NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1867

A STUDY OF EFFECTS OF HEAT TREATMENT AND HOT-COLD-WORK ON PROPERTIES OF LOW-CARBON N-155 ALLOY

By J. W. Freeman, E. E. Reynolds, D. N. Frey, and A. E. White

University of Michigan

Washington
May 1949

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1867

A STUDY OF EFFECTS OF HEAT TREATMENT AND HOT-COLD-WORK ON PROPERTIES OF LOW-CARBON N-155 ALLOY

By J. W. Freeman, E. E. Reynolds, D. N. Frey, and A. E. White

SUMMARY

Physical properties at room temperature and rupture test characteristics at 1200° F were used as criterions to evaluate the effects of systematic variations of solution treatments, aging treatments, and hot-cold-work on the properties of bar stock from one heat of low-carbon N-155 alloy. The range in yield strength for 0.02-percent offset at room temperature was from 30,000 to 134,000 psi. Rupture strengths at 1200° F ranged from 40,000 to 66,000 psi at 100 hours and from 35,000 to 56,000 psi at 1000 hours. This rupture-strength range is equivalent to such extreme variation as 100 to approximately 600,000 hours for fracture at 1200° F under a stress of 40,000 psi for the same bar stock with different treatments.

Hot-cold-work in amount of 10- to 15-percent reduction at temperatures below 1400° F produced the highest strengths at both room temperature and 1200° F. Solution temperatures prior to hot-cold-work should be between 1950° and 2100° F. The best properties from solution treatments alone were obtained by quenching from 2100° F. After this solution treatment the alloy can be expected to have a yield strength of about 40,000 psi and rupture strengths at 100 and 1000 hours of about 51,000 and 40,000 psi, respectively. Aging treatments at 1350° to 1400° F developed yield strengths between 40,000 and 50,000 psi and rupture strengths of about 50,000 and 40,000 psi at 100 and 1000 hours, respectively. Incomplete data indicate that aging treatments after hot-cold-work may be quite beneficial. The hot-worked condition provides the best all-round properties provided the hot-working conditions can be properly controlled.

Solution treatments alone result in the lowest strength for several hundred hours in the rupture test. Proper aging improves the shorter-time rupture strength but results in steep curves of stress against rupture time so that the aged condition is the weakest at the longer time periods. Hot-cold-work after the proper solution treatment produces the best rupture strength at both long and short time periods.

Solution-treating at temperatures above 2100° F yields material with excessively low ductility in the rupture test. Such materials are also subject to brittleness at points of stress concentration during rupture testing. Hot-cold-work acutely magnifies these two shortcomings.

Aging treatments are especially beneficial to ductility in the rupture test and to alleviation of the stress-concentration brittleness.

A rough correlation exists between Brinell hardness and yield strengths and rupture strengths. The correlations, together with the specific trends shown by the detailed data, permit quite close predictions of the properties of large forgings. Large forgings have properties which are slightly lower than those of the bar stock studied.

Wide ranges in properties of most of the better alloys developed for gas-turbine service have been due to the influence of heat treatment and processing conditions on properties. The treatments used have been of more influence than wide ranges in chemical composition. The properties of alloys in the hot-worked condition are quite variable because hot-working simultaneously involves solution treatments, aging, and hot-cold-work; and it is very difficult to control these under normal hot-working conditions.

It is expected that the trends shown in this investigation for the various treatments will hold for other alloys. It is not expected, however, that the optimum treatments will be the same for all alloys. A certain amount of test work on any other alloy will have to be done to establish the best conditions of treatment. It is also quite probable that the influence of the treatments on rupture strength may not be the same as their influence on the strengths for limited deformations.

Insofar as could be determined, both precipitation reactions and strain hardening control the properties. High strength at room temperature and for short time periods at 1200° F probably depends on the presence of strain hardening. High long-time strength at 1200° F is dependent on aging during testing. Hot-cold-work at temperatures below 1400° F provides the best preparation for aging to high strength during testing at 1200° F. Aging treatments to be effective in a reasonable time period require a higher temperature treatment than 1200° F. The resulting precipitation has very little effect on room-temperature strength, improves the rupture strength at shorter time periods, but results in a very low strength at prolonged time periods.

INTRODUCTION

A program of research on heat-resistance alloys has been in progress at the University of Michigan for the National Advisory Committee for Aeronautics. At the outset of this program the major emphasis was placed on a search for new alloys with outstanding properties for gas turbines on the basis of chemical composition. From this work several alloys appeared to have outstanding properties. Further experience with these alloys indicated that their properties were quite dependent on the schedule used in processing and heat-treating. (See references 1, and 3.)

This report is based on a systematic study of the effects of heat treatment and hot-cold-work on the properties of low-carbon N-155 alloy. Bar stock from one heat of the alloy was subjected to 67 different treatments. The criterions used for evaluating the effect of the treatments were physical properties at room temperature and rupture test characteristics at 1200° F.

Low-carbon N-155 was one of the outstanding alloys which evolved from the initial work in this field by the NACA. The alloy was known to have a large range in properties depending on the forging and heat-treating conditions used in its production. (See reference 4.) For these reasons and because of the potential usefulness of the alloy at high temperatures it was selected as an acceptable alloy for fundamental studies. It is expected, however, that the principles developed from the work will be applicable to other alloys with considerably less experimental work.

The criterions used were selected primarily because they were believed to be indicative of the suitability of alloys for service in the discs of rotors for gas turbines. The types of heat treatment and processing which should be used for producing such discs have not been clear and it seemed worth while to start the investigations on the effect of heat treatment and other processing variables on disc criterions.

This work was conducted at the University of Michigan under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

TEST MATERIAL

The following information concerning the low-carbon N-155 alloy used in this investigation was supplied by the alloy producers:

Alloy producers:

A special heat was melted by the Union Carbide and Carbon Research Laboratories, Inc.

The ingot was processed by the Universal-Cyclops Steel Corporation

Heat designation:

Lot 30276

Chemical composition:

The chemical composition was reported to be the following percentages:

C	Mn	Si	S	P	Cr	Ni	Co	Mo	W	Cb	N
0.12	1.64	0.39	0.003	0.026	21.33	18.88	18.60	3.21	1.97	1.10	0.12

Fabrication procedure:

The approximately 6000-pound (8- by 7-inch) ingot was hammer cogged without difficulty to 2-inch-square billets with 2050° as maximum and 1750° F as minimum working temperatures. The 2-inch-square billets were hot-rolled to 7/8-inch-square bars in one heat from 2075° F to a finishing temperature of 1725° F. One hundred feet of the 7/8-inch-square bar stock was furnished for this investigation.

Structure:

As received, the bar stock had a Brinell hardness of 233 and a 0.02-percent-offset yield strength of 72,500 psi at room temperature. The grain size was finer than 8 and there was relatively little grain-boundary precipitation, as is shown by figure 1. Considerable center segregation of excess constituents was observed however as is shown by the macrographs. After considerable study it was decided that the segregated condition was not too severe and that the stock was typical of the material being produced.

EXPERIMENTAL PROCEDURE

The experimental procedure was designed to show the effects of the following treatments on the properties of low-carbon N-155 alloy at room temperature and the rupture test characteristics at 1200° F:

(1) Hot-rolled stock

(a) Aging
(b) Hot-cold-work
(c) Agglomeration of excess constituents

(2) Solution-treated stock

(a) Temperature of solution-treating
(b) Time of solution treatment and cooling rate
(c) Aging temperature
(d) Aging time
(e) Hot-cold-work after various solution treatments
(f) Temperature of hot-cold-working
(g) Amount of hot-cold-work
(h) Aging prior to hot-cold-work
(i) Aging after hot-cold-work
(j) Effect of holding time at 1200° F before testing

Solution treatments were varied from 1800° to 2300° F, aging treatments from 1350° to 1750° F, and hot-cold-working from room temperature to 1800° F. A diagram which shows all the 67 treatments used is given in figure 2.

The individual treatments were made on bars $8\frac{1}{2}$ inches long cut from 7/8-inch-square bar stock. Solution treatments were carried out in a gas-fired furnace. Aging was done in an electric resistance furnace. Hot-cold-working was accomplished by rolling in a 5-inch, two-high rolling mill.

The general procedure for rolling was as follows: The bar was heated for 1 hour at a temperature 20° F higher than the desired rolling temperature. In two passes the bar was reduced 10 percent. Reductions of 5 and 10 percent were made with no reheat, 15 and 20 percent with one reheat, and 25 percent with two reheats. A reheat consisted in placing the partially rolled bar in the furnace to bring it back to 20° F above rolling temperature. All hot-cold-rolled bars were given a final stress relief of 1 hour at 1200° F.

The treated bars were sectioned to give a $5\frac{1}{2}$-inch-long by 0.505-inch-diameter tensile specimen from one end, four $2\frac{1}{2}$-inch-long by 0.160-inch-diameter rupture specimens from the other end, and hardness and metallographic specimens from the small piece of stock remaining.

The room-temperature tensile tests were conducted in a 60,000-pound hydraulic testing machine. The modified Martin type extensometer system used had a sensitivity of 0.000003-inch per inch.

Rupture tests were run in individual stationary units applying the stress through a simple-beam and knife-edge system. Approximately 24 hours was allowed for temperature adjustments prior to application of the stress. Only the minimum number of tests needed to indicate the 100- and 1000-hour rupture strengths were run. The effect of time at temperature prior to loading on rupture properties was studied by holding duplicate stressed specimens for 1 and 24 hours at 1200° F before applying the stress. The materials used for this study were solution-treated or solution-treated and aged.

Brinell hardness tests were run on all the bars. Original metallographic samples were prepared for observation, and photomicrographs were made of representative samples.

RESULTS

The detailed test data from the tensile tests at room temperature and rupture tests at 1200° F are given in tables I and II. The reported rupture strengths are based on the best logarithmic curves of stress against rupture time which could be drawn through the available data. Graphical presentation of the data has been used to show the findings from the various specific treatments studied.

Treatment of Hot-Rolled Stock

The effects of aging and of hot-cold-working the particular as-rolled stock used in this investigation, and summarized in figure 3, were:

Aging.- The properties of the as-rolled stock were reduced at room temperature by aging in the temperature range from 1350° to 1750° F. These same treatments had very little effect on the stress for rupture in 1000 hours. Aging at 1500° to 1750° F did reduce the stress for rupture in 100 hours and increase the ductility in the rupture test.

Hot-cold-work.- Strength and hardness at room temperature were increased and ductility reduced in proportion to the amount of reduction during hot-cold-rolling at 1200° F. A reduction of only 10 percent produced a yield strength at 0.02-percent offset of 100,000 psi.

A reduction of 15 percent developed the maximum rupture strength. Lower rupture strengths were found after larger amounts of hot-cold-work. The reduction of 15 percent increased the stress for rupture of the hot-rolled material from 49,000 to 63,000 psi at 100 hours and from 37,500 to 49,000 psi at 1000 hours. The hot-cold-work had no consistent effect on ductility in the rupture test.

The only difference between a reduction of 10 percent at room temperature and at 1200° F was somewhat lower ductility in the rupture test due to working at room temperature.

Aging at 1400° F after 15 percent hot-cold-work sharply reduced all properties over those of the hot-cold-worked material except hardness, ductility, and rupture strength at 1000 hours.

Agglomeration of excess constituents.- Severe working and annealing in the temperature range from 1800° to 1400° F to agglomerate excess constituents resulted in rupture properties similar to those obtained by aging at 1500° to 1750° F. It had been expected that such treatments would reduce rupture strengths to very low values.

Properties after Solution Treatment

The major part of the work was conducted on stock which had been solution-treated. The effects of various treatments should be more generally applicable after solution treatments than for as-rolled stock which can be a quite variable material depending on rolling conditions. Graphical treatment has been used to show the findings from the various experiments:

Time of solution treatment and cooling rate.- No variation of properties with solution time was observed at either 2050° or 2200° F solution temperatures. (See fig. 4.) Rupture properties were somewhat reduced with air-cooling when compared with those obtained by water-quenching.

Temperature of solution treatment.- The major effects of solution treatments alone were to reduce strength and increase ductility at room temperature and to reduce the stress for rupture in 100 hours and the ductility in the rupture test. (See fig. 5.) The highest rupture strengths resulted from solution-treating at 2100° F, although there was very little difference over the temperature range from 1950° to 2100° F. Higher-temperature treatments resulted in lower strengths. Ductility in the rupture test fell off rapidly with increasing solution temperature up to 2100° F.

Solution treatments decrease the slope of the curves of stress against rupture time. This was indicated by most of the observed stresses for fracture in 1000 hours being equal to or higher than those for the hot-rolled stock and the 100-hour strengths being sharply reduced.

Some susceptibility to brittleness at stress concentrations is to be expected when the solution-treatment temperature is high enough to cause low elongation in the rupture test. This was evidenced by a tendency for fracture to occur in gage marks or in fillets after the solution temperature was raised above 2100° F.

The microstructures changed gradually with increasing temperature of solution treatment. (See fig. 6.) Partial resolution of the precipitates which formed during heating up occurred at 1950° F. Insofar as could be determined, a temperature of 2050° or 2100° F was necessary to obtain complete solution of all constituents except the apparently insoluble columbium carbides. Partial grain growth started at 1950° F. Higher temperatures produced uniform grains gradually increasing in size with increasing solution-treating temperature. The grain size was not excessive, however, even after solution-treating at 2300° F.

Aging temperature.- (See fig. 7.) Aging treatments at 24 hours had relatively little effect on properties at room temperature. The major effect of aging on the results of rupture tests was to increase ductility. There was a maximum in 100-hour rupture strengths on aging at 1350° to 1400° F although the specific effects varied depending on the prior treatment and rupture time considered. Aging after solution-treating widened the difference between the strengths for rupture in 100 and 1000 hours in most cases. In general, better properties were obtained by aging as the solution temperature increased. The changes in properties seem small in comparison with the changes in microstructure shown in the typical examples in figure 8.

Aging time.- (See fig. 9.) Aging at 1400° F after a 2050° F solution treatment improved the rupture strength and ductility for 100 hours at 1200° F but did not improve the strength at 1000 hours. A period of 8 hours at 1400° F produced nearly the maximum effect.

Aging at 1400° F after a 2050° F solution treatment produced rupture strengths at 100 hours about equal to those similarly aged after a solution treatment at 2200° F. The ductility in the rupture test was much higher after a 2050° F treatment. The material solution-treated at 2050° F had somewhat lower strengths at 1000 hours than those treated at 2200° F when aged at 1400° F.

Apparently aging at 1350° F for 24 hours was slightly more beneficial to 100-hour rupture strength than aging at 1400° F. The 1000-hour strength of the material solution-treated at 2050° F was also improved but not when treated at 2200° F. Aging at 1350° F for 50 hours did not change the properties appreciably over those of material aged for 50 hours at 1400° F.

Room-temperature properties were not appreciably changed by aging at the indicated times.

Treatment prior to hot-cold-work.- (See fig. 10.) Various solution treatments prior to 15 percent hot-cold-work had very little effect on properties at room temperature. The hot-rolled stock, however, became harder and stronger than the solution-treated stocks.

The minimum rupture strength occurred when the stock was treated at 1800° F prior to hot-cold-working. Stress for rupture in 1000 hours was independent of solution temperature above 1950° F and higher for the solution-treated material than for the hot-rolled material. The 100-hour strengths were at a maximum when solution-treated at 1950°

to 2050° F; but were lower than for the as-rolled material. Increasing the solution temperature lowered the difference between the stress for rupture in 100 and 1000 hours of hot-cold-worked material.

Solution-treating above 2100° F prior to hot-cold-work resulted in severe stress-concentration brittleness. This was so severe in the material quenched from 2200° F that it was necessary to reduce the diameter of the test specimens in order to avoid fractures in fillets and threads of the specimens.

Temperature of hot-cold-working.- (See fig. 11.) Strength at room temperature fell off as the temperature of hot-cold-working was raised from 1000° to 1800° F. This decrease in resulting strength with increasing temperature of hot-cold-work was most pronounced between 1300° and 1600° F. Ductility at room temperature was not affected by the temperature of working up to 1600° F.

The temperature of hot-cold-work had practically no effect on the results from rupture tests in the range from 1000° to 1400° F. When worked at higher temperatures the resulting rupture strength was lower and ductility higher.

A solution treatment at 2200° F prior to hot-cold-work resulted in a lower stress for rupture in 100 hours than when the solution treatment was 2050° F. There was practically no difference in the rupture strength at 1000 hours. Elongation in the rupture test was low after both treatments.

In general, the properties resulting from a reduction of 10 percent at room temperature were not quite so good as when the reduction was at 1200° F.

Amount of hot-cold-work.- (See fig. 12.) Hardness and strength at room temperature were increased and ductility was reduced to a pronounced degree by increasing amounts of hot-cold-work at 1200° F. The indications are, however, that the yield strength may be adversely affected by more than limited amounts of hot-cold-work. Between 10- and 15-percent reduction, depending on the prior treatment, is needed to produce a yield strength of 100,000 psi for 0.02-percent offset.

Rupture strengths increased markedly with percent reduction. Both prior treatment and rupture time influenced the relative rupture strengths to some extent. In general, the hot-rolled material had the best strength and ductility although its 1000-hour strength did not increase with percent reduction as much as for the solution-treated materials. Apparently solution treatments in the range from 1950° to 2200° F had relatively little effect on rupture strength, except possibly at the shorter time periods for the material solution-treated at 2200° F and reduced more than 10 percent.

Hot-cold-working at 1200° F did not appreciably change the microstructure of the alloy. The photomicrographs in figure 13 show that relatively little grain distortion occurred and that the major effect was some twinning and increase in the ease of etching of grain boundaries in comparison with the plain solution-treated material.

Aging prior to hot-cold-work.- The major effect of aging solution-treated material for 24 hours at 1400° F prior to 10-percent hot-cold-work at 1200° F was a slight reduction in rupture strength and a considerable increase in rupture test ductility when compared with plain solution-treated and hot-cold-worked material. (See fig. 12.)

Aging after hot-cold-work.- Aging for 24 hours at 1400° F after 15-percent reduction at 1200° F lowered both the room-temperature and rupture strengths of 2050° F solution-treated material over the unaged material. The rupture test ductility was materially improved. (See fig. 10.)

When solution-treated at 2200° F, however, the major change produced by aging after hot-cold-work was a substantial increase in rupture strength compared with the unaged material.

Effect of Holding Time in the Rupture Test Unit before Testing

The possibility exists that the results of the rupture tests might be influenced by aging during the standard test procedure of holding specimens for approximately 24 hours in the units for temperature adjustment before applying the stress. Partial data from a study of the effect of holding time in table III are inconclusive. Materials solution-treated at 2200° F apparently were strengthened somewhat by holding 24 hours while those solution-treated at 2050° F were weakened. In either case the variation was not enough to change the results of the investigation.

DISCUSSION OF RESULTS

The properties of low-carbon N-155 alloy can be influenced to a pronounced degree by heat treatment and hot-cold-work. The ranges in properties for each type of treatment are summarized in figure 14. For the particular hot-rolled stock tested, strength at room temperature will be reduced by any heat treatment alone and only hot-cold-work will increase it. Only the rupture strength at 1000 hours can be improved by solution and aging treatments. Marked increases in room-temperature strength and in rupture strength can be obtained by hot-cold-work. For any type of treatment, however, a range in properties will result depending on the conditions of treatment.

The total range in properties produced by the treatments was very wide. Yield strengths at room temperature ranged from 30,000 to 134,000 psi at 0.02-percent offset. The stress for rupture in 100 hours at 1200° F varied from 40,000 to 66,000 psi and in 1000 hours from 35,000 to 56,000 psi. In terms of time for fracture these results mean that in its weakest condition the alloy would fracture at 1200° F under a stress of 40,000 psi in 100 hours. In the strongest condition the alloy would carry the 40,000 psi for an estimated 600,000 hours. Under a stress of 56,000 psi the strongest condition would fracture in 1000 hours at 1200° F, whereas the weakest condition would fail in less than 0.1 hour. Ductility in the rupture test also varied over wide limits. The percentage elongation for fracture in 100 hours ranged from 1 to 40 percent.

These wide variations are significant for several reasons. The most important is that processing and heat treatment must be controlled to obtain the highest strengths possible from the alloy. Rather wide variations in properties for several heats have been due to a lack of suitable control of the processing conditions. The absence of systematic correlations between chemical composition and properties for a wide range of alloys is believed due to uncontrolled comparative processing and to the possibility that optimum properties may require different treatments for each alloy. The wide range in properties which has been observed for any one alloy in the hot-worked condition quite certainly is due to the effects shown for heat treatment and hot-cold-work. During hot-working an alloy is heat-treated and hot-cold-worked simultaneously. Therefore a range in properties is to be expected depending on the conditions of hot-working.

Limitations of Data

There are several limitations to the general applicability of the data. One of the most important is that only one heat and lot of bar stock has been studied. Information is not available regarding the influence of melting and hot-working variables on the results obtained. The data shown for hot-worked material are considered to have the least general applicability because hot-worked stock could conceivably vary from a quite thoroughly solution-treated condition to a severely cold-worked and agglomerated material. Those experiments which involved a fairly thorough solution treatment should have given typical data for any heat. Further work on other heats is needed, however, to demonstrate the degree of reproducibility between heats.

All comparisons have been based on room-temperature properties and rupture test characteristics at 1200° F. Caution is needed in applying the results of the rupture tests to applications involving limited permissible deformation. There is reason to believe that the relative effects of the different treatments would vary considerably depending on the amount of deformation and the time period considered. It is also quite certain that optimum treatments would be very different at higher temperatures than 1200° F.

In all the test work the number of tests was limited to the minimum necessary to indicate the level of properties for each treatment. Some of the reported strengths may be somewhat in error because of variations in test material. Precise determination of the properties for design purposes would require a more thorough testing program.

Recommended Treatments for Gas-Turbine Discs

The problem of determining which treatments will produce the best material for the disc of a gas turbine is not clear even from the data available. The choice of any particular treatment would depend on the yield strength necessary at room temperature, the time period for rupture at 1200° F considered, and the ductility restrictions. The as-rolled stock when hot-cold-worked produced the highest yield strengths and rupture strength, except for 1000 hours for fracture, with the best ductility in the rupture test. In other words, for applications involving service of only a few hundred hours the hot-rolled and hot-cold-worked material had the best all-round properties. The difficulty with the finding is that in production it would probably be very difficult to control the hot-working conditions satisfactorily so that consistently uniform properties could be obtained, particularly long-time rupture ductility at 1200° F.

The best solution treatment alone appears to be about 2100° F. The yield strength at room temperature, however, will be below 40,000 psi. The stresses for rupture in 100 and 1000 hours should be about 51,000 and 40,000 psi.

The relative effectiveness of aging depends on prior treatment and on the rupture time at 1200° F considered. The major benefit appears to be increased ductility in the rupture test. The data indicate that an aging time of either 2 or 24 hours at 1350° to 1400° F is the best treatment although there is surprisingly little difference in properties when the aging temperature is as high as 1750° F. Aging at these temperatures should produce a yield strength at room temperature between 40,000 and 50,000 psi, a 100-hour rupture strength at 1200° F of about 51,000 psi, and a 1000-hour strength between 35,000 and 43,000 psi.

The highest possible strength at room temperature and in rupture tests at 1200° F is dependent on the presence of hot-cold-work. The hot-cold-working should be carried out at temperatures below 1400° F in order to develop maximum properties. A reduction of 10 to 15 percent in this temperature range is all that is required. Material processed in this manner can be expected to have yield strengths from 90,000 to 110,000 psi at room temperature and rupture strengths for fracture in 100 hours from 60,000 to 63,000 psi and in 1000 hours from 52,000 to 55,000 psi. Very low ductility in the rupture test will be associated with any effectively solution-treated and hot-cold-worked materials unless the working temperature is above 1400° F.

The upper limit of temperature of solution-treating prior to hot-cold-working lies between 2050° and 2200° F. A solution temperature of 2200° F will result in somewhat poorer properties than a 2050° F treatment. The major objection to the higher solution temperature, however, is the excessive brittleness under slow strain rates. The lower limit of solution-treating lies between 1950° and 1800° F. The properties obtained with a 1950° F treatment were quite similar to those with a 2050° F treatment with somewhat better ductility in the rupture test. The rupture strengths after treating at 1800° F were low.

The limited data available indicate that an aging treatment prior to hot-cold-working will not affect the room-temperature properties but will have a pronounced effect on the rupture properties. Rupture strengths apparently will be substantially lower and the ductility much better. This procedure, however, avoids the stress-concentration brittleness of the plain solution-treated and hot-cold-worked material.

Proper aging after hot-cold-working apparently will substantially improve material solution-treated at 2200° F prior to hot-cold-working. When solution-treated at 2050° F, however, aging will reduce all properties except ductility in the rupture test. The sensitivity to stress-concentration brittleness will also be removed. The potential improvements from aging after hot-cold-working are sufficient to warrant further work to establish the results of such treatments more completely.

It then appears that if high yield strength at room temperature and high rupture strength at 1200° F are adequate criterions of gas-turbine service the best procedure is to solution-treat in the temperature range from 1950° to 2050° F and then to hot-cold-work to 10- to 15-percent reduction at temperatures below 1400° F. Hot-cold-working the alloy in the hot-worked condition is not recommended, even though equal or better properties were obtained by that procedure in this investigation, because hot-worked material will probably be quite variable.

Treatments for Prolonged Service

Hot-cold-work produced the highest rupture strengths for prolonged service at 1200° F as is shown by the typical curves of stress against rupture time in figure 15.

This finding is contrary to the current metallurgical belief that the hot-cold-worked condition of all alloys is so unstable that it will lose its strength superiority at only slightly longer time periods than 1000 hours. This belief is probably correct for lower-alloyed materials but is evidently not true for more highly alloyed materials such as low-carbon N-155 alloy.

The curves in figure 15 show that the slope of the curves of stress against rupture time for properly solution-treated and hot-cold-worked low-carbon N-155 alloy is not much greater and is at a higher stress level than for the best solution-treated material. On the basis of rupture strength, therefore, the best preparation for prolonged service is to hot-cold-work properly. The highest rupture strengths were obtained by solution-treating at 2050° F prior to 15-percent reduction at 1200° F and then aging at 1400° F or by solution-treating at 1950° F followed by hot-cold-working to 15-percent reduction at 1200° F.

Only intermediate rupture strengths at prolonged time periods result from the best solution temperature of 2100° F. Aging treatments apparently result in the lowest strengths at the longer time periods.

Data Correlation

One of the objectives of this investigation is to develop relationships which will permit checking the relative properties of any lot of low-carbon N-155 alloy by means of a few simple tests. This phase has not yet been properly investigated. The relationships between Brinell hardness and properties is, however, shown in figures 16, 17, and 18. At any hardness level the yield strengths at room temperature may vary as much as 30,000 psi. Hardness is indicative of rupture strength to within about 10,000 psi.

The relationships between hardness and properties do not give consideration to the individual treatments. The data curves for various treatments in previous figures indicate that hardness would correlate much closer with properties for any one treatment. More data on several heats are needed before the degree of reproducibility of hardness for any one treatment can be determined. It is believed, however, that the general curves of figures 16, 17, and 18 are indicative of the range in properties which might be expected at any hardness level.

Two reports have been issued for low-carbon N-155 discs. (See references 4 and 5.) The degree to which the properties of these discs correlated with the results of this investigation is summarized in table IV. The average test data for the discs are compared with the data for similarly treated bar stock in this investigation. Estimated values are also included which are based on the Brinell hardness correlations and the experience gained from the trends of the effects of the treatments on bar stock. This table shows that the discs tend to have lower properties than bar stock; but the actual results from bar stock and from estimates based on hardness are of the same order as the test results from the discs.

The trends found for the types of treatment should be applicable to other alloys of the same general type. In each case, however, additional test work will have to be carried out in order to establish the optimum treatments for other alloys. Relative stability of the structures produced will probably vary for each analysis. The types of precipitates which form may require other conditions of heat treatment and hot-cold-work for best properties. The data for low-carbon N-155 alloy in this report should serve as a guide to reduce the testing of other alloys to a minimum.

Theoretical Considerations

The mechanism by which the treatments influence properties has not yet been established. Pronounced changes in precipitated constituents occur during solution and aging treatments. The most logical explanation is that the treatments change the size, dispersion, and possibly the composition of the precipitates which form during the treatments or during testing. Strain hardening may also be an important part of the pronounced effect of hot-cold-work.

The similarity in properties resulting from cold-working at room temperature and hot-cold-working at 1200° F suggests that precipitation during hot-cold-work at temperatures up to 1200° F is not a major factor. If this is the case then major effects of hot-cold-work must be through strain hardening and its influence on precipitation reactions during testing. If precipitation during hot-cold-working is appreciable then a similar amount of precipitation must occur very rapidly during testing after cold-working at room temperature. The pronounced influence of prior treatment on the properties after hot-cold-working would seem to indicate that precipitation reactions are important. In view of the similarity of the slopes of the curves of stress against rupture time after hot-cold-working and after solution-treating it seems unlikely that strain hardening alone could be the predominating factor.

The data are not complete enough to indicate how much precipitation during hot-cold-working at higher temperature influenced the properties. The indications are, however, that above 1400° F aging occurs which is not so beneficial to strength as that which occurs after working at lower temperatures.

The relatively steep slope of the curves of stress against rupture time after most aging treatments when compared with those for solution-treated materials suggests that the precipitates which form during aging are either unstable or are distributed or formed in a manner which does not provide as good strength as those which precipitate during testing. The aging treatments which were effective in changing the properties were at considerably higher temperatures than the test temperature of 1200° F. It therefore appears that the higher temperature treatments overage the alloy in comparison with the aging which takes place during prolonged rupture testing. The high strength at long time periods predicted by the relatively flat curves of stress against rupture time after solution treatment indicates that the precipitates formed during testing are distributed or formed in a manner more advantageous to strength, or of a different, more effective type, than those formed during aging treatments. The very low rupture strength at short time periods after solution treatments suggests that precipitation takes place very slowly at 1200° F and that considerable time must elapse before sufficient precipitation occurs to develop strengths equivalent to those obtained by other added treatments.

The low ductility in the rupture test and sensitivity to brittleness at stress concentrations associated with the completely solution-treated condition are also probably manifestations of precipitation during testing. The improvement in ductility and toughness through subsequent aging treatments probably results from these treatments changing the precipitate size and dispersion.

It is difficult to understand why aging treatments alone do not have more influence on the properties at room temperature. Apparently the precipitates are of a form or dispersion which do not have much effect on properties at room temperature. An unlikely alternative explanation could be that little actual precipitation occurs during the heat treatments and that the major effect of the treatments is observed at high temperatures because of their influence on precipitation during testing.

In summary then, the probable mechanism which controls rupture properties involves the following conceptions: (1) Solution treatments remove strengthening due to precipitation or strain hardening. Consequently, properties are low at room temperature and for short time periods at 1200° F. During prolonged testing at 1200° F, however, precipitation occurs slowly and develops high strength. (2) Aging treatments cause either a different form or type of precipitate to appear which gives higher short-time rupture strengths than the plain solution-treated material. The longer-time strength, however, obtained with the initial precipitation of aging is not so high as that which results from precipitation during testing of the material solution-treated only. The precipitation during aging has relatively little effect on properties at room temperature possibly because the aging treatment mainly influences precipitation during testing at high temperatures. (3) Hot-cold-work provides high strength at short time periods at 1200° F and at room temperature possibly from strain hardening. High strength in prolonged rupture tests under proper conditions of heat treatment and hot-cold-work probably results from precipitation during testing which strengthens and maintains the high level of strength developed by the strain hardening. (4) Hot-worked materials have varied properties because all the trends discussed under the first three items could be influencing the properties.

CONCLUSIONS

The properties of bar stock from one heat of low-carbon N-155 alloy, as measured by tensile tests at room temperature and rupture tests at 1200° F, have been systematically measured over wide limits after solution treatments, aging treatments, and hot-cold-work.

Yield strengths at room temperature ranging from 30,000 to 134,000 psi at 0.02-percent offset can be produced in the alloy. The same treatments will result in rupture strengths for fracture in 100 hours at 1200° F from 40,000 to 66,000 psi and for fracture in 1000 hours from 35,000 to 56,000 psi. These rupture strength ranges are equivalent to such extreme differences in actual time for fracture as 100 to 600,000 hours under a stress of 40,000 psi for the same alloy with different treatments.

On the basis of the yield strength for 0.02-percent offset at room temperature and rupture properties at 1200° F the following standard-type treatments are the best for the alloy:

1. For solution-treating the alloy only, the optimum temperature is about 2100° F. The yield strength will be below 40,000 psi and the rupture strengths for 100 and 1000 hours will be about 51,000 and 40,000 psi. Treatments at lower and higher temperatures will result in lower rupture strengths. Higher temperatures also will cause excessively low ductility and brittleness at stress concentrations during rupture testing.

2. The best aging treatment, 1350° to 1400° F for either 2 or 24 hours, will result in yield strengths between 40,000 and 50,000 psi and rupture strengths of about 50,000 psi for 100 hours and 35,000 to 43,000 psi for 1000 hours. Major effects of aging treatments will be increased ductility in the rupture test and low rupture strength for time periods longer than 1000 hours.

3. High strength is dependent on hot-cold-work. Maximum properties will be developed by 10- to 15-percent reduction at temperatures below 1400° F. The solution temperature prior to hot-cold-working should be between approximately 1950° and 2100° F. Yield strengths between 90,000 and 110,000 psi and rupture strengths for fracture in 100 and 1000 hours of better than 60,000 and 52,000 psi will be obtained. These treatments also produce the highest rupture strength at prolonged time periods.

Higher solution temperatures cause lower strengths and extreme brittleness in the rupture test.

4. Incomplete data suggest that further testing would show distinct benefits from aging after hot-cold-work.

5. Properly hot-worked, or hot-worked and then hot-cold-worked, material will have the best all-round properties. Such treatments are not recommended, however, because of the difficulty of controlling hot-working conditions. The original hot-worked material could vary from the fully solution-treated to the severely hot-cold-worked condition depending on the hot-working conditions.

There are certain limitations to the data. Testing was kept to the bare minimum to show trends. Other characteristics than physical properties at room temperature and rupture properties at 1200° F have not been considered. More work on other heats is needed to verify the reliability of the reported data. More complete design data are needed for the optimum treatments. The optimum treatments for service at higher temperatures than 1200° F are certain to be different from those found in this investigation.

The trends found for the effects of various treatments in this investigation should apply to other alloys of the same type. Optimum treatment conditions, however, will almost certainly vary for each alloy.

Rough general relationships exist between properties and Brinell hardness. By the use of these relationships and the detailed effects of various treatments the order of magnitude of test results from large forged discs can be predicted quite closely. The properties of discs will in general be somewhat lower than those of bar stock.

This investigation did not include a careful study of the mechanism by which the treatments affect properties. It appears, however, that precipitation has very little influence on room-temperature properties. The highest rupture properties result from precipitation during working or testing at 1200° F. Aging at higher temperatures adversely affects the precipitation reaction. High strength at room temperature and high rupture strength for short time periods after hot-cold-working at temperatures up to 1200° F are apparently due to strain hardening. Strain hardening probably results in very effective precipitation during rupture testing. The evidence regarding precipitation resulting from or during working at higher temperatures than 1200° F is not clear but apparently working temperatures above 1400° F are unfavorable to 1200° F strengths.

University of Michigan
Ann Arbor, Mich., September 5, 1947

REFERENCES

1. White, A. E., Freeman, J. W., and Rote, F. B.: Physical Data on Certain Alloys for High Temperature Applications. NACA ACR No. 3D28, 1943.

2. Freeman, J. W., Rote, F. B., and White, A. E.: High Temperature Characteristics of 17 Alloys at 1200° and 1350° F. NACA ACR No. 4C22, 1944.

3. Freeman, J. W., Reynolds, E. E., and White, A. E.: High Temperature Alloys Developed for Aircraft Turbosuperchargers and Gas Turbines. Symposium on Materials for Gas Turbines, A.S.T.M., 1946.

4. Freeman, J. W., and Cross, H. C.: A Metallurgical Investigation of a Large Forged Disc of Low-Carbon N-155 Alloy. NACA ARR No. 5K20, 1945.

5. Cross, Howard C., and Freeman, J. W.: A Metallurgical Investigation of Large Forged Discs of Low-Carbon N-155 Alloy. NACA TN No. 1230, 1947.

TABLE I.– ROOM-TEMPERATURE PHYSICAL PROPERTIES OF LOW-CARBON N-155 BAR STOCK

Heat treatment					Hot-cold-rolling (b)		Brinell hardness	Room-temperature tensile properties						
Solution treatment			Aging treatment (a)					Tensile strength (psi)	Offset yield strength (psi)			Proportional limit (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)
Temperature (°F)	Time (hr)	Method of cooling (c)	Temperature (°F)	Time (hr)	Temperature (°F)	Percent reduction			0.02 percent	0.1 percent	0.2 percent			
Aging and rolling hot-rolled bar stock														
(d)	(d)	(d)	-----	---	----	---	233	128,500	72,500	76,500	78,500	57,500	40.5	55.7
----	---	----	1350	24	----	---	214	124,500	52,700	62,500	66,300	37,500	36	38.2
----	---	----	1500	24	----	---	212	124,000	46,500	58,000	62,500	32,500	36	40.3
----	---	----	1750	24	----	---	210	119,625	44,500	55,100	59,000	30,000	39	42.8
----	---	----	-----	---	75	10	307	145,750	99,500	123,200	128,700	57,500	31	53.0
----	---	----	-----	---	1200	5	271	137,700	87,500	99,000	103,000	75,000	31.5	48.7
----	---	----	-----	---	1200	10	312	146,750	98,500	118,000	121,000	70,000	25.5	47.0
----	---	----	-----	---	1200	15	328	156,700	121,500	135,500	140,000	82,500	22	43.3
----	---	----	[e]1400	[e]24	1200	15	311	142,250	96,000	108,000	112,000	77,500	25	42.1
----	---	----	-----	---	1200	20	323	162,500	134,000	145,000	148,500	112,500	19	40.7
(f)	(f)	(f)	(f)	(f)	(f)	(f)	305	-------	-------	-------	-------	-------	----	----
(g)	(g)	(g)	(g)	(g)	(g)	(g)	189	-------	-------	-------	-------	-------	----	----
Solution-treated at 1800° F														
1800	2	W.Q.	-----	---	----	---	207	122,875	50,000	57,500	62,000	30,000	39	46.8
1800	2	W.Q.	-----	---	1200	15	290	145,000	104,000	122,500	127,000	80,000	24.5	42.7
Solution-treated at 1950° F														
1950	2	W.Q.	-----	---	----	---	198	120,250	50,000	57,000	61,000	40,000	49	64.8
1950	2	W.Q.	-----	---	1200	15	274	148,250	109,000	125,000	129,000	70,000	26	52.5

[a]All aging treatments preceded hot-cold-rolling except where noted.
[b]All hot-cold-rolled material was given a final stress relief at 1200° F for 1 hr.
[c]W.Q., water-quenched; A.C., air-cooled.
[d]As-hot-rolled.
[e]Aged after rolling.
[f]20-percent reduction at 1200° F; 65-percent reduction from 1800° to 1400° F.
[g]1800° F 2 hr, air-cooled to 1400° F; 20-percent reduction at 1400° F; repeated five more times; then 1800° F 2 hr, air-cooled.

TABLE I.– ROOM-TEMPERATURE PHYSICAL PROPERTIES OF LOW-CARBON N-155 BAR STOCK – Continued

Heat treatment					Hot-cold-rolling (b)		Brinell hardness	Room-temperature tensile properties						
Solution treatment			Aging treatment (a)					Tensile strength (psi)	Offset yield strength (psi)			Proportional limit (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)
Temperature (°F)	Time (hr)	Method of cooling (c)	Temperature (°F)	Time (hr)	Temperature (°F)	Percent reduction			0.02 percent	0.1 percent	0.2 percent			
Solution-treated at 2050° F														
Time and cooling rate:														
2050	1	W.Q.	-----	---	----	--	192	119,750	44,500	54,500	58,500	32,500	50	63.9
2050	2	W.Q.	-----	---	----	--	208	117,500	47,000	56,000	58,500	27,500	44	62.4
2050	2	A.C.	-----	---	----	--	189	119,800	44,500	52,500	56,500	35,000	56	63.7
2050	5	W.Q.	-----	---	----	--	189	118,450	48,500	57,000	59,000	37,500	52	64.8
Aging time and temperature:														
2050	2	W.Q.	1400	2	----	--	190	119,750	45,500	57,500	61,000	37,000	42.5	51.0
2050	2	W.Q.	1400	8	----	--	179	-------	------	------	------	------	----	----
2050	2	W.Q.	1400	16	----	--	183	-------	------	------	------	------	----	----
2050	2	W.Q.	1400	24	----	--	220	118,500	38,000	53,000	58,500	17,500	36	41.6
2050	2	W.Q.	1400	50	----	--	206	-------	------	------	------	------	----	----
2050	2	W.Q.	1350	24	----	--	190	119,625	48,500	56,400	60,000	37,500	42	50.0
2050	2	W.Q.	1500	24	----	--	213	120,750	50,000	57,000	60,500	37,500	38	41.2
2050	2	W.Q.	1600	24	----	--	209	116,150	39,000	49,500	54,000	22,500	35	39.9
2050	2	W.Q.	1750	24	----	--	185	114,900	42,000	49,500	53,000	32,500	29.5	43.9
Cold-working amount and temperature:														
2050	2	W.Q.	-----	---	75	10	296	136,100	97,250	112,800	117,000	62,500	36	60.7
2050	2	W.Q.	-----	---	1200	5	249	125,500	67,000	81,000	84,000	42,500	35.5	54.7
2050	2	W.Q.	-----	---	1200	10	301	138,750	90,000	107,500	112,000	52,500	28	49.2
2050	2	W.Q.	1400	24	1200	10	287	134,000	90,000	105,000	109,000	65,000	23.5	37.9
2050	2	W.Q.	-----	---	1200	15	296	145,500	110,500	120,500	124,500	65,000	26	53.2
2050	2	W.Q.	e1400	e24	1200	15	262	138,250	94,500	106,500	111,000	75,000	23.5	37.5
2050	2	W.Q.	-----	---	1200	20	340	154,500	121,000	134,000	138,000	85,000	23.5	49.5
							301	151,000	104,000	124,500	131,000	65,000	24	49.0
2050	2	W.Q.	-----	---	1200	25	318	156,000	104,000	130,000	137,500	70,000	22	48.1
2050	2	W.Q.	-----	---	1000	15	297	145,750	100,000	116,500	122,000	77,500	26.5	51.9
2050	2	W.Q.	-----	---	1400	15	290	141,000	95,500	110,500	116,000	77,500	25	45.7
2050	2	W.Q.	-----	---	1600	15	252	128,250	83,000	92,000	96,000	62,500	29	45.1
2050	2	W.Q.	-----	---	1700	15	255	128,750	81,000	90,200	93,700	57,500	32.5	48.6
2050	2	W.Q.	-----	---	1800	15	250	129,300	78,000	87,400	91,000	57,500	38	46.8
Solution-treated at 2100° F														
2100	1	W.Q.	-----	---	----	--	197	117,250	38,500	52,000	57,000	17,500	47	63.2

[a]All aging treatments preceded hot-cold-rolling except where noted.
[b]All hot-cold-rolled material was given a final stress relief at 1200° F for 1 hr.
[c]W.Q., water-quenched; A.C., air-cooled.
[e]Aged after rolling.

NACA

TABLE I.- ROOM-TEMPERATURE PHYSICAL PROPERTIES OF LOW-CARBON N-155 BAR STOCK - Concluded

Heat treatment					Hot-cold-rolling (b)		Brinell hardness	Room-temperature tensile properties						
Solution treatment			Aging treatment (a)					Tensile strength (psi)	Offset yield strength (psi)			Proportional limit (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)
Temperature (°F)	Time (hr)	Method of cooling (c)	Temperature (°F)	Time (hr)	Temperature (°F)	Percent reduction			0.02 percent	0.1 percent	0.2 percent			
Solution-treated at 2150° F														
2150	1	W.Q.	-----	---	----	--	193	116,250	30,000	47,000	53,000	10,000	45.5	62.2
Solution-treated at 2200° F														
Time and cooling rate:														
2200	1/2	W.Q.	-----	---	----	--	180	118,300	48,000	54,500	58,000	40,000	54	64.8
2200	1	W.Q.	-----	---	----	--	205	115,750	42,000	53,000	57,000	25,000	46.5	64.3
2200	1	A.C.	-----	---	----	--	175	118,250	42,000	48,500	52,000	30,000	54	64.6
Aging time and temperature:														
2200	1	W.Q.	1400	2	----	--	192	117,250	47,000	57,000	61,000	40,000	42	42.4
2200	1	W.Q.	1400	8	----	--	185	-------	------	------	------	------	----	----
2200	1	W.Q.	1400	16	----	--	190	-------	------	------	------	------	----	----
2200	1	W.Q.	1400	24	----	--	221	119,250	48,000	61,000	65,000	25,000	32	39.8
2200	1	W.Q.	1400	50	----	--	196	-------	------	------	------	------	----	----
2200	1	W.Q.	1350	24	----	--	205	120,125	54,000	61,000	64,000	45,000	38.5	40.9
2200	1	W.Q.	1350	50	----	--	213	118,000	50,000	57,500	60,000	32,500	36	41.9
2200	1	W.Q.	1500	24	----	--	202	121,750	50,000	48,500	63,500	40,000	36.5	40.3
2200	1	W.Q.	1600	24	----	--	212	118,250	42,500	53,000	57,500	22,500	31.5	34.3
2200	1	W.Q.	1750	24	----	--	195	115,250	43,000	50,000	53,500	30,000	39	32.4
Cold-working amount and temperature:														
2200	1	W.Q.	-----	---	1200	5	224	122,500	65,000	76,500	80,000	42,500	40	59.5
2200	1	W.Q.	-----	---	1200	10	256	132,000	90,000	99,000	102,000	77,500	33.5	55.8
							289	136,500	90,000	102,500	107,000	75,000	31.5	55.7
2200	1	W.Q.	1400	24	1200	10	288	136,250	98,500	107,500	111,000	70,000	22.5	34.7
2200	1	W.Q.	-----	---	1200	15	289	142,000	97,000	112,000	117,000	72,500	28	52.1
2200	1	W.Q.	e1400	e24	1200	15	293	142,000	103,000	115,000	118,500	85,000	24	37.8
2200	1	W.Q.	-----	---	1000	15	294	145,500	105,000	119,000	123,000	80,000	27.5	56.0
2200	1	W.Q.	-----	---	1400	15	289	140,500	94,000	111,000	116,000	67,500	26.5	46.2
2200	1	W.Q.	-----	---	1600	15	249	128,500	80,000	92,000	96,000	62,500	26	40.7
Solution-treated at 2250° F														
2250	1/2	W.Q.	-----	---	----	--	178	116,000	44,500	52,000	55,000	30,000	53	64.1
Solution-treated at 2300° F														
2300	1/2	W.Q.	-----	---	----	--	163	116,250	48,000	53,000	57,000	40,000	56.5	65.8

[a]All aging treatments preceded hot-cold-rolling except where noted.
[b]All hot-cold-rolled material was given a final stress relief at 1200° F for 1 hr.
[c]W.Q., water-quenched; A.C., air-cooled.
[e]Aged after rolling.

NACA

TABLE II.– RUPTURE TEST CHARACTERISTICS AT 1200° F OF LOW-CARBON N-155 BAR STOCK

Heat treatment					Hot-cold-rolling (b)		Rupture properties at 1200° F					
Solution treatment			Aging treatment (a)									
Temperature (°F)	Time (hr)	Method of cooling (c)	Temperature (°F)	Time (hr)	Temperature (°F)	Percent reduction	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)	Rupture strength (psi) 100 hr	Rupture strength (psi) 1000 hr
Aging and rolling hot-rolled bar stock												
(d)	(d)	(d)	(d)	(d)	(d)	(d)	55,000	8.5	[e]9.5	8.5	49,500	37,500
							50,000	75	17	23.3		
							45,000	252	19	23.3		
							40,000	610	34	48.3		
----	---	----	1350	24	----	------	50,000	123	12	49.2	51,000	35,500
							45,000	241	38	55.3		
							41,000	411	33	55.3		
----	---	---	1500	24	----	------	50,000	54	16	46.5	47,000	36,000
							45,000	166	12	50.1		
							40,000	430	40	58.6		
----	---	---	1750	24	----	------	50,000	40	49	51.9	45,000	37,000
							45,000	101	38	44.7		
							40,000	430	36	53.0		
----	---	---	-----	---	75	10 (9.8)	60,000	73	4	4.0	58,500	49,000
							55,000	230	13	32.4		
							50,000	809	10	16.7		
----	---	---	-----	---	1200	5 (4.5)	60,000	48	8	22.2	56,000	[f]46,000
							55,000	216	8	32.2		
							50,000	387	12	36.0		
----	---	---	-----	---	1200	10	65,000	36	5	12.5	61,000	47,000
							60,000	115	[e]16	28.8		
							55,000	302	16	38.8		
							50,000	528	15	40.8		
----	---	---	-----	---	1200	15 (14.1)	60,000	157	6	20.6	63,000	49,000
							55,000	325	8	24.1		
							50,000	845	6.5	17.9		
----	---	---	[g]1400	24	1200	15 (15.6)	55,000	72	16	51.9	53,000	47,000
							52,500	108	27	40.8		
							50,000	364	19	38.8		
----	---	---	-----	---	1200	20	65,000	84	10	21.8	62,000	46,000
							60,000	112	10	23.3		
							55,000	210	18	44.7		
							50,000	536	15	33.5		
(h)	(h)	(h)	(h)	(h)	(h)	(h)	60,000	25	30	50.4	49,000	35,000
							50,000	85	26	36.6		
							40,000	429	16	24.8		
							36,000	785	12	19.0		
(i)	(i)	(i)	(i)	(i)	(i)	(i)	50,000	23	36	41.1	43,500	35,000
							40,000	240	34	44.6		
							44,000	163	35	41.5		
							35,000	1086	28	35.6		
Solution-treated at 1800° F												
1800	2	W.Q.	-----	---	----	------	45,000	51	40	58.6	42,000	35,000
							40,000	120	32	56.1		
							39,700	175	36	55.3		
							35,000	1313	38	52.0		
1800	2	W.Q.	-----	---	1200	15	55,000	103	13	41.5	55,000	40,000
							50,000	241	9	32.8		
							45,000	415	14	46.0		
Solution-treated at 1950° F												
1950	2	W.Q.	-----	---	----	------	45,000	92	27	35.0	45,000	38,000
							40,000	318	25.5	40.8		
							37,500	1107	30	40.8		
1950	2	W.Q.	-----	---	1200	15	64,000	59	4	8.1	61,000	52,000
							60,000	168	5	17.2		
							55,000	517	5	16.3		

[a]All aging treatments preceded hot-cold-rolling except where noted.
[b]All hot-cold-rolled material was given a final stress relief at 1200° F for 1 hr.
[c]W.Q., water-quenched; A.C., air-cooled.
[d]As-hot-rolled.
[e]Fractured in gage mark.
[f]Estimated.
[g]Aged after rolling.
[h]20-percent reduction at 1200° F; 65-percent reduction from 1800° to 1400° F.
[i]1800° F 2 hr, air-cooled to 1400° F, 20-percent reduction at 1400° F; repeated five more times; then 1800° F 2 hr, air-cooled.

NACA

TABLE II.– RUPTURE TEST CHARACTERISTICS AT 1200° F OF LOW-CARBON N-155 BAR STOCK – Continued

Heat treatment					Hot-cold-rolling (b)		Rupture properties at 1200° F					
Solution treatment			Aging treatment (a)									
Temperature (°F)	Time (hr)	Method of cooling (c)	Temperature (°F)	Time (hr)	Temperature (°F)	Percent reduction	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)	Rupture strength (psi) 100 hr	Rupture strength (psi) 1000 hr
Solution-treated at 2050° F												
Time and cooling rate												
2050	1	W.Q.	----	--	-----	-------	45,000	25	[e]1	17.8	45,000	40,000
							44,000	420	18	22.6		
							43,000	619	24	26.7		
							40,000	1138	17	15.6		
2050	2	W.Q.	----	--	-----	-------	48,000	33	[e]3	17.3	45,500	39,000
							45,000	180	10	18.9		
							40,000	687	19	23.3		
2050	2	A.C.	----	--	-----	-------	45,000	35	[e]7.5	14.4	43,000	39,000
							42,000	119	5	7.3		
							40,000	614	[e]8.5	17.8		
2050	5	W.Q.	----	--	-----	-------	51,000	62	(e)	8.0	49,000	40,500
							48,000	181	12	12.5		
							45,000	141	10	10.9		
							40,000	1138	21	25.6		
Aging time and temperature												
2050	2	W.Q.	1400	2	-----	-------	54,000	35	21	14.4	49,000	39,000
							50,000	116	11	18.9		
							45,000	163	12	10.9		
							40,000	825	17	20.4		
2050	2	W.Q.	1400	8	-----	-------	50,000	118	28	24.5	51,000	40,000
							45,000	310	24	23.3		
							40,000	954	29	35.8		
2050	2	W.Q.	1400	16	-----	-------	50,000	97	29	34.0	50,000	39,500
							45,000	300	27	40.8		
							40,000	860	33	41.2		
2050	2	W.Q.	1400	24	-----	-------	55,000	31	24	21.2	50,500	35,000
							50,000	123	38	33.0		
							45,000	205	37	36.9		
							40,000	436	44	44.7		
2050	2	W.Q.	1400	50	-----	-------	50,000	75	9	38.8	48,000	36,500
							45,000	300	33	37.9		
							42,500	285	37	40.8		
							40,000	423	5	25.6		
2050	2	W.Q.	1350	24	-----	-------	50,000	145	13	12.5	52,000	40,000
							45,000	343	12	21.0		
							40,000	1078	20	29.7		
2050	2	W.Q.	1500	24	-----	-------	50,000	87	40	36.9	48,000	36,000
							45,000	122	24	35		
							40,000	462	37	48.3		
2050	2	W.Q.	1600	24	-----	-------	50,000	74	40	41.8	47,500	[f]35,000
							45,000	132	31	43.7		
							40,000	361	38.5	45.8		
2050	2	W.Q.	1750	24	-----	-------	50,000	121	33	29.8	51,500	38,000
							45,000	306	39	52.8		
							39,000	659	36	53		

[a]All aging treatments preceded hot-cold-rolling except where noted.
[b]All hot-cold-rolled material was given a final stress relief at 1200° F for 1 hr.
[c]W.Q., water-quenched; A.C., air-cooled.
[e]Fractured in gage mark.
[f]Estimated.

NACA

TABLE II.– RUPTURE TEST CHARACTERISTICS AT 1200° F OF LOW-CARBON N-155 BAR STOCK – Continued

Heat treatment					Hot-cold-rolling (b)		Rupture properties at 1200° F					
Solution treatment			Aging treatment (a)									
Temperature (°F)	Time (hr)	Method of cooling (c)	Temperature (°F)	Time (hr)	Temperature (°F)	Percent reduction	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)	Rupture strength (psi) 100 hr	Rupture strength (psi) 1000 hr
Solution-treated at 2050° F												
Cold-working amount and temperature												
2050	2	W.Q.	-----	--	75	10 (9.8)	60,000	24	[e]1	5.3	56,000	50,000
							55,000	275	4	11.2		
							50,000	1068	5	20.6		
2050	2	W.Q.	-----	--	1200	5	55,000	46	2	5.6	52,000	44,000
							52,500	86	2	9.7		
							50,000	261	[e]4	8.5		
							45,000	821	18	23.3		
2050	2	W.Q.	-----	--	1200	10	60,000	69	[e]1	2.7	59,000	52,000
							55,000	614	4	11.0		
							50,000	1465	8.5	23.2		
2050	2	W.Q.	1400	24	1200	10	55,000	88	22	39.8	54,000	43,500
							50,000	268	18	31.3		
							47,000	302	[e]15	23.3		
							44,000	920	15	40.0		
2050	2	W.Q.	-----	--	1200	15 (14.3)	60,000	167	1	1.5	62,000	53,500
							55,000	389	8	21.0		
							52,000	1556	4	16.4		
2050	2	W.Q.	[g]1400	24	1200	15	55,000	110	18	37.9	55,500	48,000
							52,500	365	19	37.9		
							50,000	576	13.5	37.9		
2050	2	W.Q.	-----	--	1200	20 (18.9)	63,000	102	1.5	2.8	62,000	56,000
							60,000	95	2	6.9		
							60,000	243	1.5	4.1		
							57,500	773	3	7.0		
							55,000	1348	3	7.8		
2050	2	W.Q.	-----	--	1200	25	70,000	19	2	5.7	66,000	56,000
							65,000	200	4	11.0		
							60,000	493	5	18.9		
							55,000	1142	5	21.6		
2050	2	W.Q.	-----	--	1000	15 (15.6)	65,000	79	2	2.5	63,500	53,000
							60,000	208	1.5	2.8		
							55,000	389	9	21.3		
							50,000	2087	4.5	19.1		
2050	2	W.Q.	-----	--	1400	15 (15.3)	65,000	66	3	10.9	62,500	52,000
							60,000	176	3.5	13.2		
							55,000	551	6	25.6		
2050	2	W.Q.	-----	--	1600	15 (14.3)	60,000	40	15	29.8	56,000	45,000
							55,000	188	11	37.2		
							50,000	321	13	40.2		
							45,000	1013	14	29.5		
2050	2	W.Q.	-----	--	1700	15 (15.7)	55,000	61	24.5	36.9	52,000	39,000
							50,000	123	25	36.9		
							45,000	342	28	39.8		
2050	2	W.Q.	-----	--	1800	15 (15.0)	54,000	48.5	25	36.9	51,000	43,000
							50,000	125	19	35.0		
							45,000	535	20	33.0		

[a]All aging treatments preceded hot-cold-rolling except where noted.
[b]All hot-cold-rolled material was given a final stress relief at 1200° F for 1 hr.
[c]W.Q., water-quenched; A.C., air-cooled.
[e]Fractured in gage mark.
[g]Aged after rolling.

NACA

TABLE II.– RUPTURE TEST CHARACTERISTICS AT 1200° F OF LOW-CARBON N-155 BAR STOCK – Continued

Heat treatment					Hot-cold-rolling (b)		Rupture properties at 1200° F					
Solution treatment			Aging treatment (a)									
Temperature (°F)	Time (hr)	Method of cooling (c)	Temperature (°F)	Time (hr)	Temperature (°F)	Percent reduction	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)	Rupture strength (psi) 100 hr	Rupture strength (psi) 1000 hr
Solution-treated at 2100° F												
2100	1	W.Q.	----	--	----	-----	50,000	35	[e]9	17.8	46,500	40,000
							45,000	140.5	[e]6	10.9		
							40,000	1003	16	17.8		
Solution-treated at 2150° F												
2150	1	W.Q.	----	--	----	-----	45,000	83	[e]5	14.4	42,500	38,000
							41,000	47	[e]5.5	15.6		
							40,000	312	[e]6.5	9.7		
							37,000	1743	13	16.7		
Solution-treated at 2200° F												
Time and cooling rate												
2200	1/2	W.Q.	----	--	----	-----	45,000	14	[e]8.5	14.4	42,000	38,000
							42,500	149	[e]7	9.1		
							40,000	420	[e]9	6.2		
2200	1	W.Q.	----	--	----	-----	50,000	4	[e]5	26.7	42,000	38,000
							45,000	29	4	15.6		
							40,000	247	[e]6	6.2		
							37,500	1500	----	----		
2200	1	A.C.	----	--	----	-----	45,000	30	6	10.9	40,000	[f]35,000
							40,000	77	[e]3	9.7		
							37,000	396	[e]5	9.7		
Aging time and temperature												
2200	1	W.Q.	1400	2	----	-----	53,000	60	13	15.4	51,000	44,000
							50,000	113	15	13.3		
							45,000	658	14	20.0		
2200	1	W.Q.	1400	8	----	-----	50,000	36	5	11.5	47,000	40,000
							45,000	178	8	7.3		
							42,000	558	[e]8	7.3		
2200	1	W.Q.	1400	16	----	-----	50,000	67	12	17.8	48,500	41,000
							45,000	384	[e]12	16.5		
							42,000	510	15	17.8		
2200	1	W.Q.	1400	24	----	-----	54,000	48.5	[e]12	18.3	50,000	42,000
							50,000	118	14	17.8		
							47,000	133	18	23.3		
							45,000	398	21	30.8		
2200	1	W.Q.	1400	50	----	-----	50,000	88	20	33.0	49,000	38,500
							45,000	234	20	21.2		
							41,000	573	20	22.0		
2200	1	W.Q.	1350	24	----	-----	50,000	170	15	23.3	53,000	39,500
							45,000	335	21	20.0		
							40,000	918	36	35.0		
2200	1	W.Q.	1350	50	----	-----	50,000	53	[e]12	13.3	47,000	37,000
							45,000	145	[e]10	16.7		
							40,000	479	[e]14	21.2		
							35,000	3301	19	21.6		
2200	1	W.Q.	1500	24	----	-----	50,000	76	25	35.0	49,000	35,000
							45,000	209	22	25.6		
							40,000	346	30	39.6		
2200	1	W.Q.	1600	24	----	-----	50,000	141	36	37.9	51,000	35,500
							45,000	216	32	36.0		
							40,000	468	35	43.8		
							35,000	1168	28	31.4		
2200	1	W.Q.	1750	24	----	-----	50,000	78	30	39.8	49,000	40,000
							45,000	245	27.5	39.8		
							41,000	696	33	36.0		

[a]All aging treatments preceded hot-cold-rolling except where noted.
[b]All hot-cold-rolled material was given a final stress relief at 1200° F for 1 hr.
[c]W.Q., water-quenched; A.C., air-cooled.
[e]Fractured in gage mark.
[f]Estimated.

NACA

TABLE II.– RUPTURE TEST CHARACTERISTICS AT 1200° F OF LOW-CARBON N-155 BAR STOCK – Concluded

Heat treatment												
Solution treatment			Aging treatment (a)		Hot-cold-rolling (b)		Rupture properties at 1200° F					
											Rupture strength (psi)	
Temperature (°F)	Time (hr)	Method of cooling (c)	Temperature (°F)	Time (hr)	Temperature (°F)	Percent reduction	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)	100 hr	1000 hr
Solution-treated at 2200° F												
Cold-working amount and temperature												
2200	1	W.Q.	-----	--	1200	5	55,000	76	1.5	7.0	54,000	[f]47,000
						(5.1)	50,000	333	2	12.2		
2200	1	W.Q.	-----	--	1200	10	60,000	37	1.5	4.5	57,000	51,000
							50,000	1914	3.5	7.0		
2200	1	W.Q.	1400	24	1200	10	58,000	101	11	17.8	56,000	[f]47,000
							55,000	87	[e]12	14.4		
							52,500	200	10	14.4		
							50,000	403	15	24.5		
2200	1	W.Q.	------	--	1200	15	55,000	12	[e]1	4.3	[f]54,000	52,000
						(14.3)	52,000	2115	2	6.0		
							45,000	[j]1943	-----	----		
2200	1	W.Q.	[g]1400	24	1200	15	65,000	78	4.5	10.9	64,000	53,500
							60,000	228	5.5	9.7		
							55,000	693	[e]3	5.0		
2200	1	W.Q.	-----	--	1000	15	55,000	77	1.5	4.1	54,000	49,000
						(15.6)	52,500	134	.5	1.7		
							50,000	574	1	1.5		
2200	1	W.Q.	-----	--	1400	15	60,000	40	1	1.5	56,000	51,000
						(14.9)	55,000	146	1	4.2		
							52,500	581	1	1.4		
							50,000	1646	1.5	3.5		
2200	1	W.Q.	-----	--	1600	15	55,000	110	4.5	13.8	55,500	43,500
						(14.3)	50,000	235	6.5	19.0		
							45,000	736	10	25.4		
Solution-treated at 2250° F												
2250	1/2	W.Q.	-----	--	----	------	50,000	8.5	[e]5	16.5	41,000	38,000
							40,000	120	4	16.0		
							35,000	[j]2251	-----	----		
							37,500	3122	10	15.3		
Solution-treated at 2300° F												
2300	1/2	W.Q.	-----	--	----	------	45,000	98	6	12.8	44,000	37,500
							40,000	260	[e]7	7.7		
							36,000	[k]1247	-----	----		
							38,000	978	4.5	12.1		

[a]All aging treatments preceded hot-cold-rolling except where noted.
[b]All hot-cold-rolled material was given a final stress relief at 1200° F for 1 hr.
[c]W.Q., water-quenched; A.C., air-cooled.
[e]Fractured in gage mark.
[f]Estimated.
[g]Aged after rolling.
[j]Discontinued at this time.
[k]Overheated at this time.

NACA

TABLE III.– STUDY OF EFFECT OF HOLDING TIME AT 1200° F IN TEST UNIT BEFORE LOADING ON RUPTURE LIFE OF LOW-CARBON N-155 BAR STOCK AT 1200° F

Treatment (1)	Holding time (hr)	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)
2200° F 1 hr W.Q.	0.8 24.0	45,000 45,000	60 108	4 4	17.8 13.3
2200° F 1 hr W.Q.; 1600° F 24 hr	.9 24.0	50,000 50,000	15 48	28 26	43.7 36.2
2050° F 2 hr W.Q.	.5 24.0	45,000 45,000	180 130	8 12.5	14.4 14.4
2050° F 2 hr W.Q.; 1400° F 24 hr	.7 24.0	50,000 50,000	98 79	31 27.5	34 30.8
2050° F 2 hr W.Q.; 1400° F 24 hr	.5 24.0	50,000 50,000	41 44	36 45	37.9 40.8

[1]W.Q., water quenched.

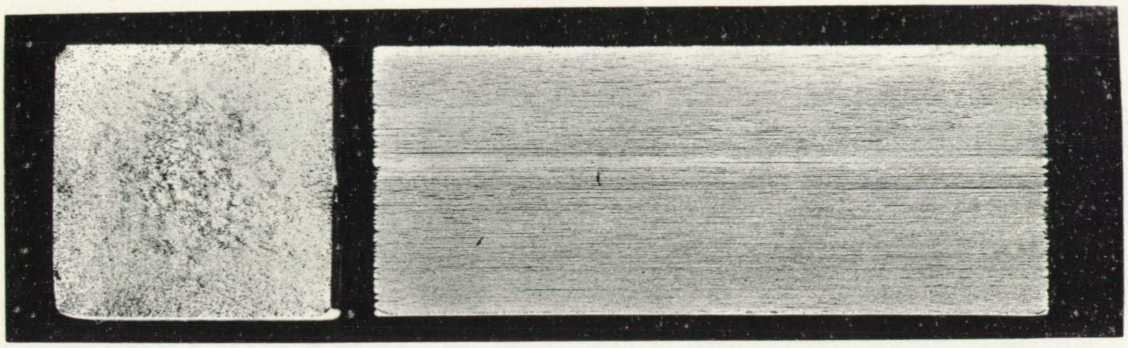
NACA

TABLE IV.– COMPARATIVE PROPERTIES OF LOW-CARBON N-155 DISCS AND BAR STOCK

Material	Treatment (1)	Room-temperature properties					Rupture properties at 1200° F			Data source (2)
		Brinell hardness	Tensile strength (psi)	Offset yield strengths (psi) 0.02 percent	Offset yield strengths (psi) 0.2 percent	Elongation (percent)	100 hr (psi)	1000 hr (psi)	100-hr elongation (percent)	
Disc	As-forged; 2 hr at 1200° F	235	120,350	58,750	72,650	34.5	55,000	42,000	11	Reference 1
		---	-------	65,000	80,000	40	54,000	45,000	15	A
Disc	As-forged	210	119,800	------	65,000	44	46,000	38,500	9	Reference 2
		---	-------	50,000	70,000	40	48,000	38,000	15	A
Bar	As-rolled	233	128,500	72,500	78,500	40.5	49,500	37,500	17	B
Disc	As-forged; 24 hr at 1500° F	232	-------	------	------	----	47,000	33,500	36	Reference 2
		---	-------	60,000	70,000	35	45,000	36,000	15	A
Bar	As-rolled; 24 hr at 1500° F	212	124,000	46,500	62,500	36	47,000	36,000	14	B
Disc	2200° F W.Q.; 24 hr at 1350° F	173	106,000	------	53,500	38	41,500	36,000	12	Reference 2
		---	-------	40,000	50,000	38	44,500	37,000	12	A
Bar	2200° F W.Q.; 24 hr at 1350° F	205	120,125	54,000	64,000	38.5	53,000	39,500	15	B
Disc	2200° F W.Q.; 24 hr at 1500° F	207	114,000	------	61,500	22.5	44,000	35,000	18	Reference 2
		---	-------	45,000	60,000	36	47,000	38,500	25	A
Bar	2200° F W.Q.; 24 hr at 1500° F	202	121,750	50,000	63,500	36.5	49,000	35,000	25	B
Disc	2250° F W.Q.; 3-percent hot-cold-work at 1500° F; 24 hr at 1500° F	222	-------	------	------	----	46,000	34,000	21	Reference 2
		---	-------	52,000	70,000	----	48,000	37,500	20	A

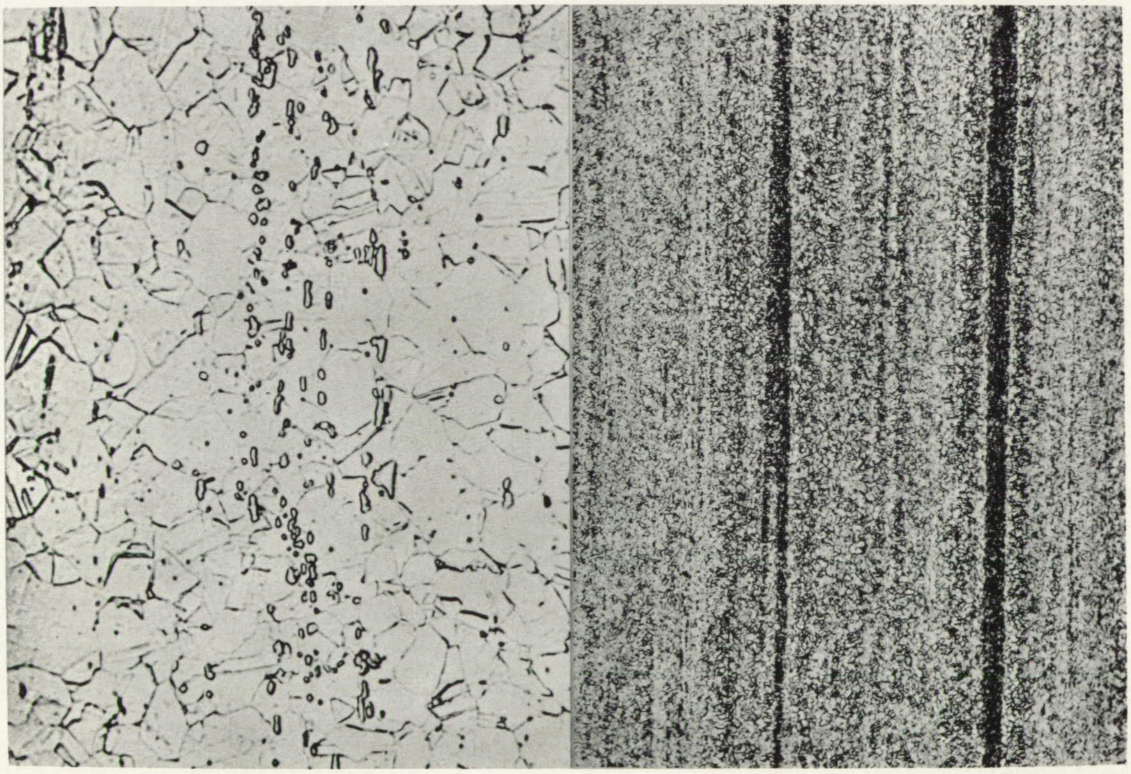
[1] W.Q., water-quenched.

[2] A estimated from Brinell hardness and data for bar stock in this report.
B test data from this report.



Cross section $1\frac{1}{2}$X Longitudinal section near center of bar

(a) Macrostructure of low-carbon N-155 hot-rolled bar stock. Etchant: 2 hours in Marble's Reagent at 160° F plus 15 minutes in aqua regia in glycerine at 120° F.



1000X 100X

(b) Microstructure of low-carbon N-155 hot-rolled bar stock. (Electrolytic chromic acid etch.)

Figure 1.- Structure of original bar stock.

Page intentionally left blank

Page intentionally left blank

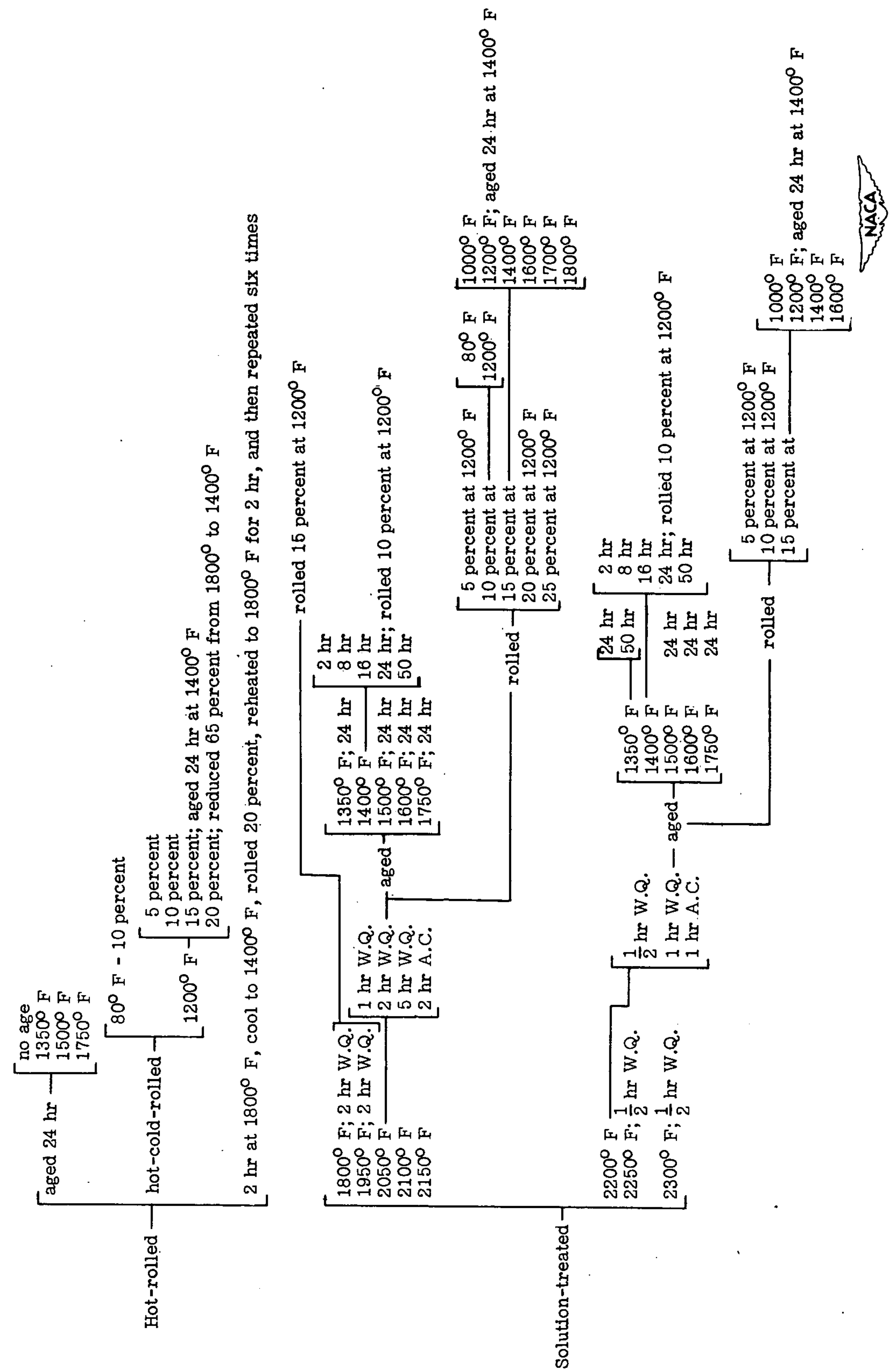


Figure 2.- Diagram showing treatments used on the low-carbon N-155 bar stock.

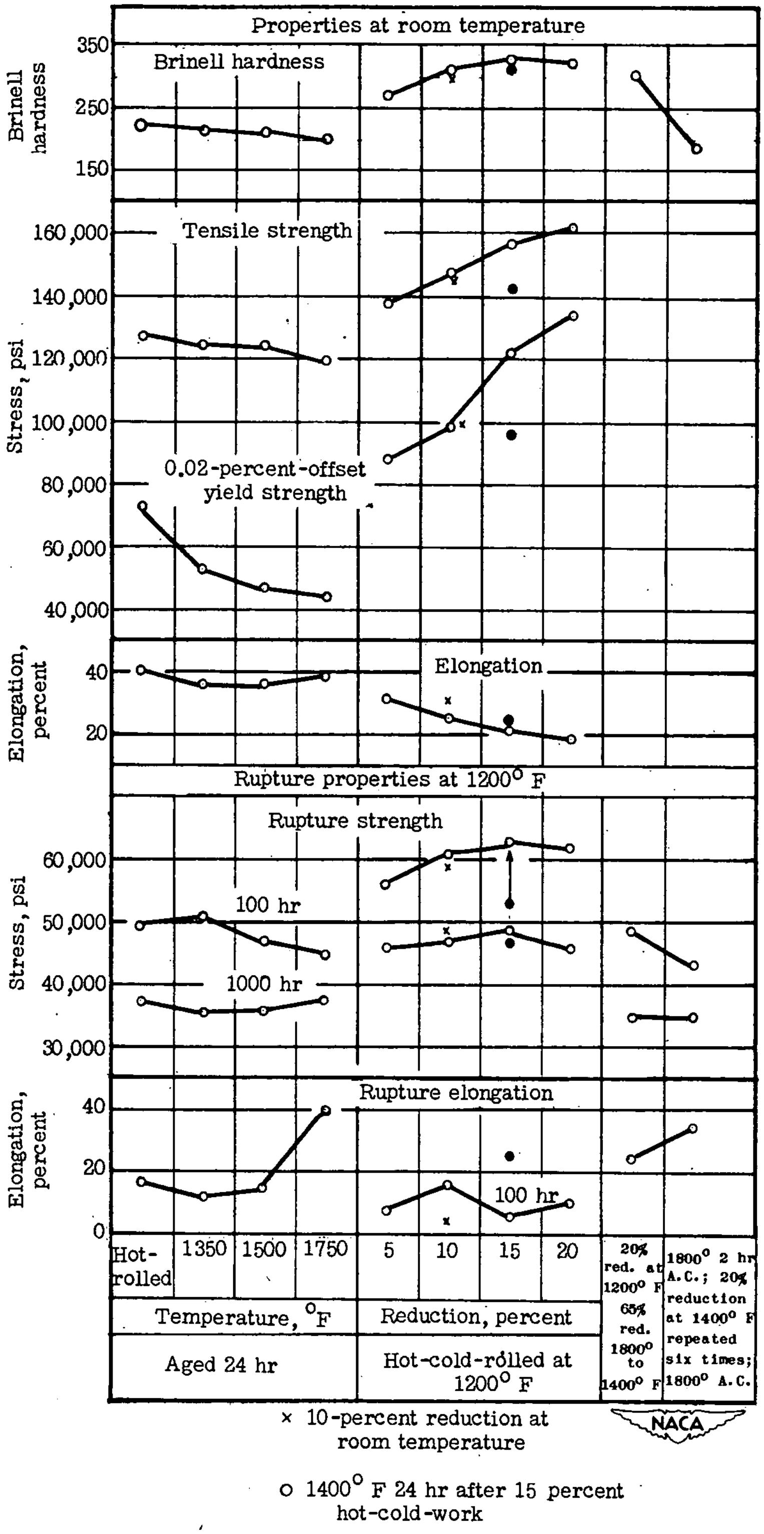


Figure 3.- Effect of aging and rolling on properties of hot-rolled bar stock of low-carbon N-155 alloy.

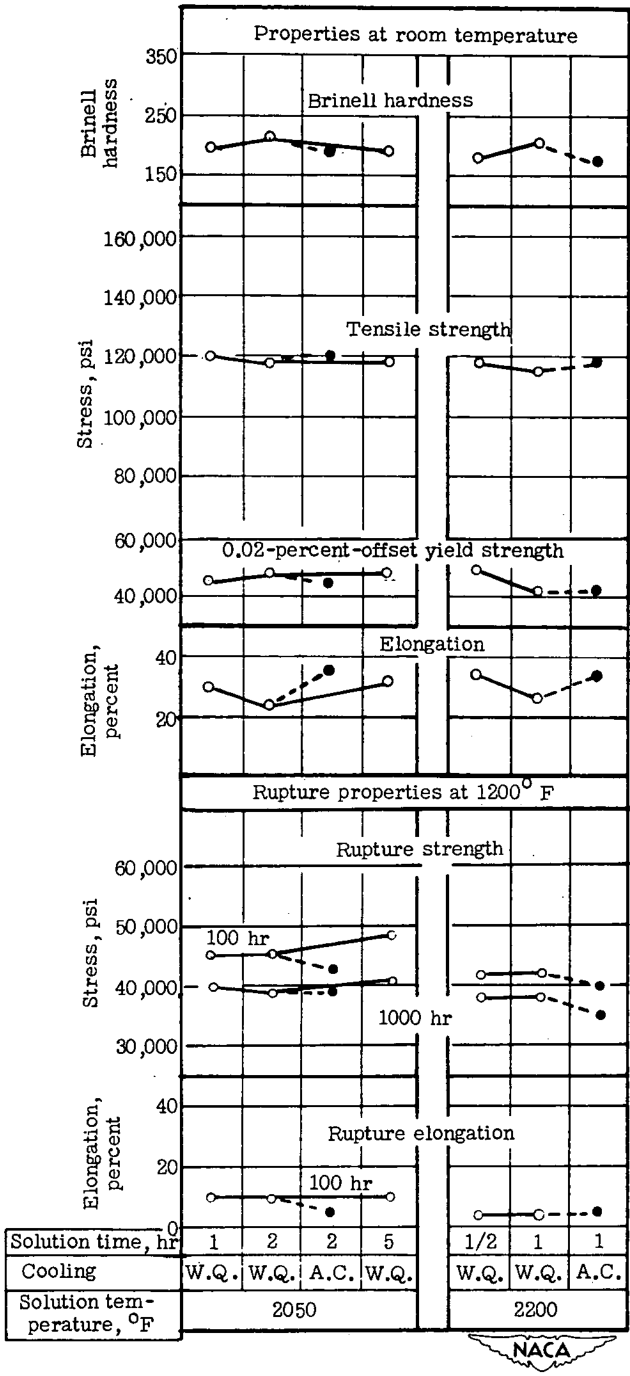


Figure 4.- Effect of time and cooling rate on properties of solution-treated bar stock of low-carbon N-155 alloy.

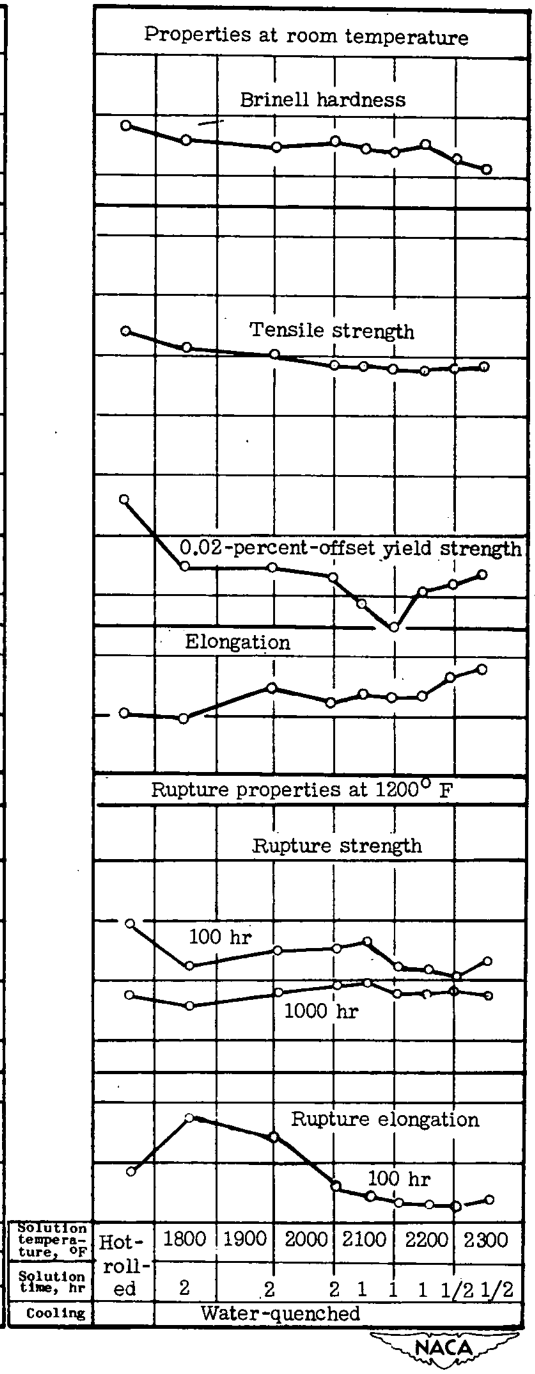
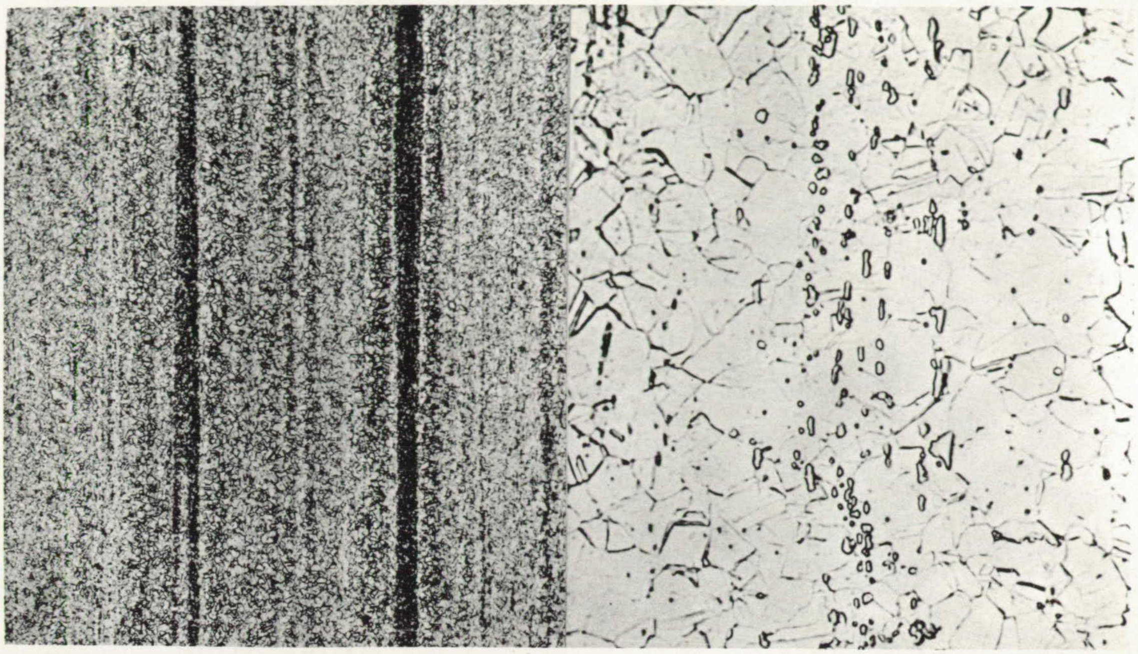


Figure 5.- Effect of solution-treating temperature on properties of low-carbon N-155 alloy bar stock.

Page intentionally left blank

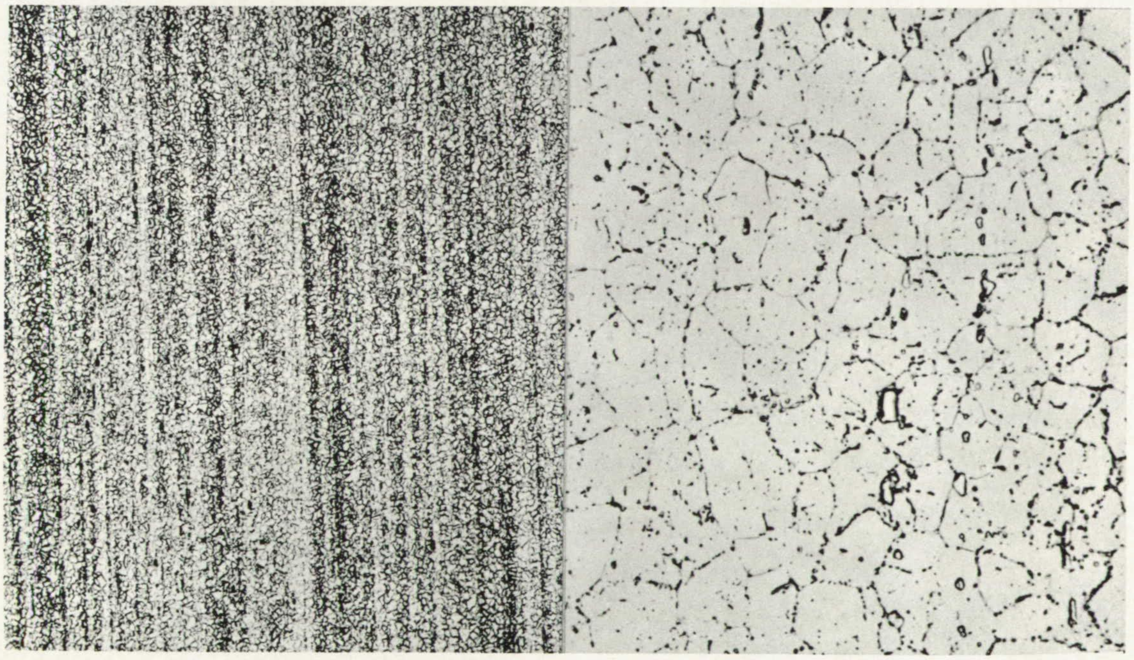
Page 37 — 52 (every other page is blank)

Page intentionally left blank



100X 1000X

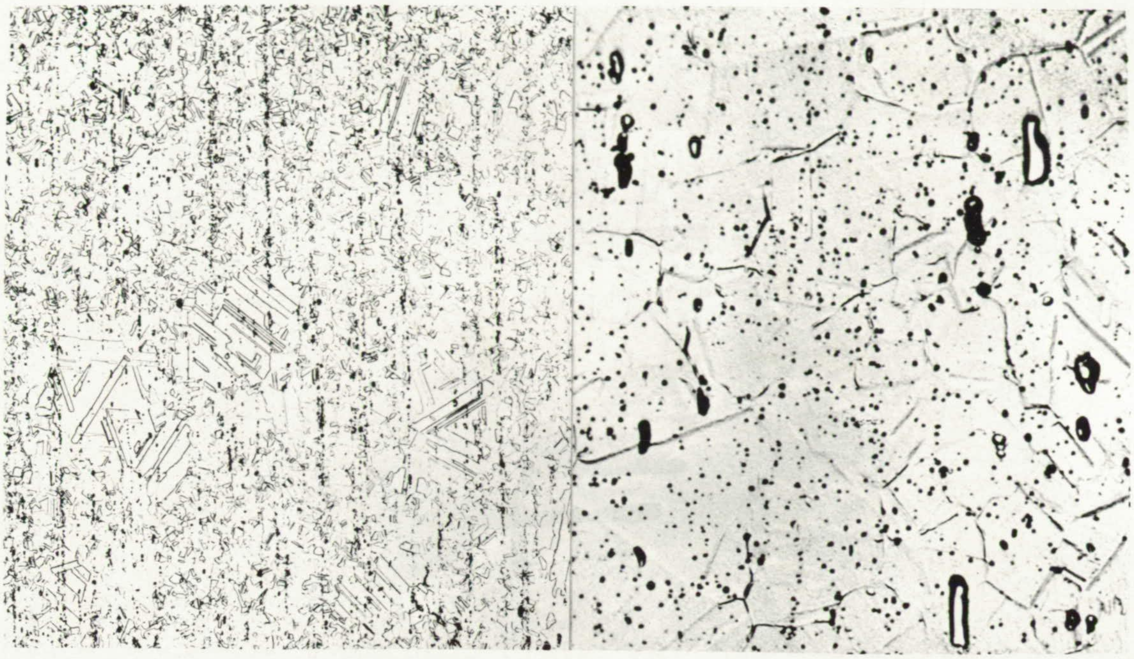
(a) As-rolled.



100X 1000X

(b) 1800° F 2 hours.

Figure 6.- Effect of solution-treating temperature on the microstructures of low-carbon N-155 bar stock. All specimens were water-quenched from temperature. Electrolytic chromic acid etch.



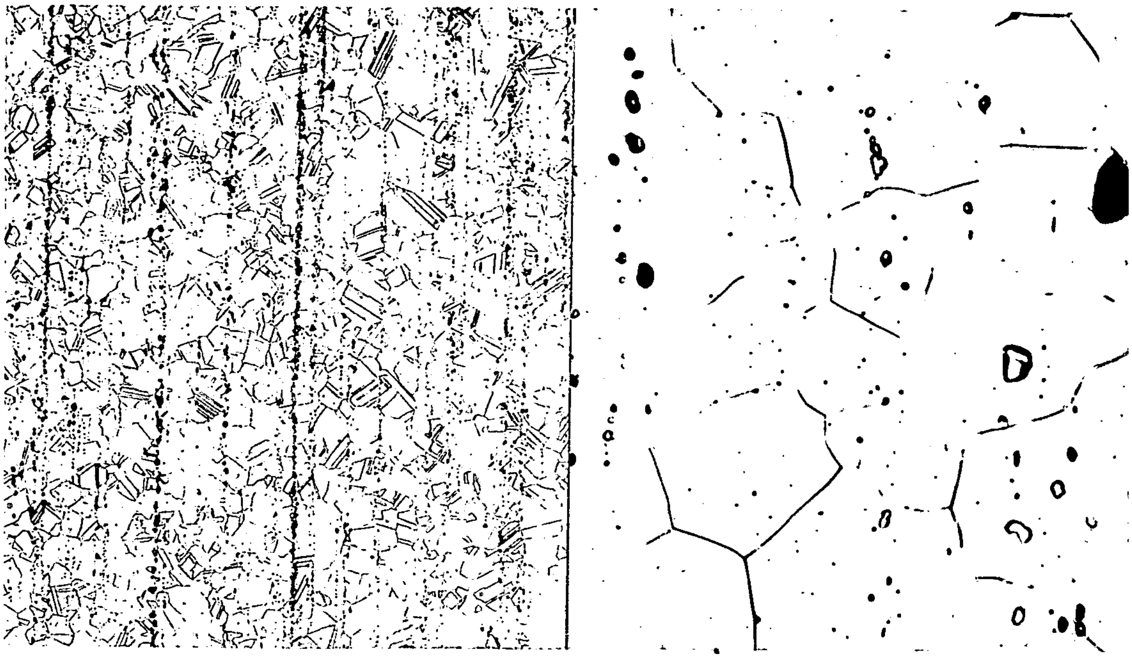
100X 1000X

(c) 1950° F 2 hours.

100X 1000X

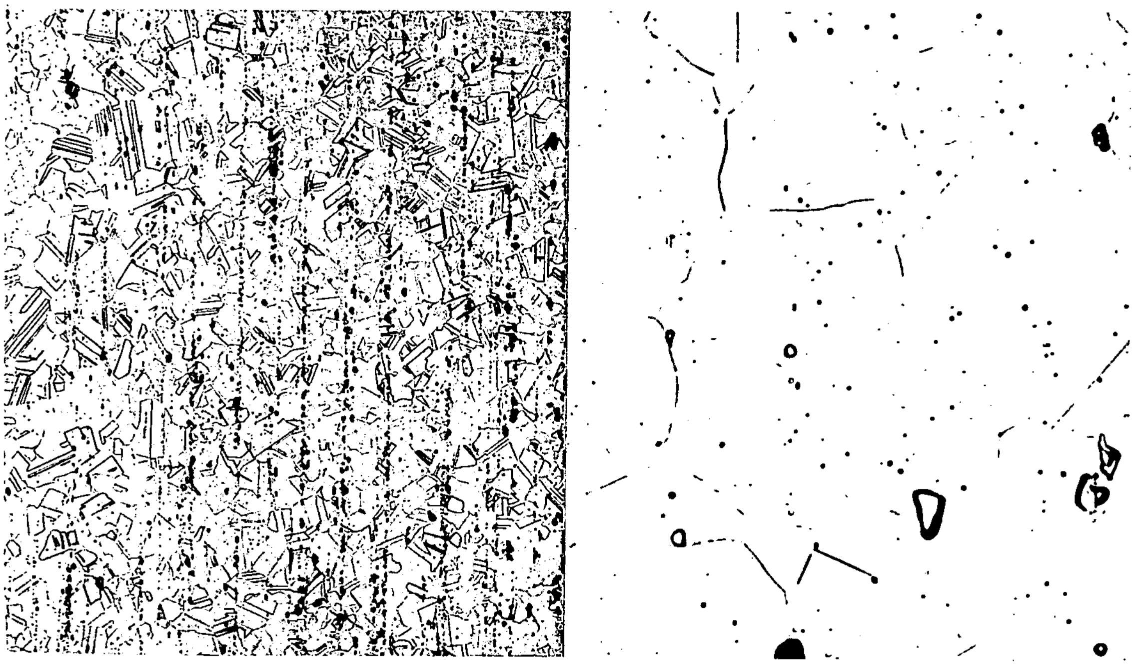
(d) 2050° F 2 hours.

Figure 6.- Continued.



100X 1000X

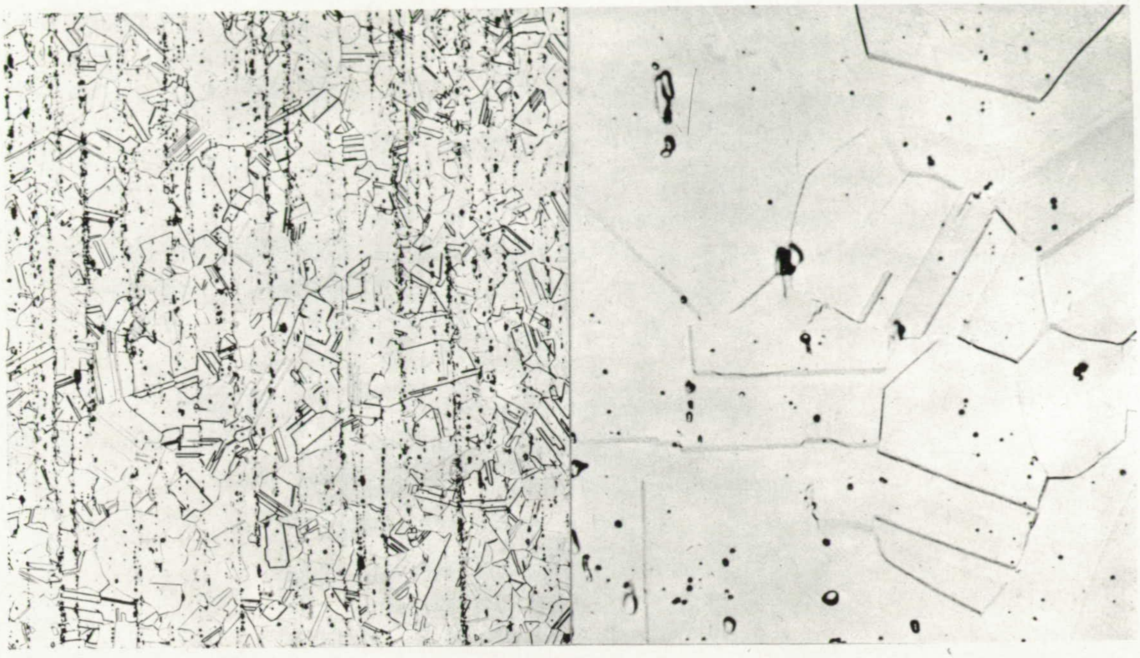
(e) 2100° F 1 hour.



100X 1000X

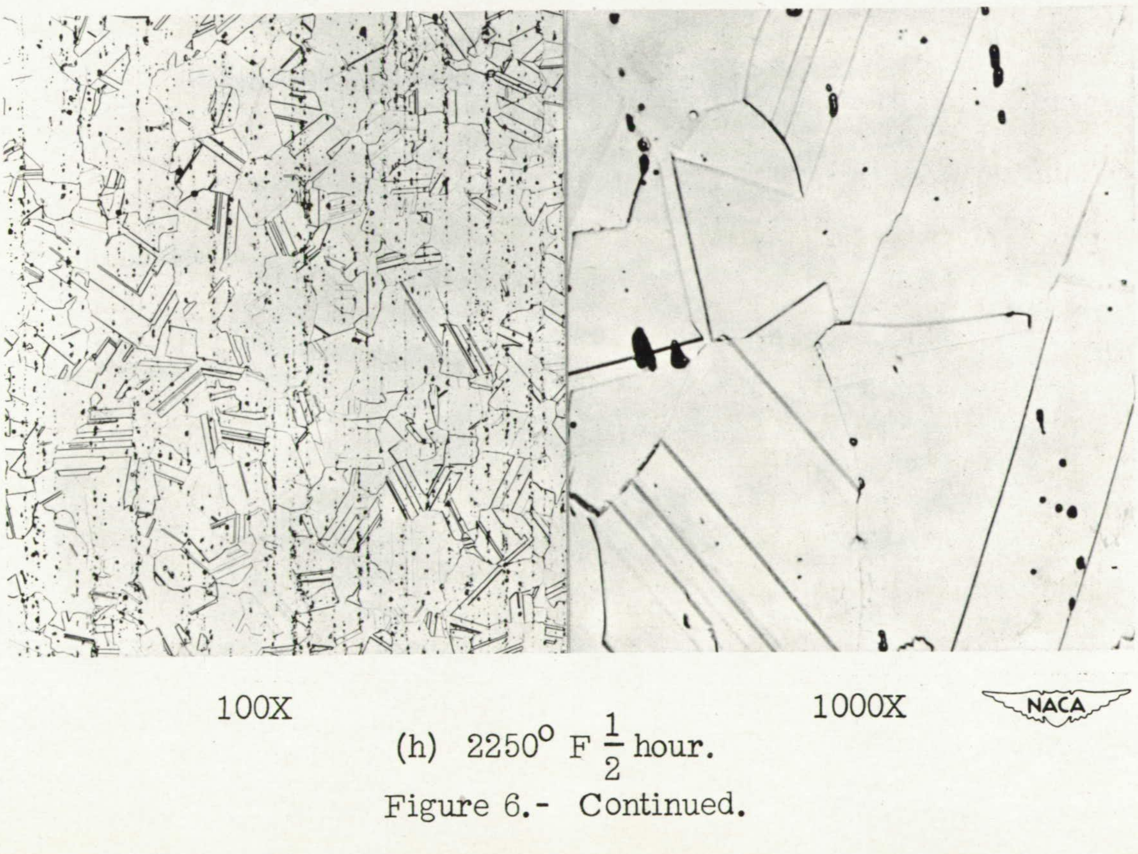
(f) 2150° F 1 hour

Figure 6.- Continued.



100X 1000X

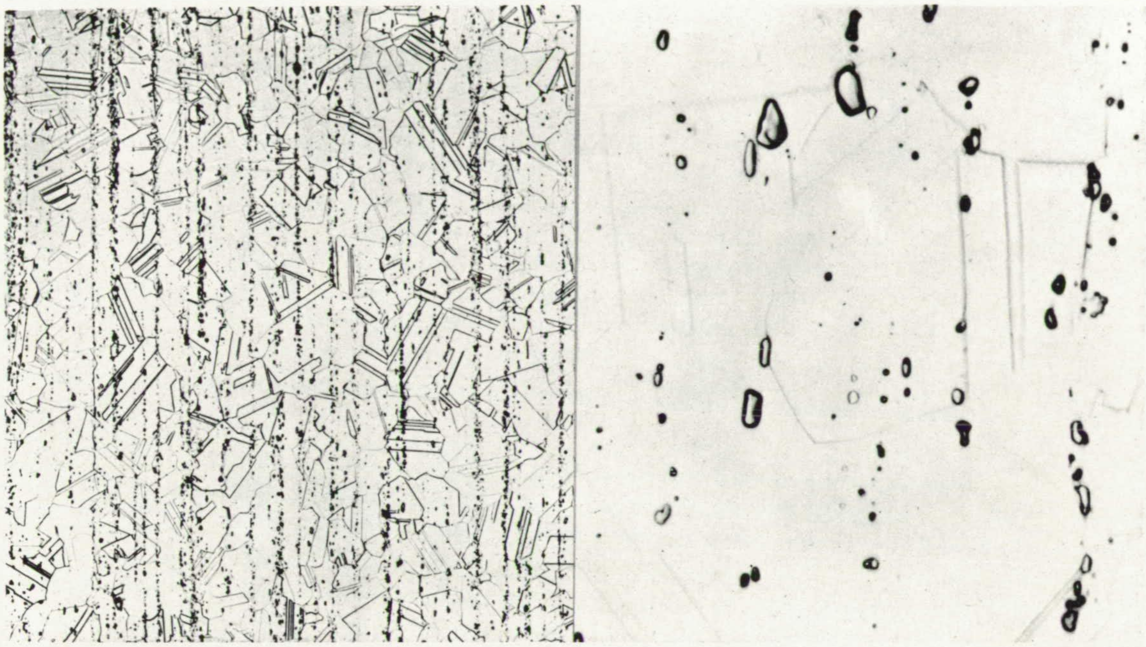
(g) 2200° F 1 hour.



100X 1000X

(h) 2250° F $\frac{1}{2}$ hour.

Figure 6.- Continued.



100X 1000X

(i) 2300° F $\frac{1}{2}$ hour.

Figure 6.- Concluded.

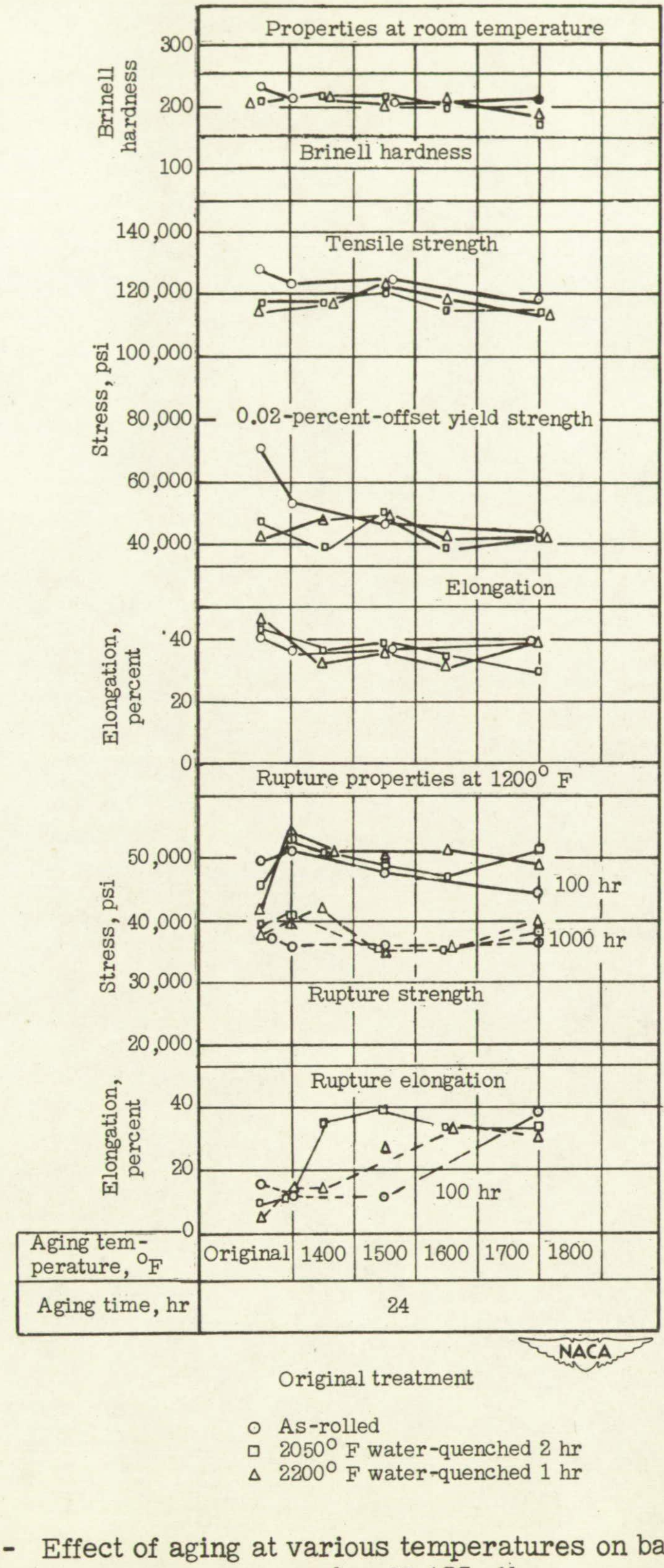
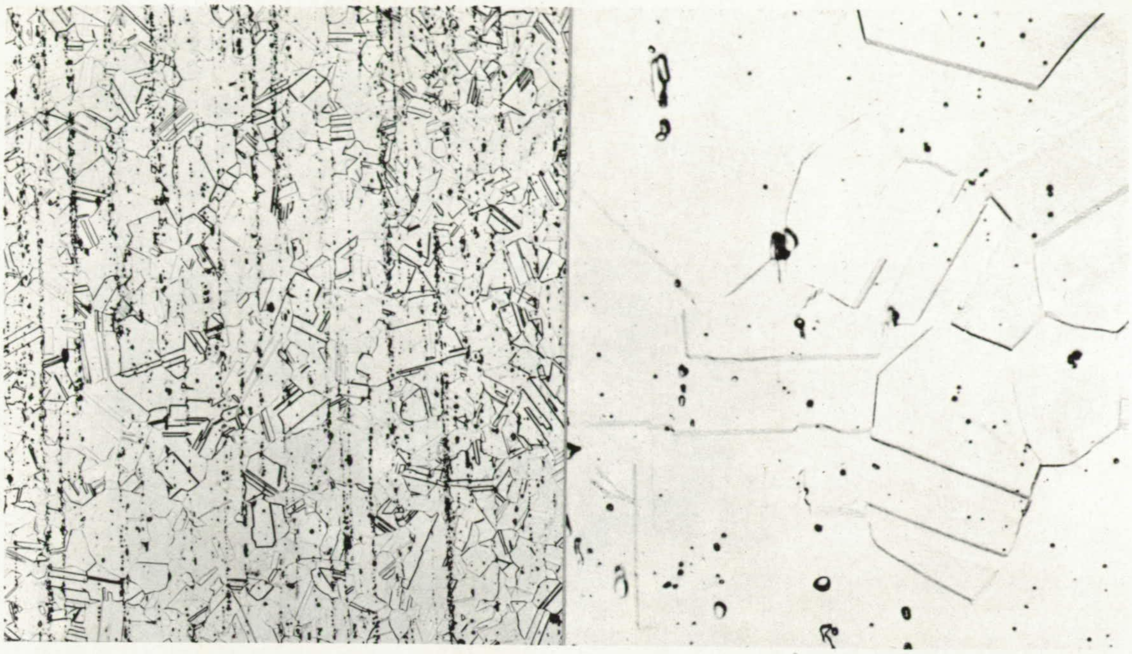
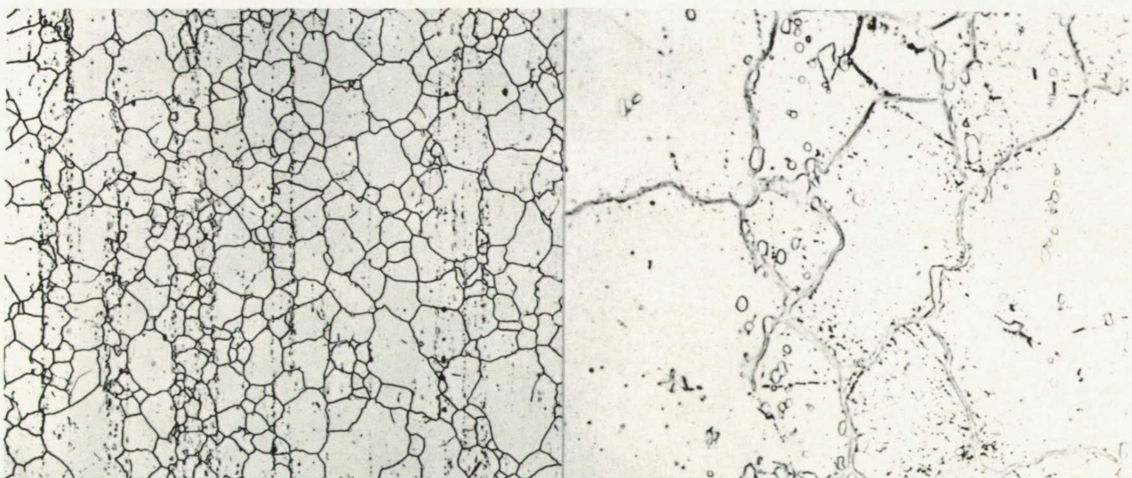


Figure 7.- Effect of aging at various temperatures on bar stock of low-carbon N-155 alloy.



100X 1000X

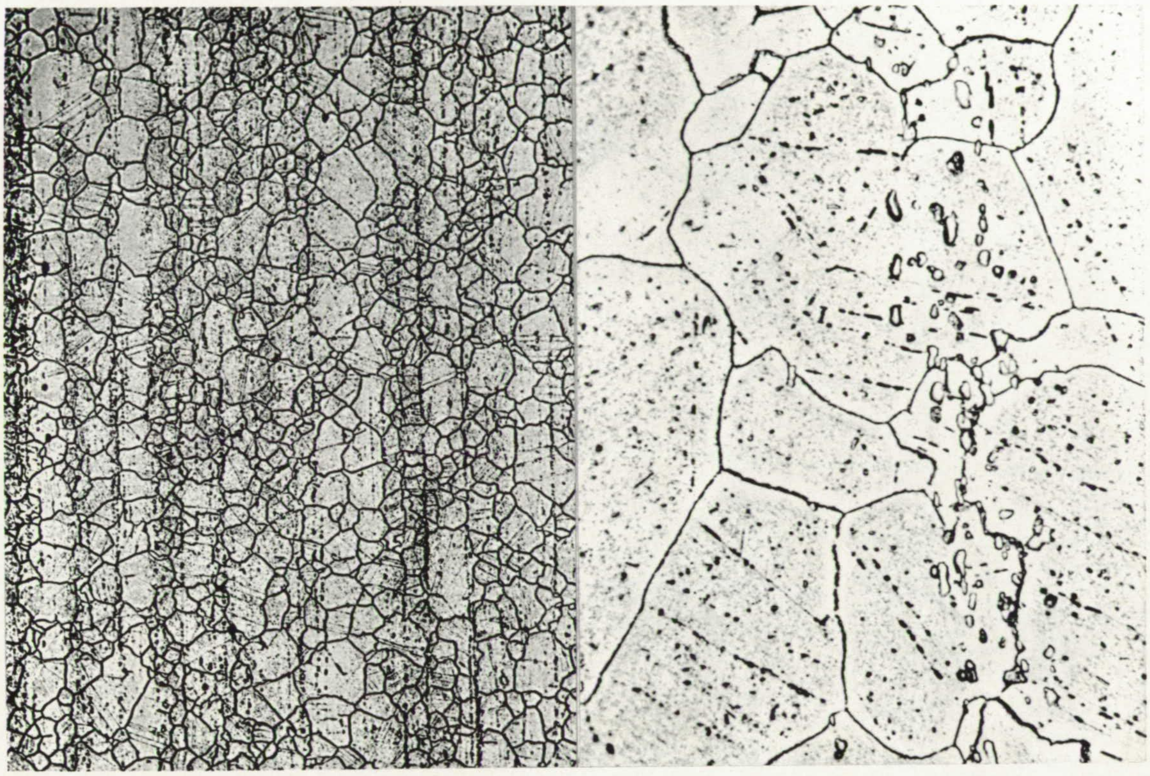
(a) Solution-treated 2200° F
1 hour, water-quenched.



100X 1000X

(b) 1400° F 24 hours.

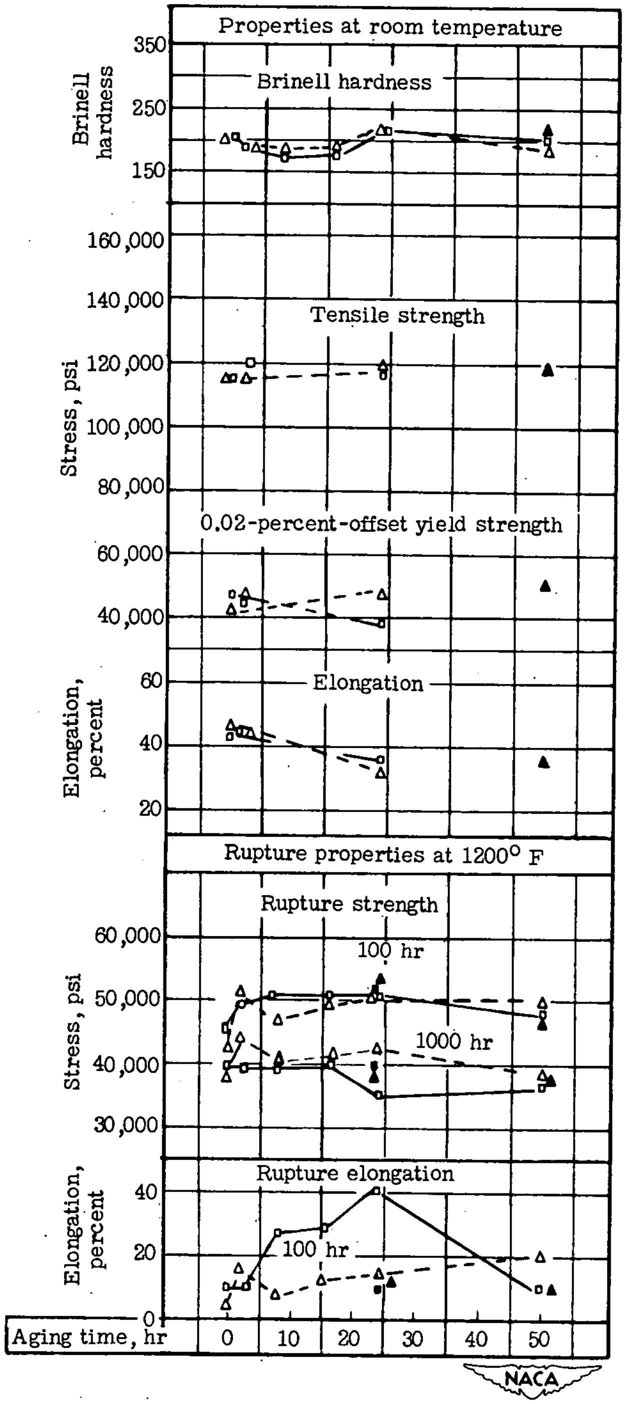
Figure 8.- Effect of aging at two temperatures on microstructure of low-carbon N-155 bar stock.



100X 1000X

(c) 1600° F 24 hours.

Figure 8.- Concluded.



Original treatment

□ 2050° F water-quenched; aged at 1400° F
△ 2200° F water-quenched; aged at 1400° F
▲ 2200° F water-quenched; aged at 1350° F

Figure 9.- Effect of aging time on properties of solution-treated bar stock of low-carbon N-155 alloy.

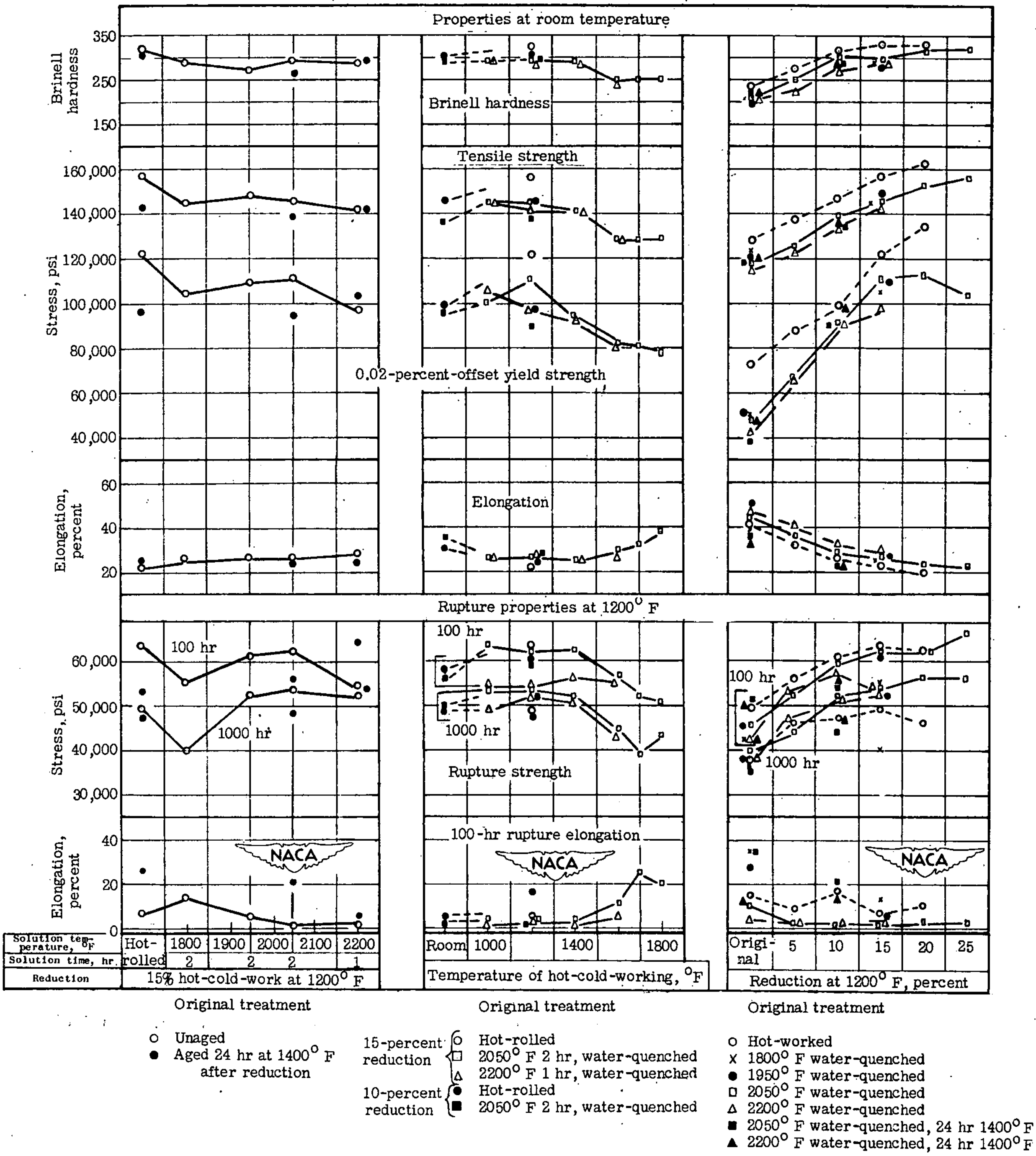
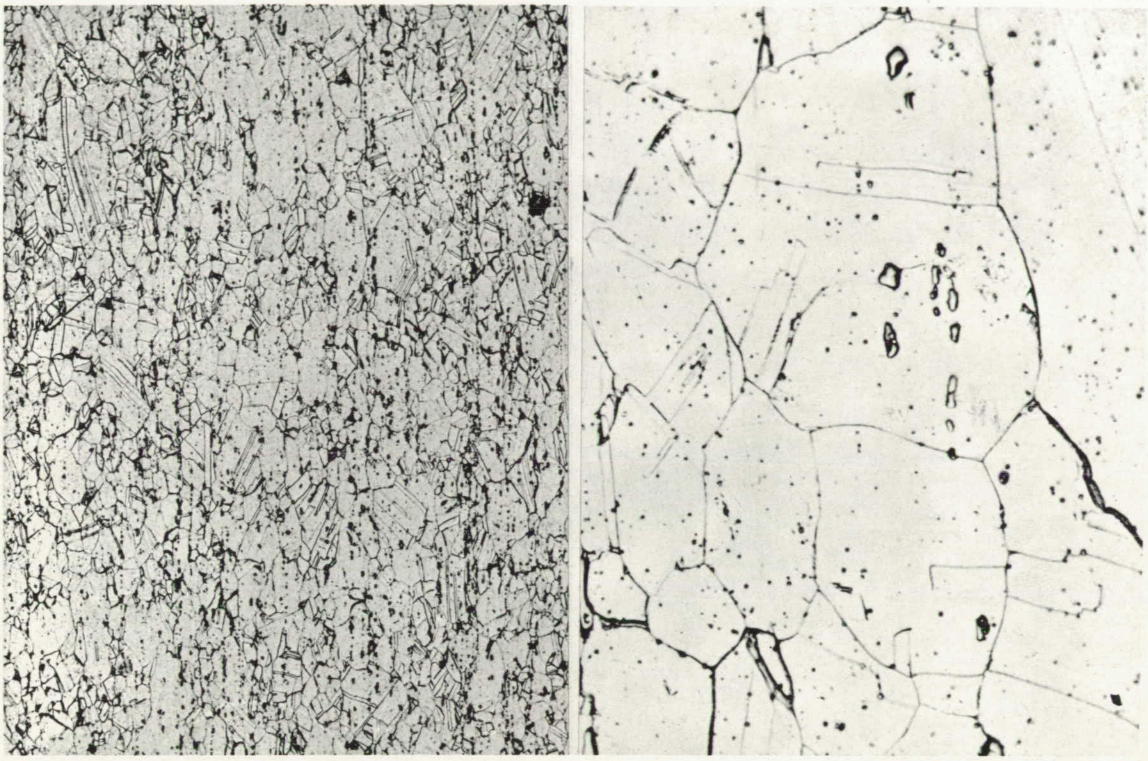


Figure 10.- Effect of prior treatment on properties of 15 percent hot-cold-worked bar stock of low-carbon N-155 alloy.

Figure 11.- Effect of hot-cold-work at various temperatures on properties of bar stock of low-carbon N-155 alloy.

Figure 12.- Effect of hot-cold-work at 1200° F on properties of bar stock of low-carbon N-155 alloy.



100X 1000X

Figure 13.- Microstructure of solution-treated and hot-cold-worked low-carbon N-155 bar stock. (Solution-treated 2050° F 2 hr, water-quenched; 25 percent hot-cold-work at 1200° F. Electrolytic chromic acid etch.)

Page intentionally left blank

Page intentionally left blank

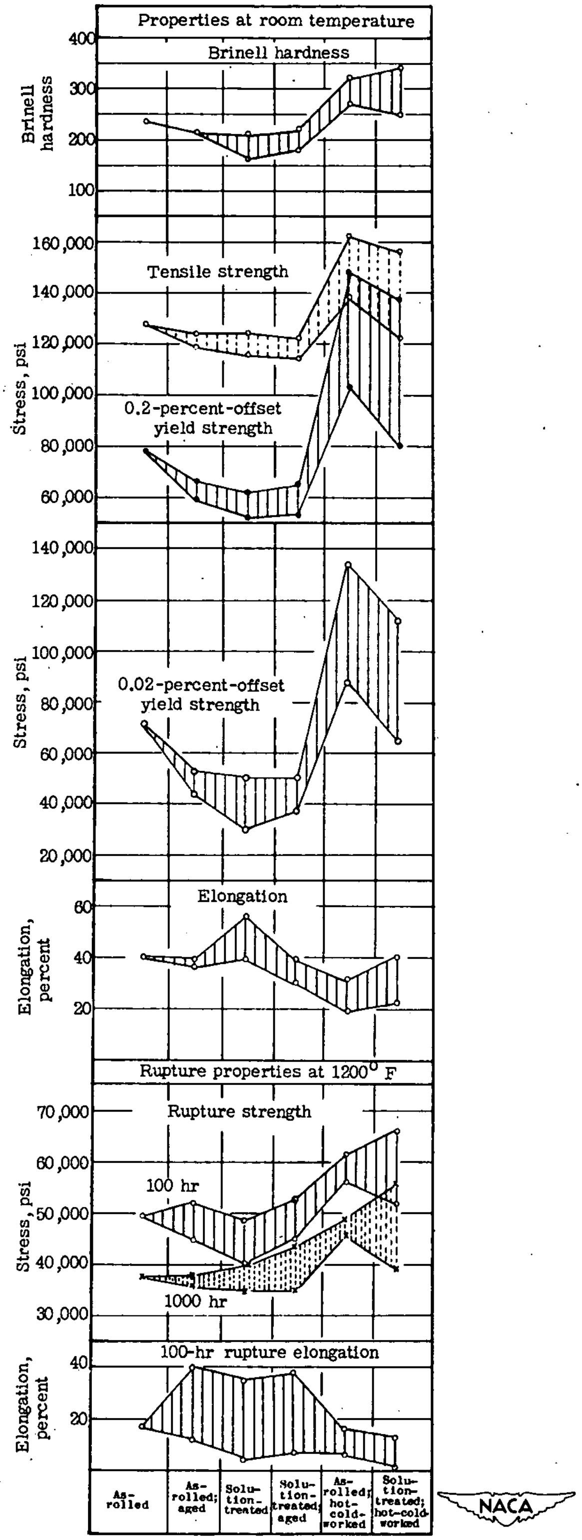
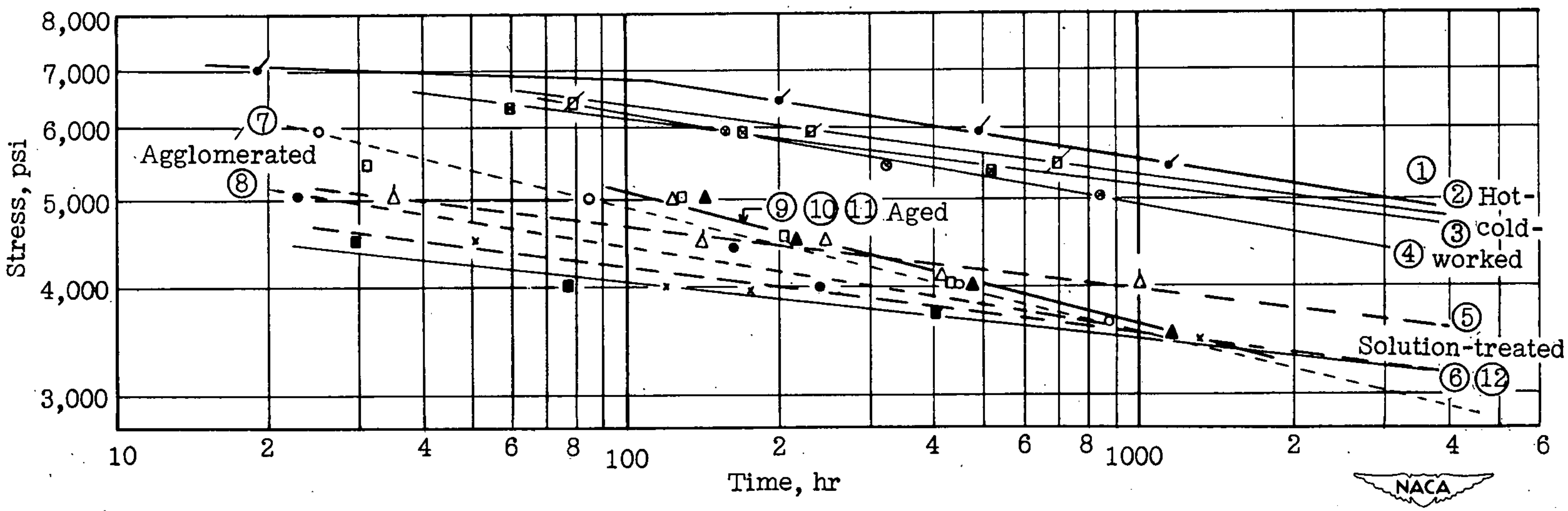


Figure 14.- Range in properties of low-carbon N-155 alloy for various types of treatment. Ranges shown are those now available and may not cover all possible treatment. (Aging treatments: 1350° - 1750° F; solution treatments: 1800° - 2300° F; hot-cold-work: 5- to 25-percent reduction at 1000° - 1800° F.)



		Solution treatment			Aging		Hot-cold-work	
		Temperature (°F)	Time (hr)	Cooling	Temperature (°F)	Time (hr)	Temperature (°F)	Reduction (percent)
1	●	2050	2	W.Q.	- -	- -	1200	25
2	⌀	2200	1	W.Q.	[a]1400	[a]24	1200	15
3	⊠	1950	2	W.Q.	- -	- -	1200	15
4	⊗	As-rolled			- -	- -	1200	15
5	Δ	2100	1	W.Q.	- -	- -	- -	- -
6	×	1800	2	W.Q.	- -	- -	- -	- -
7	○	20-percent reduction at 1200° F; 65-percent reduction from 1800° to 1400° F						
8	•	1800	2	Cool to	- -	- -	1400	[b]20
9	△	As-rolled			1350	24	- -	- -
10	□	2050	2	W.Q.	1400	24	- -	- -
11	▲	2200	1	W.Q.	1600	24	- -	- -
12	■	2200	1	A.C.	- -	- -	- -	- -

[a]Aged after hot-cold-work
[b]Process repeated six times

Figure 15.- Typical curves of stress against rupture time for low-carbon N-155 alloy.

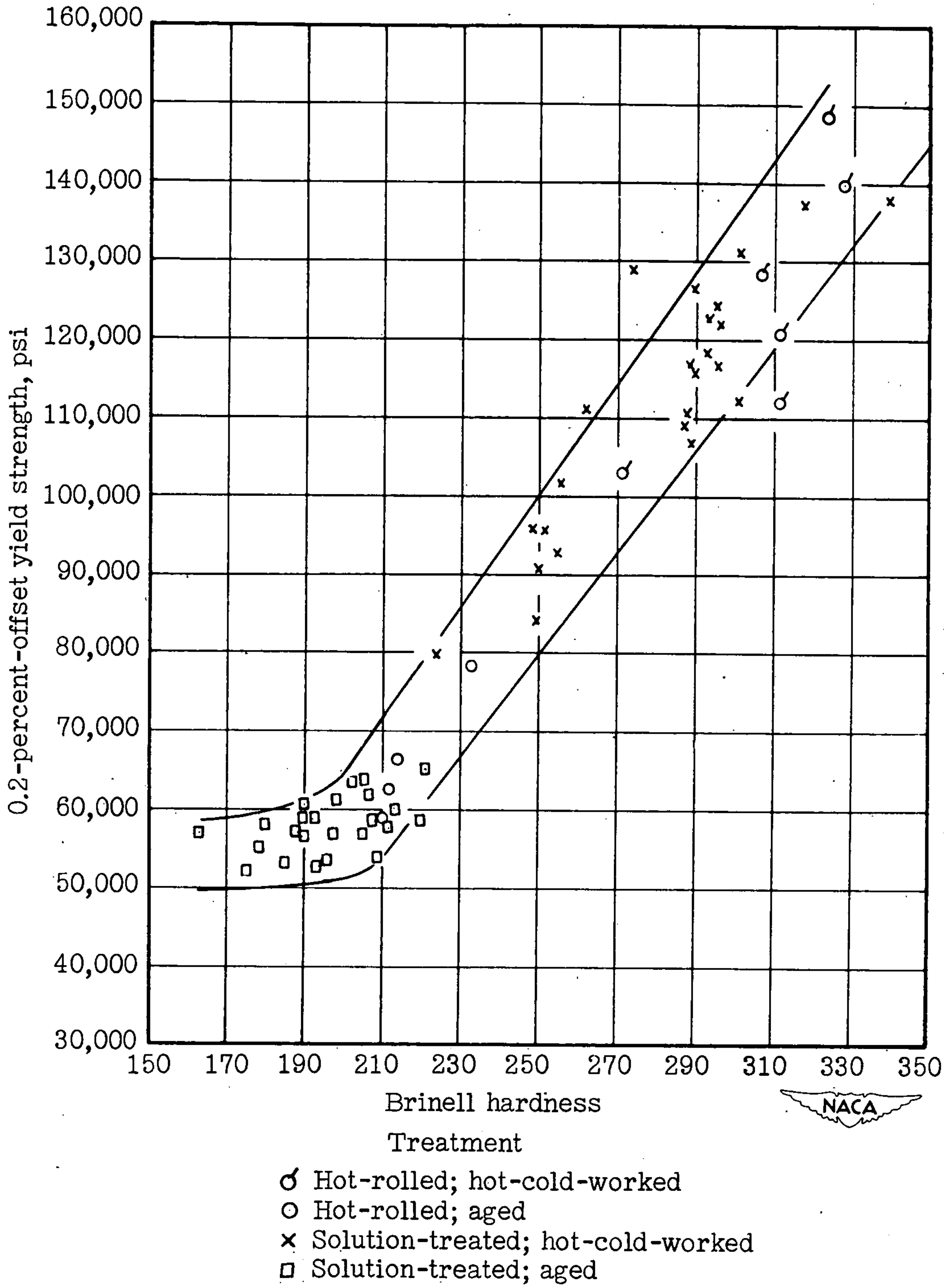


Figure 16.- Relationship between 0.2-percent-offset yield strength of low-carbon N-155 alloy at room temperature and Brinell hardness.

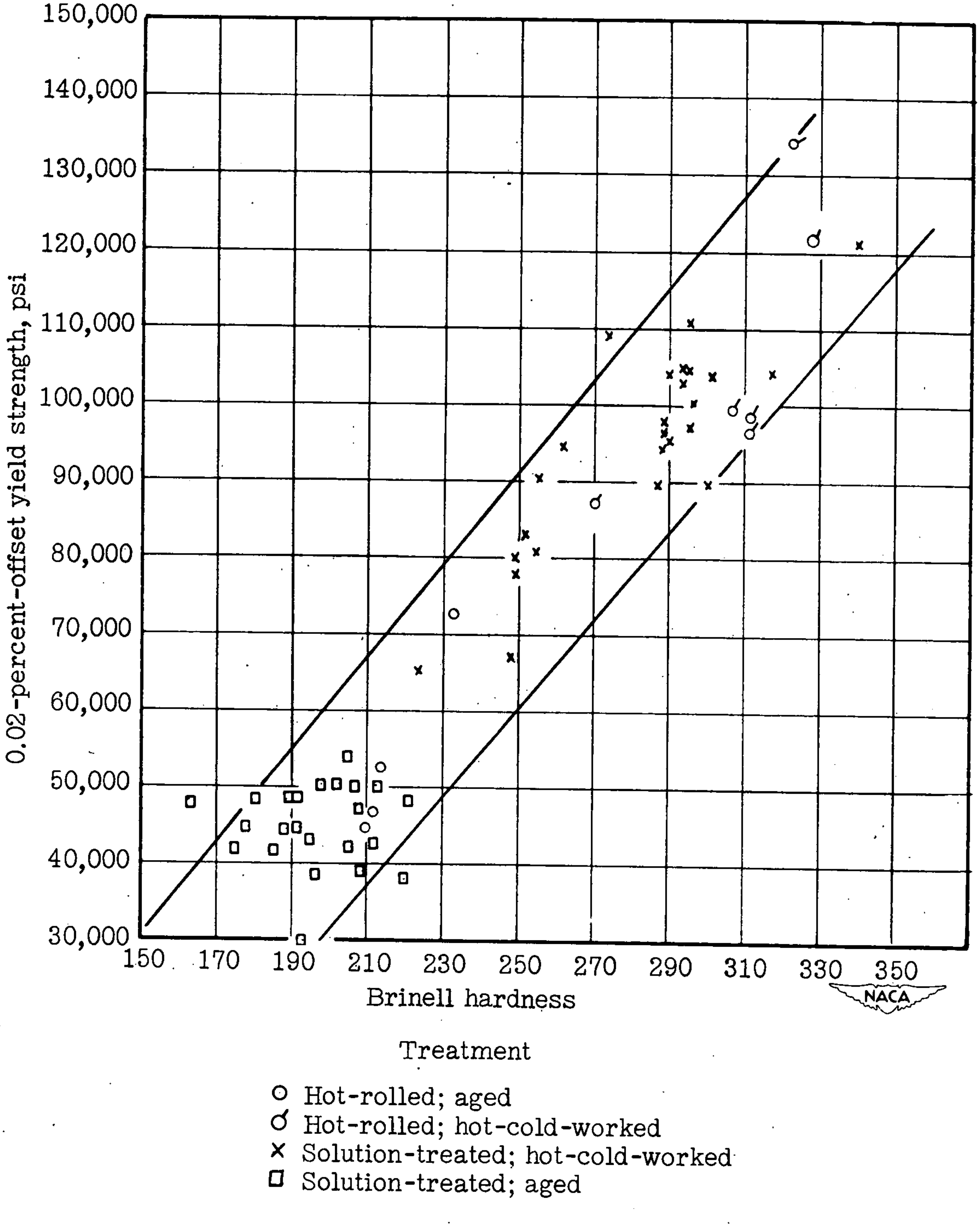


Figure 17.- Relationship between 0.02-percent-offset yield strength of low-carbon N-155 alloy at room temperature and Brinell hardness.

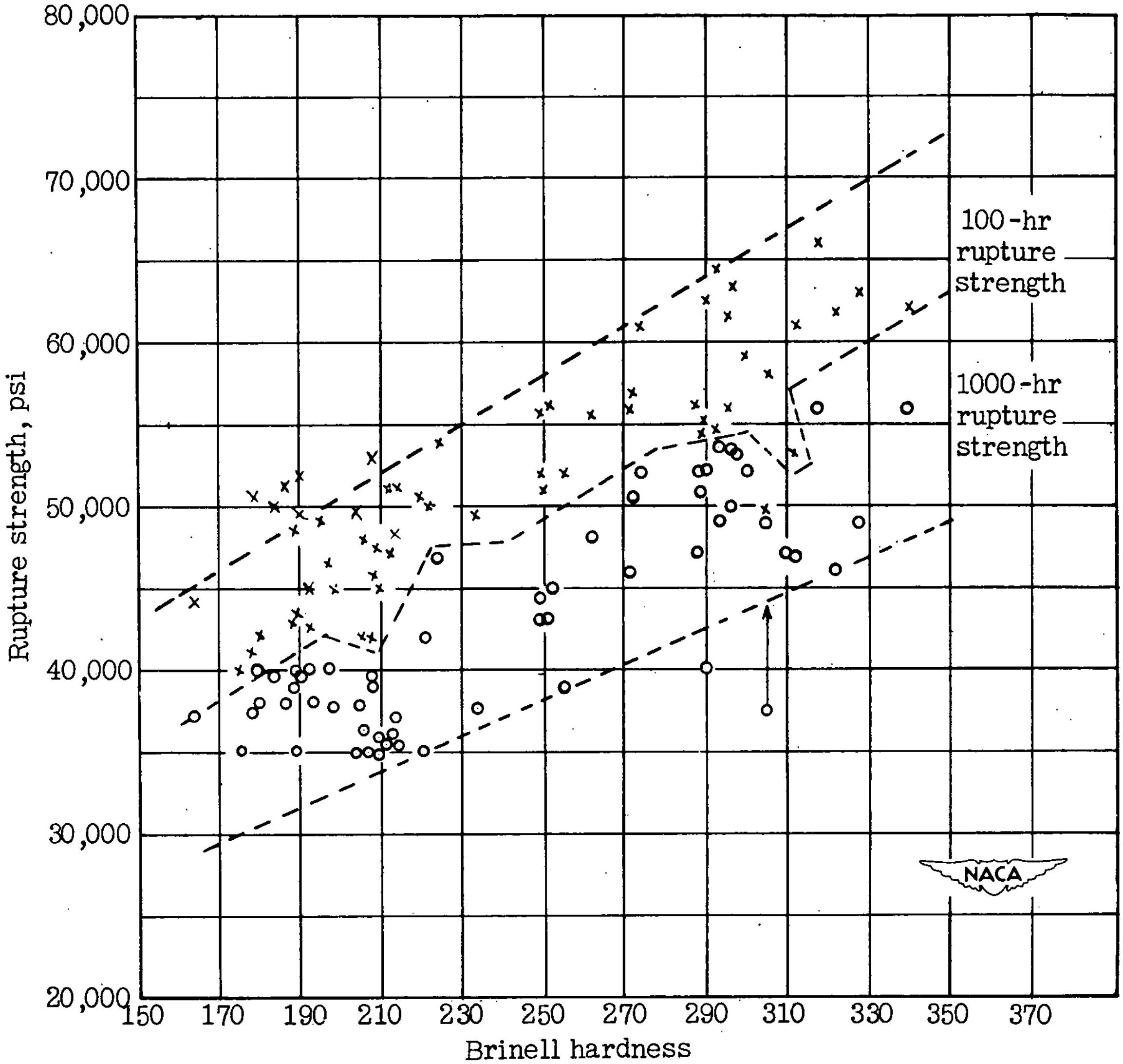


Figure 18.- Relationship between rupture strength of low-carbon N-155 alloy at 1200° F and Brinell hardness.