NACA

RESEARCH MEMORANDUM

COOPERATIVE INVESTIGATION OF RELATIONSHIP BETWEEN STATIC AND FATIGUE PROPERTIES OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURES

By NACA Subcommittee on Heat-Resisting Materials

NACA Headquarters

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The Subcommittee on Heat-Resisting Materials of the National Advisory Committee for Aeronautics is sponsoring a cooperative investigation of the relationship between the static and dynamic properties of heat-resistant alloys at high temperatures. An auxiliary objective is to provide a better basis for evaluating the results from the various types of fatigue machines.

While the investigation is still in progress the results obtained to date are of sufficient general interest so that this interim progress report has been issued. Data from static tensile and rupture tests, combined dynamic and static stress tests, and completely reversed stress fatigue tests are reported for a typical heat-resistant alloy at room temperature, 1000°, 1200°, 1350°, and 1500° F. The results are summarized as curves of alternating stress against mean stress for fracture in 50, 150, and 500 hours. Some creep data under combined stress conditions and a summary of the fracture characteristics of the specimens in the various tests are included.

INTRODUCTION

This report describes the results obtained to date from a cooperative investigation to establish the relationship between the static stress-rupture and dynamic fatigue properties of heat-resistant alloys at high temperatures. The data reported cover combinations of steady tensile stress with superimposed dynamic stress as well as completely reversed stress fatigue tests. Although the investigation is still in progress, a report is being issued at this time because the partial results are of too great interest and value to warrant delay of publication until all phases are complete.

At ordinary temperatures the strength of metals under combined static and dynamic stresses is well-known. However, information is very scarce for elevated temperatures where failure by creep as well as by fatigue can occur. Furthermore, there is considerable uncertainty regarding the interpretation of data from the various types of fatigue machines used for elevated temperature testing.

A Special Panel was appointed by the NACA Subcommittee on Heat-Resisting Materials to investigate the relationship between static and fatigue strengths of heat-resistant alloys at high temperatures. The Panel decided that the best procedure would be to organize a cooperative testing program to obtain reasonably complete data from one representative heat-resistant alloy. The specific objective was to develop curves relating alternating stress to mean stress for fracture in 50, 150, and 500 hours at 1000°, 1200°, 1350°, and 1500° F. Arrangements were made to obtain data under various combinations of static and dynamic stress ranging from the static rupture test to the completely reversed stress fatigue test. Special effort was made to include representative types of fatigue testing machines. Particular care was exercised to provide test specimens from uniform material and with uniform surface finish regardless of the shape of the test specimen.

The cooperators in the program include:

1. The Elliott Company

2. General Motors Corporation, Research Division

3. National Advisory Committee for Aeronautics by contract with the Engineering Research Institute of the University of Michigan

4. National Advisory Committee for Aeronautics by contract with Battelle Memorial Institute

5. National Advisory Committee for Aeronautics, Lewis Flight Propulsion Laboratory

6. Office of Naval Research, U. S. Navy, by contract with Battelle Memorial Institute

7. Rolls Royce Company, England

8. United States Naval Engineering Experiment Station

9. Westinghouse Electric Corporation, Research Division

10. Wright-Patterson Air Force Base, U. S. Air Force, by contract with the Institute of Industrial Research, Syracuse University

PROCEDURE

A Special Panel of the NACA Subcommittee on Heat-Resisting Materials arranged the cooperative program. An attempt was made to obtain data from representative types of test machines and particularly to have data from at least two types of testing machines in all cases.

A procedure was adopted to reduce variations from test material and surface finish to a minimum because the program was set up to obtain objective data on the relation between static and dynamic properties at elevated temperatures. Low-carbon N-155 alloy bar stock solution-treated for 1 hour at 2200° F, water-quenched, and then aged for 16 hours at 1400° F was selected because it met two requirements. One was that this material treated in this manner had the most uniform properties at high temperatures of any representative "super-alloy" known to the Panel. Secondly, it was metallurgically similar to several forged alloys of the type of interest for application in the gas turbines of jet engines. An additional factor in the choice was that there was more experimental metallurgical background available for this alloy than for any other choice. The NACA purchased 271 feet of 1-inch round bar stock for the test program.

In order to insure uniformity of test specimens, the NACA sponsored the preparation of the specimens at the Engineering Research Institute of the University of Michigan. A system of sampling was set up so that any lot of specimens sent to a cooperator was made from material representative of the complete length of the original ingot. This avoided misleading trends which might have occurred from segregation effects in specimens taken from one hot-rolled length of bar stock. The bar stock was cut to the lengths required for specimens and heat-treated. All specimens were prepared using elaborate procedures to keep the surface of the gage sections constant regardless of shape.

Arrangements were made to have all fractured specimens examined. Westinghouse, Syracuse University, and the Lewis Laboratory of the NACA elected to examine the specimens which they tested. All others were returned to the University of Michigan for visual and metallographic examination under sponsorship of the NACA.

Under sponsorship of the NACA, the University of Michigan served as secretary to the Panel to compile data and issue reports.

TEST MATERIAL

Two hundred and seventy-one feet of 1-inch round bar stock from one ingot of heat A-1726 were supplied as twenty-six mill length bars in the as-rolled condition.

The chemical analysis of heat A-1726 was as follows:

Chemical composition (Weight percent)										
C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	N	
0.13	1.64	0.42	21.22	19.00	19.70	2.90	2.61	0.84	0.13	Suppliers' heat analysis
0.14	1.43	0.35	20.80	18.80	19.65	3.00	2.00	0.99	0.135	U.M. check on bar stock

The manufacturing conditions were reported to be as described in table I.

Coupons about 1 inch long were cut from both ends and the center of each bar, heated at 2200° F for 1 hour, water-quenched, and then aged at 1400° F for 16 hours. The Brinell hardness was then determined on the surface of each coupon and at the center of the cross section. The hardness values shown in table II indicate good uniformity. Metallographic examination of specimens cut from the top, middle, and bottom bars of the ingot had similar structures after the heat treatment.

TYPES OF TESTING MACHINES AND COOPERATING LABORATORIES

1. The NACA sponsored standard short-time tensile and rupture tests on 0.505-inch-diameter specimens by the University of Michigan at room temperature, 1000°, 1200°, 1350°, and 1500° F. Time-elongation data were obtained from the rupture tests.

2. Completely reversed bending fatigue tests were made at room temperature, 1000°, 1200°, 1350°, and 1500° F by the Research Laboratories of the Westinghouse Electric Corporation. Round profile specimens

(fig. 1(a)) were tested in the Westinghouse 7200-cpm electronic fatigue machine. The specimen was vibrated electrically at resonance in one plane so that maximum stress occurred on the surface at two diametrically opposite points.

3. Completely reversed bending fatigue tests were run at room temperature and 1350° F in Westinghouse electronic 7200-cpm machines by the Lewis Laboratory of the NACA. Their tests differed in two respects from the tests run by Westinghouse. The NACA used the smaller specimen described in figure 1(b), and they machined the specimens which they tested from stock heat-treated by the University of Michigan. Hand polishing was used for a final finish of about the same surface roughness as that of the specimens prepared by the University of Michigan.

4. Dynamic creep tests were run at 1350° and 1500° F by the Institute of Industrial Research of Syracuse University under sponsorship of Wright-Patterson Air Force Base, Air Materiel Command. Uniform gage length specimens (fig. 1(c)) were tested with steady axial tension loads and no alternating stress and with steady axial tension loads with superimposed alternating axial loads at 3600 cpm so as to give ratios of alternating to mean stress of 0, 0.25, and 0.67. The specimens were loaded by a constant-force spring mechanism in a machine designed by Syracuse University. Combinations of alternating and steady loads were used to give fracture times out to several thousand hours. Creep data were obtained from the tests.

5. Axial tension-compression fatigue tests were run at 1350° and 1500° F by the Institute of Industrial Research of Syracuse University under sponsorship of Wright-Patterson Air Force Base, Air Materiel Command. A profile specimen (fig. 1(d)) was tested in the same machine described under item 3. Compression tests were made having a ratio of alternating to mean stress of 2, as well as tests with completely reversed tension-compression (zero mean stress) loads.

6. Axial tension-compression tests in the Krause fatigue machine at 1200°, 1350°, and 1500° F were run by Battelle Memorial Institute under sponsorship of the Office of Naval Research, U. S. Navy. Profile specimens (fig. 1(e)) were tested at varying mean stress with superimposed axial dynamic loads of ±25,000, ±15,000, and ±7500 psi, the stresses in all tests staying in tension. A steady load was applied through a load maintainer and a constant-amplitude alternating load at 1500 cpm was applied by a crank mechanism.

7. Axial tension-compression fatigue tests in compression in the Krause fatigue machine at 1350° F were run by Battelle Memorial Institute under sponsorship of the Office of Naval Research, U. S. Navy. Special adapters were developed to permit testing with completely reversed axial

tension-compression loads and with steady tension loads less than the alternating load using the profile specimen shown by figure 1(f).

8. Axial tension=compression fatigue tests at 1000° and 1350° F in the Sonntag SF-4 machine were made by The Elliott Company. Profile specimens (fig. 1(g)) were tested at 1000° F with various combinations of 3600-cpm alternating stress and steady stress, but with the specimens always staying in tension. The effect of superimposing alternating stress on the steady stress (28,000 psi) to cause rupture in 175 hours at 1350° F was determined. The Sonntag SF-4 machine applies constant-force loads through a spring mechanism.

9. The Research Laboratories of the General Motors Corporation conducted tests at 1350° F with combined rotating bending and steady axial tension loads. A uniform gage length specimen (fig. 1(h)) was loaded in steady tension under the stress to cause rupture in 175 hours (28,000 psi) and then rotating bending stresses were applied at 10,800 cpm by causing one end of the system to rotate in a circle.

10. Rotating cantilever beam tests were made at 1350° F by the Engineering Experiment Station, U. S. Navy, in a machine of their design. Tapered gage length specimens (fig. 1(i)) loaded at one end were rotated at 1700 cpm.

11. In addition to the above tests the following are in progress:

(a) Axial tension-compression tests at room temperature and 1000° F in the Syracuse University Machine

(b) Additional Sonntag SF-4 tests at 1000° F and 1200° F by The Elliott Company

(c) Krause tests to complete the curves at 1200° and 1350° F in compression to completely reversed stress tests by Battelle Memorial Institute under sponsorship of the NACA

(d) Rotating cantilever beam tests at 1350° and 1500° F by Syracuse University under sponsorship of Wright-Patterson Air Force Base, Air Materiel Command

(e) Rotating beam tests at 1200°, 1350°, and 1500° F by the Rolls Royce Company of England

SPECIMEN PREPARATION

All specimens were prepared by the Metal Processing Department of the University of Michigan under NACA sponsorship. Preliminary investigations of machining and finishing operations on the test material were made in order to arrive at a procedure which would as nearly as possible meet the requirements of constant surface roughness and constant surface cold-work for all types of specimens included in the program. These requirements were established because these two variables were considered to be possible sources of variable fatigue test data. The objectives of the program required avoiding the possibility of surface finish effects influencing the results from the various types of test.

The surface roughness was maintained at 2 to 4 microinches rms. This quality of surface finish was established to meet the most severe specification of the several cooperators.

The amount of cold-work on the surface after finishing was not measured. Extreme precautions, however, were taken to reproduce the method of metal removal on all specimens in order to keep surface cold-work constant. This requirement imposed severe restrictions because the very close dimensional tolerances of the specimens had to be met with a fixed procedure for metal removal. The result was that the specimen preparation was very time consuming and expensive. Because emphasis was placed on reproducibility of surface finish on the various specimens and not on minimizing cold-work or surface roughness, the following details of machining and finishing operations should not be accepted as the most desirable for preparing fatigue specimens for testing at high temperatures.

Machining Procedure

All of the several types of test specimens submitted to the University of Michigan for machining were processed by substantially traditional methods. All gage sections were turned on a lathe with the exception of the Battelle specimen for tests in compression. This specimen was turned on a milling machine in a setup wherein the specimen was mounted between centers in the spindle and the cutting tool was mounted on a rotary table in turn mounted on the table of the milling machine; the rotary table was rotated manually through a worm gearset for the feeding motion. All turning tools were 18-4-1 high-speed steel machine ground to the following shape: 10° back rake angle, 15° side rake angle, 10° relief angle, and 0.010-inch nose radius. All cutting speeds were confined to the range 30 to 40 fpm; the depth of cut was selected in a descending sequence ranging from the maximum of 0.030 inch to a minimum of 0.005 inch, while the feed rate was held constant at 0.005 inch per revolution in every case except for manual feed where an attempt was made to keep the feed above a minimum of 0.005 inch per revolution.

The above conditions were set up in the belief that the amount of cold flow was directly proportional to the size of cut. Consequently, it was expected that the progressively decreasing series of depth of cut used consistently would establish a degree of control as well as lead to a minimum of cold flow. The unique characteristics of the specimen material make it unusually susceptible to burnishing and related effects resulting from dull cutting edges which behave even duller at light feed rates. This latter reason was the basis for establishing a minimum feed rate.

Finishing Procedure

The original finishing setup was on a Kent-Owens 2-20 milling machine. The milling-machine setup was characterized by a continuous belt and was unique in that a system of counterbalances was used in an attempt to minimize and control the pressure between the cloth-backed abrasive and the specimen. However, irregularities developed and the mass of the counterbalance system made it impossible to achieve control over the pressure between the abrasive and the specimen.

The Battelle specimens in figure 1(d) were finished on the Kent-Owens setup using only cloth-backed abrasives as belts down through 500 grit, wherein the final step involved the use of chrome-oxide polishing stick rubbed on thoroughly worn 500-grit belts. Irregularities of the belts and the light pressures used made it impossible to improve the accuracy of the machined specimens and it is probable in some cases that the runout and out-of-roundness increased as a consequence of the finishing process.

The Westinghouse specimens were finished on a special setup wherein strips of cloth-backed abrasive were fastened to the surface of an oscillating sector while the specimen was mounted between centers and rotated. By this time all attempts to control finishing pressure by counterbalancing had been abandoned in favor of precision positioning of the specimens relative to the abrasive so that greater accuracy could be obtained. Pressure control was achieved somewhat arbitrarily by holding back on the rate of cutting so that the specimen did not heat. The finishing procedure used on the Westinghouse specimens is considered to be the most satisfactory in terms of the original objective although it was very slow and very expensive as a consequence of the relatively small amount of abrasive available during each setup.

All subsequent specimens were finished by one of two arrangements of a new set-up shown schematically in figure 2. The specimen is mounted between centers and rotated. A continuous belt is operated over a system of driving and idler pulleys with the motion of the belt oriented longitudinally to the specimen. When the longitudinal section of the specimen is a radius, a pulley or wheel with a corresponding radius is mounted in place of the form block shown in the sketch although a form block can be used for these specimens. The pulley or wheel is substituted for the form block in this case so as to reduce the heat arising from friction between the belt and the form block. Control of both pressure and size, to the extent that it is achieved, is obtained through screw adjustments of the position of the axis of the specimen relative to the form block or wheel.

The procedure for finishing specimens involved the use of continuous abrasive belts used in sequence of decreasing grain size with the following grain sizes: 60, 120, 240, 320, 400, and 500. This is followed by a final step wherein a standard tallow stick such as is used for grease polishing was smeared on a well-worn 500-grit belt to inhibit further its cutting action. It is vitally important to use this belt at highly specific operating conditions.

It is possible with such a combination to produce a highly burnished surface by exerting considerable pressure between the belt and the specimen to be finished. However, much less cold flow and an even smoother finish can be obtained by using a very light pressure between the belt and the specimen. So far as is known now this is a unique property of the type of specimen material.

It is significant that, as mentioned earlier in this report, chrome oxide was first used for this final step although tallow is now being used. By experimentation it became apparent that there was little or no value in the chrome-oxide stick as an abrasive, but rather that the beneficial effects arose from the ability of the stearate base or bond to inhibit the abrasive and cutting action of the belt. It was this experience which led to the current practice of using tallow on a well-worn 500-grit belt for the final finishing step.

The belts were made from commercial rolls of Behr-Manning cloth-backed abrasive. Appropriate lengths were cut on a bias and the belt was formed with a butt joint backed up with a manila paper of about 0.006-inch thickness and cemented with a commercial grinding disc cement (Gardner No. 2 Disc Wheel cement).

RESULTS AND DISCUSSION

The curves of alternating stress against mean stress for fracture in 50, 150, and 500 hours of figure 3 summarize most of the results. The tests to determine the effect on fracture time of superimposing dynamic loading on a steady stress of 28,000 psi are summarized by figure 4. Table III is a tabulation of the tensile, rupture, and fatigue properties. The detailed test results are included as tables IV to XIII and figures 5 to 13.

Additional points are being obtained for the curves of figure 3 by the tests still in progress. In particular the indicated approach of the curves for 1000° F to those for 1200° F, suggesting the possibility of strengths at 1200° F equal to those at 1000° F for certain combinations of static and dynamic stress, is being checked. The compression range is being filled in at all temperatures.

The increase in mean stress required for fracture in a given time period indicated by figure 3 for low values of superimposed alternating stress at the higher temperatures has been determined to be a true behavior of the test material and not a testing-technique effect. All of the completely reversed stress fatigue tests reached a fatigue limit at less than 50 hours except at 1500° F, so that the stress for fracture in the three time periods was identical except at 1500° F. The curves indicate that a superimposed alternating stress was less effective in reducing load-carrying ability as the testing temperature increased.

The results of superimposed alternating stress on the fracture time at 1350° F under a steady stress of 28,000 psi (fig. 4) were normal except for the superimposed bending tests in the General Motors Research Laboratory machine. However, since the points from the General Motors test which deviated from the curve did not show fracture at the point of calculated maximum bending stress, the results of these tests are considered to be due to a testing-machine effect, and are therefore not a true effect of bending stress.

The relationships between tensile properties and reversed-stress fatigue limits are shown by figure 14. The ratio of fatigue strength to tensile strength increased with testing temperature, ranging from 0.46 to 0.65. This figure also shows that the maximum alternating stress for failure by fatigue becomes successively higher than the static strength (rupture strengths) for the three time periods considered in the temperature range from 1160° to 1275° F.

The agreement in results from the various tests was surprisingly close. In all cases the deviation between the various types of tests was less than could be accounted for by experimental error. The rotating cantilever beam fatigue limit at 1350° F indicated by data from the U. S. Naval Engineering Experiment Station was less than for the reversed bending and completely reversed axial stress tests because they reported their S-N curve on the basis of the lower limit of the scatter of their data (fig. 11) rather than on the basis of the average curves reported for the other tests. The rotating cantilever beam data actually fall very close to the other test data.

The data show very little effect from speed of stress reversal probably because the slopes of the S-N curves are very small. This results in very little change in stress for fracture in the three time periods considered for the various types of tests even though there may be large differences in the number of cycles of alternating stress between the various tests. Work is in progress to establish if the differences between Krause and Syracuse machine data can be accounted for on the basis of number of cycles involved. A larger effect may show up in the lower-temperature data being obtained.

No effect from section size in the test specimens has been observed. The slight variation in rupture test results between Syracuse and Michigan tests has been checked for this effect. The cause was determined to be for other unknown reasons rather than for differences in specimen diameter or heat-treatment variation. The Westinghouse machine data from the Lewis Laboratory of the NACA checked very well with those from the Westinghouse Laboratory (fig. 6), even though there was a considerable difference in the size of the section tested. Therefore the heat treatment used is considered to have eliminated variations from bar to bar in the test material since the scatter in data for the individual tests appears to be no more than normal.

As far as can be deduced from the data, surface finish effects were constant. There is some question whether the elaborate precautions taken to insure uniform surface finish were necessary. Westinghouse ran tests with specimens prepared by ordinary shop practice with hand polishing and obtained good checks at 1200° and 1500° F (fig. 6) with those carefully prepared. The Lewis Laboratory of NACA checked the Westinghouse data quite well (fig. 6) at room temperature and 1350° F with specimens prepared in their own laboratory by techniques which differed widely from those used at Michigan. This indicates that the results of this investigation were not influenced by surface finish variations. It is not evidence, however, that surface finish variations cannot influence results of tests at high temperatures. It is known that there can be large effects from this source at low temperatures. The effect of surface finish variations at high temperatures has not yet been established.

Creep data were obtained from the Syracuse dynamic creep tests, the General Motors Research Laboratory combined stress tests, and the rupture tests. The results are included in figures 7, 12, 13, and 15. The relationships between dynamic stress and mean stress for various amounts of total deformation are similar to those for fracture time. Dynamic stress does increase the secondary creep rate, as is shown by figure 15, but the effect on stress for a given creep rate is rather small. Syracuse University has determined that the main effect of superimposed alternating stress is on the amount of third-stage creep, suggesting that the creep-rate effects shown in figure 15 may be due to the stress differences rather than the presence of dynamic stresses.

Examination of Fractured Specimens

All of the specimens tested to date have been examined both visually and microscopically. It appears that some minimum amount of alternating stress must be superimposed on a steady stress for a fatigue nucleus to appear in the fracture. The cases where fatigue nuclei have been observed are indicated in figures 10, 16, and 7. The microstructures of the fractures were identical to those of static rupture tests unless a fatigue nucleus was present.

Fatigue nuclei always had straight transgranular fractures. Rupture and combined stress tests had mixed intergranular and transgranular fractures which varied in detail with the testing temperature and time period for fracture. The appearance of intergranular cracks on the surface of completely reversed stress test specimens was less extensive and the time period required for their appearance greatly increased as compared with those in static tests. No definite correlation between the presence of intergranular cracks and susceptibility to, or initiation of, fatigue failure has yet been observed.

Typical microstructures for the original test material, for a fatigue nucleus, and for a comparable rupture test are shown in figures 18, 19, and 20.

NACA Headquarters
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TABLE I - PROCESSING OF LOW-CARBON N-155 1-INCH ROUND BAR STOCK

[Reported by the Universal-Cyclops Steel Corporation]

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

1. Hammer cogged to a 13-inch square from a $15\frac{1}{2}$-inch ingot
   Furnace temperature, 2210° to 2220° F
   Three heats - Starting temperature on die, 2050° to 2070° F
   Finish temperature on die, 1830° to 1870° F

2. Hammer cogged to a $10\frac{3}{4}$-inch square
   Furnace temperature, 2200° to 2220° F
   Three heats - Starting temperature on die, 2050° to 2070° F
   Finish temperature on die, 1790° to 1800° F

3. Hammer cogged to a 7-inch square
   Furnace temperature, 2200° to 2220° F
   Three heats - Starting temperature on die, 2050° to 2070° F
   Finish temperature on die, 1790° to 1890° F
   Billets ground to remove surface defects

4. Hammer cogged to a 4-inch square
   Furnace temperature, 2190° to 2210° F
   Three heats - Starting temperature on die, 2040° to 2060° F
   Finish temperature on die, 1680° to 1880° F
   Billets ground to remove surface defects

5. Hammer cogged to a 2-inch square
   Furnace temperature, 2180° to 2210° F
   Three heats - Starting temperature on die, 2050° to 2065° F
   Finish temperature on die, 1730° to 1870° F
   Billets ground to remove surface defects

6. One-inch rounds were rolled from 2-inch-square billets in one heat. The 2-inch bars were heated in a furnace at 2100° to 2115° F; the temperature at the start of rolling was 2050° to 2060° F; and the finishing temperatures were from 1820° to 1840° F. The bars were numbered in order of their position in the ingot.

7. Bars were assigned letters from A through Z; bar A represented the extreme bottom of ingot and bar Z the extreme top position. All billets were kept in number sequence throughout all processing, so that ingot position of any bar could be determined by its letter.

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

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TABLE II - BRINELL HARDNESS RANGES

[Heat treatment: 2200° F for 1 hr, water-quenched, and 16 hr at 1400° F; NACA data from University of Michigan]

Bar (1)	Brinell hardness (2)		
	Surface	Cross section	Range
JA	207-220	217-218	207-220
JB	197-212	207-214	197-214
JC	210-212	214-216	210-216
JD	207-208	210-214	207-213
JE	204-216	212-217	204-217
JF	199-214	212-214	199-214
JG	198-215	201-216	198-216
JH	203-212	205-212	203-212
JI	192-215	201-213	192-215
JJ	209-212	210-211	209-212
JK	203-208	205-213	203-213
JL	211-214	211-215	211-215
JM	203	200	200-203
JN	205-208	213-214	205-214
JO	206-208	212-214	206-214
JP	201-213	211-211	201-213
JQ	201-215	213-216	201-216
JR	211-215	212-216	211-216
JS	206-211	208-212	206-212
JT	205-211	206-210	205-211
JU	204-208	213-215	204-215
JV	205-207	211-212	205-212
JW	208-208	210-216	208-216
JX	203-211	210-214	203-214
JY	211-212	211-216	211-216
JZ	202-205	209-211	202-211
Over-all range	192-220	200-218	192-220

[1]Specimens taken from 26 bars marked A through Z. A represents bottom bar from ingot and Z, top bar from ingot; others lettered consecutively in between.

[2]Hardness values were taken on samples cut from center and each end of every bar.

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TABLE III -. COMPARATIVE STRESSES FOR FRACTURE IN 50, 150, AND 500 HOURS FOR VARIOUS TESTS

Type test	Data source	Test temp. (°F)	Tensile test properties: Ultimate (psi)	Tensile test properties: 0.2-percent offset (psi)	Tensile test properties: Proportional limit (psi)	Stress (psi) for fracture in - 50 hours	Stress (psi) for fracture in - 150 hours	Stress (psi) for fracture in - 500 hours
Tensile	U. of M.	Room	119,000	60,500	40,500	------	------	------
Reversed bending	Westinghouse	Room				±55,000	±55,000	±55,000
Reversed bending	Lewis Laboratory, NACA	Room				±55,000	±55,000	±55,000
Tensile	U. of M.	1000	94,000	38,000	26,000	------	------	------
Rupture	U. of M.	1000	-------	------	------	82,500	74,000	67,000
Sonntag axial fatigue	Elliott	1000	-------	------	------	75,000 ± 13,000	75,000 ± 10,000	------
						60,000 ± 21,000	60,000 ± 18,000	60,000 ± 13,000
						45,000 ± 25,000	45,000 ± 22,000	45,000 ± 49,000
Reversed bending	Westinghouse	1000	-------	------	------	±49,000	±49,000	±49,000
Tensile	U. of M.	1200	80,500	35,500	26,000	------	------	------
Rupture	U. of M.	1200	-------	------	------	54,000	44,000	41,000
Krause axial fatigue	Battelle	1200	-------	------	------	49,500 ± 7,500	45,000 ± 7,500	40,500 ± 7,500
						44,000 ± 15,000	40,500 ± 15,000	36,500 ± 15,000
						36,000 ± 25,000	33,000 ± 25,000	29,000 ± 25,000
Reversed bending	Westinghouse	1200	-------	------	------	±46,500	±46,500	±46,500
Tensile	U. of M.	1350	60,000	37,000	23,000	------	------	------
Rupture	U. of M.	1350	-------	------	------	32,000	28,500	25,000
Rupture	Syracuse	1350	-------	------	------	32,000	28,000	23,750
Axial fatigue	Syracuse	1350	-------	------	------	31,250 ± 7,800	28,000 ± 7,000	24,000 ± 6,000
						26,500 ± 17,700	24,500 ± 16,400	22,000 ± 14,700
Krause axial fatigue	Battelle	1350	-------	------	------	33,000 ± 7,500	28,750 ± 7,500	24,000 ± 7,500
						29,000 ± 15,000	26,500 ± 15,000	23,000 ± 15,000
						26,000 ± 25,000	10,000 ± 35,000	
							0 ± 40,000	
Reversed bending	Westinghouse	1350	-------	------	------	±39,000	±39,000	±39,000
Rotating cantilever beam	NEES	1350	-------	------	------	±36,000	±36,000	±36,000
Reversed bending	Lewis Laboratory, NACA	1350	-------	------	------	±39,000	±39,000	±39,000
Tensile	U. of M.	1500	44,600	35,800	20,000	------	------	------
Rupture	U. of M.	1500	-------	------	------	20,000	17,000	14,500
Rupture	Syracuse	1500	-------	------	------	19,000	16,250	12,750
Axial fatigue	Syracuse	1500	-------	------	------	19,750 ± 4,900	17,250 ± 4,300	14,500 ± 3,600
						18,500 ± 12,300	15,500 ± 10,400	13,000 ± 8,700
						13,000 ± 26,000	12,000 ± 24,000	10,750 ± 21,000
Zero mean	Syracuse	1500				±29,300	±28,000	±27,500
Krause axial fatigue	Battelle	1500	-------	------	------	19,750 ± 7,500	17,000 ± 7,500	14,000 ± 7,500
						18,500 ± 15,000	16,000 ± 15,000	13,750 ± 15,000
Reversed bending	Westinghouse	1500	-------	------	------	±29,500	±27,500	±25,500

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TABLE IV - TENSILE TEST DATA

[Speed of testing, 0.05 in./min; NACA data from University of Michigan]

Specimen	Test temp. (°F)	Tensile strength (psi)	Proportional limit (psi)	Offset yield strengths (psi)				Elongation in 2 in. (percent)	Reduction of area (percent)
				0.01 percent	0.02 percent	0.10 percent	0.20 percent		
JM1	Room	119,100	41,000	46,000	48,700	56,100	59,500	45.0	46.2
JY1	Room	119,000	40,000	47,600	50,500	58,500	61,500	42.5	45.5
JF1	1000	91,250	26,750	31,750	32,500	34,800	35,800	44.5	49.3
JW1	1000	93,900	26,000	31,750	34,000	38,750	40,000	39.5	45.7
JM4	1000	94,250	26,250	32,500	33,800	37,000	37,750	42.0	47.1
JP1	1200	81,200	25,750	29,500	30,500	34,250	35,250	35.0	38.0
JG1	1200	79,600	26,000	29,500	31,000	34,900	35,800	33.0	34.5
JX1	1350	60,250	22,250	27,500	29,750	34,750	36,500	27.5	28.5
JN1	1350	60,125	23,500	28,750	30,750	35,250	37,200	26.0	28.5
JE1	1500	45,600	20,000	26,250	28,500	33,800	35,800	19.5	26.8
JR1	1500	43,625	20,500	26,800	28,500	33,200	35,800	25.5	27.1

TABLE V - RUPTURE DATA

[NACA data from University of Michigan]

Specimen	Test temp. (°F)	Stress (psi)	Rupture time (hr)	Elongation in 2 in. (percent)	Reduction of area (percent)
JI10	1000	85,000	36	24	28
JT9		80,000	70	25	25
JH9		75,000	128	17	17
JP10		70,000	345	14	13
JL9		63,000	790	12	13
JX8	1200	65,000	26	12	14
JB12		55,000	47	10	11
JA1		50,000	61	10	11
JM2		47,000	83	16	10
JQ1		43,000	195	15	8.5
JM8		40,000	668	10	16
JD1		38,000	1107	20	18
JS1	1350	32,000	55	20	23
JC1		29,000	112	37	40
JB1		28,000	248	25	35
JJ1		26,000	336	30	43
JT1		24,000	665	20	30
JI1		22,000	1361	12	20
JU1	1500	20,000	51	34	37
JK1		18,000	108	28	32
JO1		16,000	203	25	37
JH1		14,000	575	26	33
JS10		12,500	1361	13	20

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TABLE VI - REVERSED BENDING FATIGUE DATA

FROM WESTINGHOUSE 7200-CPM MACHINE

[Westinghouse data for 0.550-in.-diam. specimens]

Test temp. (°F)	Alternating stress (psi)	Cycles to failure	Time for fracture (hr)
Room	69,000	0.195×10^6	0.45
	64,000	.37	.86
	59,500	1.1	2.55
	57,000	1.1	2.55
	56,000	.69	1.6
	55,500	[a]711	1645
	54,500	[a]150	347
1000	59,000	.19	.44
	51,000	.85	1.97
	50,500	.90	2.08
	49,000	1.22	2.82
	48,500	[a]210	487
1200	51,000	.55	1.27
	47,000	2.35	5.44
	46,500	.79	1.8
	46,000	200	463.0
1200	[b]48,500	1.77	4.1
	[b]46,500	2.05	4.75
	[b]45,000	[a]508	1175
1350	46,000	1.5	3.47
	44,000	1.75	4.05
	43,500	1.88	
	41,500	4.4	10.17
	39,500	64	148
	39,500	[a]430	994
	39,000	115.8	268
	38,500	52	120
1500	35,000	.43	.99
	33,500	5.9	13.7
	31,500	4.9	11.3
	30,500	20.5	47.5
	28,000	12.8	29.6
	26,500	109	252
	25,500	190	440
1500	[b]30,500	7.2	16.7
	[b]27,000	138	320
	[b]26,000	33.45	77.4

[a]Discontinued.

[b]Specimens machined by ordinary shop practice.

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TABLE VII - REVERSED BENDING FATIGUE DATA FROM

WESTINGHOUSE 7200-CPM MACHINE

[Lewis Laboratory, NACA, data for 0.333-in.-diam. specimens]

Specimen	Test temp. (°F)	Alternating stress (psi)	Cycles to failure	Time for fracture (hr)
Specimens ground to shape and polished				
JB20	Room	±65,000	0.389×10^6	0.90
JS20		±58,800	2.764	6.4
JC19		±57,100	1.598	3.7
JK21		±55,700	1.64	3.8
JI20		±54,100	1.252	3.0
JT20	1350	±46,400	.173	.4
JI20		±44,100	1.771	4.1
JL17		±42,200	4.363	10.1
JE20		±40,700	43.3	100.2
Specimens turned to shape and polished				
JY11	1350	±49,700	0.108×10^6	0.25
JK14		±45,000	.95	2.2
JI16		±44,000	1.21	2.8
JW11		±41,500	5.57	12.8
JO10		±41,700	17.58	40.7
JP17		±40,600	22.12	51.2
JU16		±39,700	30.15	69.8
JV16		±38,900	24.62	57.0
JJ13		±38,100	[a]123.85	286.7

[a]Discontinued.

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TABLE VIII - DYNAMIC CREEP TEST DATA FROM SYRACUSE UNIVERSITY 3600-CPM FATIGUE MACHINE

[Wright-Patterson Air Force Base data from Syracuse University; specimens with a uniform 0.252-in.-diam. gage section, $1\frac{9}{16}$ in. long]

Specimen	Test temp. (°F)	Ratio of alternating to mean stress	Stress (psi)	Cycles to failure	Time for fracture (hr)	Elongation in 2 in. (percent)
JJ-6	1350	0	40,000 ± 0	------------	4.0	18.4
JY-6			35,000 ± 0	------------	22.8	31.4
JM-22			30,000 ± 0	------------	58.3	24.7
JA-20			25,000 ± 0	------------	208.8	28.5
JC-5			22,000 ± 0	------------	1114.7	17.9
JN-6	1350	.25	37,000 ± 9,200	1.64×10^6	7.6	18.5
JB-13			33,000 ± 8,250	5.88	27.2	17.4
JC-10			27,500 ± 6,875	35.8	165.7	24.9
JF-11			25,000 ± 6,250	112	518.3	20.8
JG-5			23,200 ± 5,800	147.2	682.2	22.3
JV-13			19,000 ± 4,750	580	2683	25.8
JK-5	1350	.67	29,000 ± 19,332	2.44	11.3	12.6
JZ-19			27,000 ± 18,000	4.97	23.0	8.7
JO-4			26,000 ± 17,332	12.96	60.0	14.5
JM-20			25,000 ± 16,666	23.55	109.0	9.8
JZ-20			24,000 ± 16,000	65.5	303.6	7.5
JY-4			22,800 ± 15,200	85.75	397.2	11.9
JA-19			21,600 ± 14,400	114.5	530.0	7.9
JD-13			18,000 ± 12,000	540	(a)	----
JB-5	1500	0	22,500 ± 0	------------	20.7	36.4
JO-6			20,000 ± 0	------------	24.9	34.4
JA-16			19,000 ± 0	------------	47.9	28.0
JV-8			17,500 ± 0	------------	67.2	25.2
JH-10			15,000 ± 0	------------	[b]221.2	[b]17.0
JE-5			13,000 ± 0	------------	398.5	11.7
JI-5			11,000 ± 0	------------	1004.6	11.6
JW-4	1500	.25	24,000 ± 6,000	1.728	8.0	28.1
JM-21			22,000 ± 5,500	3.22	14.9	30.0
JL-5			19,200 ± 4,800	18	83.4	19.9
JE-12			16,800 ± 4,200	45.2	209.5	21.3
JT-5			15,200 ± 3,800	82.5	[b]382.3	9.6
JF-5			14,000 ± 3,500	86.6	410.9	15.4
JH-5			10,000 ± 2,500	602.5	2790.0	11.9
JV-13	1500	.67	22,200 ± 14,800	2.36	10.9	19.9
JG-12			21,000 ± 14,000	4.26	[c]19.7	13.7
JL-10			18,600 ± 12,400	7.84	36.3	21.8
JD-5			16,800 ± 11,200	18.4	85.1	18.3
JW-6			15,000 ± 10,000	48.1	226.1	15.8
JT-11			12,000 ± 8,000	138.2	640.3	10.2
JS-5			8,000 ± 5,333	878	406.6	5.88

[a]Controller failed at 2126 hr. Estimated rupture time is 2500 hr.

[b]Test discontinued at indicated time because thermocouple or other difficulties caused overheating or overloading.

[c]20° F low for 2 hr at beginning of test.

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TABLE IX - TENSION-COMPRESSION FATIGUE DATA FOR PROFILE SPECIMENS

FROM SYRACUSE UNIVERSITY 3600-CPM FATIGUE MACHINE

[Wright-Patterson Air Force Base data from Syracuse University]

Specimen	Test temp. (°F)	Ratio of alternating to mean stress	Stress (psi)	Cycles to fracture	Time for fracture (hr)
JR-14	1500	2	15,000 ± 30,000	0.0864×10^6	0.4
JW-9		2	14,000 ± 28,000	3.18	14.7
JS-13		2	13,000 ± 26,000	10.96	50.7
JY-10		2	12,000 ± 24,000	32.4	150
JK-11		2	11,000 ± 22,000	74.3	343.7
JY-9		2	9,000 ± 18,000	275	1273.0
JS-14	1500	[a]∞	± 30,000	1.7	8.3
JI-15		∞	± 29,000	23	106.1
JX-9		∞	± 27,000	230	1048.0
-----	1500	.67	17,000 ± 11,390	29.16	135

[a]Completely reversed (zero mean) stress tests.

TABLE X - KRAUSE AXIAL TENSION 1500-CPM FATIGUE TESTS

[Office of Naval Research data from Battelle Memorial Institute]

Specimen	Test temp. (°F)	Stress (psi)	Cycles to failure	Time for failure (hr)
JL7	1200	40,000 ± 25,000	1.32×10^6	14.7
JD2		38,000 ± 25,000	6.16	68.5
JP2		35,000 ± 25,000	5.27	58.6
JG7		35,000 ± 25,000	5.63	62.5
JI-2		32,500 ± 25,000	11.90	132
JT-7		30,000 ± 25,000	37.10	412
JE7	1200	55,000 ± 15,000	.31	3.45
JV6		45,000 ± 15,000	2.63	29.2
JJ2		39,000 ± 15,000	27.04	300.5
JC3	1200	50,000 ± 7,500	4.18	46.4
JQ2		45,000 ± 7,500	11.79	131
JQ6		39,000 ± 7,500	69.01	767
JP7	1350	30,000 ± 25,000	.378	4.2
JC7		28,000 ± 25,000	.66	7.3
JG2		26,000 ± 25,000	5.23	58.2
JM18	1350	32,500 ± 15,000	2.25	25
JN2		27,500 ± 15,000	5.10	56.6
JR2		25,000 ± 15,000	22.0	244
JD8		22,500 ± 15,000	55.0	611
JZ6	1350	32,500 ± 7,500	5.62	62.4
JZ8		30,000 ± 7,500	9.04	100.3
JK2		25,000 ± 7,500	36.67	408
JO8	1350	15,000 ± 35,000		
JQ11		10,000 ± 35,000	17.94	197
JD12	1350	0 ± 45,000	.005	.055
JC9		0 ± 42,500	.022	.244
JV12		0 ± 41,000	.016	.18
JK12		0 ± 40,000	13.19	146.5
JM6	1500	20,000 ± 15,000	2.15	23.9
JS2		17,500 ± 15,000	11.58	128.7
JA12		16,000 ± 15,000	18.72	208
JK7		16,000 ± 15,000	13.63	151.5
JT2	1500	20,000 ± 7,500	4.0	44.4
JH7		17,500 ± 7,500	11.8	131
JV3		16,000 ± 7,500	21.91	244
JZ13		14,500 ± 7,500	39.78	442

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TABLE XI - SONNTAG SF-4 3600-CPM TENSILE FATIGUE DATA

[Elliott Company data]

Specimen	Test temp. (°F)	Steady stress (psi)	Alternating stress (psi)	Cycles to failure	Time for fracture (hr)
JX-5	1000	75,000	±14,470	1.65×10^6	7.63
JV-11		75,000	±4,840	51.5	239
JT-12		60,000	±29,880	.421	1.95
JS-11		60,000	±19,910	17.16	79.5
JW-5		60,000	±16,500	53.7	249
JY-5		45,000	±26,880	6.181	28.6
JR-8		45,000	±19,410	[a]77.242	[a]357.0
JE-11	1350	28,000	±25,000	(b)	(b)
JG-11		28,000	±25,000	(c)	(c)
JI-11		28,000	±19,080	12.84	59.5
JC-8		28,000	±15,039	11.67	54
JH-8		28,000	±7,469	25.75	119
JD-11		28,000	±7,469	33.88	157
JF-10		28,000	±3,969	46.94	217

[a]Interrupted at 77,121,000 cycles to change bearings in machine.
[b]Failed during starting.
[c]Excessive deformation during starting stopped test.

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TABLE XII - STRESS-RUPTURE TESTS WITH SUPERIMPOSED ALTERNATING BENDING STRESS

[Research Laboratories Division, General Motors Corporation, machine and data]

Specimen	Test temp. (°F)	Steady tensile stress (psi)	10,800-cpm bending stress (psi)	Cycles to failure	Fracture time (hr)	Elongation (percent)
JV17	1350	28,000	±19,250	24.6×10^6	[a]38.0	6.78
JX14		28,000	±12,800	35.3	[b]54.5	11.75
JW12		28,000	±5,100	34	[c]52.5	13.05
JO11		28,000	±7,250	33	[b]51.0	13.95
JW14		28,000	±0	0	[d]>180	15.37

[a]Fatigue failure at point of maximum stress (3/8 in. above lower shoulder of specimen).

[b]Rupture failure at thermocouple strap weld remote from point of maximum stress ($1\frac{3}{16}$ in. from upper shoulder of specimen).

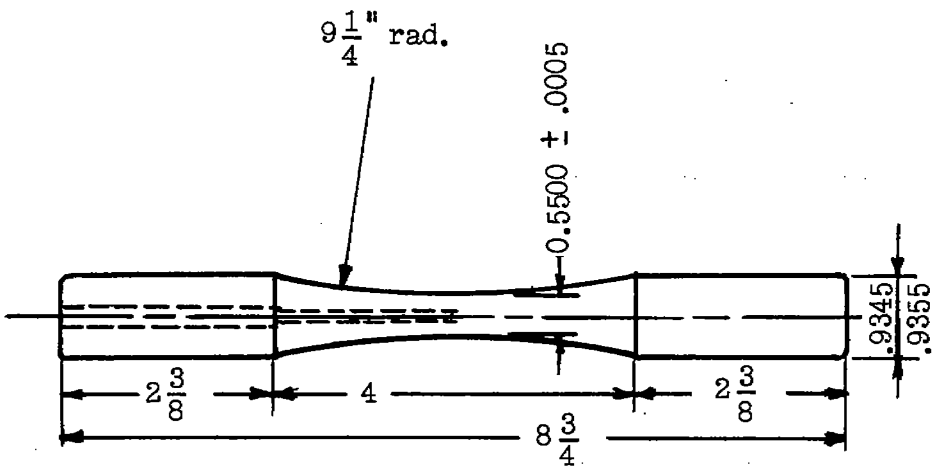
[c]Rupture failure remote from point of maximum stress and thermocouple welds.

[d]Specimen deformation reached limit of machine at 180 hr; creep data indicated failure before 200 hr.

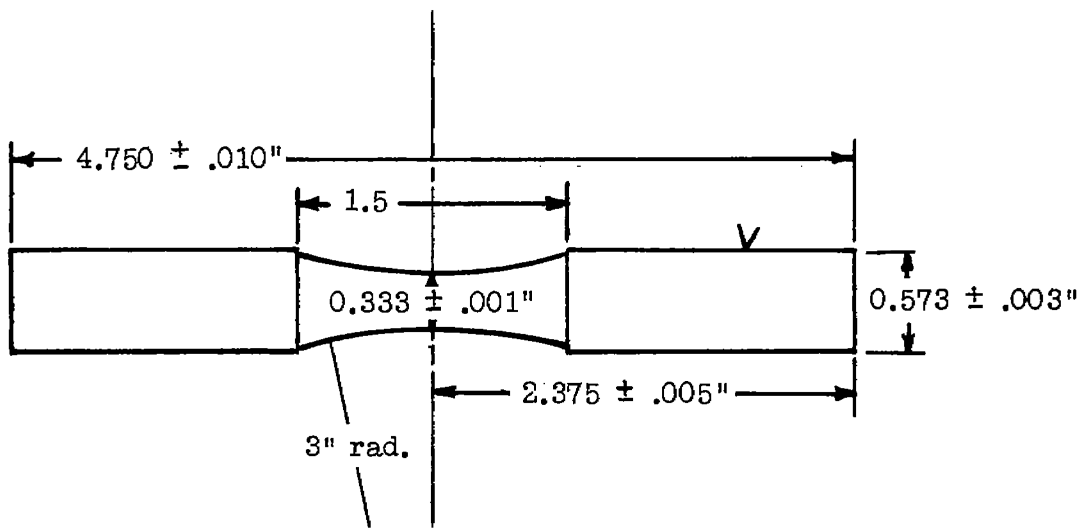
TABLE XIII - ROTATING CANTILEVER FATIGUE TEST DATA

[U. S. Naval Engineering Experiment Station 1700-cpm machine and data]

Specimen	Test temp. (°F)	Alternating stress (psi)	Cycles to failure	Time for fracture (hr)
JX12	1350	43,000	0.09×10^6	0.88
JJ15		40,000	37.69	369
JY13		38,000	7.79	76.3
JW12		37,000	5.22	51.1
JX13		35,000	56.75	556.4

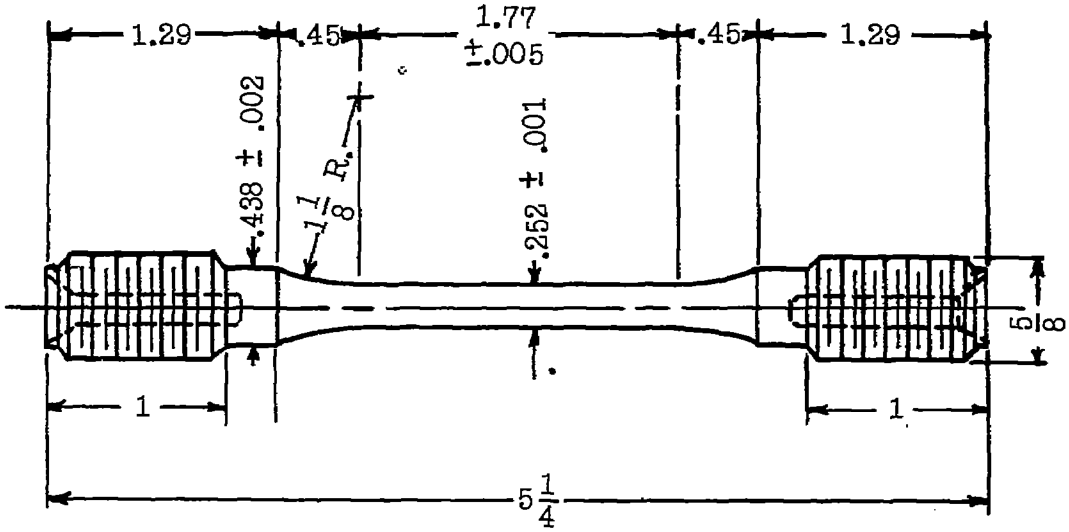


(a) Westinghouse high-frequency fatigue specimen. One-half scale.

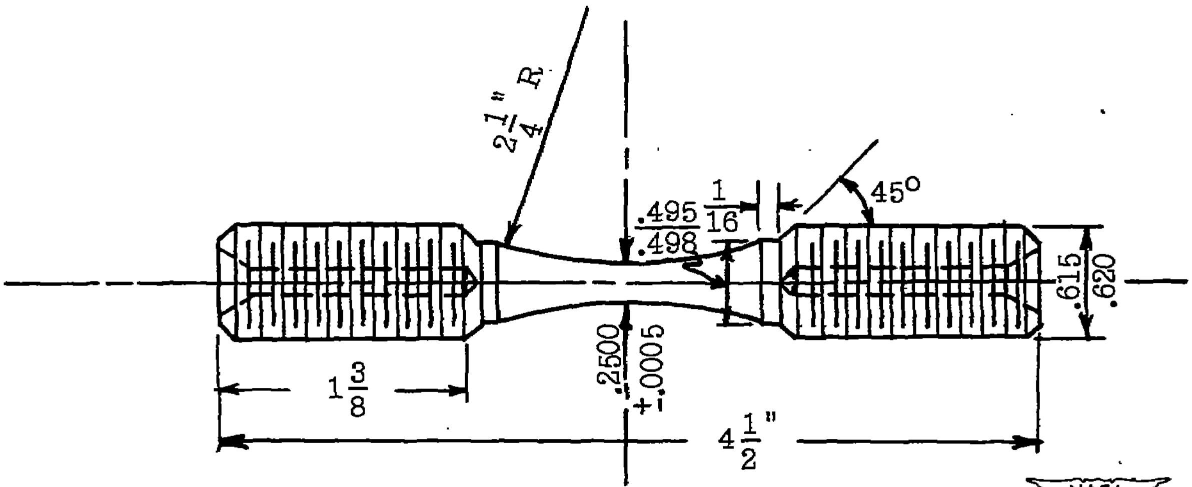


(b) NACA modified Westinghouse fatigue specimen.

Figure 1.- Fatigue specimens used by the cooperators in the investigation. (All dimensions in inches.)

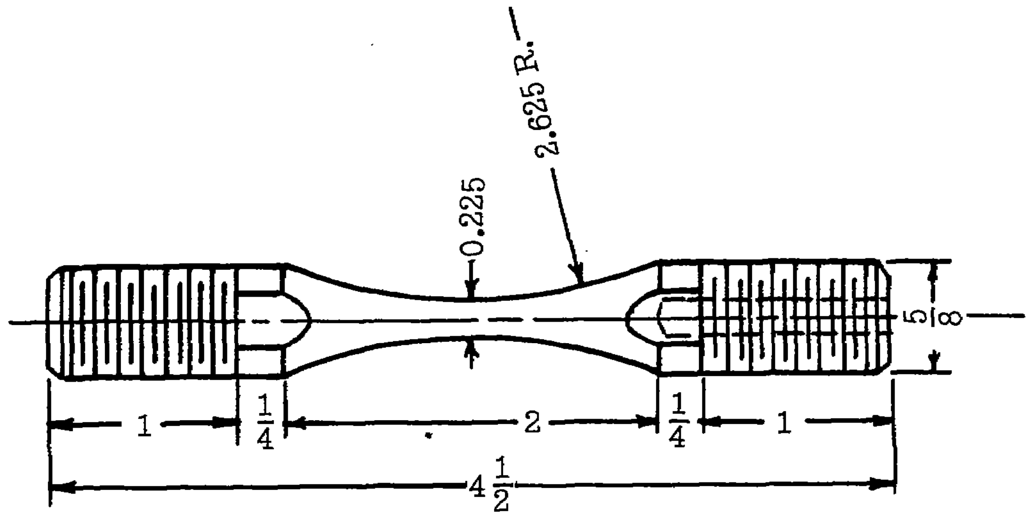


(c) Syracuse dynamic creep specimen.

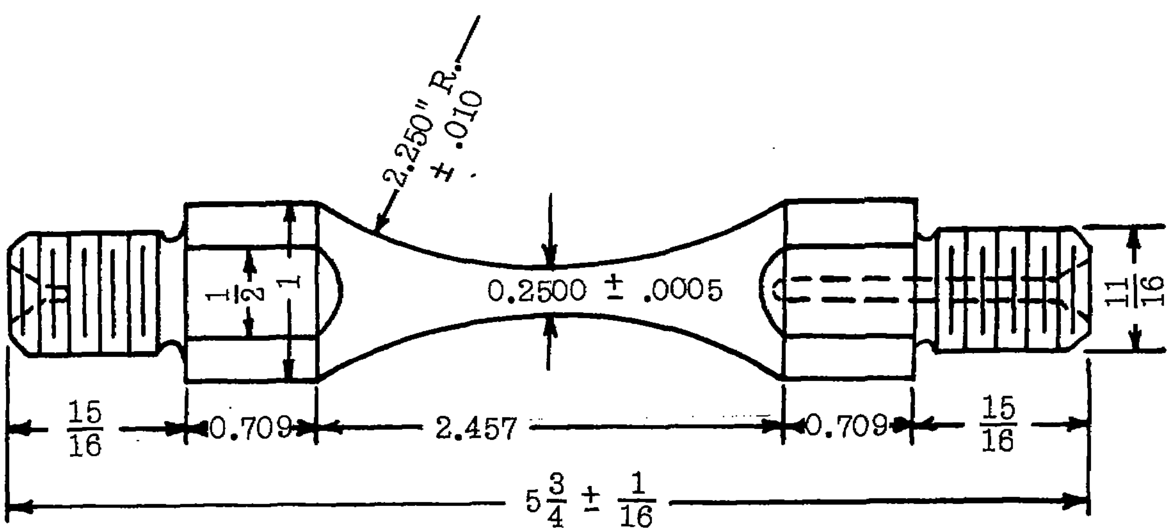


(d) Syracuse radius fatigue specimen.

Figure 1.- Continued.

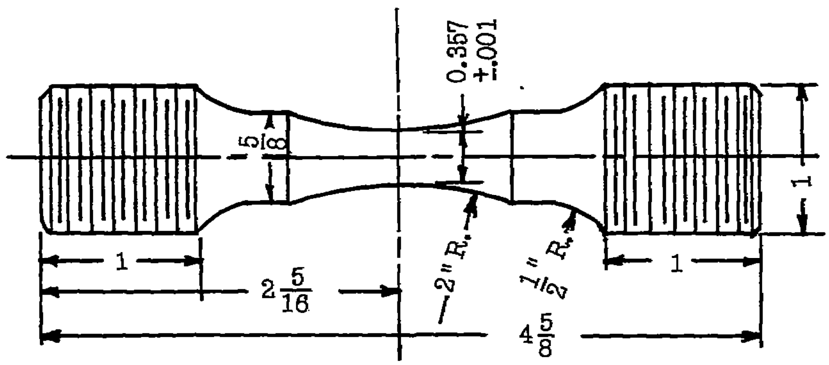


(e) Battelle axial fatigue specimen.

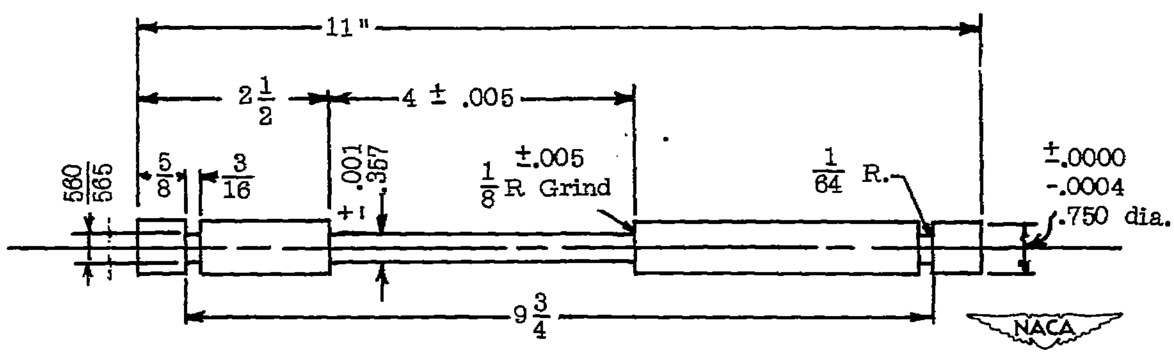


(f) Battelle zero mean stress axial fatigue specimen.

Figure 1.- Continued.

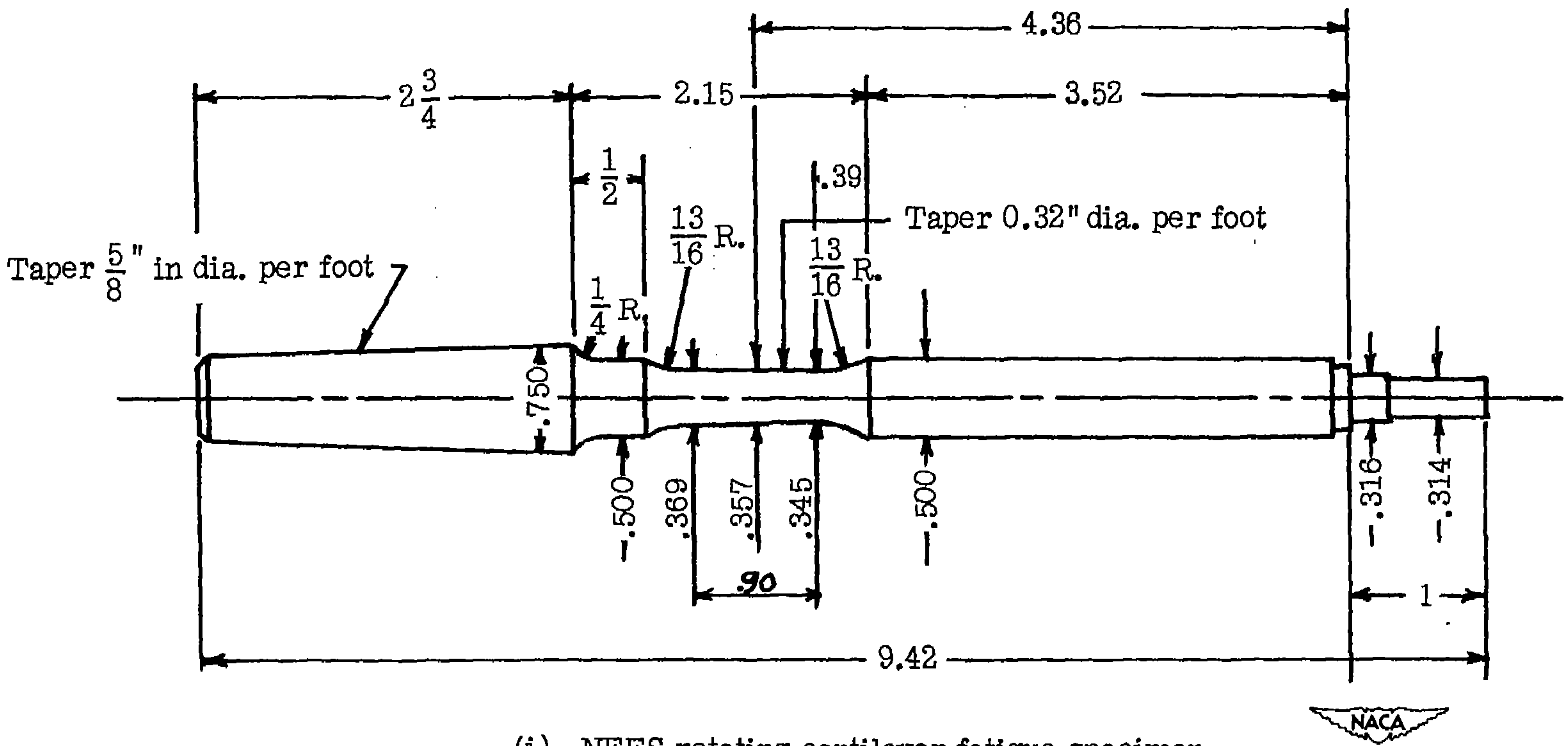


(g) Sonntag SF-4 axial fatigue specimen used by Elliott.



(h) General Motors combined stress fatigue specimen. One-half scale.

Figure 1.- Continued.



(i) NEES rotating cantilever fatigue specimen.

Figure 1.- Concluded.

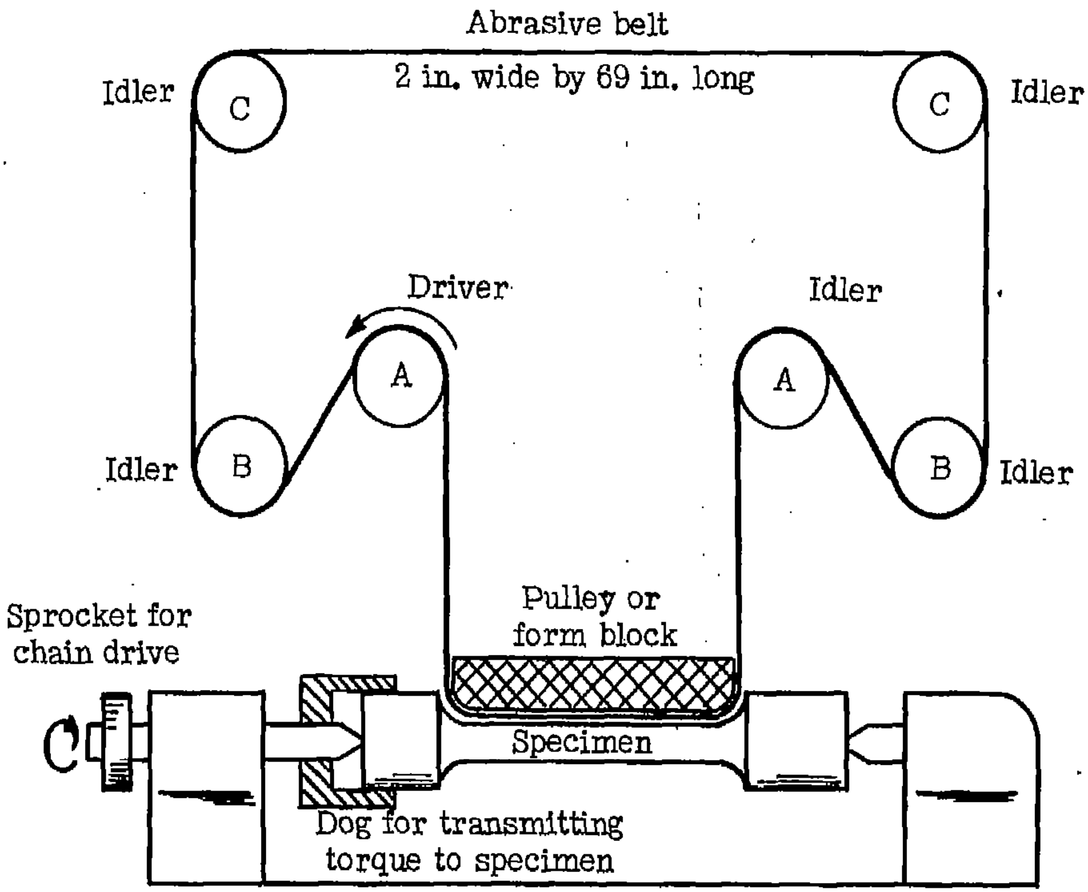


Figure 2.- Polishing machine.

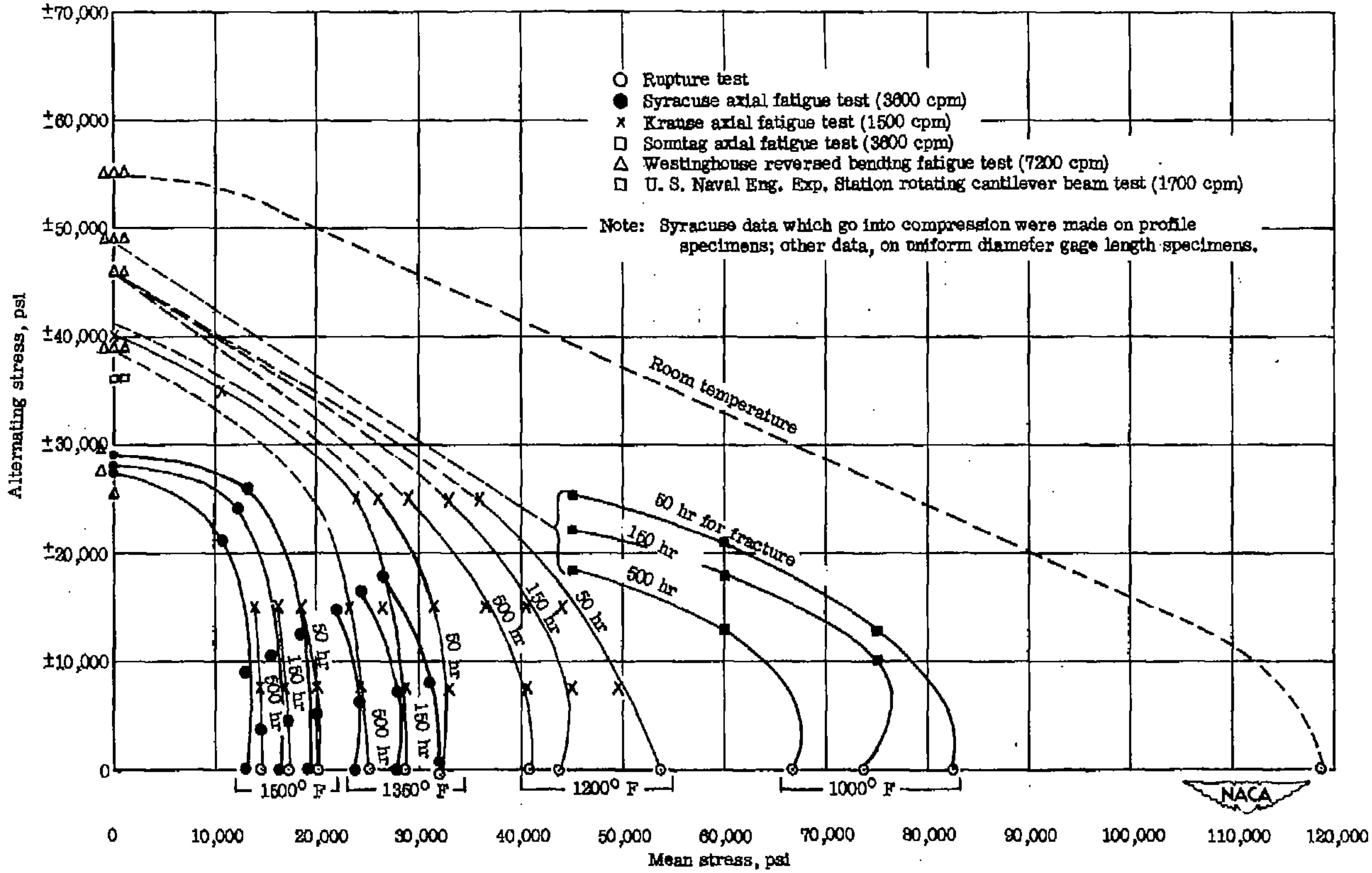
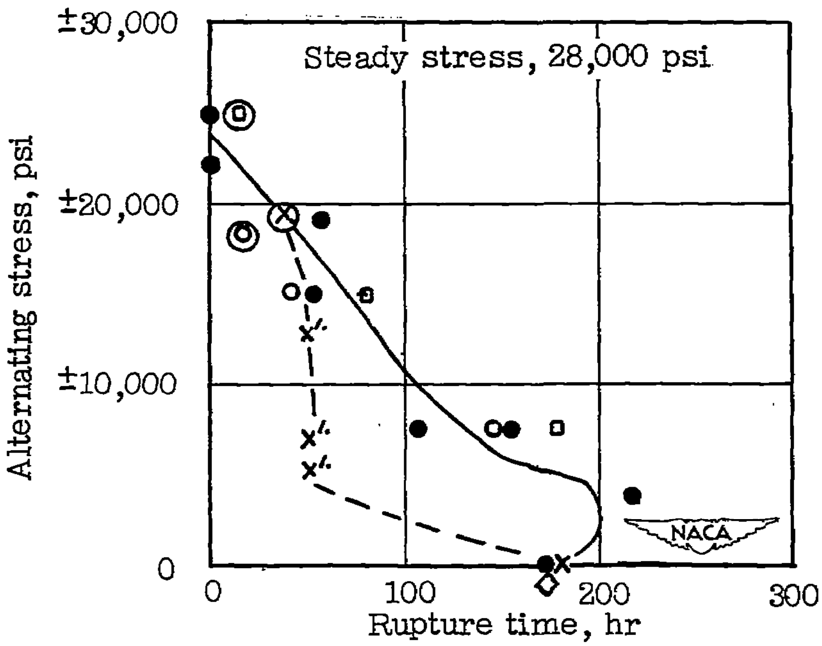


Figure 3.- Relationship between alternating and mean stresses for fracture in 50, 150, and 500 hours at room temperature, 1000°, 1200°, 1350°, and 1500° F.



● Sonntag SF-4 - 3600 cpm
□ Krause - 1500 cpm
○ Syracuse machine - 3600 cpm
} Superimposed axial alternating stress test
x General Motors combined stress machine - 10,800-cpm superimposed bending stress
◯ Indicates fatigue nucleus in fractured surface of specimen
◇ Rupture test
⸝ Specimen failed away from point of calculated maximum stress

Figure 4.- Influence of superimposed alternating stress on rupture time at 1350° F under a steady stress of 28,000 psi.

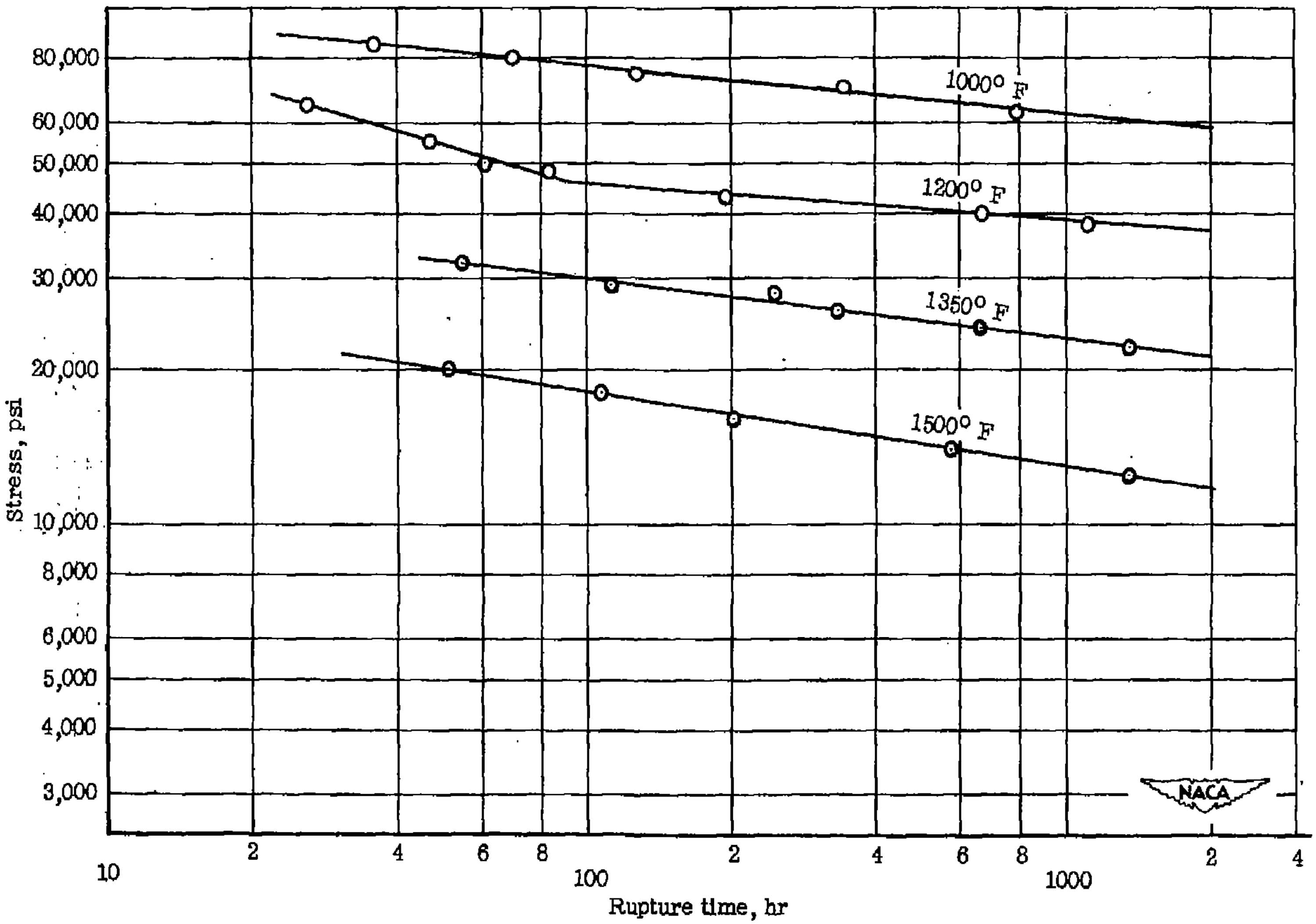
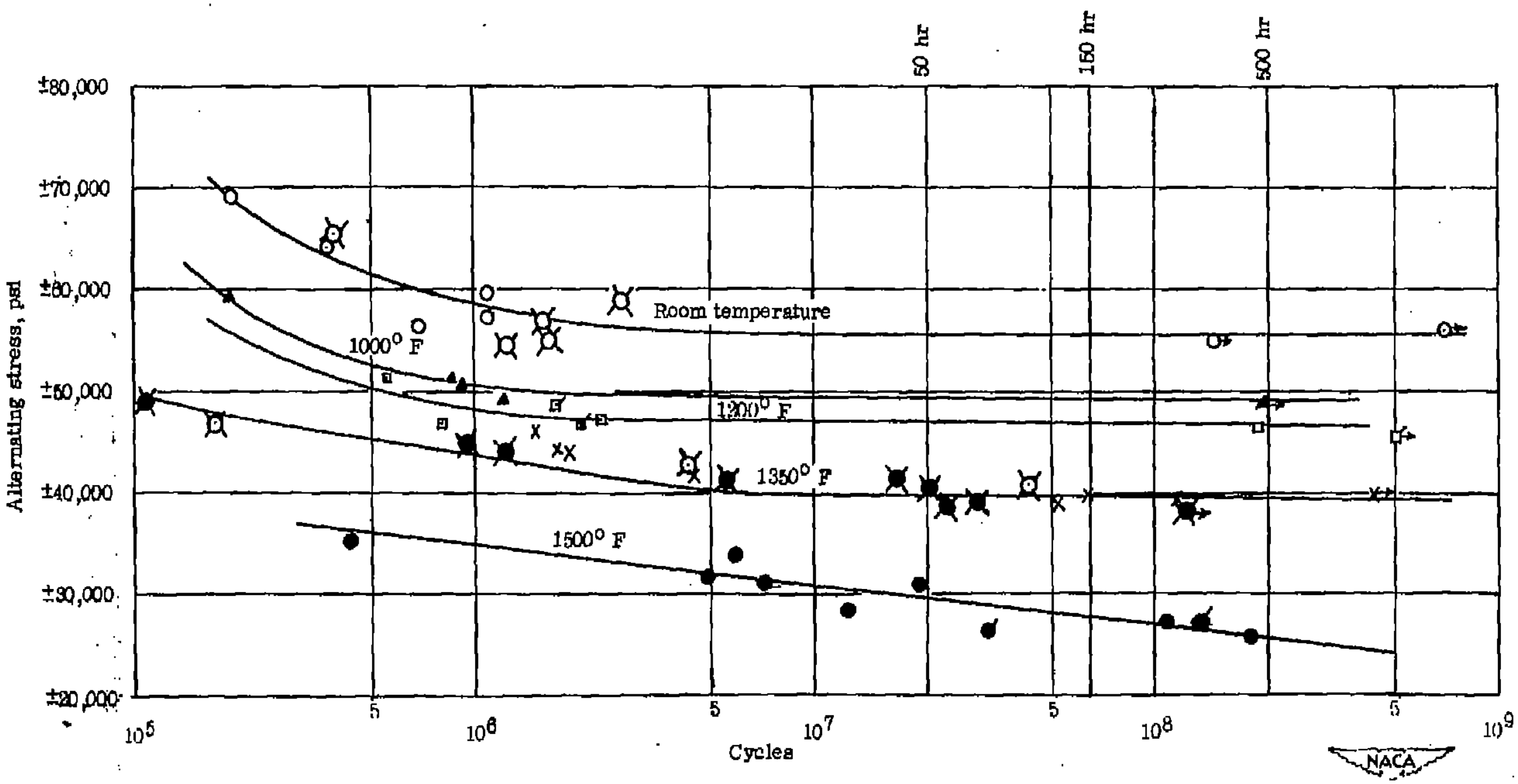


Figure 5.- Curves of stress against time for rupture at 1000°, 1200°, 1350°, and 1500° F (University of Michigan rupture test data).



Westinghouse data for 0.550-inch-diameter specimens
- ○▲□X ● Specimens prepared by specially controlled machining practice at University of Michigan
- □́ ●́ Specimens prepared by ordinary machine shop practice at University of Michigan

Data from Lewis Laboratory, NACA, for 0.333-inch-diameter specimens
- ¤ Specimens ground to shape and polished by NACA
- ■ Specimens turned to shape and polished by NACA

Figure 6.- Reversed bending S-N fatigue curves at room temperature, 1000°, 1200°, 1350°, and 1500° F from Westinghouse 7200-cpm machine.

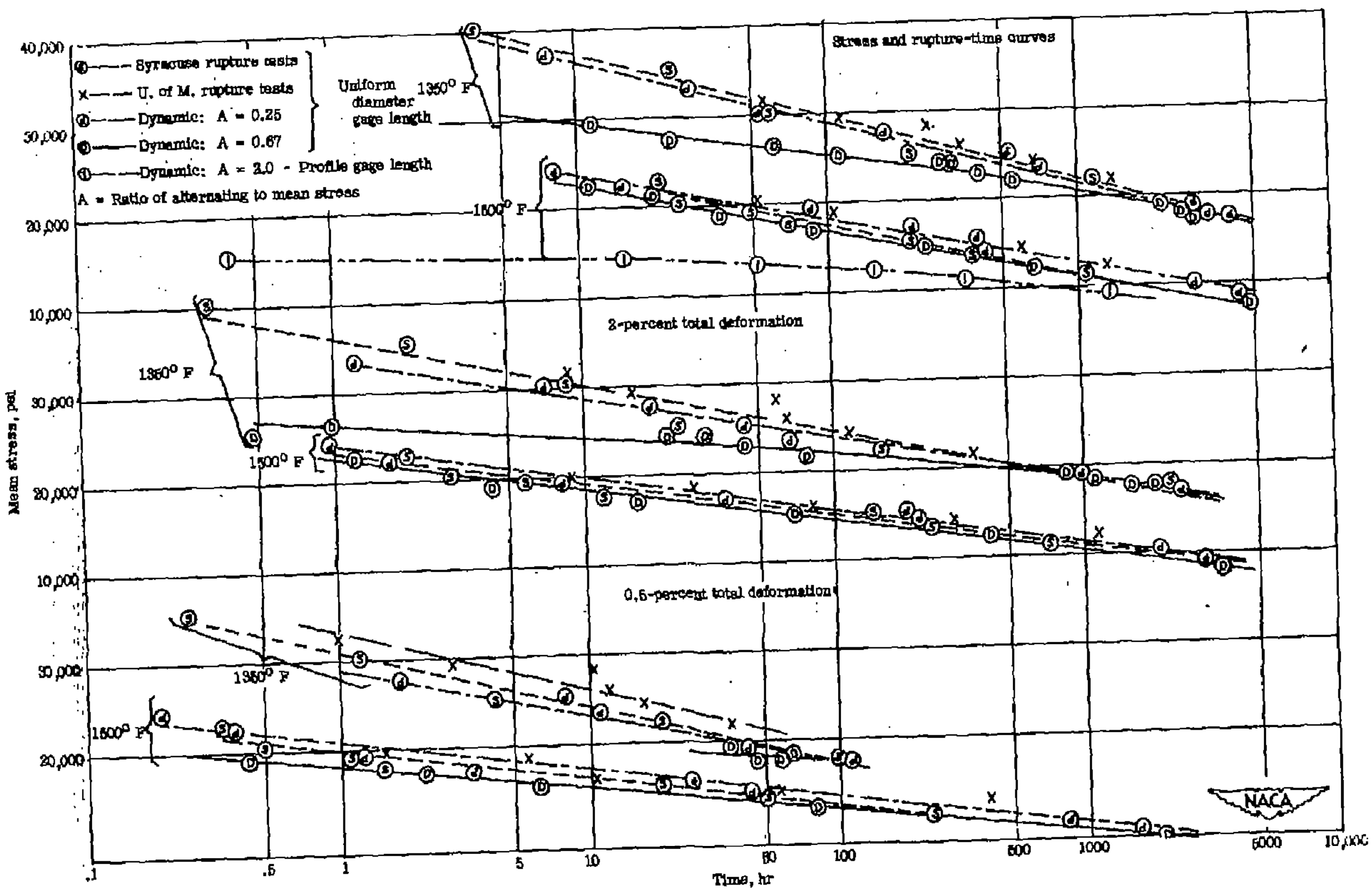


Figure 7.- Curves of mean stress against time for rupture and time for total deformation of 0.5 and 2.0 percent for rupture tests and Syracuse dynamic creep tests.

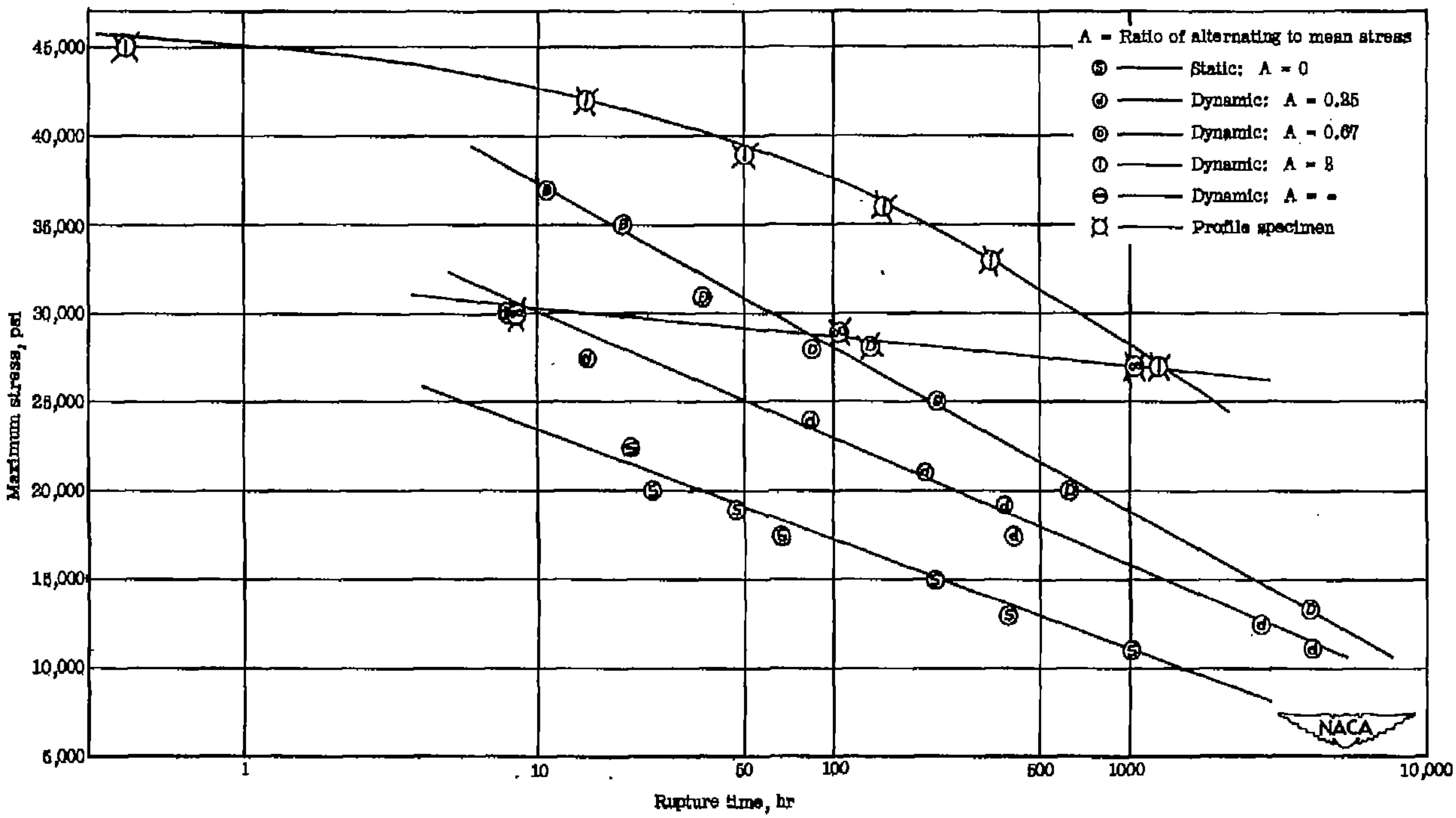


Figure 8.- Curves of maximum stress against rupture time for indicated ratios of alternating to mean stress at 1500° F in the Syracuse axial fatigue machine.

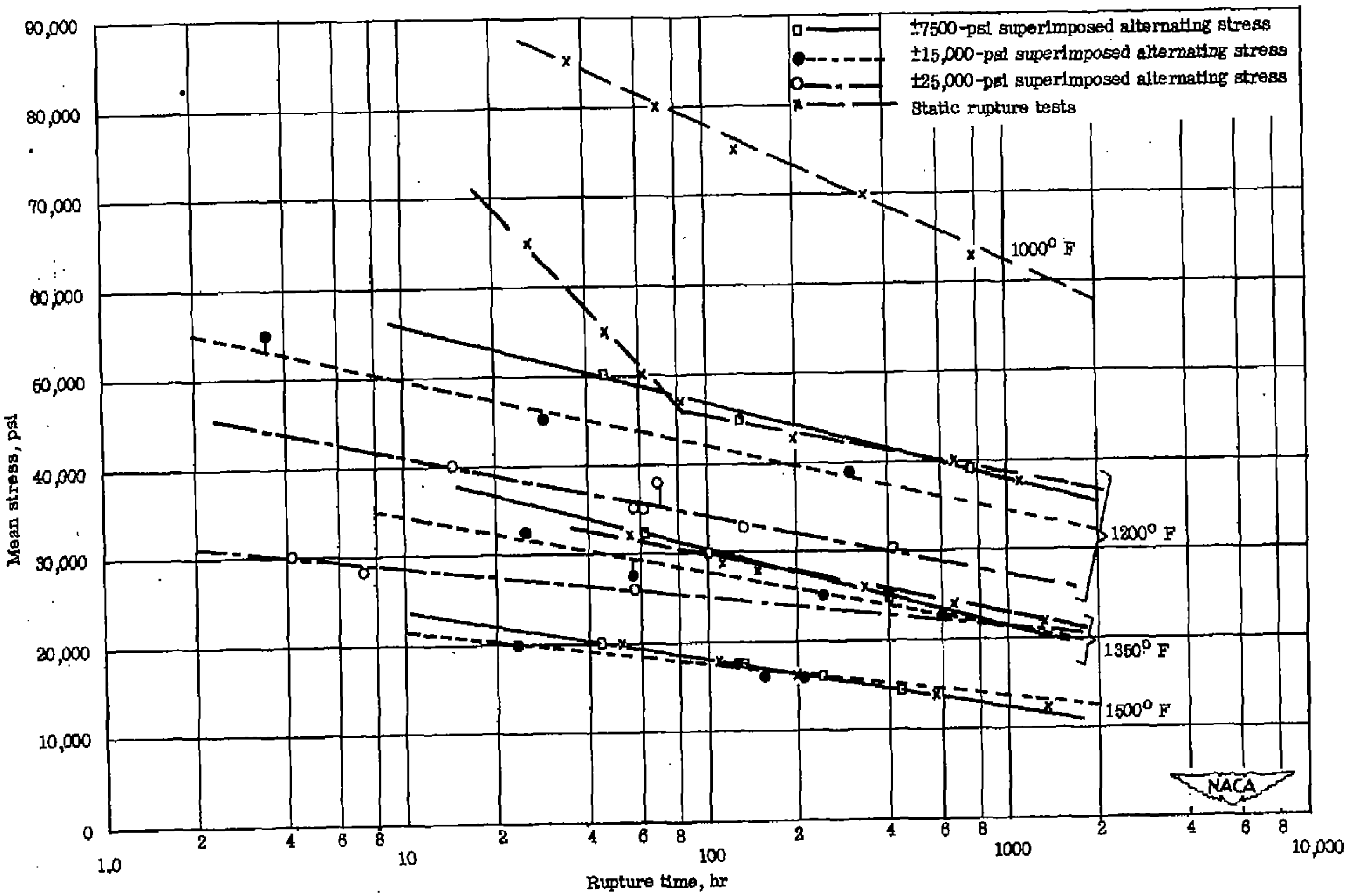


Figure 9.- Comparative curves of stress against rupture time at 1200°, 1350°, and 1500° F for Krause axial fatigue tests and for static rupture tests.

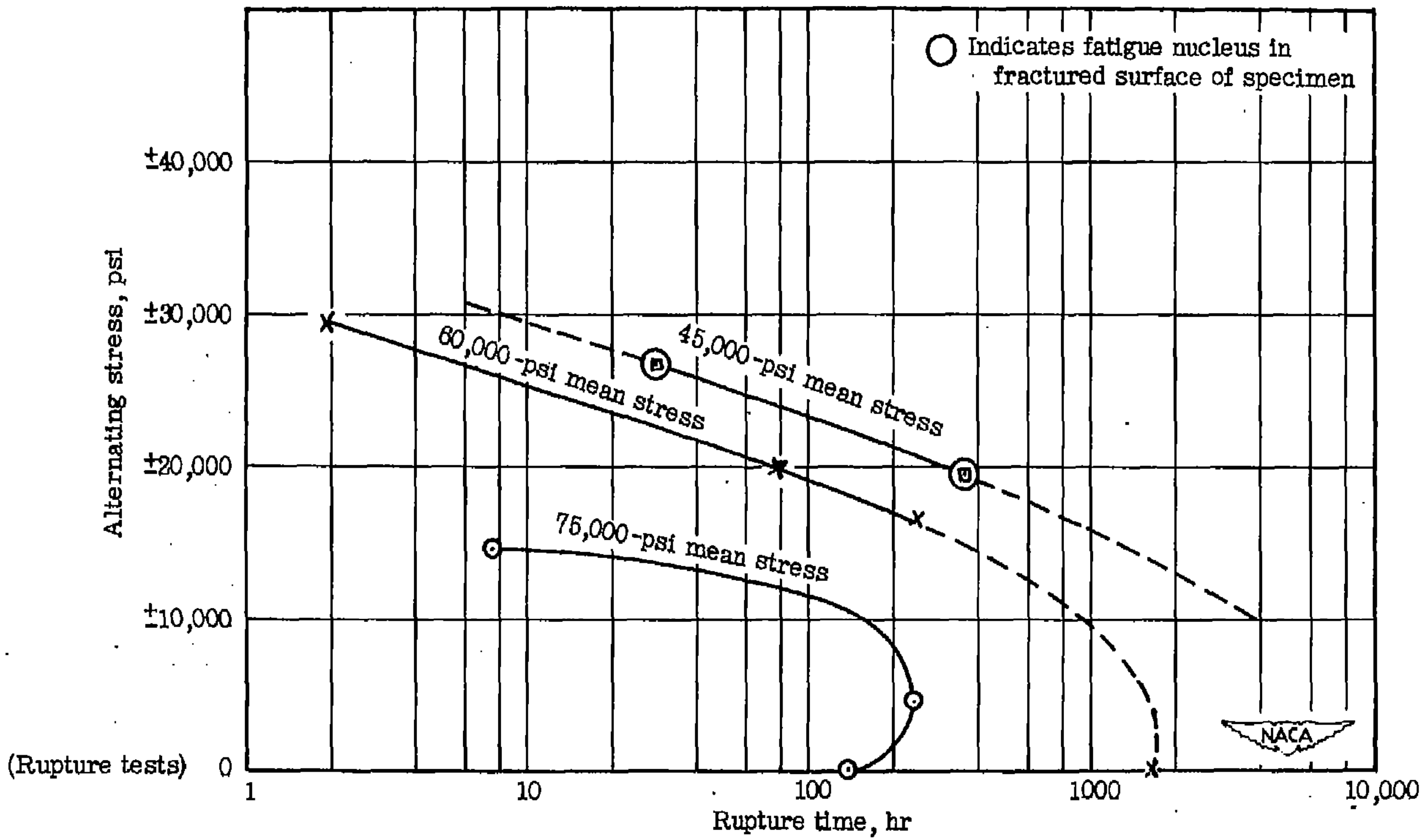


Figure 10.- Effect of superimposed alternating stress in the Sonntag SF-4 3600-cpm machine on time for rupture at 1000° F.

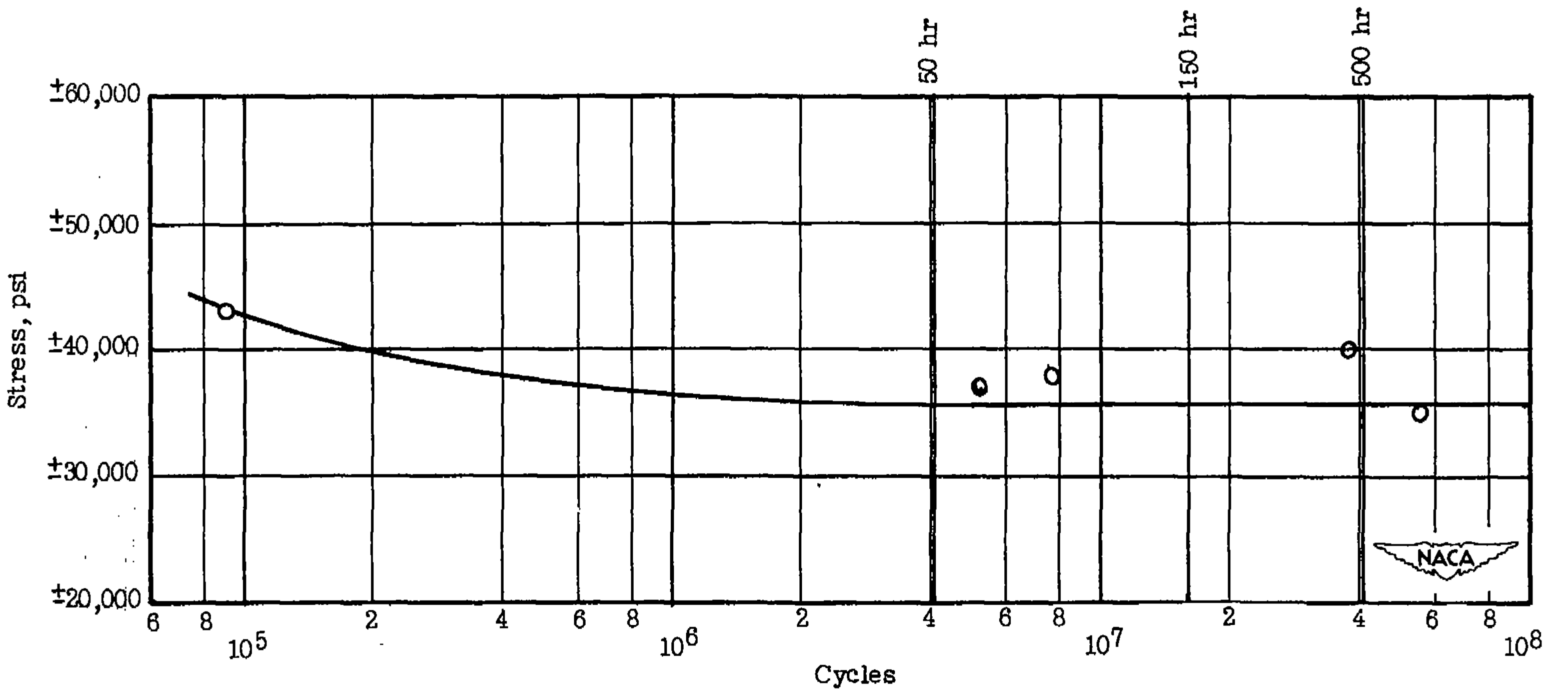


Figure 11.- Rotating cantilever beam S-N fatigue curve at 1350° F (U. S. Naval Engineering Experiment Station, 1700-cpm machine).

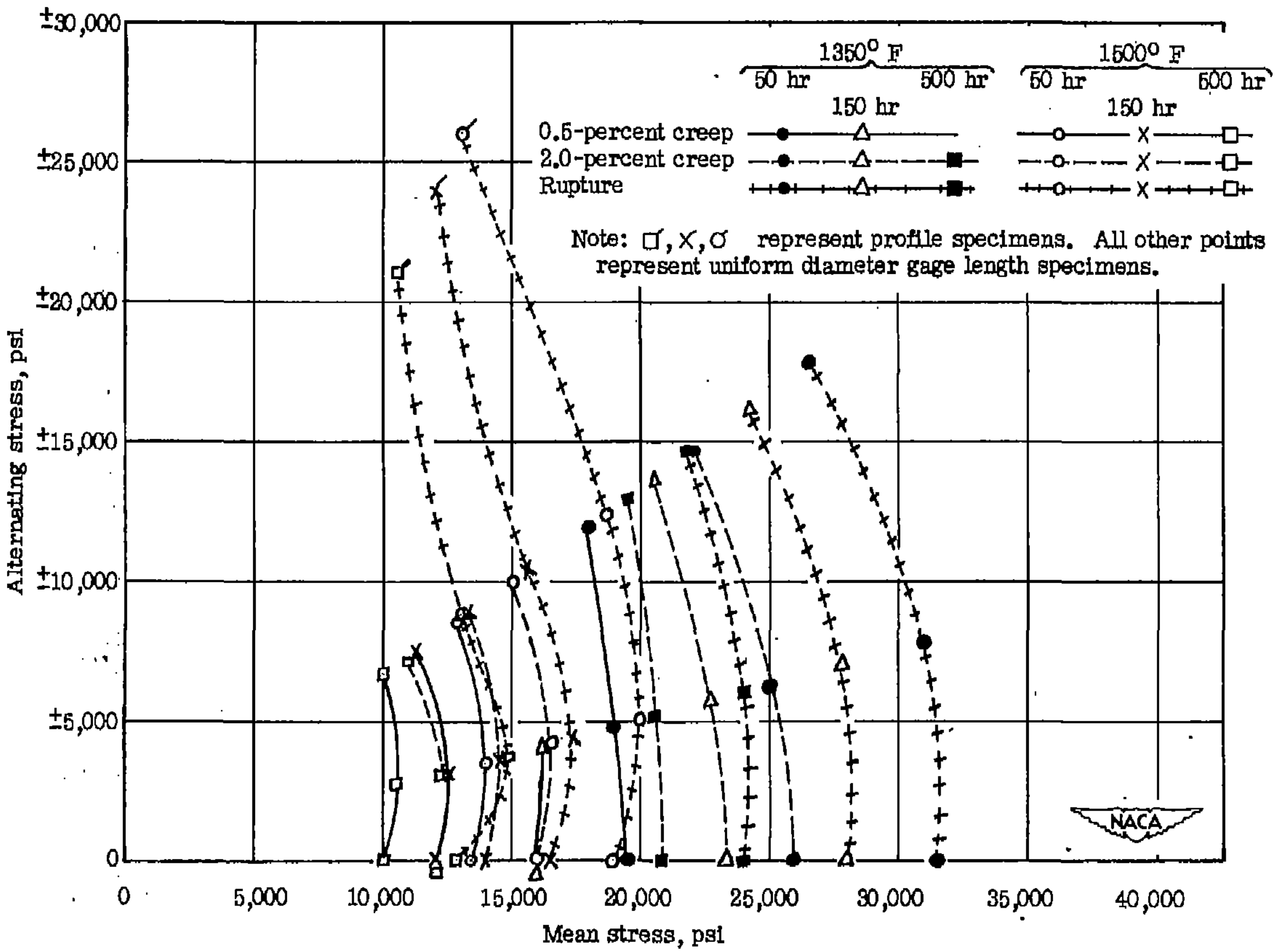


Figure 12.- Relationship between alternating and mean stresses for 0.5 percent creep, 2 percent creep, and fracture in 50, 150, and 500 hours at 1350° and 1500° F (Syracuse machine).

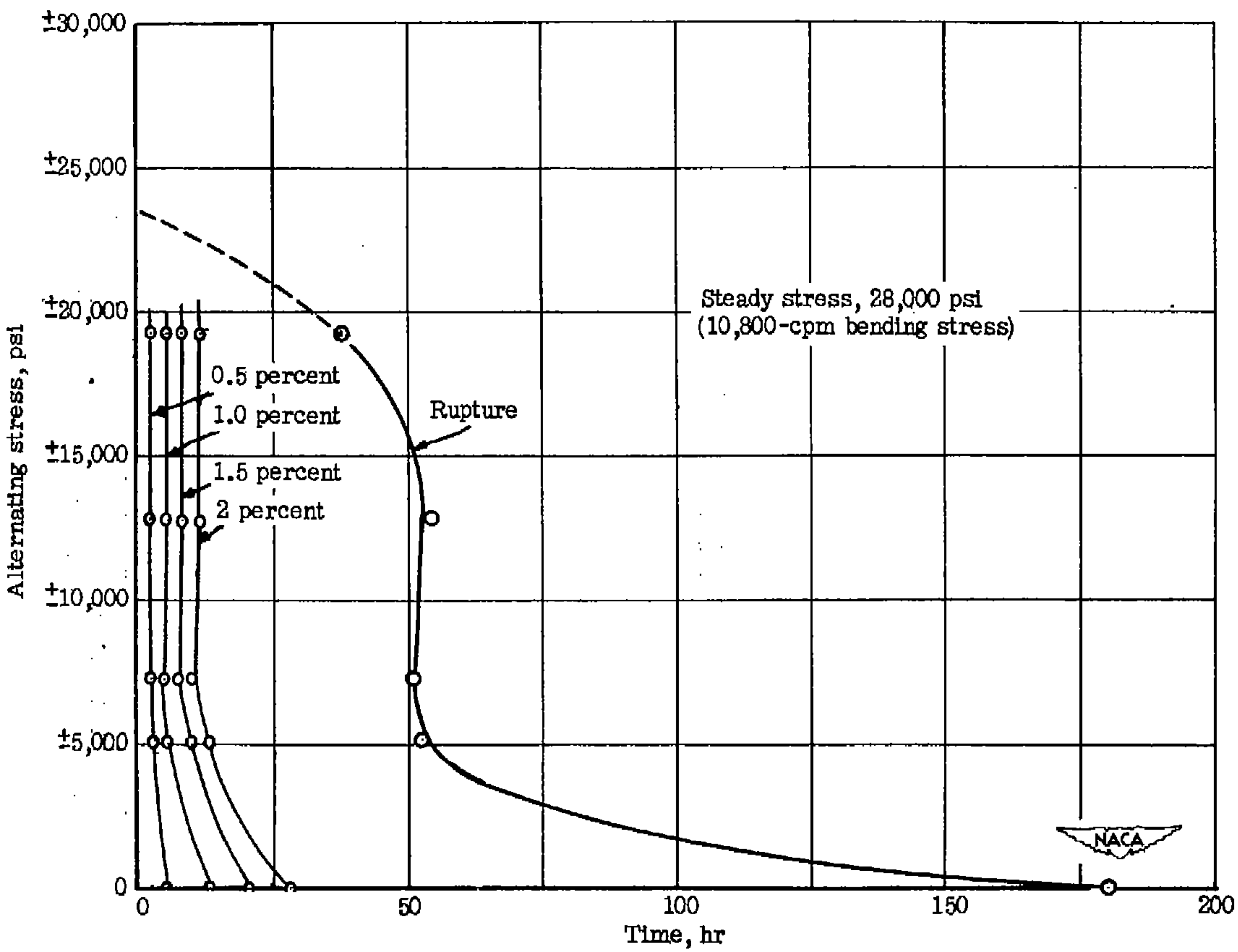


Figure 13.- Influence of alternating bending stress at 1350° F on time for 0.5-, 1.0-, 1.5-, and 2-percent total deformation and rupture time under a steady stress of 28,000 psi. (General Motors machine.)

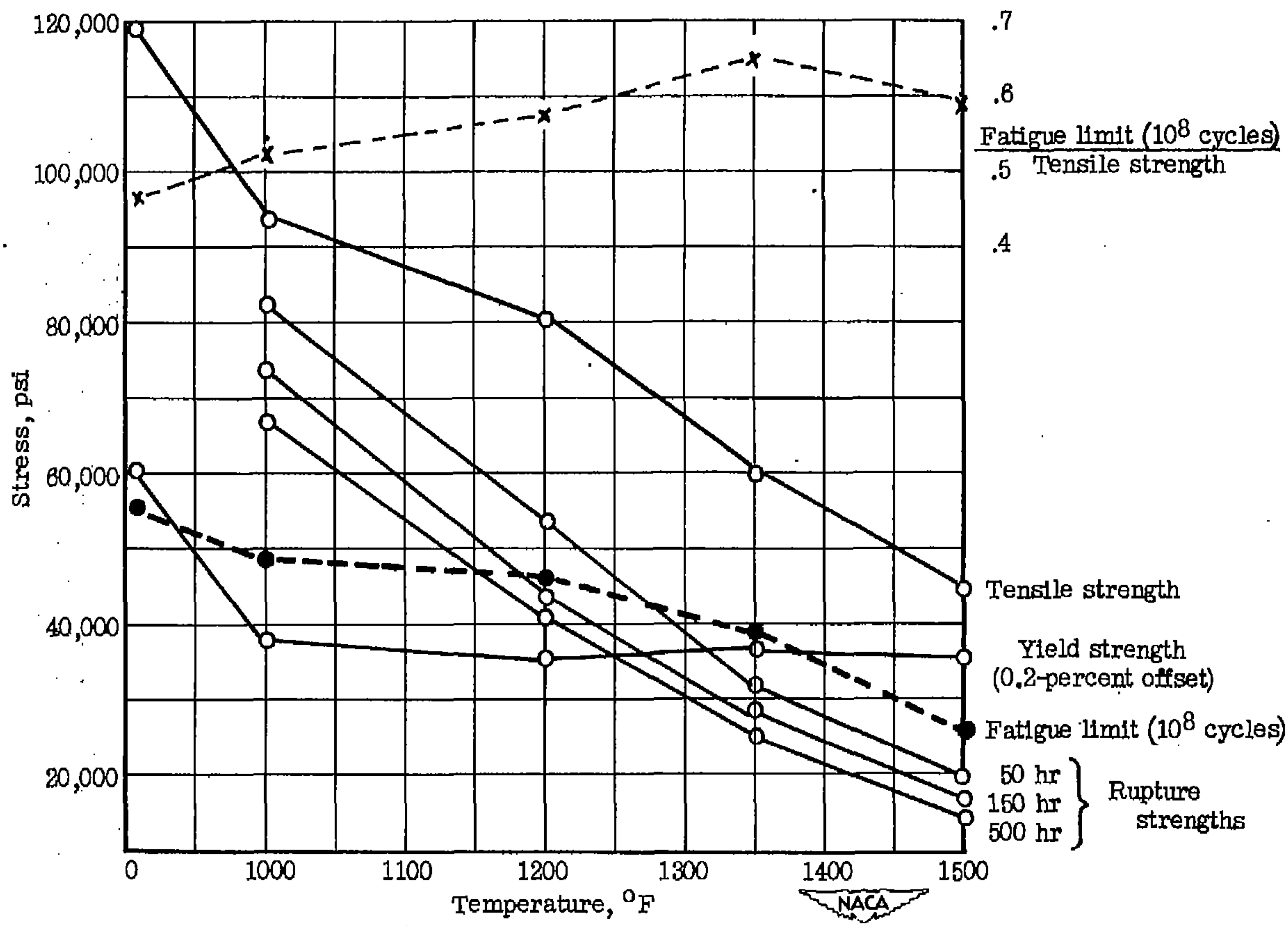


Figure 14.- Comparison of reversed bending fatigue limit values with static tensile and rupture strengths from room temperature, 1000°, 1200°, 1350°, and 1500° F tests.

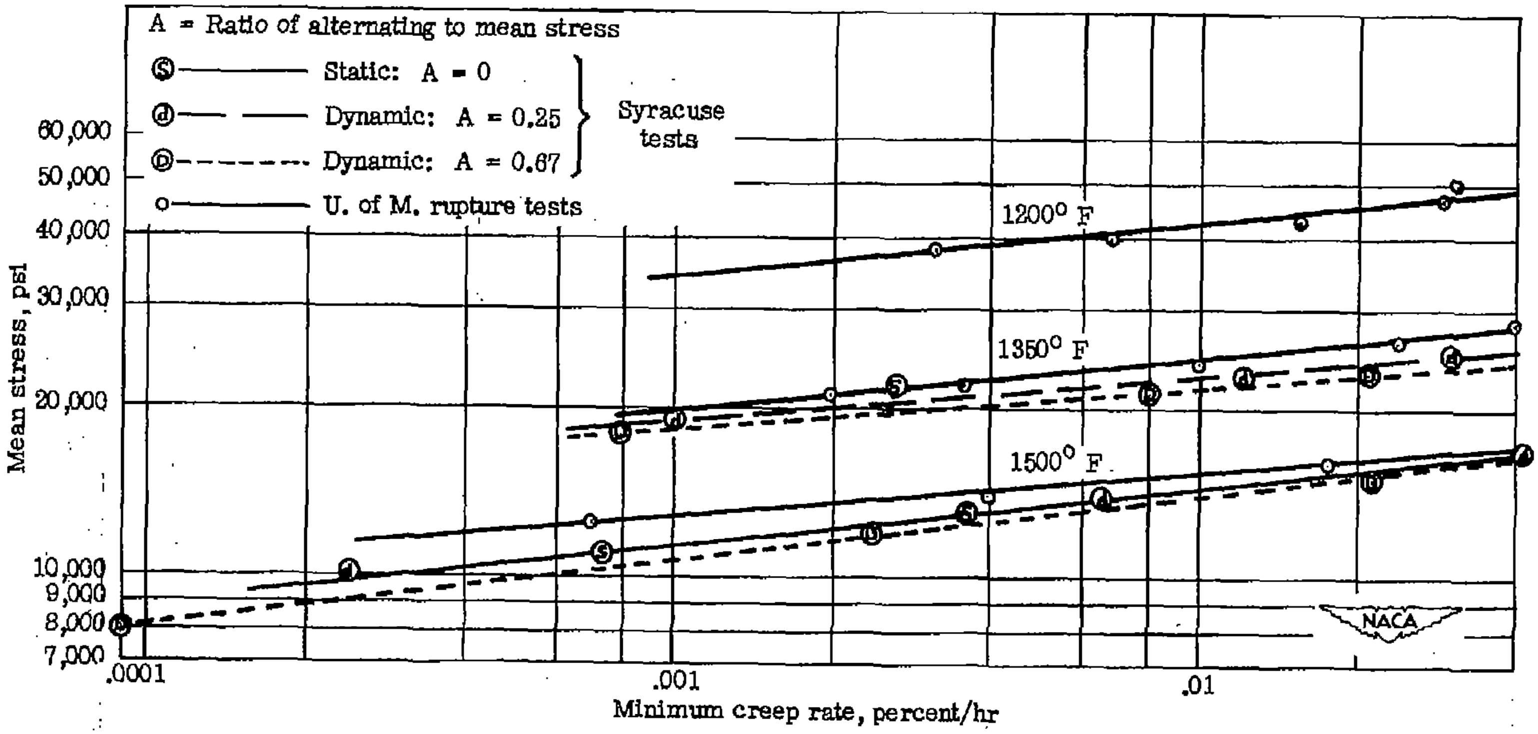


Figure 15.- Minimum creep rates for rupture and dynamic creep tests at 1200°, 1350°, and 1500° F.

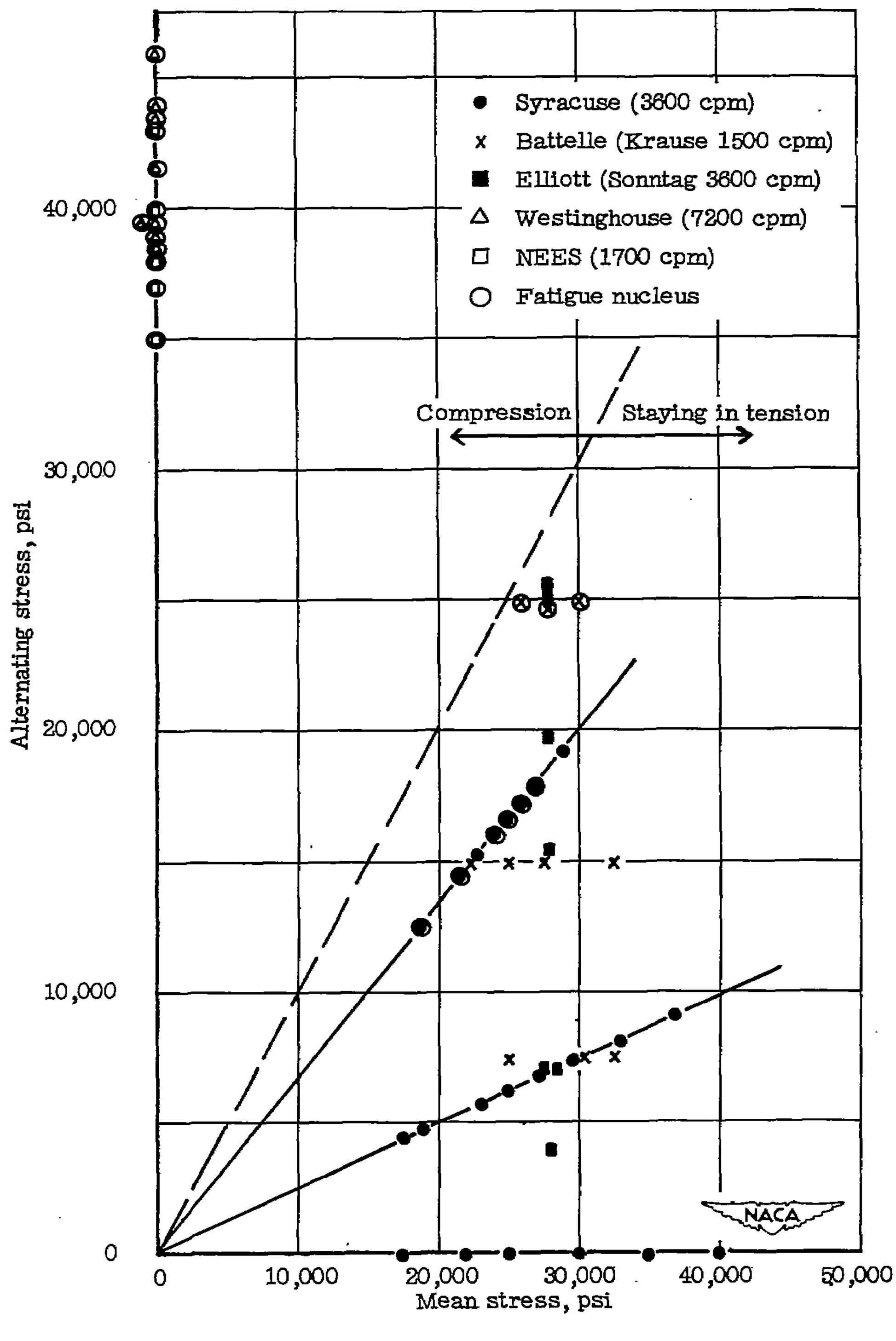


Figure 16.- Graphical representation relating appearance of fracture of low-carbon N-155 alloy bar stock with the type of loading at 1350° F.

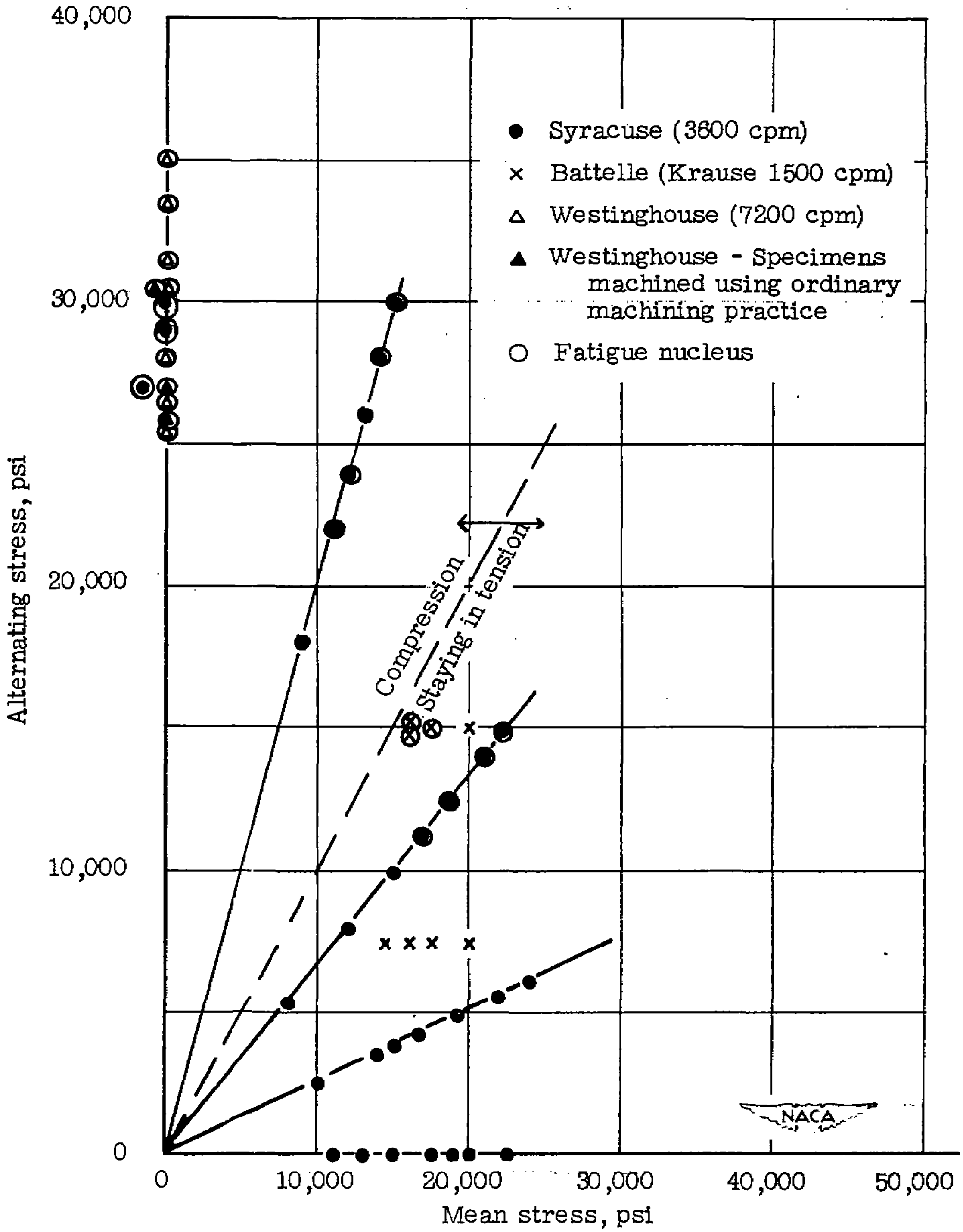
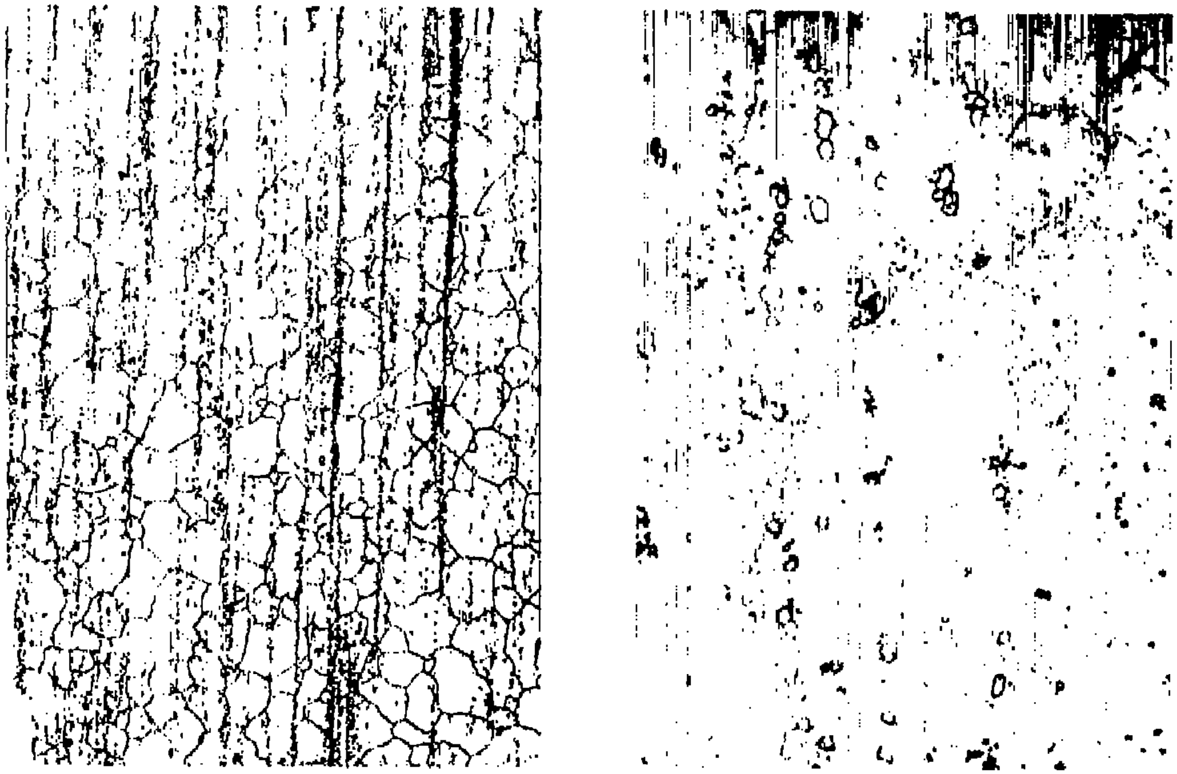
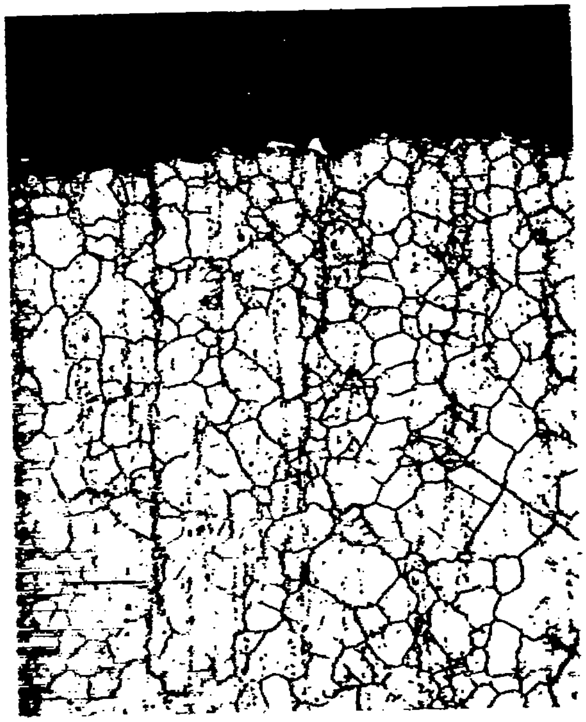


Figure 17.- Relationship between stress conditions and appearance of fatigue nucleus in tests at 1500° F.



X100 X1000

Figure 18.- Original microstructure of low-carbon N-155 alloy bar stock. Electrolytically etched in 10 percent chromic acid.



X100

Figure 19.- Typical microstructure of a fatigue fracture at fatigue nucleus. (Fractured in 369 hr at 1350° F under an alternating stress of ±40,000 psi.) Electrolytically etched in 10 percent chromic acid.

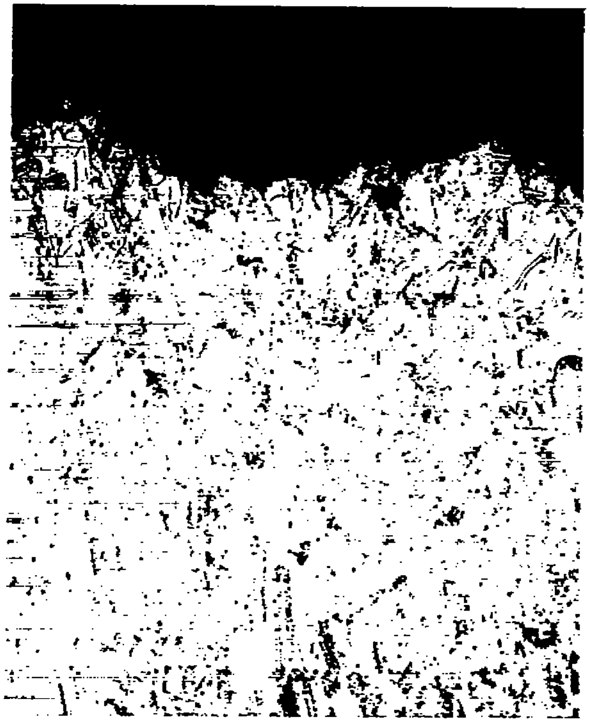


Figure 20.- Typical microstructure of a rupture fracture. (Fractured in 248 hr at 1350° F under a stress of 28,000 psi.) Electrolytically etched in 10 percent chromic acid.