1126

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1126

STRESS RUPTURE OF HEAT-RESISTING ALLOYS AS A RATE PROCESS

By E. S. Machlin and A. S. Nowick

Aircraft Engine Research Laboratory
Cleveland, Ohio

Washington
September 1946

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1126

STRESS RUPTURE OF HEAT-RESISTING ALLOYS AS A RATE PROCESS

By E. S. Machlin and A. S. Nowick

SUMMARY

The equations of the theory of rate processes are applied to stress rupture and predict the experimental stress and temperature dependence of the time for rupture for three heat-resisting alloys. It is concluded that, although this successful prediction for three alloys did not conclusively prove that stress rupture was a rate process, it did provide a basis for recommending that the rate-process stress-rupture equations obtained should be used to interpolate and extrapolate data for different temperatures and to reduce the number of stress-rupture tests.

It is indicated that stress may have an effect on the crystal structure by causing a phase change. Also it appears that the same rate-process mechanism is responsible for both transcrystalline and intercrystalline failure and that a correlation may exist between stress rupture and creep.

The recommendation is made that the method of presenting stress-rupture data on a semilog plot (logarithm of rupture time against stress), which has a basis in theory, be investigated for use in place of the present empirical method of presenting stress-rupture data on log-log plots of time for rupture against stress.

INTRODUCTION

One of the main criteria used to rate the heat-resisting properties of alloys is stress rupture (reference 1). During a stress-rupture test a tensile specimen is held under a constant load at a constant temperature until the specimen fractures. The chief measurement made during this test is the time required for rupture at the specific test stress and temperature. It was empirically found from a series of stress-rupture tests at a constant temperature that when the logarithm of the time for rupture is plotted against the logarithm of stress, a straight line is obtained within experimental error (references 2 and 3). This method of showing stress-rupture data has been adopted by many investigators and is presently used in the reports of the NRC-8 project (reference 1) and the NACA (reference 4). By interpolation and extrapolation from these plots, values of the stresses required to rupture the specimens (the rupture strengths) in 10, 100, and 1000 hours are obtained for specific temperatures. Alloys are then rated for a particular application on the basis of their rupture strengths at the rupture life that most nearly represents the application.

Inasmuch as stress rupture is an important criterion in rating heat-resisting alloys, it would be advantageous to know the quantitative dependence of the time for rupture on stress, temperature, composition, and structure. In order to obtain this information, an investigation was made at the NACA Cleveland laboratory during the spring of 1945 using the theory of rate processes. This theory was used because it has been found to apply to certain processes such as chemical reactions, viscous flow, and creep that occur at a definite rate for given conditions. It was thought that stress rupture was such a process. An equation was derived that gives, for a given composition and structure, the dependence of the time for rupture on stress and temperature. The investigation is part of a general program to provide information that will ultimately lead to the development of better alloys in order that the efficiency and power output of gas turbines used in aircraft propulsion can be increased.

The reader who is solely interested in the practical application of the fundamental equations, which give the dependence of the time for rupture on stress, temperature, composition and structure, may proceed directly to PRACTICAL APPLICATION OF STRESS-RUPTURE EQUATIONS.

SYMBOLS

The following symbols are used in the report:

c	proportionality constant
ΔF_a	free energy of activation per molecule
$\Delta F_a'$	apparent free energy of activation per molecule
h	Planck's constant, 6.62×10^{-27} erg seconds
ΔH_a	heat of activation per molecule

ΔH_{a0}	heat of activation per molecule at temperature of absolute zero
k	Boltzmann's constant, 1.38×10^{-16} ergs per molecule per °K
r	rate of reaction per unit concentration of reactants
r_f	rate of occurrence of the unit process
ΔS_a	entropy of activation per molecule
$\Delta S_a'$	apparent entropy of activation per molecule
t_r	time for rupture
T	absolute temperature
β	proportionality constant
σ	externally applied tensile stress
τ	shear stress

THEORY

The theory of rate processes will first be discussed as a general theory. It will then be shown that if stress rupture of heat-resisting alloys can be treated as a rate process, certain equations must be satisfied. Later sections will then show that these equations are satisfied.

General Theory of Rate Processes

The theory of rate processes (reference 5) developed by Eyring and others has been applied to chemical reactions as well as other processes such as viscosity of liquids and diffusion. In every case to which rate-process theory can be applied, there is a small subdivision such that the macroscopic process is the net effect of all the small processes. This smallest subdivision is called the unit process. For example, in a chemical reaction the unit process is the reaction between the atoms reacting in numbers given by the stoichiometric chemical equation. Rate-process theory can be applied to any process provided that the corresponding unit process involves a molecule or group of molecules that, in passing from the initial to the final state, must first attain a certain minimum thermal energy. This energy is often considerably greater than the ordinary thermal energy of molecules; therefore the molecule or group of molecules participating in the unit process is said to be "activated" or to have formed an "activated complex" when the minimum energy is attained. The unit process is best illustrated by the potential-energy curve for the reaction, illustrated in figure 1. The height of the barrier, which is the minimum energy required for passage into the final state, is called the heat of activation ΔH_a. This energy bears no relation to the heat of the reaction ΔH, the energy difference between the initial and final states also shown. By the "reaction coordinate" is meant the most favorable reaction path on the polydimensional potential-energy surface.

The basic assumption of rate-process theory is that the initial reactants and activated complexes are always in equilibrium. Statistical mechanical considerations then give (reference 5) for the rate of the process (number of unit process taking place/unit time) the equation

$$r = (kT/h)\, e^{-\Delta F_a/kT} \tag{1}$$

The term kT/h can be regarded as the effective frequency at which activated complexes cross over the barrier. In the calculation of ΔF_a, the contribution due to the translational degree of freedom along the reaction coordinate has been disregarded because it is included in the factor kT/h. The factor ΔF_a is interpreted as an ordinary free-energy term and can be expressed as

$$\Delta F_a = \Delta H_a - T\Delta S_a \tag{2}$$

The entropy of activation has the usual physical significance. It is related to the relative probability of the initial and activated states excluding the energy difference or what may be called the relative freedoms of the two states. A negative value of ΔS_a means therefore that the activated state involves greater restrictions on the degrees of freedom of the molecules than the initial state in addition to the energy difference between the two states.

A process will be termed a "rate process" if equations (1) and (2) can be applied to it; that is, if the unit process can be treated as involving the passing of activated complexes over a potential-energy barrier.

Stress-Dependent Rate Processes

In some rate processes the height of the potential-energy barrier is a function of the applied shear stress. The unit processes in these cases may generally take place in either of two opposite directions involving the same energy barrier as shown by the solid curve of figure 2, thus the net rate is zero. If the shear stress τ is applied, it may lower the barrier in one direction and raise it in the opposite direction as shown by the dashed curve (fig. 2). The activation energies for the two directions are no longer equal and the process takes place with a definite net rate. The direction to the right in figure 2 is designated positive.

Examples of such a process are the flow of viscous liquids (reference 5) where the unit process is the jump of one molecule past another and the creep of metals (reference 6) where the generation of a dislocation is the unit process. In both these processes, the energy by which the barrier is lowered in the positive and raised in the negative direction was shown to be approximately proportional to the shear stress. The heat of activation for the stress-dependent process in the positive direction (the height of the barrier in the positive direction) is therefore $\Delta H_a - \beta\tau$ and in the negative direction $\Delta H_a + \beta\tau$. The free energy of activation in the positive direction is $\Delta H_a - \beta\tau - T\Delta S_a$ and in the negative direction $\Delta H_a + \beta\tau - T\Delta S_a$. Inasmuch as $\Delta F_a = \Delta H_a - T\Delta S_a$ the rate of occurrence of unit processes in the positive direction is therefore

$$r^{+} = (kT/h)\ e^{-(\Delta F_a - \beta\tau)/kT}$$

and in the negative direction

$$r^{-} = (kT/h)\ e^{-(\Delta F_a + \beta\tau)/kT}$$

The net rate in the positive direction is therefore

$$r' = r^{+} - r^{-} = (2kT/h)\ e^{-\Delta F_a/kT} \sinh\ (\beta\tau/kT) \qquad (3)$$

The factor β is, in general, a function of temperature.

Application of Rate-Process Theory to Stress Rupture

The supposition is made that stress rupture of heat-resisting alloys is a rate process in the sense of the definition presented in this report. When the unit process is considered in an abstract sense, it is possible to determine only the temperature and stress dependence of the rate r. A definite physical unit process such as the generation of a dislocation (reference 6) would enable the prediction of the dependence of the rate r on the physical structure and properties of materials. This report, however, considers the unit process only in the abstract sense and therefore the contribution that will be expected is a knowledge of the temperature and stress dependence of the time for rupture for a constant composition and structure.

If stress rupture is a rate process, the time for rupture t_r is to be expected to be inversely proportional to a rate r_f or

$$t_r = c/r_f \tag{4}$$

The unit process is expected to be stress dependent. If the effect of stress is similar to other stress-dependent rate processes, that is, if the amount by which the barrier is lowered or raised by shear stress is approximately proportional to the shear stress, then r_f would be given by equation (3). If, as in the theory of creep (reference 6), the grains are taken to be oriented such that the unit process occurs under maximum shear stress, where $\tau = \sigma/2$, this equation becomes in logarithmic form

$$\log_e r_f = \log_e (2kT/h) - (\Delta F_a/kT) + \log_e \sinh (\beta\sigma/2kT) \tag{5}$$

The factor β may include a stress concentration factor if the unit process takes place at stress raisers.

Inasmuch as $\sinh x = \frac{e^x - e^{-x}}{2}$, when x becomes large, e^{-x} rapidly approaches zero and $\sinh x$ then is given to a good approximation by $\frac{1}{2} e^x$. Thus for sufficiently high values of applied stress

$$\sinh (\beta\sigma/2kT) = \frac{1}{2} e^{\beta\sigma/2kT} \tag{6}$$

If equation (6) is substituted in equation (5) and combined with equation (4), the resulting equation for the time for rupture is

$$\log_e t_r = \log_e (h/kT) + (\Delta F_a'/kT) - (\beta\sigma/2kT) \tag{7}$$

where

$$\Delta F_a' = \Delta F_a - CT = \Delta H_a - T\,(\Delta S_a + C) \tag{8}$$

$$C \equiv -k \log_e c$$

The term $\Delta S_a + C$ is therefore the apparent entropy of activation.

For the purpose of checking the validity of equation (7), common logarithms are most convenient. Equation (7) can be written

$$\log t_r = \log (h/kT) + (\Delta F_a'/2.3kT) - (\beta\sigma/4.6kT) \tag{9}$$

A plot of $\log t_r$ against σ for a fixed temperature should then be a straight line of negative slope $\beta/4.6kT$ and intercept

$$\log t_i = \log (h/kT) + (\Delta F_a'/2.3kT) \tag{10}$$

From equation (10), $\Delta F_a'$ can be obtained for each temperature. The heat of activation per molecule ΔH_a is usually either constant or expressible to a good approximation as a linear function of T according to

$$\Delta H_a = \Delta H_{a0} + \Delta H_a' T \tag{11}$$

Thus a linear plot of $\Delta F_a'$ against T should be a straight line

$$\Delta F_a' = \Delta H_{a0} - T\Delta S_a' \tag{12}$$

where $\Delta S_a'$ is given by

$$\Delta S_a' = \Delta S_a - \Delta H_a' + C \tag{13}$$

If stress rupture is given by equation (9), practical use of this equation for design can be made by letting $\log (h/kT)$ equal a constant. The approximation that $\log T$ is constant relative to the term in T will involve no detectable error over a large range of temperature. This approximation was made for the equation given in the section entitled "PRACTICAL APPLICATION OF STRESS-RUPTURE EQUATIONS."

SOURCES AND PRECISION OF DATA

Stress-rupture data were obtained from reference 4, from the Allegheny Ludlum Steel Corporation, and from the University of Michigan for three different alloys: S816 cast, S816 forged, and low carbon N155 hot worked. These alloys were chosen because enough stress-rupture data were available for them in the literature at different temperatures and stresses.

An examination of the data, in general, showed that a particular rupture life might vary by as much as 100 percent. Approximate experimental errors for the factors β, ΔH_{a0}, and $\Delta S_a'$ are ±30 percent, $\pm 5 \times 10^{-13}$ ergs, and $\pm 5 \times 10^{-16}$ ergs per °K, respectively, but the errors in ΔH_{a0} and $\Delta S_a'$ will generally be in opposite directions and therefore tend to compensate. Reference 7 gives an approximate value of the reproducibility of stress-rupture data obtained from duplicate tests on specimens from the same heat. This value is ±25 percent for two-thirds of the tests conducted. For one-third of the tests the variation was much larger than ±25 percent

RESULTS AND DISCUSSION

Stress Dependence of $\log t_r$

Equation (9) states that at constant temperature a plot of $\log t_r$ against stress at high stresses will yield a straight line having the negative slope $\beta/4.6kT$. An examination of the primary data for S816 cast, S816 forged, and low carbon N155 hot worked showed that the plots of $\log t_r$ against stress for these alloys were straight lines whose slopes varied with the temperature. (See figs. 3, 4, and 5.) The literature, however, shows straight-line plots of $\log t_r$ against $\log \sigma$ for these same alloys. Inasmuch as both plots are not mathematically consistent, only one plot is correct. It will be shown that stress rupture is a rate process and therefore the semilog plot should be used. The magnitude of the experimental error explains why both plots can be simultaneously obtained. Previous investigators have also noticed that straight-line plots could be obtained by plotting $\log t_r$ against σ (discussion of reference 3). Inasmuch as no basis for choosing between the plots had been available, stress-rupture data were standardized on plots of $\log t_r$ against $\log \sigma$.

The change in slope that occurs because of oxidation on the log-log plots of rupture time against stress (reference 3) also occurs on the semilog plot at approximately the same rupture time and stress. At the same temperature, transcrystalline-type failures will occur at higher stresses than intercrystalline-type failures. No correlation exists, however, between the change in slope and the transition between transcrystalline and intercrystalline regions of failure. A number of the lines shown in figures 3 and 4 show changes in slope that cannot be explained by either intercrystalline oxidation or the hyperbolic sine dependence of stress. The change in slope is opposite in sign to that expected for intercrystalline oxidation and also is much sharper than that expected for a hyperbolic sine dependence of stress. It is believed that the change in slope is due to a change of structure as a result of the effect of stress. Reference 8, for example, has shown that stress at high temperatures can induce an age-hardening reaction.

Temperature Dependence of Slope Factor β

In reference 6 it was empirically found that the temperature dependence of the β factor for creep could be described by the following relation:

$$\beta = Pe^{QT}$$

The data for stress rupture were investigated to show whether a similar relation existed for stress rupture. A plot of $\log \beta$ against T, which gives straight lines within experimental error for the three alloys studied, is shown in figure 6. The β values of figure 6 are of the same order of magnitude as those obtained for creep of iron (reference 6).

Temperature Dependence of Apparent Free Energy of Activation $\Delta F_a'$

Equation (12) predicts that the quantity $\Delta F_a'$, the apparent free energy of activation, will be linearly dependent on temperature.

Values of $\Delta F_a'$ were computed from data substituted in equation (10) and were plotted against temperature for S816 cast, S816 forged, and low carbon N155 hot worked. The results are shown in figure 7, which substantiates the prediction made by the theory of rate processes that $\Delta F_a'$ would be linearly dependent on temperature.

Values of ΔH_{a0} and $\Delta S_a'$ for stress rupture, the intercepts and slopes, respectively, of the lines in figure 7, are given in the following table. The values of similar parameters for creep obtained from reference 6 are given for comparison. The parameters ΔH_{a0} and $\Delta S_a'$ for the creep process are approximately the energy of activation and the entropy of activation, respectively, involved in the generation of a dislocation and are A and B, respectively, in the notation of reference 6.

Type of test	Material (a)	ΔH_{a0} (ergs)	$\Delta S_a'$ (ergs/°K)
Stress rupture	S816 cast	1.71×10^{-12}	5.7×10^{-15}
Stress rupture	S816 forged	2.98	4.2
Stress rupture	N155 low carbon hot worked	4.19	2.75
Creep	Iron	2.10	4.0
Creep	Nickel	2.67	4.0

[a] No creep data were available for cobalt but the values of its constants would be expected to approximate closely those for iron and nickel.

The table shows that ΔH_{a0} and $\Delta S_a'$ are of the same order of magnitude for the stress-rupture rate process as for the creep rate process, respectively. It therefore appears that the entropy of activation ΔS_a for the stress-rupture rate process is probably a large negative value of the same order of magnitude as the entropy of activation for the generation of a dislocation and that the parameter C is small compared with ΔS_a. (See equation (13).)

EVALUATION OF RESULTS

The theory of rate processes has predicted the temperature dependence of the time for rupture and this prediction has been substantiated by the data for three heat-resisting alloys. This successful prediction is the justification for applying the theory of rate processes to stress rupture. Because it is indicated that stress rupture is a rate process, plots of the log time for rupture against stress should be investigated for use in place of the log-log plots now used. Not only is the semilog plot based on theory but it is also the only plot from which data can be obtained to predict stress-rupture data at additional temperatures. An example of the accuracy with which data at different temperatures can be predicted is given in the section entitled "PRACTICAL APPLICATION OF STRESS-RUPTURE EQUATIONS."

The data have revealed that a given material may have three different sets of constants dependent on the stress and temperature to which the specimen is subjected. Two sets of these parameters hold for the unchanged material (stable structure) and for the material in the range of intercrystalline oxidation, respectively. The third set, which describes the region of highest stress, is best explained on the basis of a change induced in the original structure by shear stress. Whether this explanation is correct could be determined by means of an X-ray analysis of the crystal structures in two different regions having different sets of material parameters.

On a log-log plot of rupture time against stress, the line that represents the region of intercrystalline failure in the absence of oxidation is an extension of the line of the region of transcrystalline failure (reference 3). In the plot of log rupture time against stress for the same data, the line obtained is also unbroken. In terms of the theoretical equation (9), the $\Delta F_a'$ and β values for transcrystalline failure are exactly equal to the $\Delta F_a'$ and β values for intercrystalline failure in the absence of oxidation. It therefore appears that the rate-process mechanism responsible for the transcrystalline failure is the same rate-process mechanism responsible for the intercrystalline failure. This fact leads to the belief that a correlation may exist between creep and stress rupture. From reference 9 it can be implied that during the transcrystalline mode of failure, a relatively large amount of creep takes place. If transcrystalline failure finally results from a shearing of the individual grains, then creep may be the controlling factor. Further evidence of a correlation between creep and stress rupture was the agreement of the order of magnitudes and temperature dependence of similar terms in the equations for creep and stress rupture. Further tests, however, are necessary in order to prove whether such a correlation exists.

The practical application of the stress-rupture theory to engineering problems is extensively described in the next section. On the basis of the theory given in this report, the present engineering method of presenting stress-rupture data should be revised to prevent inaccurate application of the results to the design of parts for high-temperature use and to facilitate the method of rating the stress-rupture resistance of heat-resisting alloys.

PRACTICAL APPLICATION OF STRESS-RUPTURE EQUATIONS

The equation

$$\log t_r = \frac{A + BT - D\sigma}{T} \qquad (14)$$

where

t_r time for rupture, hours

T absolute temperature, $^{\circ}R$

σ applied tensile stress, pounds per square inch

A, B constants of structure and composition

and

$$\log D = E + FT \qquad (15)$$

where

E, F constants of structure and composition

was derived in the theory section of this report from the theory of rate processes as developed by Eyring and others (reference 5). Equation (15) was found empirically. The predictions of equation (14), especially in regard to the temperature dependence of stress rupture, were investigated and verified for a number of heat-resisting alloys. Equation (14) is therefore valid and could be used to obtain the dependence of time for rupture on stress and temperature for a given structure and composition.

In order to obtain an evaluation of the constants A, B, E, and F, it is necessary to determine at each of three or four temperatures the time for rupture for at least four different stresses. The constants E and F are evaluated by plotting $\log t_r$ against σ at a constant temperature. The slope of the straight line obtained is equal to $-\frac{D}{T}$. When values of $\log D$ so obtained are plotted against temperature, a straight line is obtained. The slope of the straight line is equal to F and the intercept (at $T = 0$) is equal to E.

The constants A and B are evaluated by obtaining values of the intercept ($\sigma = 0$) of the plot of $\log t_r$ against stress. From equation (14) this intercept, $\log t_i$, will satisfy the relation

$$T \log t_i = A + BT \qquad (16)$$

When values of $T \log t_i$ are plotted against T, a straight line is obtained. The slope of this line is equal to B and the intercept ($T = 0$) is equal to A.

It should be understood that the parameters A, B, E, and F will be constant only for a given composition and structure and in the absence of intercrystalline oxidation. If a heat-resisting alloy should have different structures, as is sometimes the case, then the values of the parameters for one structure would not apply to predicting stress-rupture data for the other structure. For example, the break in the stress-rupture curve at 1350° F in figure 4 indicates that the structure in the high-stress range differs from that in the low-stress range because the values of the structure parameters A, B, E, and F for both ranges are not the same. In the event that intercrystalline oxidation takes place, the set of parameters will no longer be valid. These limitations, however, are not severe for the data presented in this report.

In order to illustrate the use of the equations in predicting data, the primary data for forged S816 given in figure 4 for 1350, 1500, 1600, and 1700° F will be used to compute values of A, B, E, and F. Then these values will be used to obtain a stress-rupture curve for 1800° F, which will then be compared to the experimental stress-rupture curve for 1800° F.

The absolute slope of the 1350° F stress-rupture curve is

$$\frac{D}{T} = \frac{\log t_{r1} - \log t_{r2}}{\sigma_1 - \sigma_2} = \frac{3.00 - 2.00}{30,000 - 41,200} = 0.0000900$$

which then gives

$$D_{1350} = T \times 0.0000900 = 1810 \times 0.0000900 = 0.163$$

Similarly,

$$D_{1500} = 0.264$$

$$D_{1600} = .350$$

$$D_{1700} = .435$$

The plot of log D against T is given in figure 8. The slope of the straight line in figure 8 is

$$F = \frac{\log 0.381 - \log 0.169}{2100 - 1810} = 1.218 \times 10^{-3}$$

The intercept of this straight line is

$$E = \log 0.381 - 1.218 \times 10^{-3} \times 2100 = -2.977$$

Equation (15) then gives for D at 1800° F

$$\log D = E + FT = -2.977 + 1.218 \times 2260 \times 10^{-3} = -0.220$$

$$D = 0.600$$

The intercept of the 1350° F stress-rupture curve in figure 4 is

$$\log t_i = \log t_r + \frac{D}{T}\sigma = \log 1000 + \frac{0.163}{1810} \times 30,000$$

$$\log t_i = 5.70$$

Then

$$T \log t_i = 10,300$$

Similarly,

$$T \log t_i \ (1500) = 10,580$$

$$(1600) = 9320$$

$$(1700) = 8650$$

The plot of $T \log t_i$ against T is given in figure 9. The slope of the straight line obtained is

$$B = \frac{10,420 - 9030}{1900 - 2100} = -6.950$$

The intercept is

$$A = 10,420 - (-6.95 \times 1900) = 23,630$$

Equation (14) was used, with the value of D at 1800° F and the values of A and B just determined, to obtain the stress-rupture curve for 1800° F that is shown plotted in figure 4 as a dotted line. The experimental points are given by the symbol o and give a measure of the accuracy that can be obtained using equations (14) and (15) to predict stress-rupture data. It should be noted that the predicted values fall within the reproducibility of ±25 percent found by reference 7. This reproducibility figure was obtained from a duplicate series of stress-rupture tests of specimens taken from the same heat.

The number of stress-rupture tests that are required at present can be materially reduced by using the method just described to predict data at new temperatures. Specifically, if it is desired to extend the stress-rupture data to higher temperatures, it is necessary according to present methods to obtain values of t_r for at least four different stresses at the higher temperature in order to be able to plot a curve of $\log t_r$ against $\log \sigma$. If values of A, B, E, and F were computed for this alloy from the available data, then only one test at the higher temperature would be required to check whether the alloy structure was stable at this higher temperature. If the alloy structure was found to be stable, that is, the experimental value of t_r at the higher temperature checked within experimental error with the value predicted by equations (14) and (15), then the equations could be used for predicting the stress dependence of the rupture time at this higher temperature. Thus, about three-fourths of the additional stress-rupture tests would be eliminated.

The metallurgist who performs stress-rupture tests in order to rate the heat-resisting properties of alloys can now make use of the four parameters A, B, E, and F as a means of rating the alloys. In order to have long rupture lives (high t_r) at constant stress and temperature, it is necessary that A and B be large and E and F small. (See equations (14) and (15).) When A and B are larger and E and F are smaller simultaneously for one alloy than for another, the first alloy will have longer rupture life over the range of stress and temperature where the values of A, B, E, and F apply. Where the four parameters do not compare in this simple fashion, the stress-rupture ratings of various alloys will generally not be the same for different ranges of stress and temperature. These alloys can therefore be rated only with respect to their proposed use. For example, alloys for gas-turbine buckets can be rated on the basis of the design temperature and stress. Values of the structure parameters can then be used to obtain easily an order of merit rating at the set of conditions that correspond to the proposed use.

RECOMMENDATION

It is recommended that the method of presenting stress-rupture data on a semilog plot (logarithm of rupture time against stress), which has a basis in theory, be investigated for use in place of the present empirical method of presenting stress-rupture data on log-log plots of time for rupture against stress. In addition, the use of the stress-rupture equations presented in this report are recommended to permit temperature interpolation and extrapolation and to reduce the number of stress-rupture tests required.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 8, 1946.

REFERENCES

1. Cross, Howard C., and Simmons, Ward F.: Progress Report on Heat-Resisting Metals for Gas-Turbine Parts (N-102). OSRD No. 4717, Ser. No. M-477, NDRC, OSRD, War Metallurgy Committee, Feb. 20, 1945.

2. White, A. E., Clark, C. L., and Wilson, R. L.: The Rupture Strength of Steels at Elevated Temperatures. Am. Soc. Metals Trans., vol. 26, March 1938, pp. 52-69; discussion, pp. 69-80.

3. White, A. E., Clark, C. L., and Wilson, R. L.: The Fracture of Carbon Steels at Elevated Temperatures. Am. Soc. Metals. Trans., vol. 25, Sept., 1937, pp. 863-884; discussion, pp. 885-888.

4. 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.

5. Glasstone, Samuel, Laidler, Keith J., and Eyring, Henry: The Theory of Rate Processes. Chs. I, IV, VII. McGraw-Hill Book Co., Inc., 1941, pp. 1-27, 153-201, 477-551.

6. Nowick, A. S., and Machlin, E. S.: Quantitative Treatment of the Creep of Metals by Dislocation and Rate-Process Theories. NACA TN No. 1039, 1946.

7. Anon.: Statistical Analysis of Effect of Chemical Composition on Stress-Rupture Properties of a Group of Alloys Tested at M.I.T. AMP Rep. 122.1R, SRG Rep. 485, Columbia Univ., Statistical Res. Group, Appl. Math. Panel, NDRC, May 1945.

8. Harrington, R. H.: The Role of Strain in Precipitation Reactions in Alloys. Age Hardening of Metals, Symposium on Precipitation Hardening, Twenty-First Annual Convention, Am. Soc. Metals (Chicago), Oct. 23-27, 1939, pp. 314-340; discussion, p. 341.

9. Thielemann, R. H., and Parker, E. R.: Fracture of Steels at Elevated Temperatures after Prolonged Loading. Tech. Pub. 1034, Trans. Am. Inst. Mining and Metallurgical Eng., Iron and Steel Div., vol. 135, 1939, pp. 559-575; discussion, pp. 576-582.

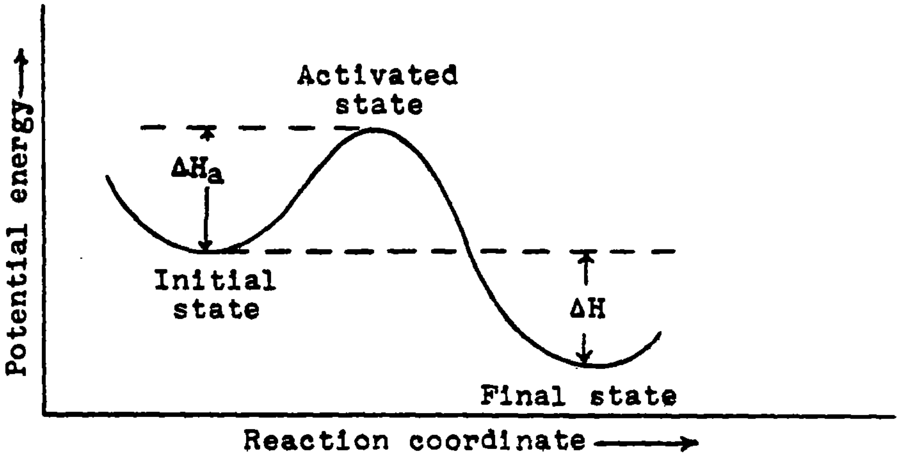

Figure 1. - Schematic representation of potential barrier.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

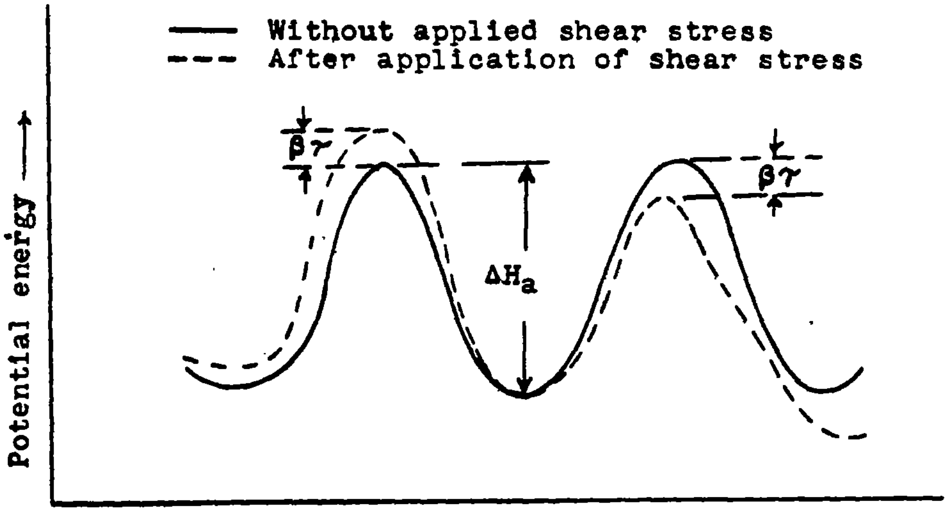

Figure 2. - Potential barrier for stress-dependent rate process.

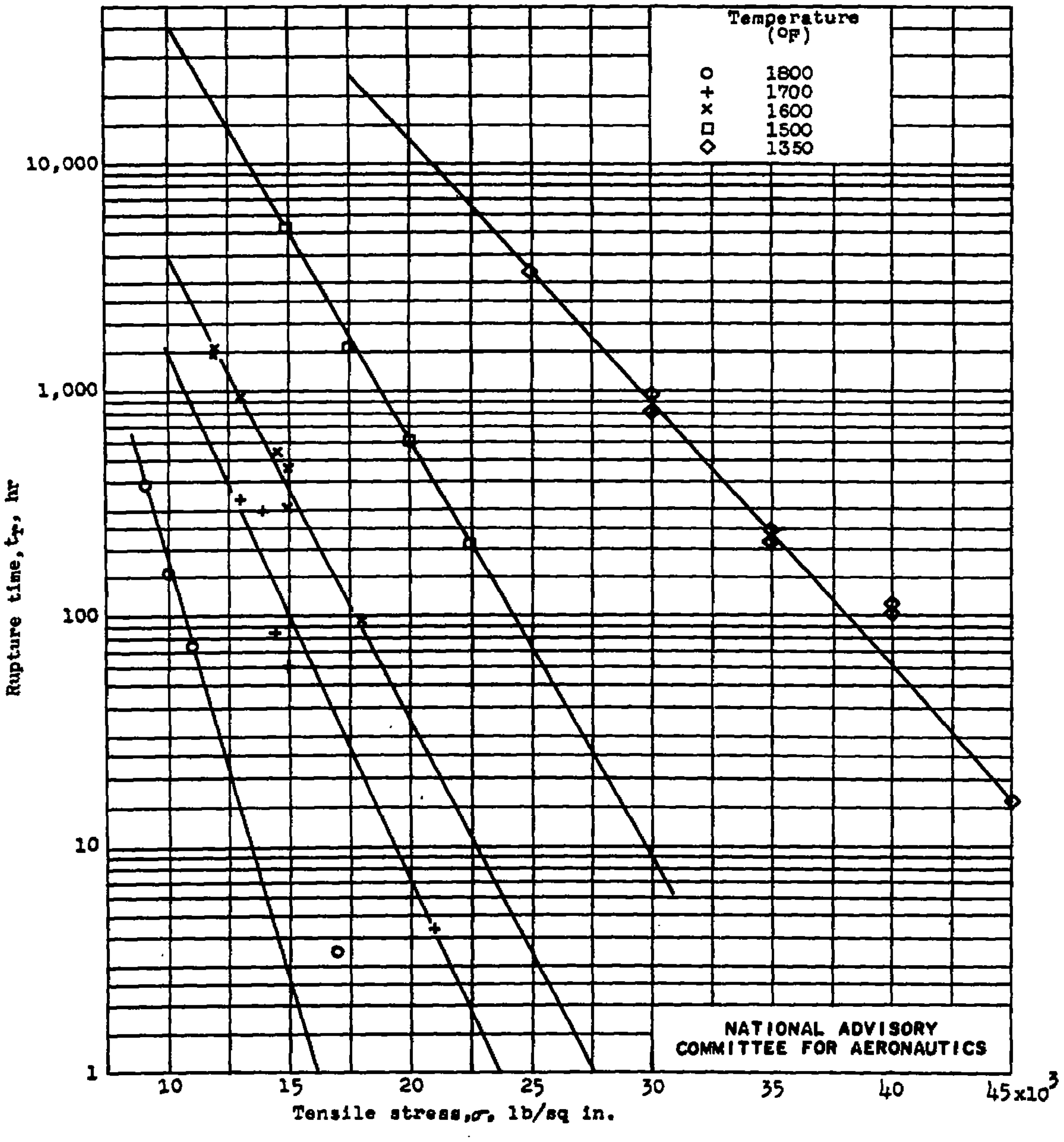

Figure 3. - Variation of rupture time with tensile stress σ for cast S816.

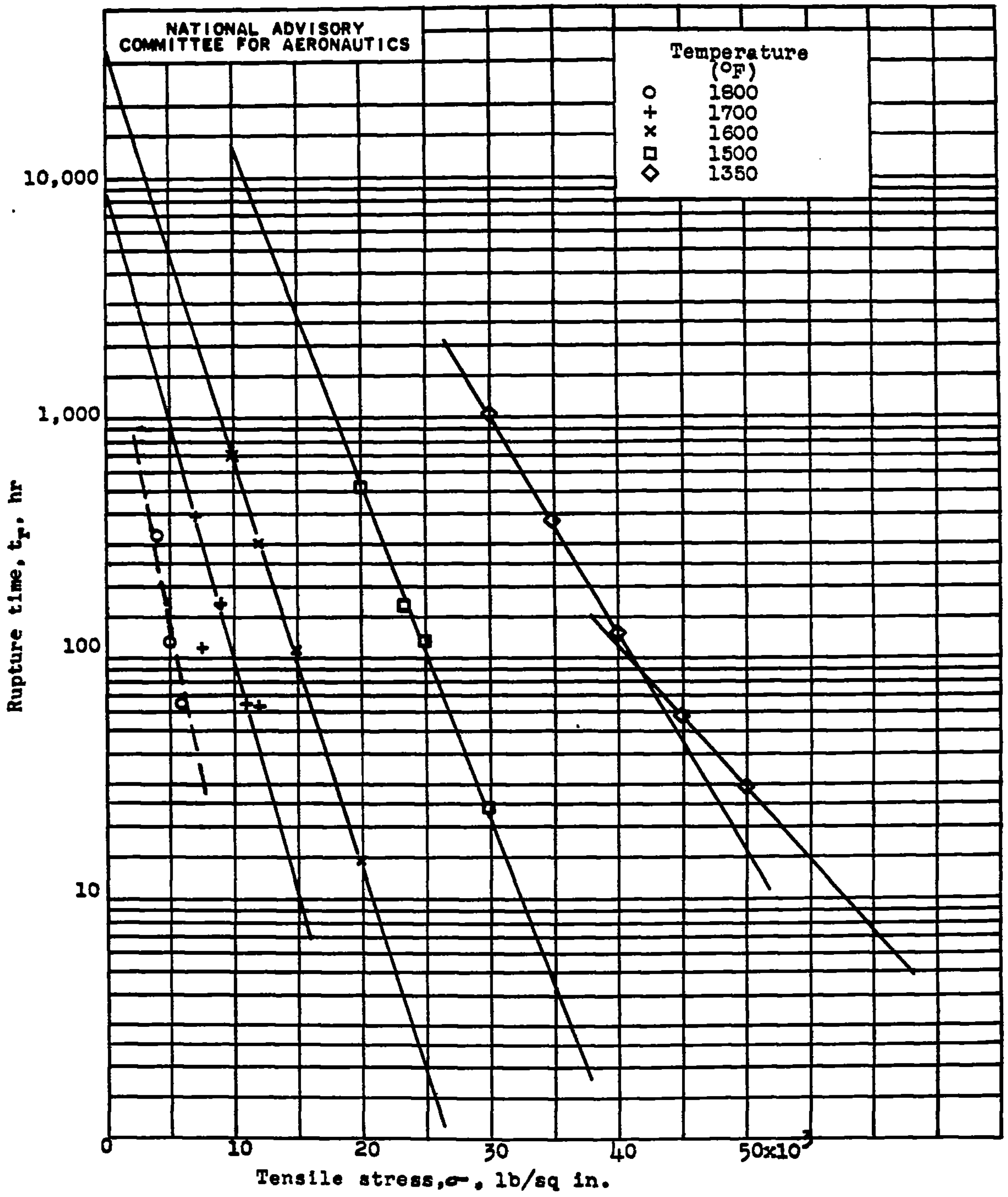

Figure 4. - Variation of rupture time with tensile stress σ for forged S816.

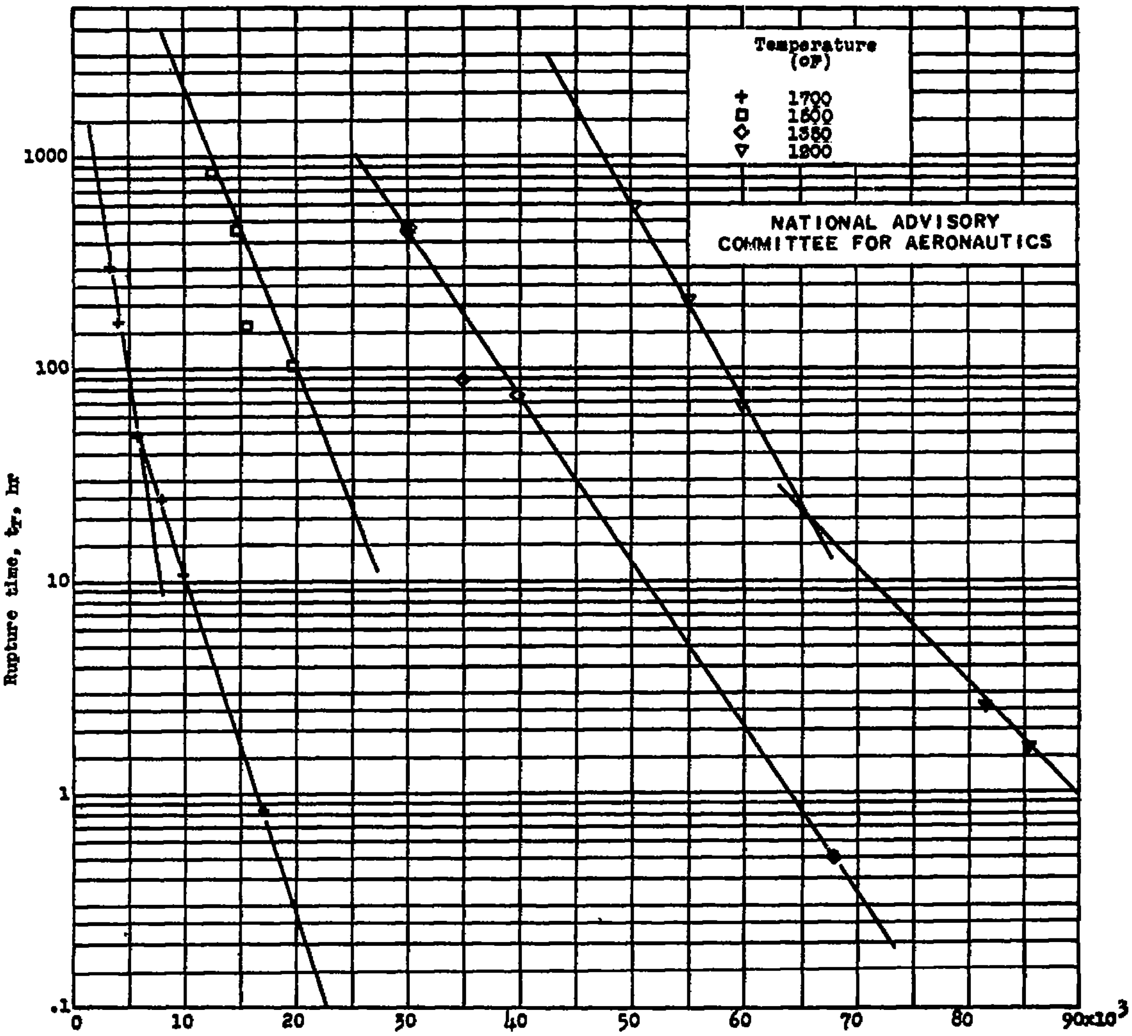

Figure 5. - Variation of rupture time with tensile stress σ for low carbon N155 hot worked.

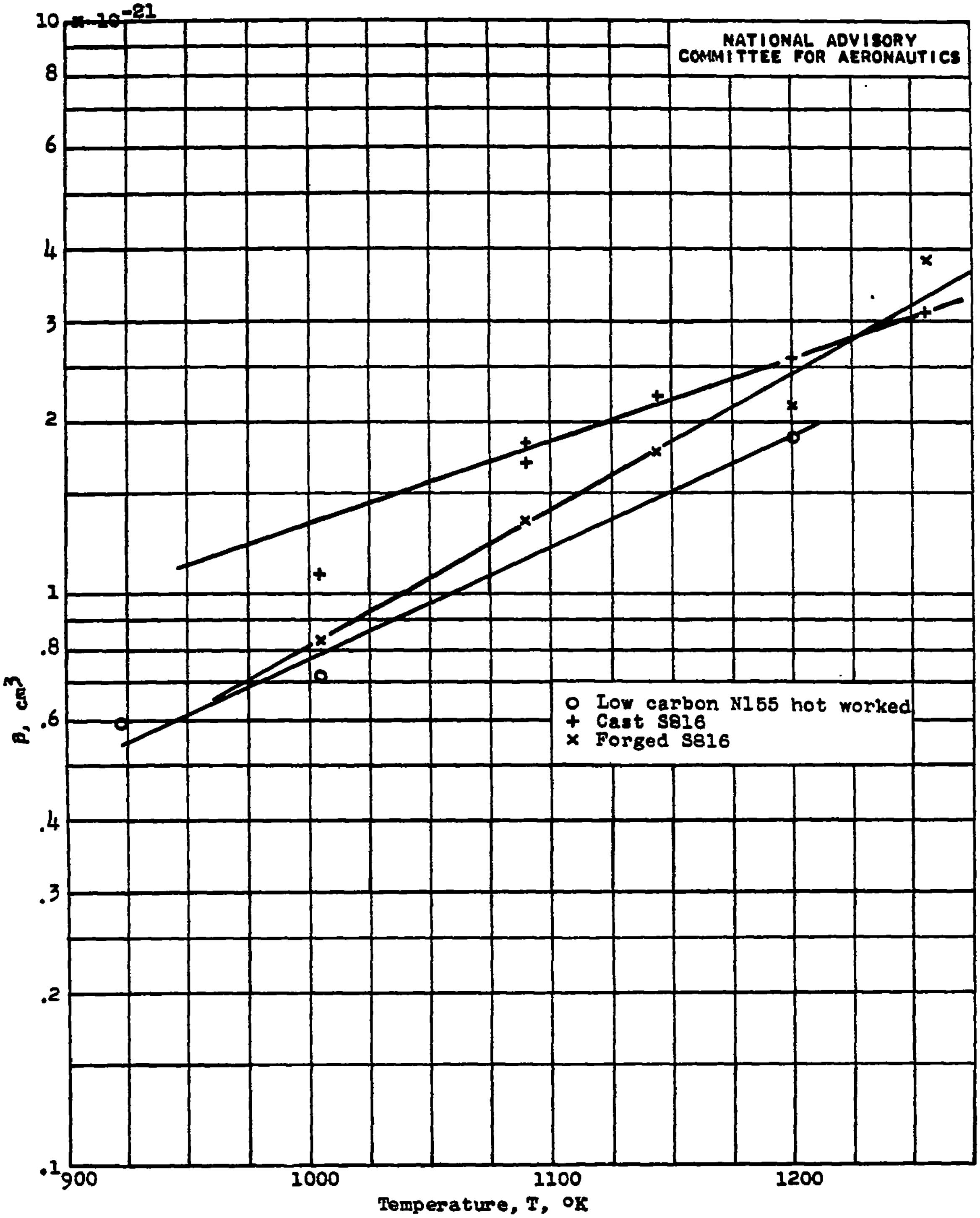

Figure 6. - Dependence of β on temperature T.

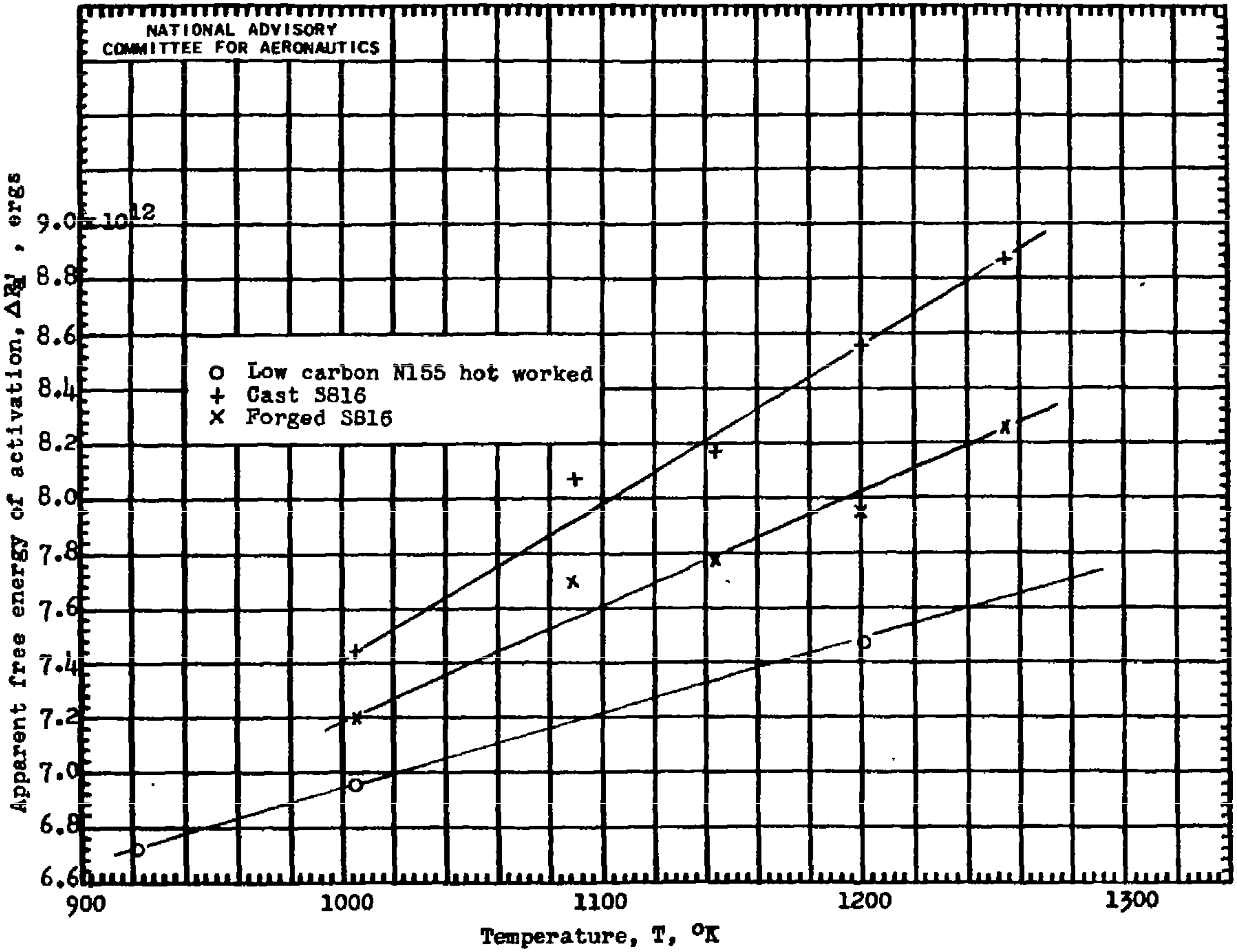

Figure 7. - Dependence of the apparent free energy of activation $\Delta F_a'$ on temperature T.

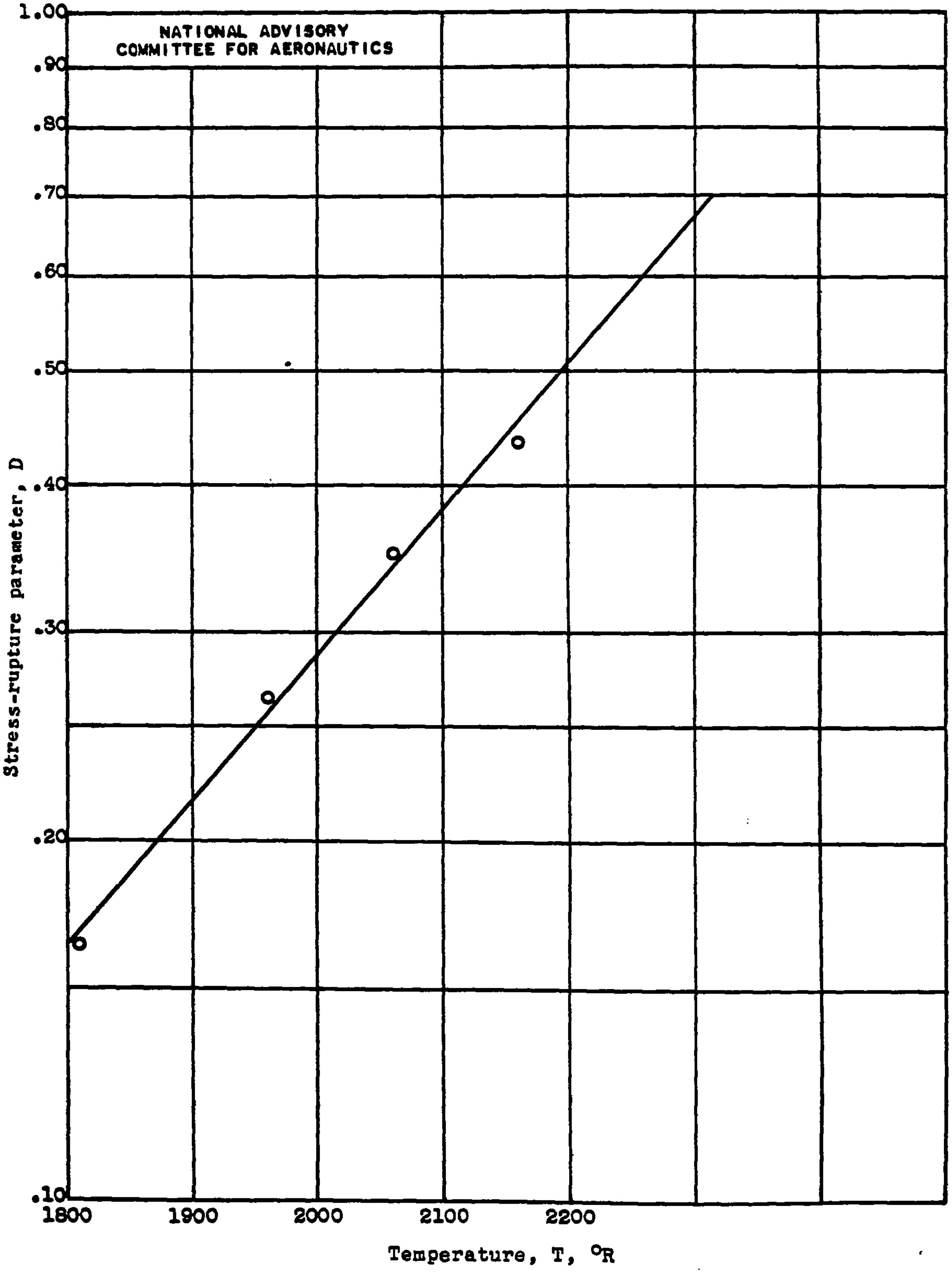

Figure 8. - Variation of log of stress-rupture parameter D with temperature T for forged S816.

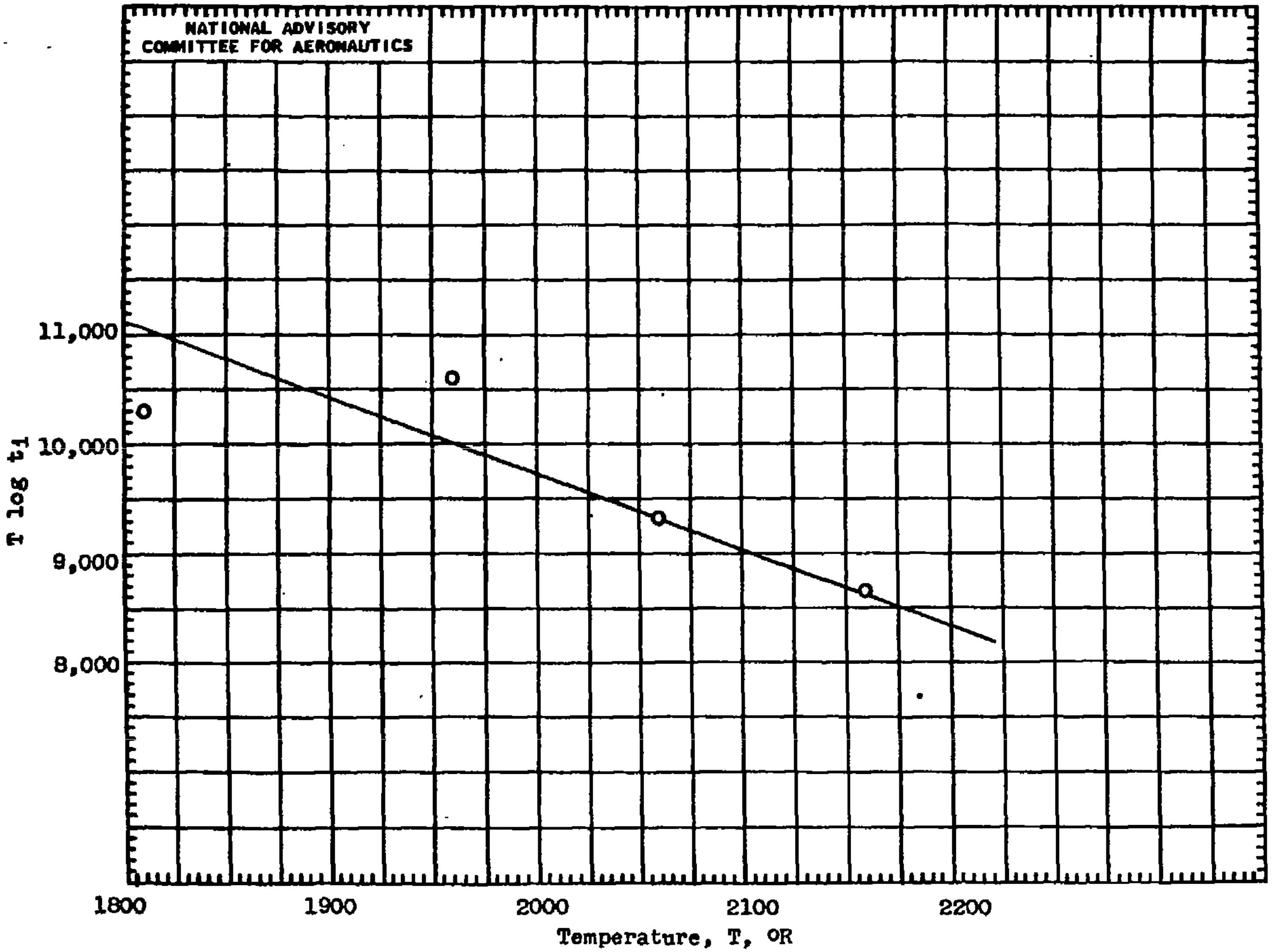

Figure 9. - Variation of T log t_1 with temperature T for forged S816.