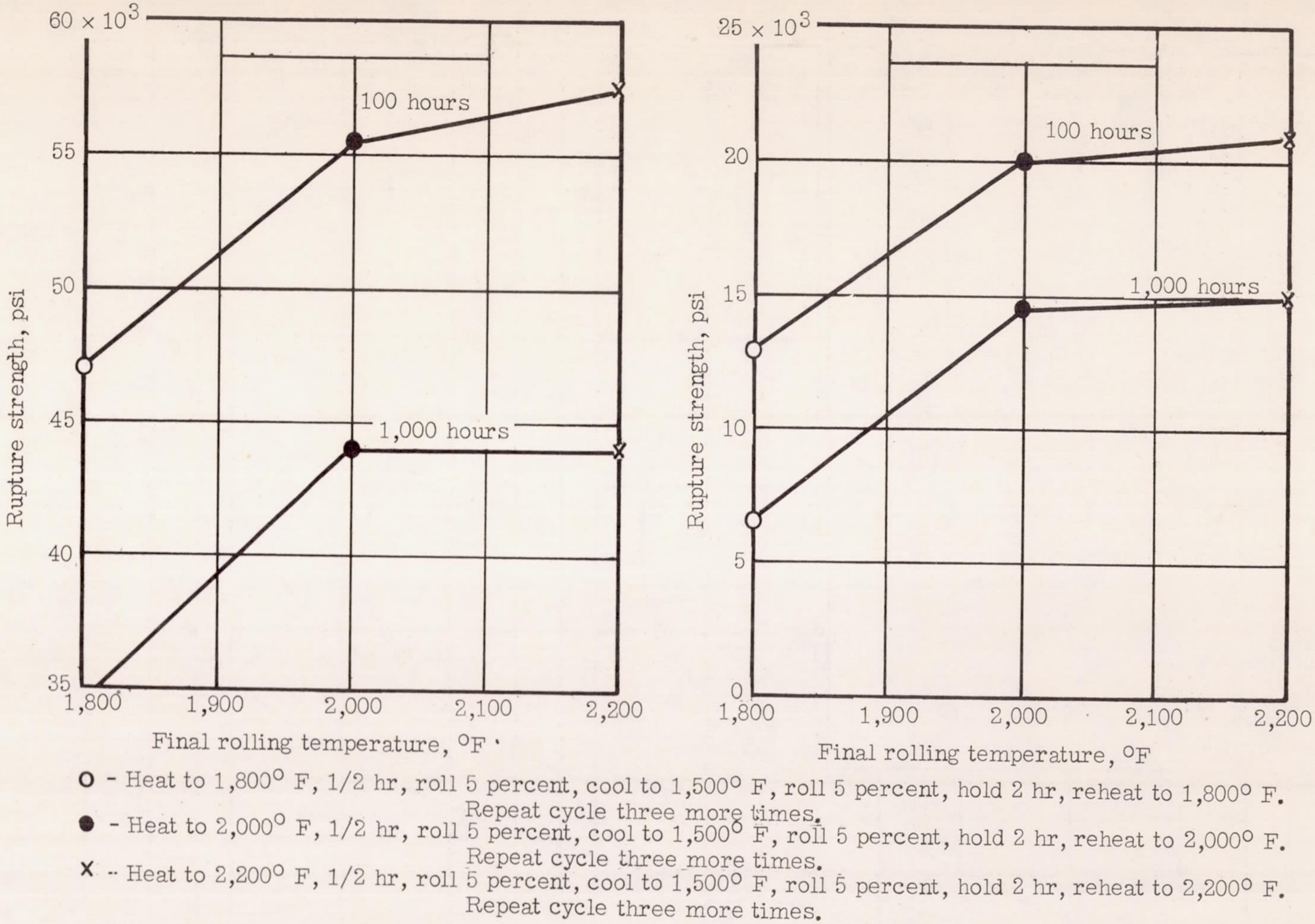
X100

X1000

L-93496

(d) Rolled 25 percent at 2,000° F plus 15 percent at 1,600° F (1,178 hours).

Figure 37.- Concluded.



(a) Tested at 1,200° F.

(b) Tested at 1,500° F.

Figure 38.- Effect of cyclic rolling on the 100- and 1,000-hour rupture strengths at 1,200° and 1,500° F.

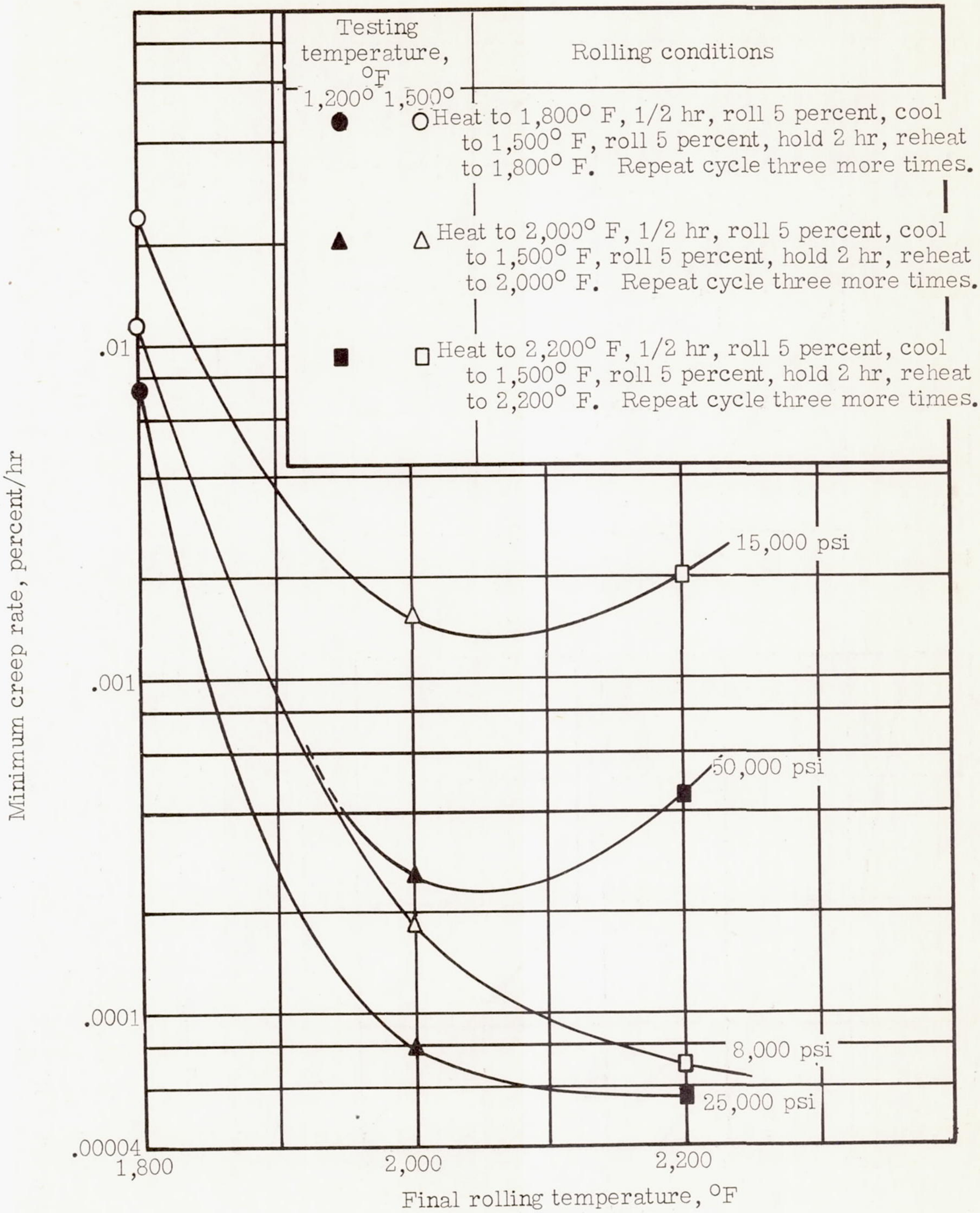
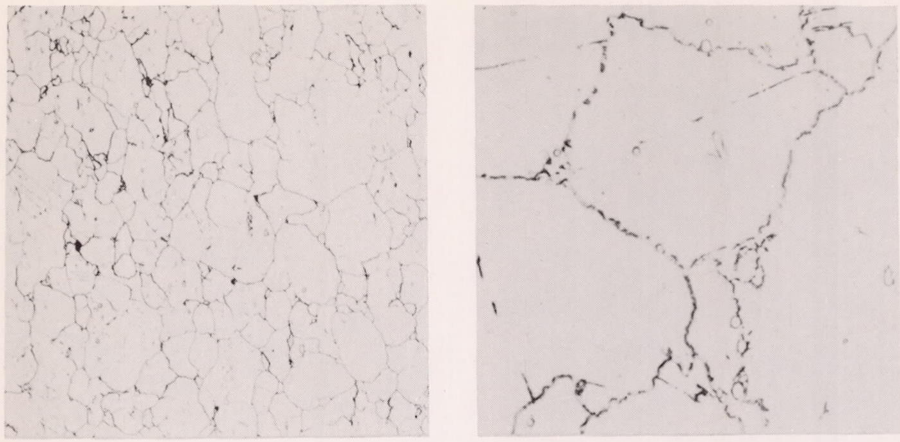
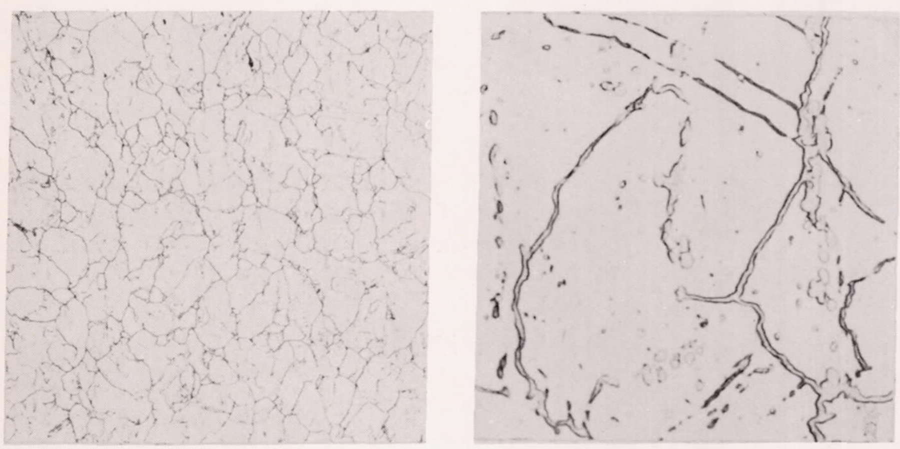


Figure 39.- Effect of cyclic rolling on minimum creep rates at 1,200° and 1,500° F for indicated initial stresses.



X100 X1000

(a) Heated to $2,200^{\circ}$ F, 1/2 hour, rolled 5 percent, cooled to $1,500^{\circ}$ F, rolled 5 percent, held 2 hours, and reheated to $2,200^{\circ}$ F. Repeated cycle three more times.

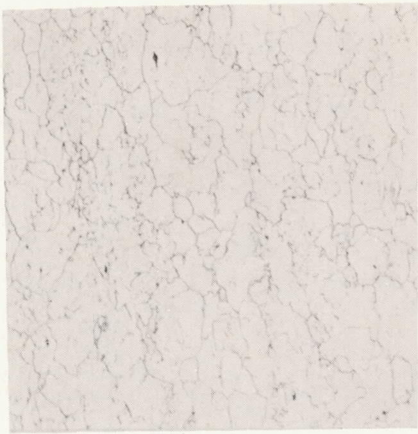


X100 X1000

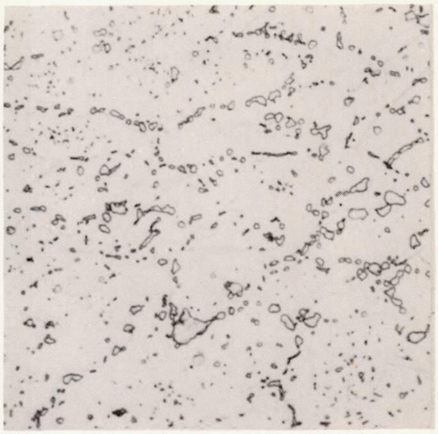
L-93497

(b) Heated to $2,000^{\circ}$ F, 1/2 hour, rolled 5 percent, cooled to $1,500^{\circ}$ F, rolled 5 percent, held 2 hours, reheated to $2,000^{\circ}$ F. Repeated three more times.

Figure 40.- Effect of cyclic rolling on microstructures. Bar stock was solution treated at $2,200^{\circ}$ F, 1 hour, water quenched, and rolled as indicated. (Electrolytically etched in 10 percent chromic acid.)



X100



X1000

L-93498

(c) Heated to 1,800° F, 1/2 hour, rolled 5 percent, cooled to 1,500° F, rolled 5 percent, held 2 hours, reheated to 1,800° F. Repeated cycle three more times.

Figure 40.- Concluded.

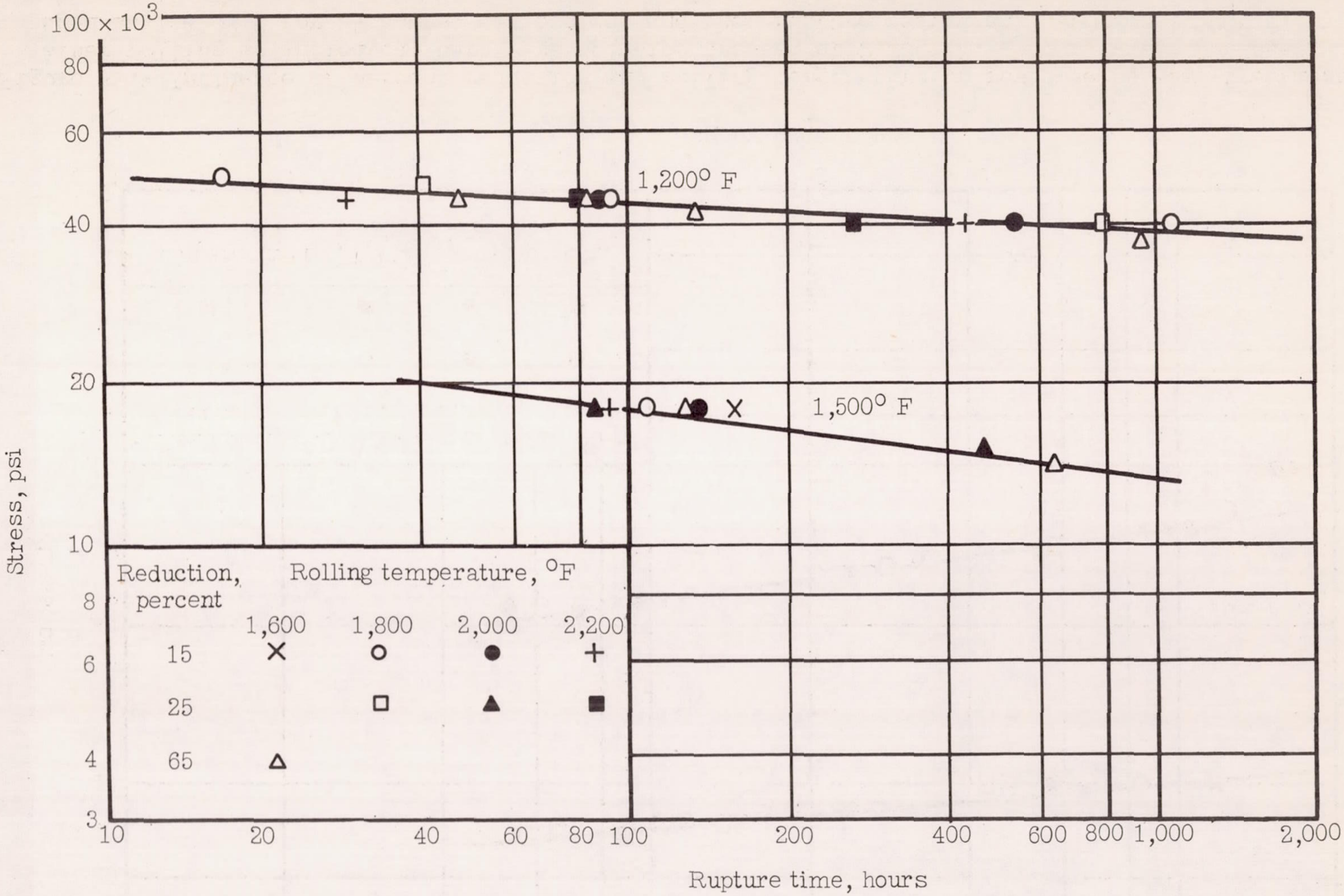


Figure 41.- Influence of rolling temperature and amount of reduction on response to heat treatment. After rolling as indicated, bars were solution treated at 2,200° F, 1 hour, water quenched, and then rupture tested at 1,200° or 1,500° F.

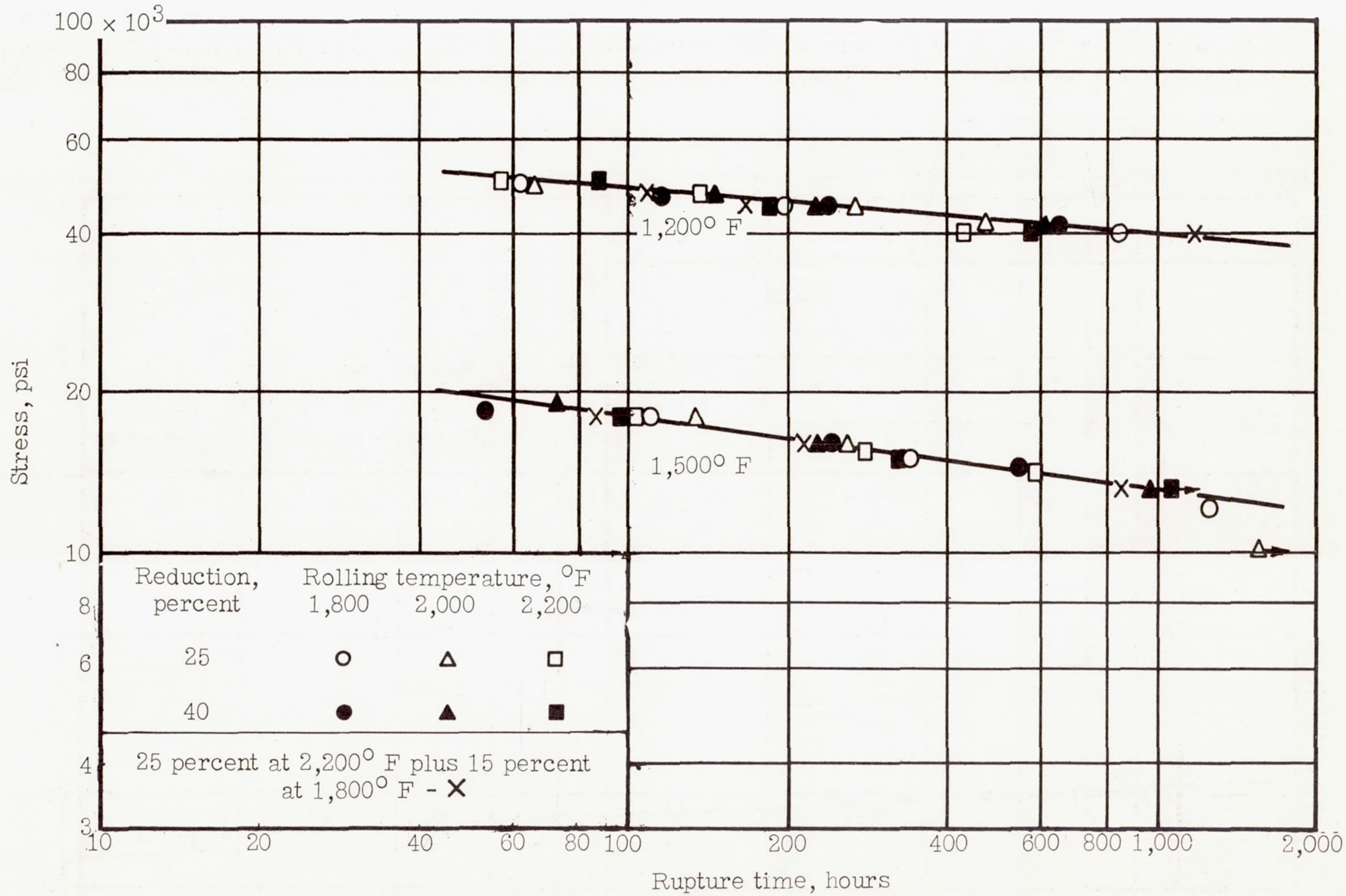


Figure 42.- Influence of percent reduction and rolling temperature on response to heat treatment. After rolling as indicated, bars were solution treated at 2,200° F, 1 hour, water quenched, aged at 1,400° F for 24 hours, air cooled, and then rupture tested at 1,200° or 1,500° F.

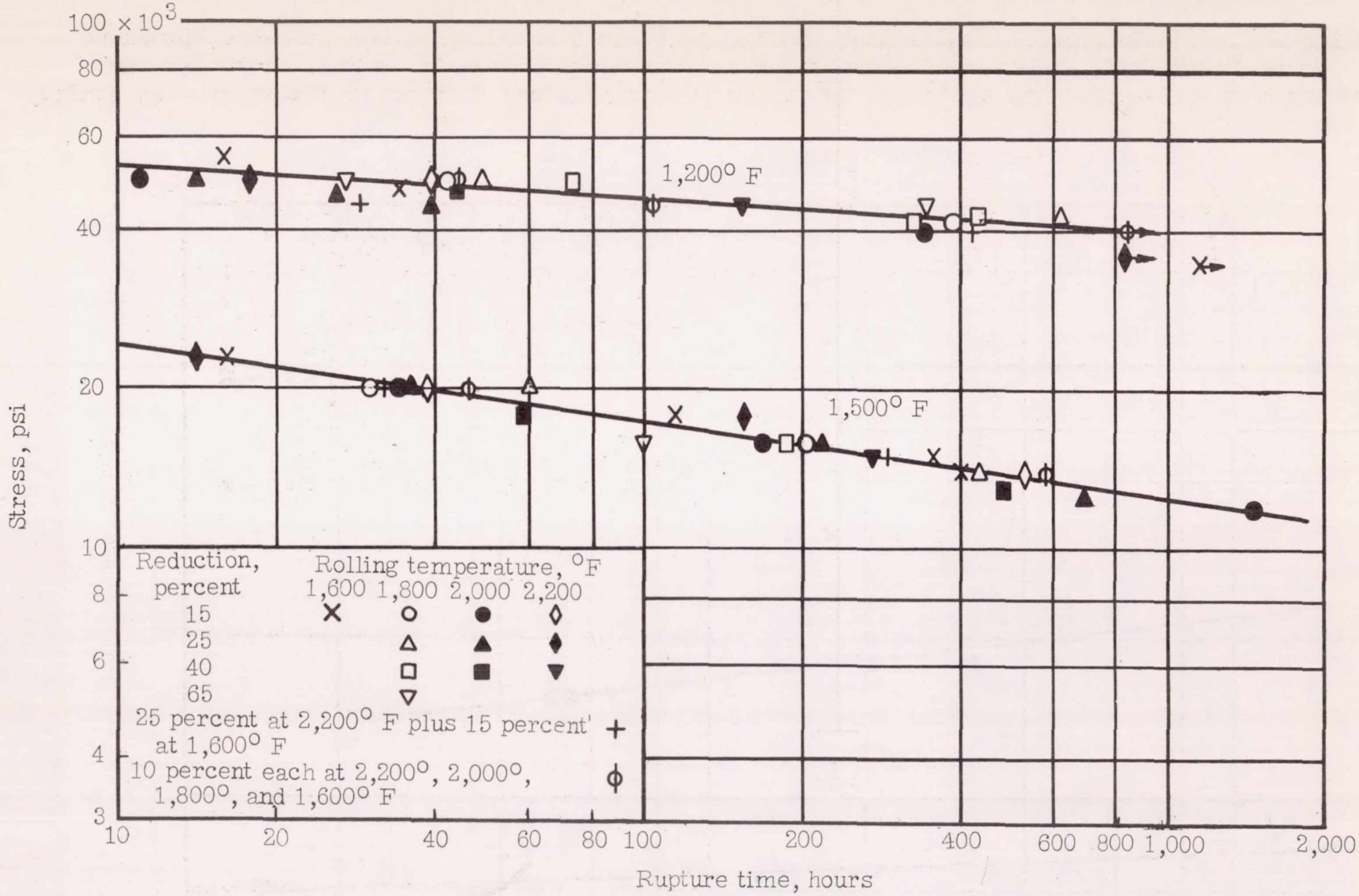


Figure 43.- Influence of rolling temperature and amount of reduction on response to heat treatment. After rolling as indicated, bars were solution treated at 2,050° F, 2 hours, water quenched, and then rupture tested at 1,200° or 1,500° F.

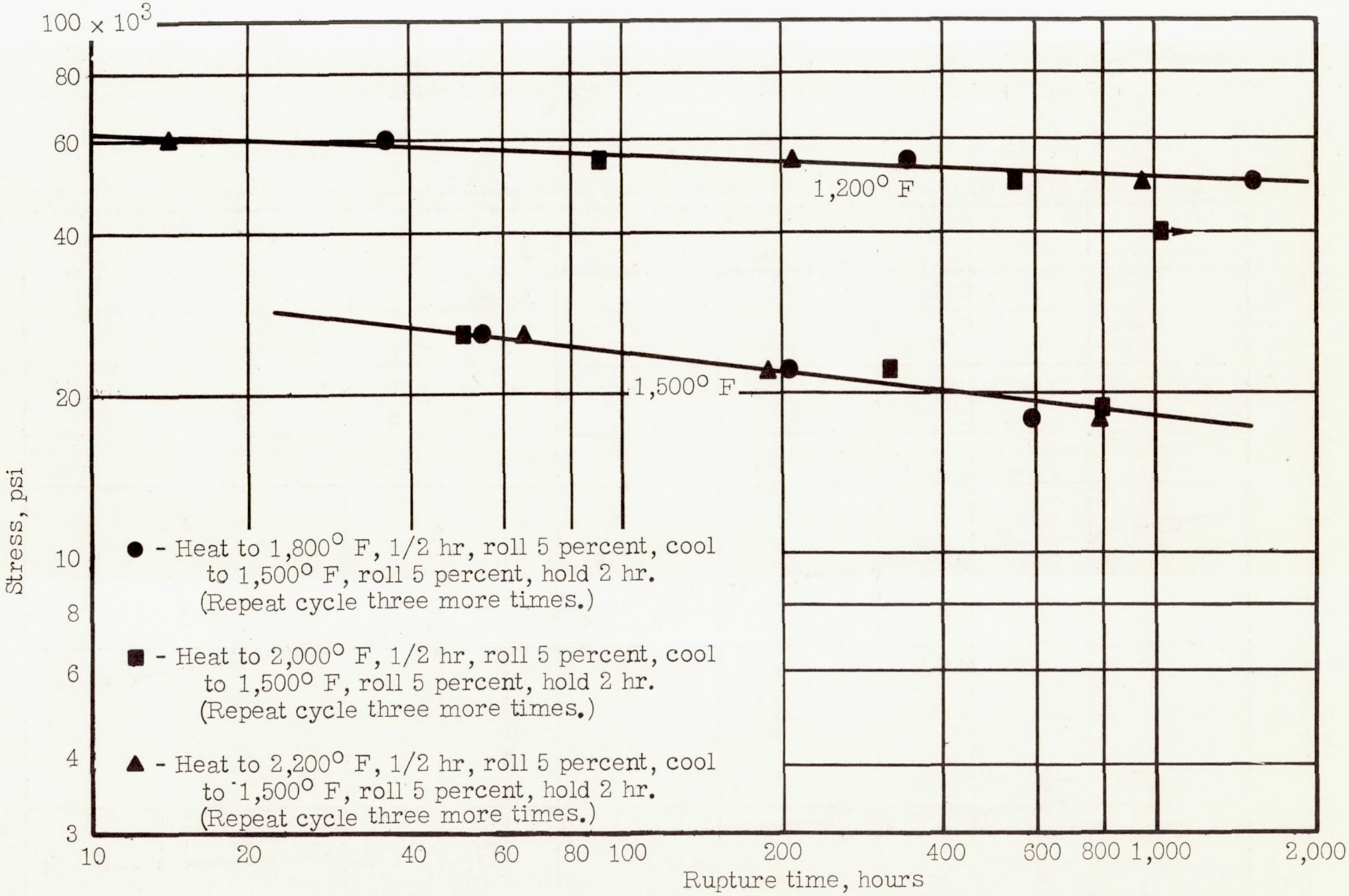
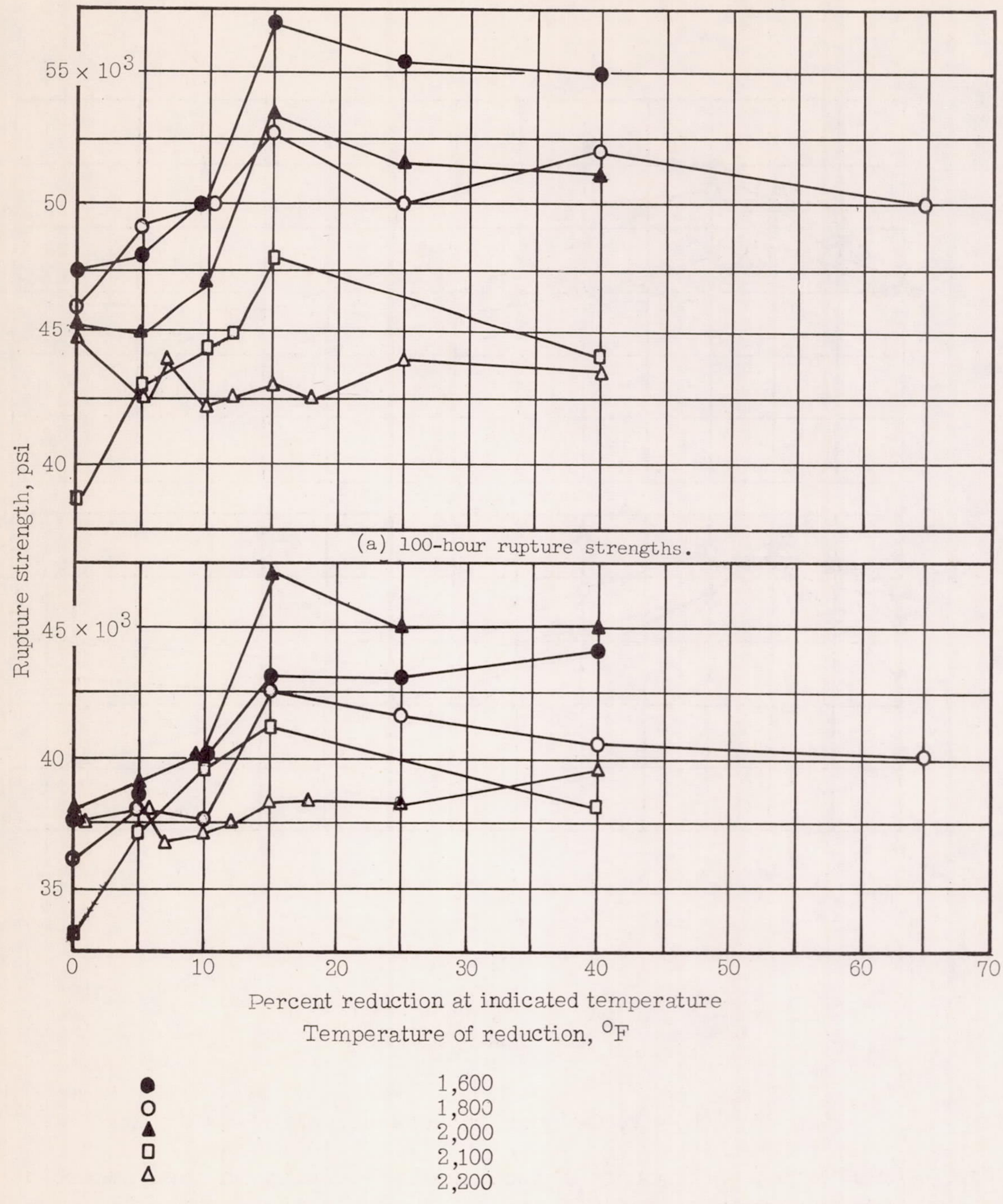
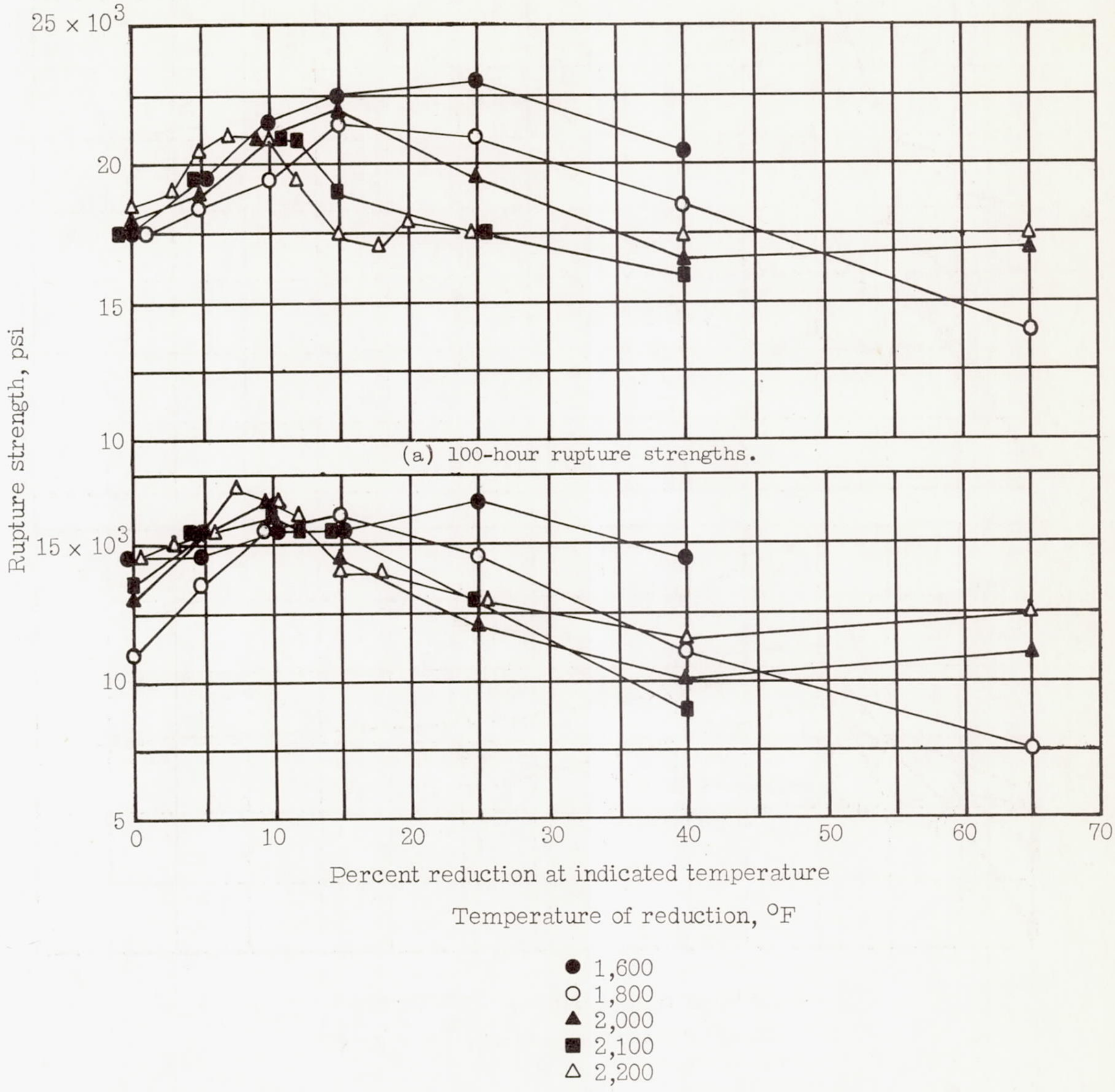


Figure 44.- Influence of rolling temperature and amount of reduction on response to heat treatment. After rolling as indicated, bars were solution treated at 2,050° F, 2 hours, water quenched, hot-cold-worked 15 percent at 1,200° F, and then rupture tested at 1,200° or 1,500° F.



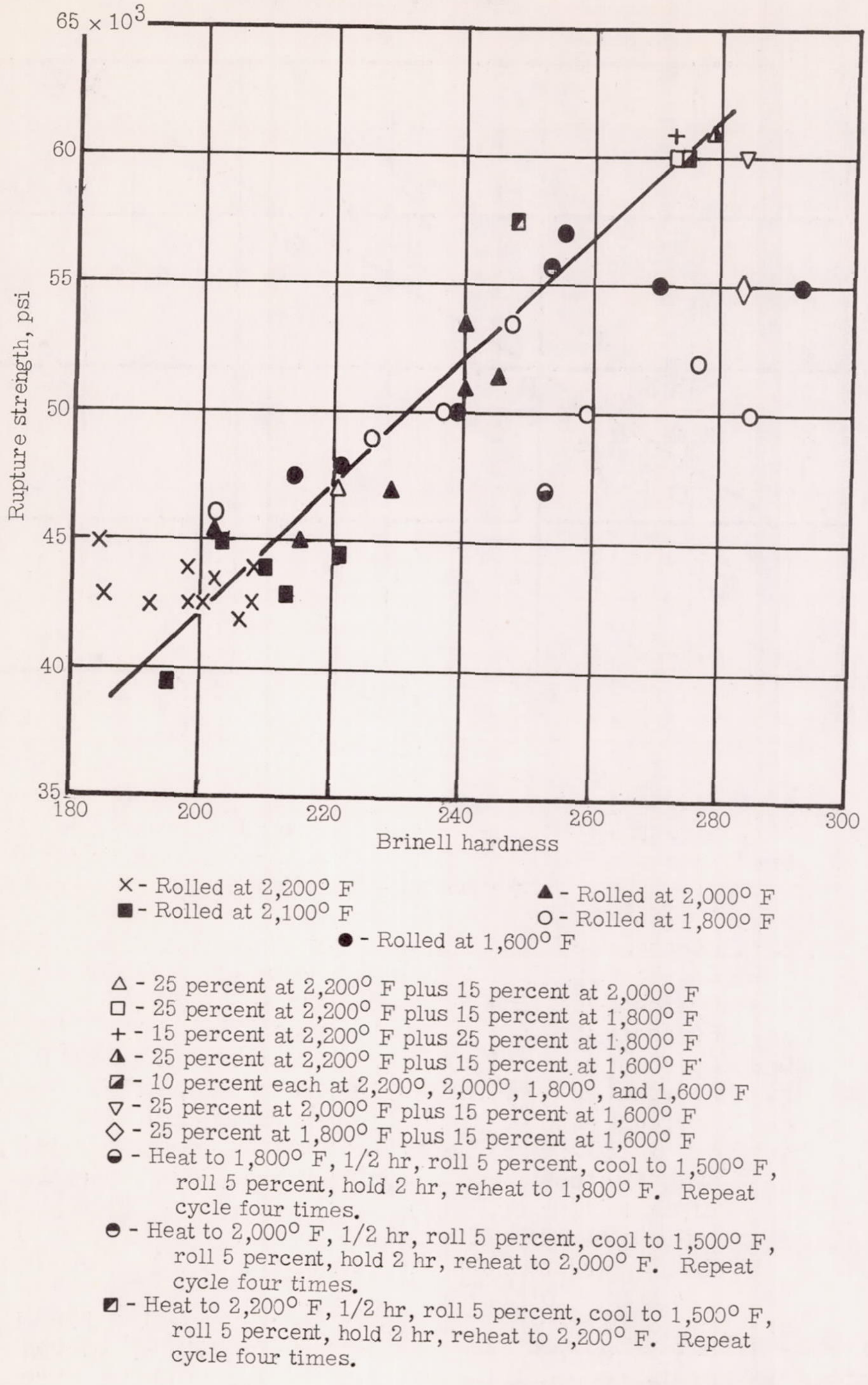
(b) 1,000-hour rupture strengths.

Figure 45.- Effect of amount of isothermal reduction in open passes at various temperatures on 100- and 1,000-hour rupture strengths at 1,200° F.



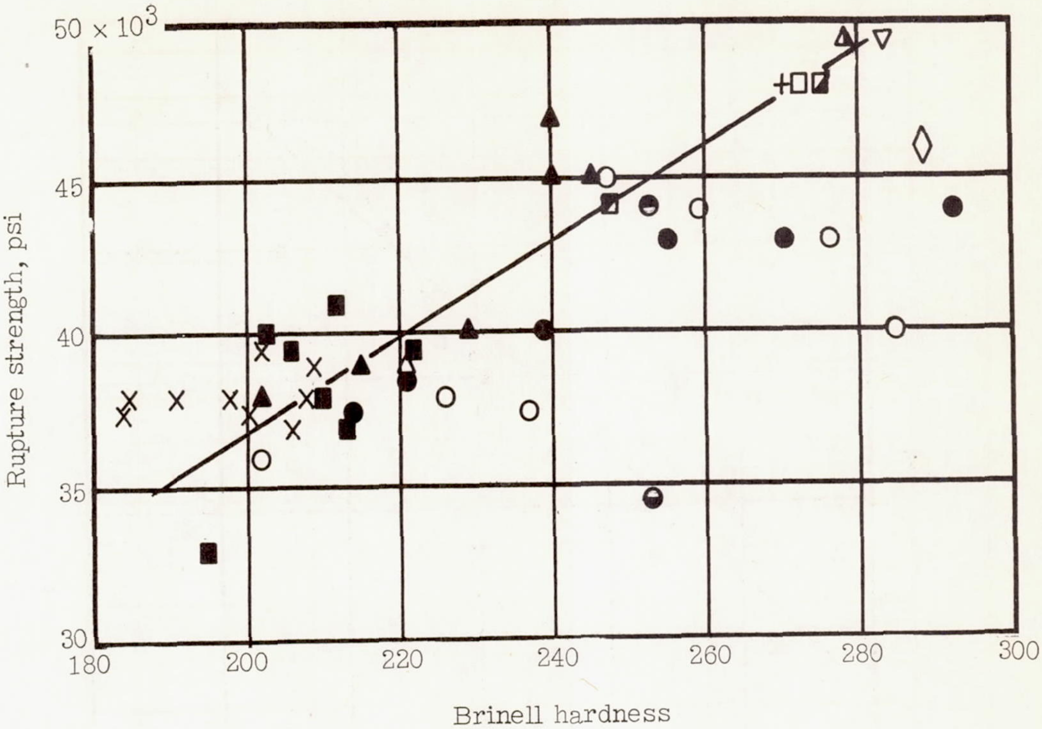
(b) 1,000-hour rupture strengths.

Figure 46.- Effect of amount of isothermal reduction in open passes at various temperatures on 100- and 1,000-hour rupture strengths at 1,500° F.



(a) 100-hour rupture strengths.

Figure 47.- Correlation of 100-hour and 1,000-hour rupture strengths at 1,200° F with as-rolled Brinell hardness.

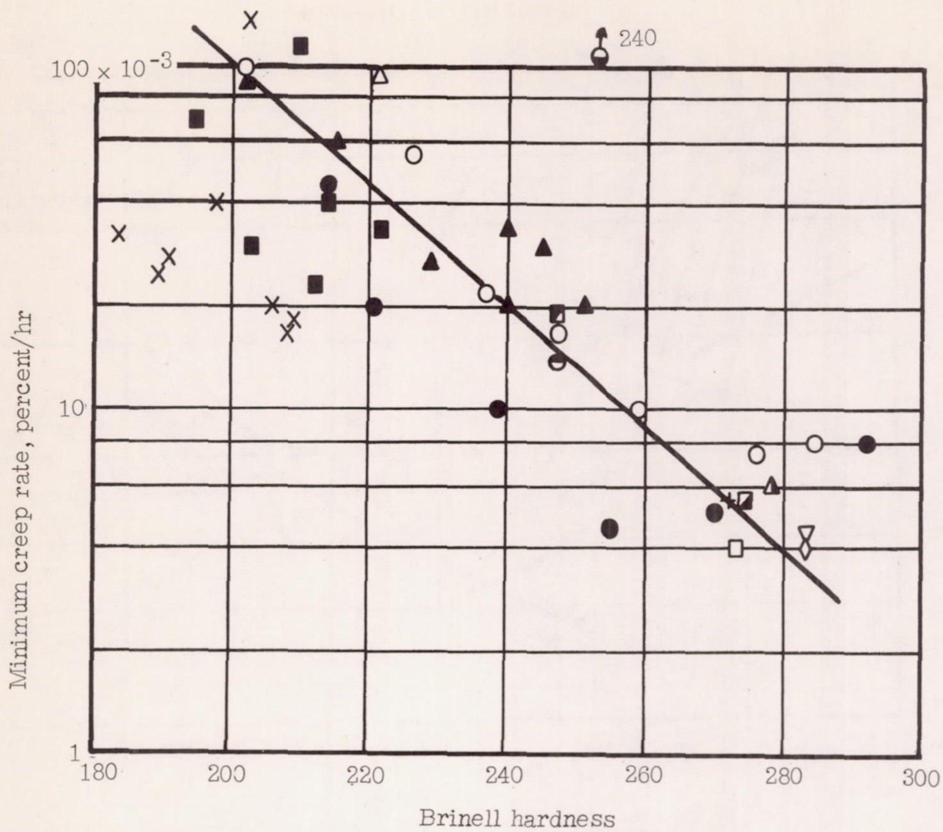


× - Rolled at 2,200° F
■ - Rolled at 2,100° F
▲ - Rolled at 2,000° F
○ - Rolled at 1,800° F
● - Rolled at 1,600° F

△ - 25 percent at 2,200° F plus 15 percent at 2,000° F
□ - 25 percent at 2,200° F plus 15 percent at 1,800° F
\+ - 15 percent at 2,200° F plus 25 percent at 1,800° F
▲ - 25 percent at 2,200° F plus 15 percent at 1,600° F
◪ - 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F
▽ - 25 percent at 2,000° F plus 15 percent at 1,600° F
◇ - 25 percent at 1,800° F plus 15 percent at 1,600° F
⊖ - Heat to 1,800° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 1,800° F. Repeat cycle four times.
◓ - Heat to 2,000° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle four times.
◩ - Heat to 2,200° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,200° F. Repeat cycle four times.

(b) 1,000-hour rupture strengths.

Figure 47.- Concluded.

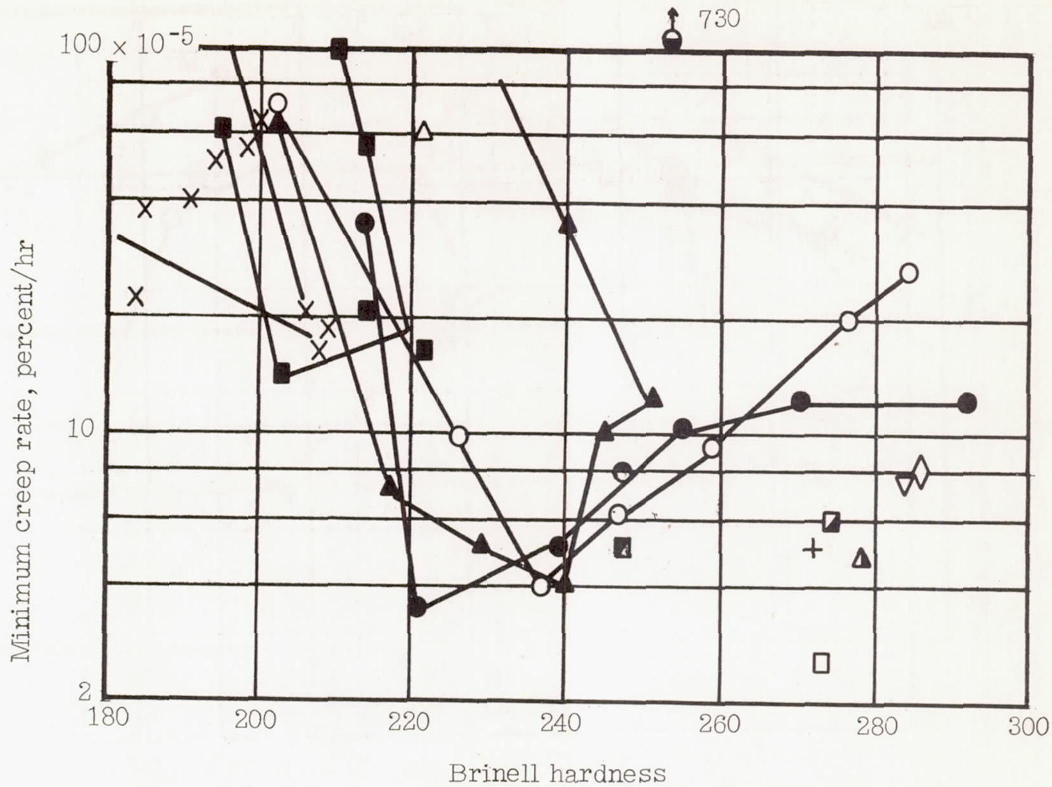


× - Rolled at 2,200° F
■ - Rolled at 2,100° F
▲ - Rolled at 2,000° F
○ - Rolled at 1,800° F
● - Rolled at 1,600° F

△ - 25 percent at 2,200° F plus 15 percent at 2,000° F
□ - 25 percent at 2,200° F plus 15 percent at 1,800° F
+ - 15 percent at 2,200° F plus 25 percent at 1,800° F
◬ - 25 percent at 2,200° F plus 15 percent at 1,600° F
◪ - 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F
▽ - 25 percent at 2,000° F plus 15 percent at 1,600° F
◇ - 25 percent at 1,800° F plus 15 percent at 1,600° F
◒ - Heat to 1,800° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 1,800° F. Repeat cycle four times.
◓ - Heat to 2,000° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle four times.
◩ - Heat to 2,200° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,200° F. Repeat cycle four times.

(a) Initial stress, 50,000 psi.

Figure 48.- Correlation of minimum creep rate for initial stresses of 50,000 and 25,000 psi at 1,200° F with as-rolled Brinell hardness.

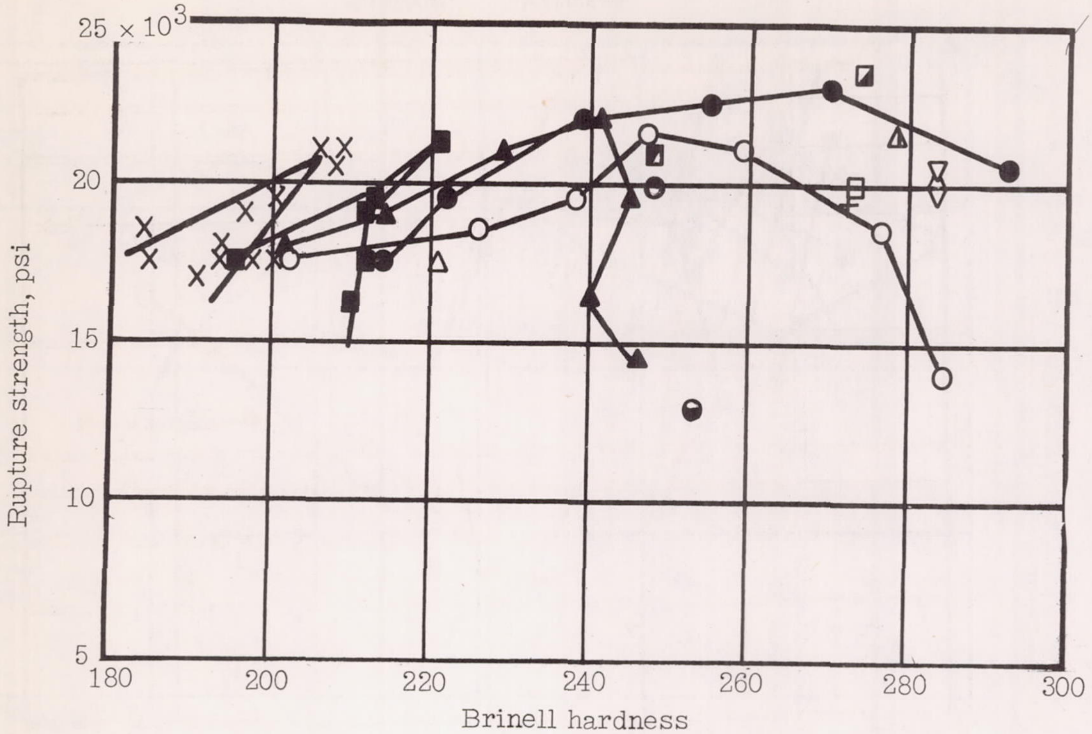


× - Rolled at 2,200° F
■ - Rolled at 2,100° F
▲ - Rolled at 2,000° F
○ - Rolled at 1,800° F
● - Rolled at 1,600° F

△ - 25 percent at 2,200° F plus 15 percent at 2,000° F
□ - 25 percent at 2,200° F plus 15 percent at 1,800° F
+ - 15 percent at 2,200° F plus 25 percent at 1,800° F
◭ - 25 percent at 2,200° F plus 15 percent at 1,600° F
◪ - 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F
▽ - 25 percent at 2,000° F plus 15 percent at 1,600° F
◇ - 25 percent at 1,800° F plus 15 percent at 1,600° F
◒ - Heat to 1,800° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 1,800° F. Repeat cycle four times.
◓ - Heat to 2,000° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle four times.
◩ - Heat to 2,200° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,200° F. Repeat cycle four times.

(b) Minimum creep rate in 1,000 hours; initial stress, 25,000 psi.

Figure 48.- Concluded.

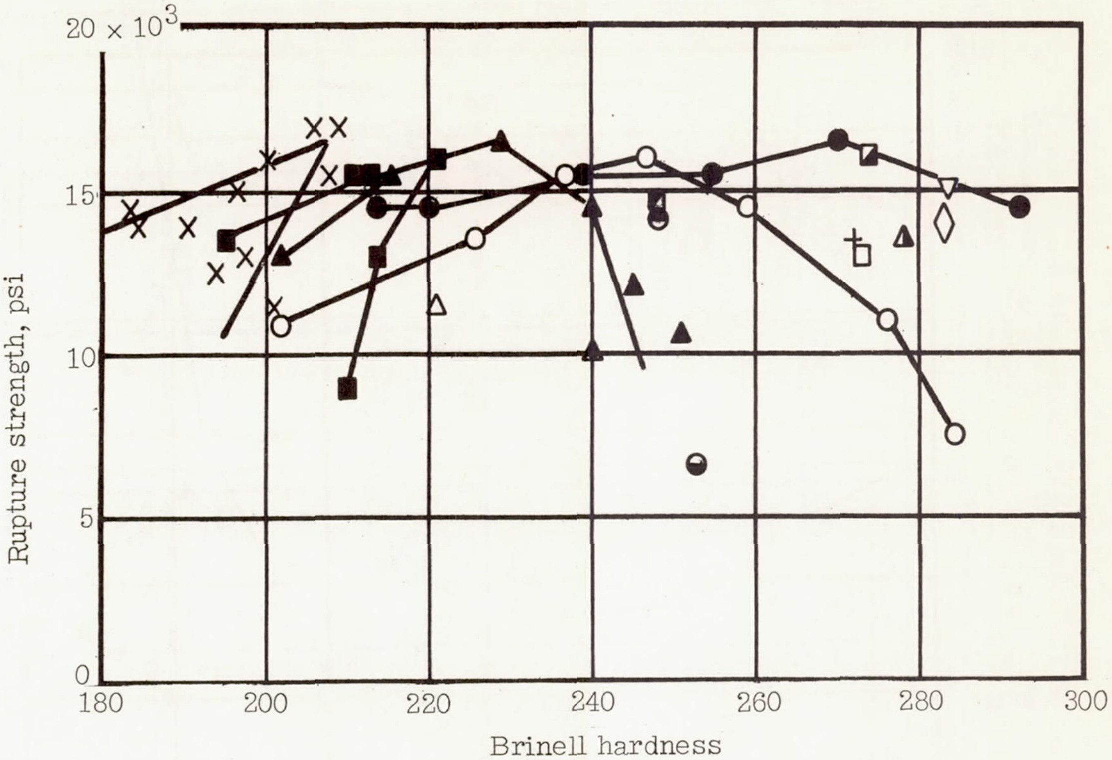


× - Rolled at 2,200° F
■ - Rolled at 2,100° F
▲ - Rolled at 2,000° F
○ - Rolled at 1,800° F
● - Rolled at 1,600° F

△ - 25 percent at 2,200° F plus 15 percent at 2,000° F
□ - 25 percent at 2,200° F plus 15 percent at 1,800° F
+ - 15 percent at 2,200° F plus 25 percent at 1,800° F
◭ - 25 percent at 2,200° F plus 15 percent at 1,600° F
◪ - 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F
▽ - 25 percent at 2,000° F plus 15 percent at 1,600° F
◇ - 25 percent at 1,800° F plus 15 percent at 1,600° F
◒ - Heat to 1,800° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 1,800° F. Repeat cycle four times.
◓ - Heat to 2,000° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle four times.
◩ - Heat to 2,200° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,200° F. Repeat cycle four times.

(a) 100-hour rupture strengths.

Figure 49.- Correlation of 100-hour and 1,000-hour rupture strengths at 1,500° F with as-rolled Brinell hardness.

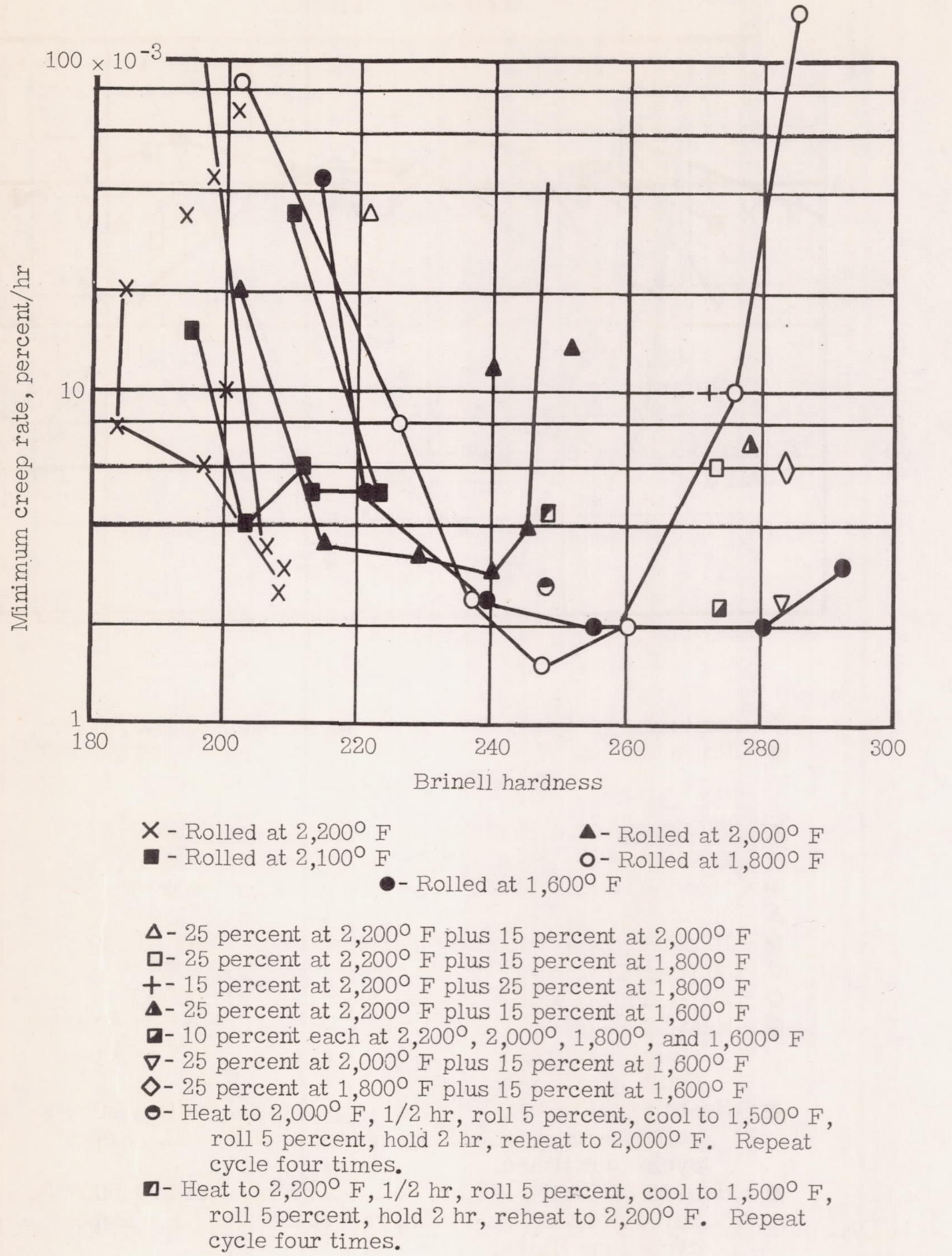


× - Rolled at 2,200° F
■ - Rolled at 2,100° F
▲ - Rolled at 2,000° F
○ - Rolled at 1,800° F
● - Rolled at 1,600° F

△ - 25 percent at 2,200° F plus 15 percent at 2,000° F
□ - 25 percent at 2,200° F plus 15 percent at 1,800° F
+ - 15 percent at 2,200° F plus 25 percent at 1,800° F
▲ - 25 percent at 2,200° F plus 15 percent at 1,600° F
◪ - 10 percent each at 2,200°, 2,000°, 1,800°, and 1,600° F
▽ - 25 percent at 2,000° F plus 15 percent at 1,600° F
◇ - 25 percent at 1,800° F plus 15 percent at 1,600° F
◒ - Heat to 1,800° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 1,800° F. Repeat cycle four times.
◓ - Heat to 2,000° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,000° F. Repeat cycle four times.
◩ - Heat to 2,200° F, 1/2 hr, roll 5 percent, cool to 1,500° F, roll 5 percent, hold 2 hr, reheat to 2,200° F. Repeat cycle four times.

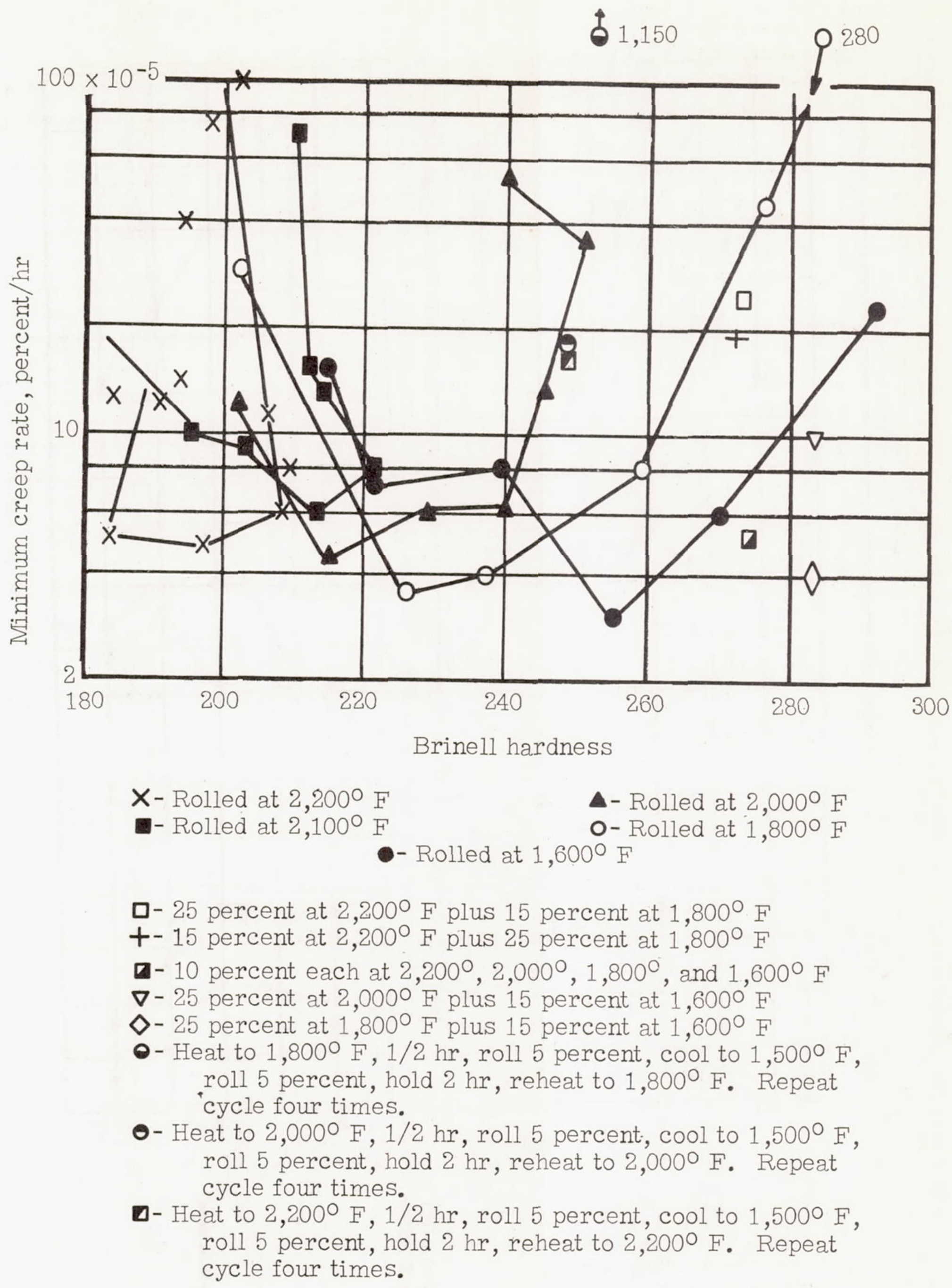
(b) 1,000-hour rupture strengths.

Figure 49.- Concluded.



(a) Initial stress, 15,000 psi.

Figure 50.- Correlation of minimum creep rate for initial stresses of 15,000 and 8,000 psi at 1,500° F with as-rolled Brinell hardness.



(b) Minimum creep rate in 1,000 hours; initial stress, 8,000 psi.

Figure 50.- Concluded.

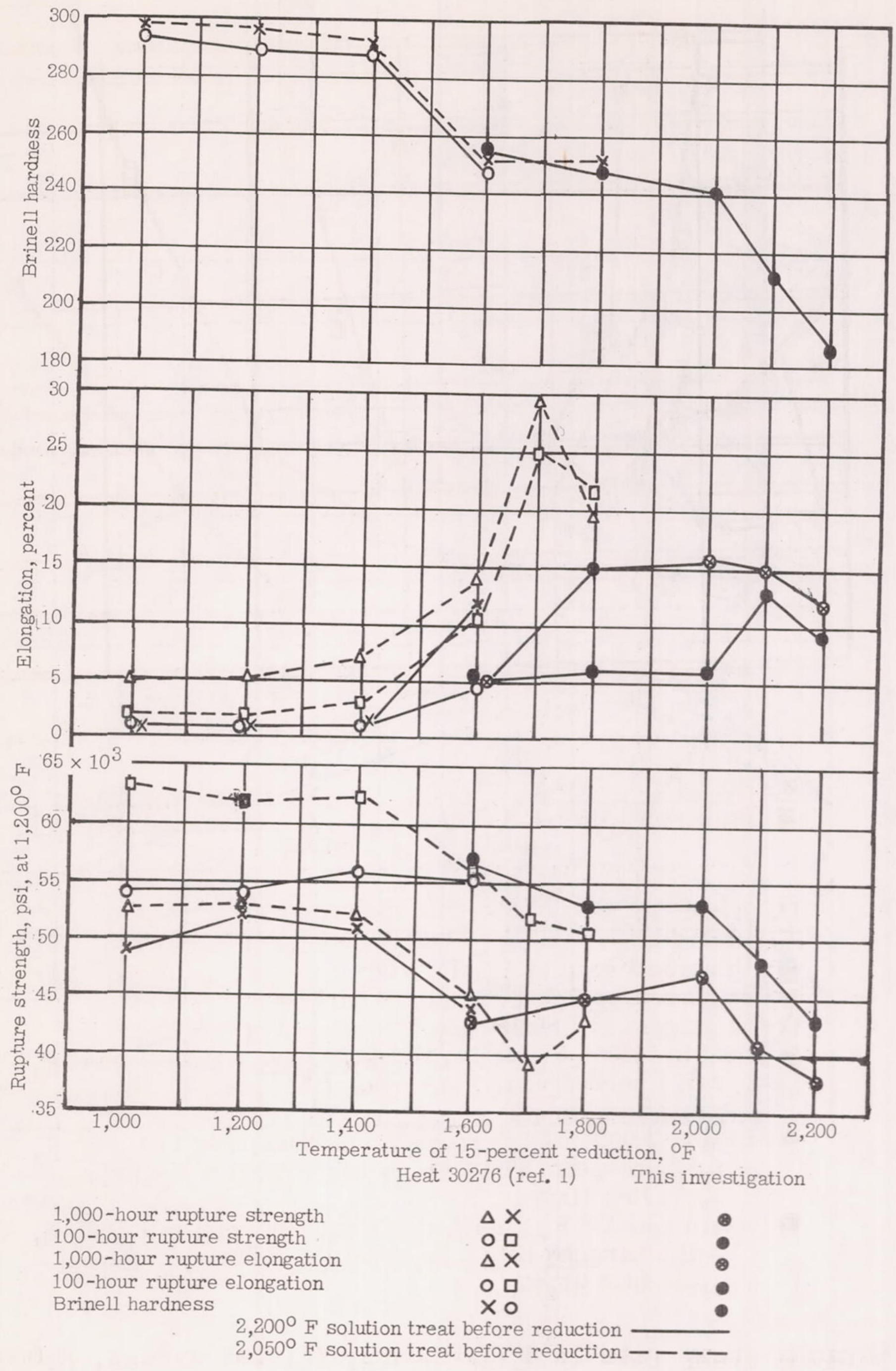
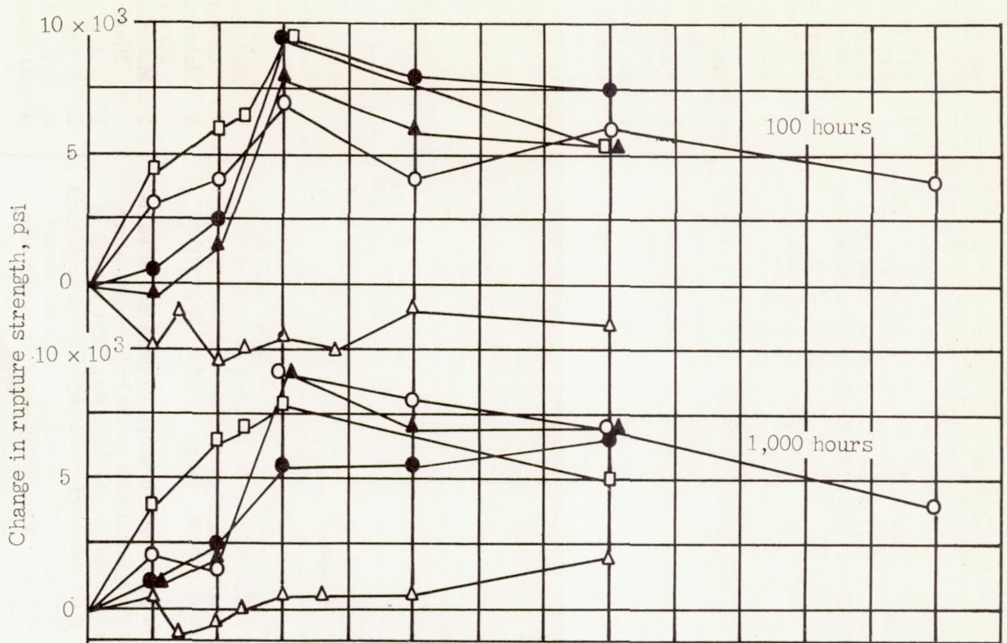
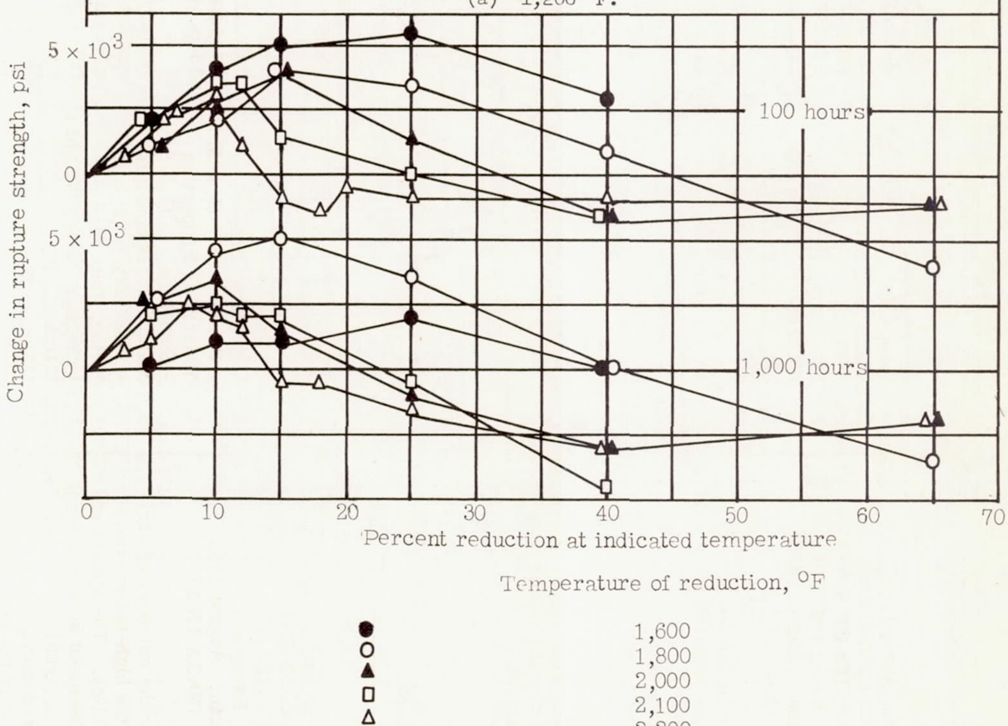


Figure 51.- Comparison of 1,200° F rupture strengths, rupture elongation, and Brinell hardness after 15-percent reduction at various temperatures for this investigation and another heat of same alloy (heat 30276, ref. 1).



(a) 1,200° F.



(b) 1,500° F.

Figure 52.- Effect of amount of isothermal reduction in open passes at various temperatures on change in 100- and 1,000-hour rupture strengths at 1,200° and 1,500° F.