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RESEARCH MEMORANDUM

DETERMINATION OF STRESS-RUPTURE PARAMETERS FOR FOUR HEAT-RESISTING ALLOYS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Stress-rupture data for four heat-resisting alloys are analyzed according to the equations of the theory of rate processes. A method for determining the four parameters of structure and composition is demonstrated and the four parameters are determined for each of the alloys: forged S816, cast S816, cast S590, and cast Vitallium. It is concluded that parameters can be determined for an alloy provided sufficient reliable experimental data are available.

INTRODUCTION

One of the most important criterions in evaluating an alloy for high-temperature application is the time required for rupture at elevated temperature when a specimen is subjected to a constant load. A number of such investigations, which vary in length from a few hours to several thousands of hours, must be conducted when it is desired to compare the stress-rupture properties of a series of alloys. The theoretical considerations of reference 1 suggest that the equations of the theory of rate processes may be applied to the process of stress rupture. Reference 1 provides a basis for the theory that the rate-process stress-rupture equation developed therein can be used to interpolate and extrapolate data for different temperatures.

The following alloys were chosen for investigation because the available data cover a sufficiently wide range of temperatures and stresses to permit determination of the values of the stress-rupture parameters: forged S816, cast S816, cast S590, and cast Vitallium. An analysis of existing stress-rupture data was made according to this theory. The compositions and the heat treatments of the alloys are given in tables I and II.

APPLICATION OF STRESS-RUPTURE EQUATIONS

The equations, developed in reference 1, which treats stress rupture as a rate process, are

$$\log t_r = \frac{A + BT - D\sigma}{T} \tag{1}$$

where

t_r time for rupture, hour

A,B parameters of structure and composition

T temperature, °R

D slope of stress-rupture curve multiplied by temperature

σ applied stress in tension, pounds per square inch

and

$$\log D = E + FT \tag{2}$$

where

E,F parameters of structure and composition

The data for alloys forged S816, cast S816, cast S590, and cast Vitallium obtained from the Allegheny Ludlum Steel Corporation and from references 2, 3, and 4 are plotted in figure 1 on semilog coordinates, as recommended in reference 1.

Because of limited stress-rupture data at some temperatures and because of the experimental error involved in reproducing stress-rupture data, it is difficult to determine the true slopes of the stress-rupture curves. In figure 1(a), for example, the curve for 2260° R is fixed by three points and in figure 1(c) the curve for 2060° R is fixed by only two points. As a first approximation of the true slopes of the stress-rupture curves, the slopes of the curves in figure 1 were determined. Figure 2 was then obtained by plotting D (slope of stress-rupture curve multiplied by temperature) against temperature on semilog coordinates. Corrected values of D taken from figure 2, when divided by the corresponding temperatures, yielded values that were more likely to be closer to the true slopes of the stress-rupture curve than were originally obtained. By use of these corrected slopes, the intercepts of the stress-rupture curves t_i when extrapolated to zero stress were determined. Figure 3 was obtained by plotting $T \log t_i$ against temperature. Parameters E and F, which were determined from figure 2, and parameters A and B, which were determined from figure 3 (see appendix) are presented in table III.

RESULTS AND DISCUSSION

The use of the stress-rupture equations is not limited by a change in structure or by oxidation of the alloy. In ranges of stress and temperature in which an alloy is susceptible to a change in structure or to surface or intergranular oxidation, the stress-rupture equations are still valid; however, a different set of parameters must be determined for these ranges. The range in which oxidation or structural instability of an alloy is encountered is shown as a break in the slope on the stress-rupture curve for the alloy. It is therefore important to realize when stress-rupture life is predicted by use of these parameters that several experiments may be necessary to determine whether an alloy of the type under investigation is susceptible to these changes and whether the parameters determined apply only for the range of test conditions.

In the direct comparison of two alloys at the same conditions of stress and temperature, the time for rupture for each material is determined by use of the equations. Then, according to the results obtained by using the parameters and equations, the alloy that has the longer rupture life would have the better stress-rupture properties at the conditions in question. Lengthy stress-rupture investigations may be eliminated by the prediction of additional data at stresses and temperatures at which no experimental data are available. Ordinarily, when it is desired to obtain sufficient data to plot a stress-rupture curve at a specified temperature, four or five stress-rupture investigations must be conducted to obtain the data. By use of the equations, the number of investigations required is reduced because the curve that is desired may be extrapolated from the data that are already available.

The reliability of results from the extension of data using the stress-rupture equation is dependent upon the accuracy of the experimental data from which the parameters are determined. Reference 5 reports that approximate values of variation in time for rupture of specimens at the same stress and temperature deviate ± 25 percent from the average for two-thirds of the investigations conducted and greater than 25 percent for the remainder of the investigations.

For best results the original data should be obtained from specimens of the same melt and heat treatment; however, it may be frequently desirable to use data obtained from specimens of different metallurgical backgrounds. The case in which data are used from specimens of different metallurgical backgrounds is illustrated by the determination of parameters for Vitallium, the data for which were obtained from three independent sources (references 2, 3, and 4). It may be difficult to obtain good correlation of data from specimens of different metallurgical backgrounds if the physical properties of the alloy are sensitive to slight variations in composition, heat treatment, or testing procedures.

CONCLUSION

The results of this investigation show that the four parameters of structure and composition that are used to predict stress-rupture data can be determined for an alloy when the available stress-rupture data cover a sufficiently wide range of temperature and stress.

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APPENDIX - PRACTICAL APPLICATION OF STRESS-RUPTURE EQUATIONS

In order to illustrate the method used in calculating parameters A, B, E, and F, the data for cast S816 given in figure 1(b) will be used.

The absolute slope of the 1960° R stress-rupture curve is

$$\frac{D}{T} = \frac{\log t_{r,1} - \log t_{r,2}}{\sigma_1 - \sigma_2} - \frac{4.00 - 1.00}{13{,}300 - 29{,}600} = 0.000184$$

where subscripts 1 and 2 indicate initial and final points on the curve.

Then

$$D_{1960} = T \times 0.000184 = 1960 \times 0.000184 = 0.360$$

Simarily

$$D_{1810} = 0.210$$

$$D_{2060} = .412$$

$$D_{2160} = .486$$

$$D_{2260} = .700$$

The plot of log D against T for cast S816 is given in figure 2(b). The slope of the straight line in figure 2(b) is

$$F = \frac{\log 0.700 - \log 0.21}{2260 - 1810} = 1.160 \times 10^{-3}$$

The intercept of this line is

$$E = \log 0.700 - 1.16 \times 10^{-3} \times 2260 = -2.778$$

The corrected value of D for 1960° R as taken from figure 2(b) is

$$D = 0.313$$

which then gives the corrected slope

$$\frac{D}{T} = \frac{0.313}{1960} = 0.000160$$

similarly the slopes of the other curves become

$$\left(\frac{D}{T}\right)_{1810} = 0.000116$$

$$\left(\frac{D}{T}\right)_{2060} = .000199$$

$$\left(\frac{D}{T}\right)_{2160} = .000246$$

$$\left(\frac{D}{T}\right)_{2260} = .000310$$

The intercept of the 1960° R stress-rupture curve in figure 1(b) is

$$\log t_i = \log t_r + \frac{D}{T}\sigma = \log 900 + 1.60 \times 19{,}000 \times 10^{-3} = 5.994$$

Then

$$T \log t_i = 5.994 \times 1960 = 11.749$$

Similarly

$$T \log t_i \ (1810) = 11{,}624$$

$$T \log t_i \ (2060) = 11{,}400$$

$$T \log t_i \ (2160) = 12{,}169$$

$$T \log t_i \ (2260) = 11{,}964$$

The plot of $T \log t_i$ against T for cast S816 is given in figure 3(b). The slope of the straight line obtained is

$$B = \frac{12{,}000 - 11{,}600}{2260 - 1850} = 0.970$$

The intercept is

$$A = 12,000 - (0.97 - 2260) = 9810$$

REFERENCES

1. Machlin, E. S., and Nowick, A. S.: Stress Rupture of Heat-Resisting Alloys as a Rate Process. NACA TN No. 1126, 1946.

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. Cross, Howard C.: Progress Report on Heat-Resisting Metals for Gas Turbine Parts (N-102). OSRD No. 1871, Ser. No. M-147, NDRC, OSRD, War Metallurgy Div., Oct. 1, 1943.

4. Freeman, J.W., Reynolds, E. E., and White, A. E.: The Rupture Test Characteristics of Six Precision Cast and Three Wrought Alloys at 1700° and 1800° F. NACA ARR No. 5J16, 1945.

5. 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.IR, SRG Rep. 485, Columbia Univ., Statistical Res. Group, Appl. Math. Panel, NDRC, May 1945.

TABLE I - CHEMICAL COMPOSITION OF ALLOYS

Alloy	Chemical composition, percent									
	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	Fe
[a]S816	0.35-.45	2.00 max.	1.00 max.	18-22.00	18-22.00	38.00 min.	3-5.00	3.5-6.0	2.5-5.0	5.00 max.
[a]S590	0.35-.50	2.00 max.	1.00 max.	19.5-22.00	19-21.00	19-21.00	3.5-4.5	3.5-4.5	3.3-4.5	Bal.
[b]Vitallium	0.24			28.70		Bal.	5.57			
[c]Vitallium	0.20			28.0		65.0	6.0			
[d]Vitallium	0.24	0.98	0.63	27.6	3.06	Bal.	5.13			1.76
[d]Vitallium	0.21			26.66			5.57	Co + Ni = 65.56		

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[a]Analysis reported by Allegheny Ludlum Steel Corporation.
[b]Reference 2.
[c]Reference 3.
[d]Reference 4.

TABLE II - HEAT TREATMENT OF ALLOYS

Alloy	Heat treatment
[a]S816	Solution-treated at 2250-2300° F, 1 hour; water quench; aged at 1400° F, not less than 6 hours; air-cooled
[a]S590	Solution-treated at 2250-2300° F, 1 hour; water quench; aged at 1400-1500° F, 16 hours; air-cooled
[b]Vitallium	[c]Aged at 1810° R, 50 hours [d]As cast and aged

[a]Heat treatment reported by Allegheny Ludlum Steel Corporation.
[b]Heat treatment reported in references 2, 3, and 4.
[c]Specimens tested at 1810° R.
[d]Specimens tested at 1960°, 2060°, and 2260° R.

TABLE III - STRESS-RUPTURE PARAMETERS OF ALLOYS

Alloy	Parameter			
	A (1)	B (1)	E (2)	F (2)
Forged S816	25,664	-7.88	-2.687	0.00108
Cast S816	9,810	.97	-2.778	.00116
Cast S590	10,869	1.06	-2.941	.00132
Cast Vitallium	12,739	-1.23	-2.477	.00100

[1]Determined from figure 3.
[2]Determined from figure 2.

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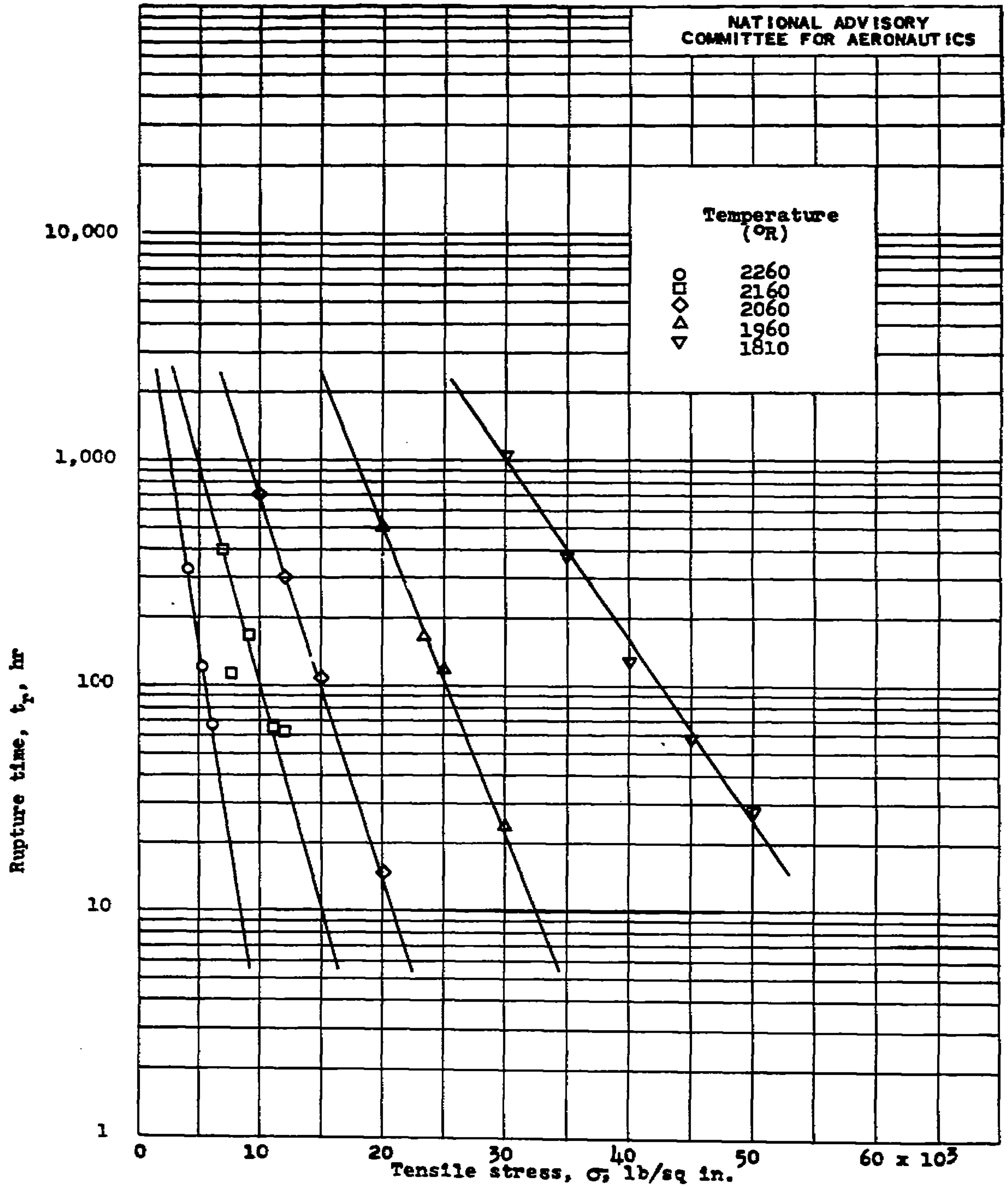
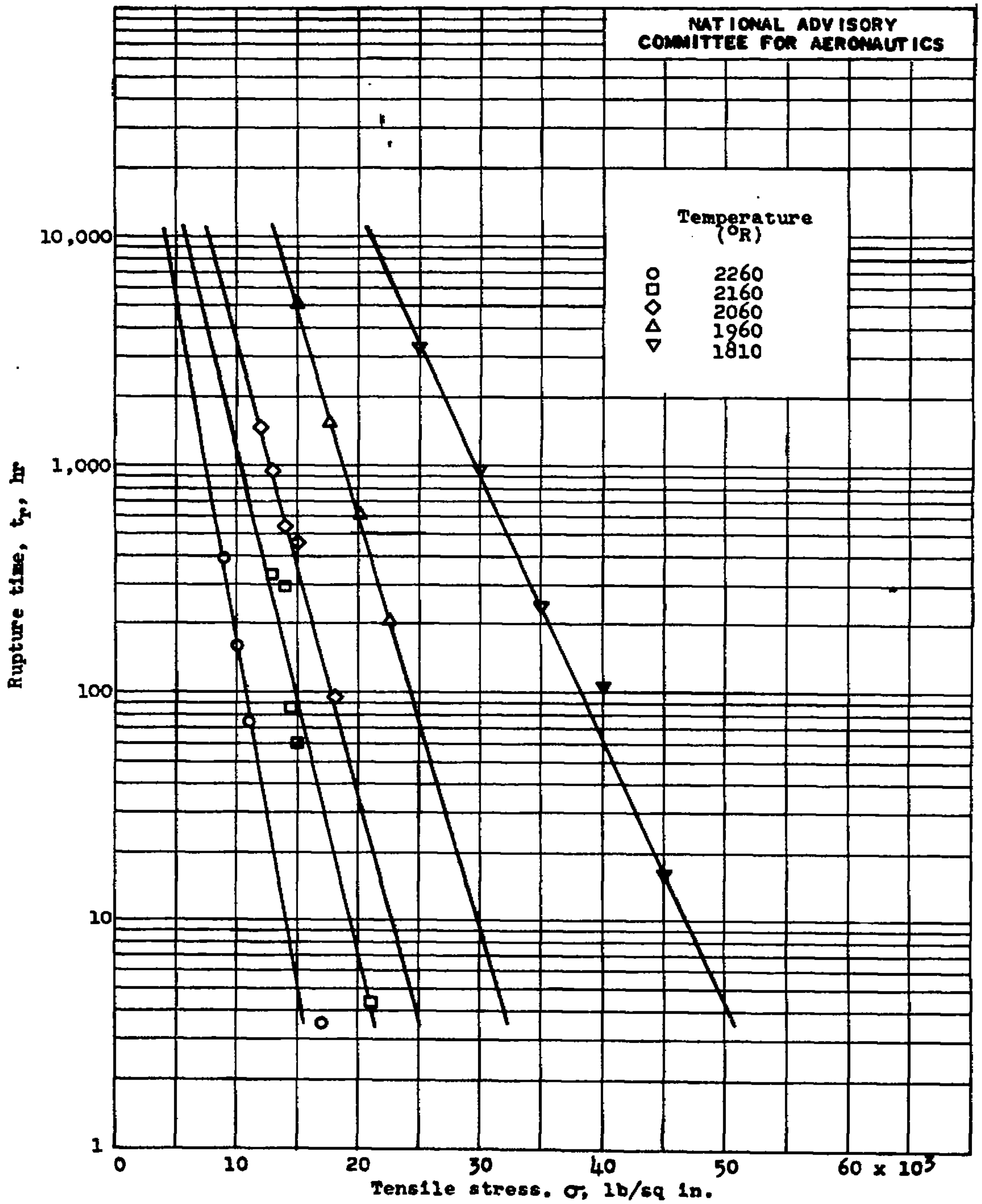


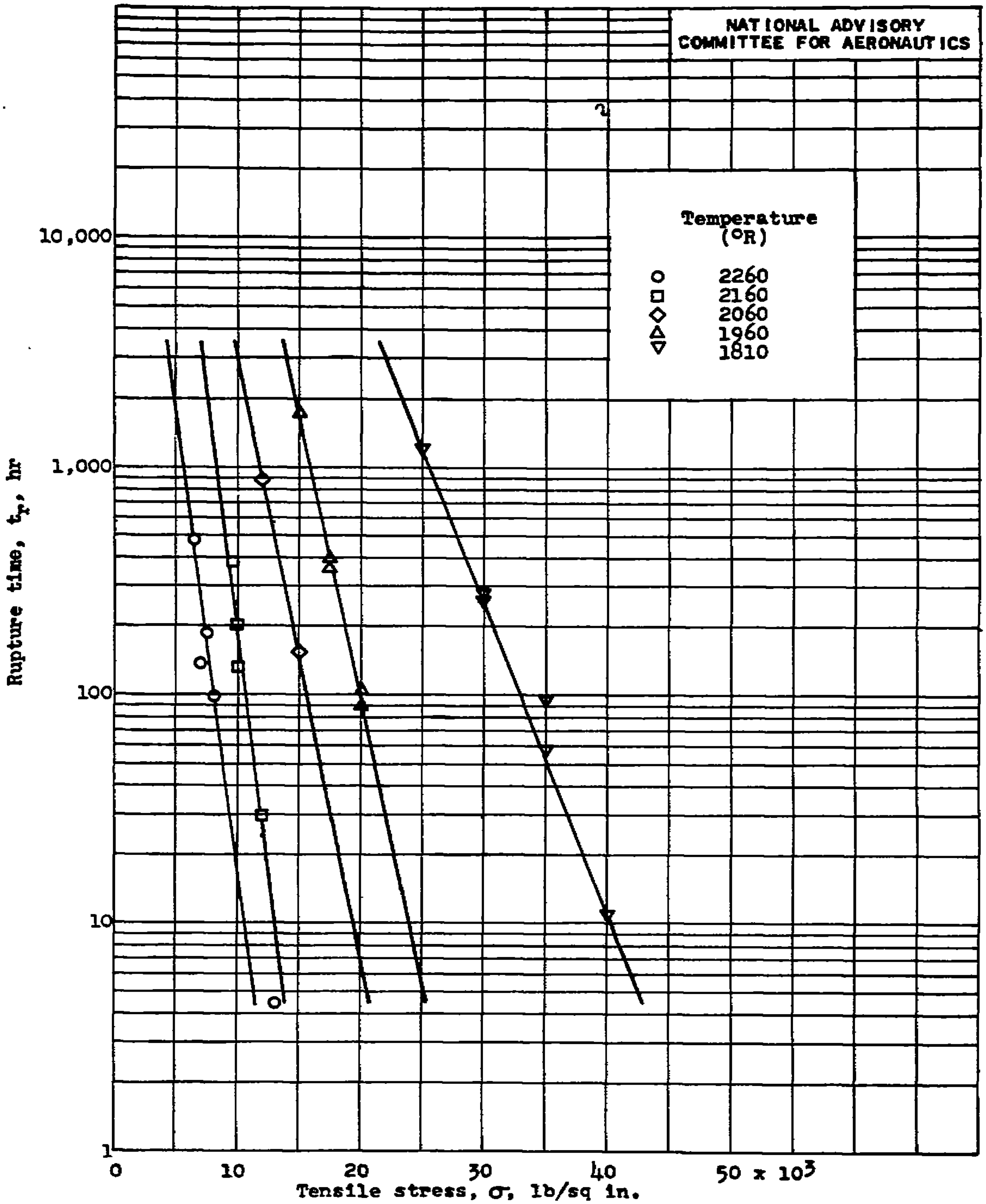
(a) Forged S816.

Figure 1. - Variation of rupture time t_r with tensile stress σ.



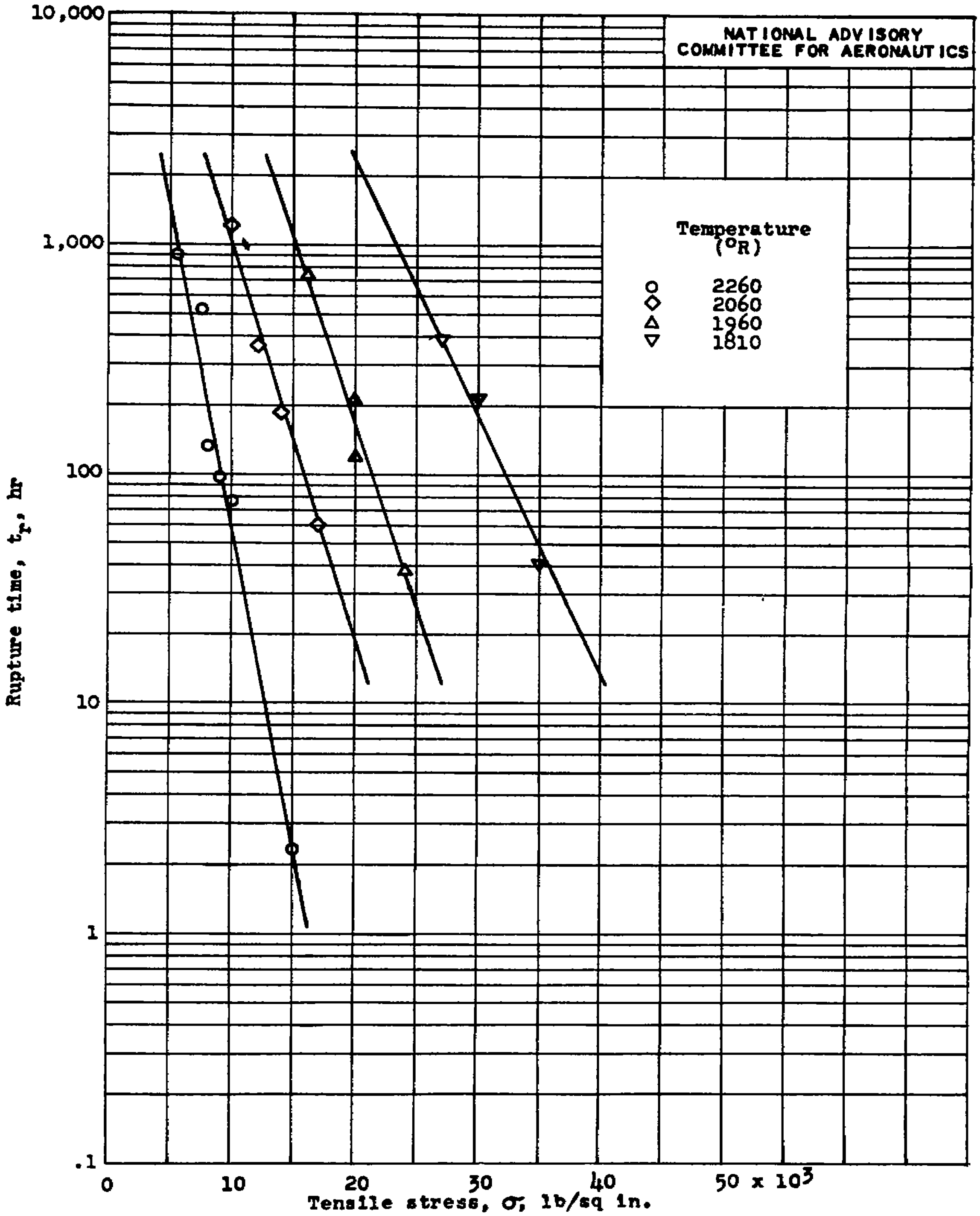
(b) Cast S816.

Figure 1. - Continued. Variation of rupture time t_r with tensile stress σ.



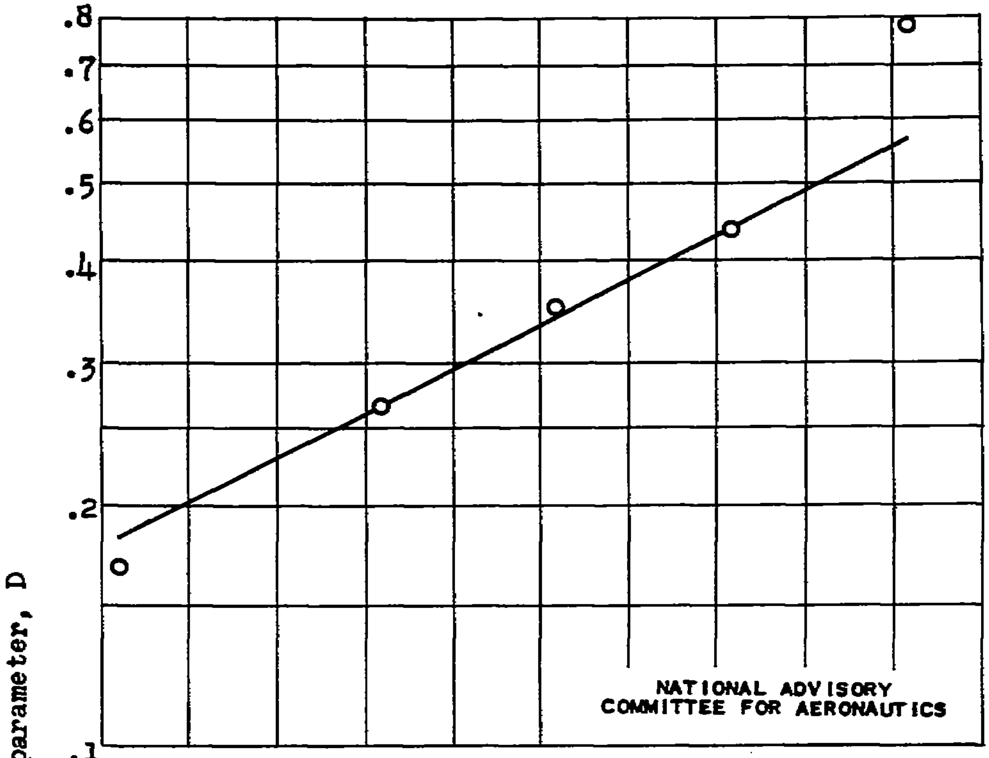
(c) Cast S590.

Figure 1. - Continued. Variation of rupture time t_r with tensile stress σ.

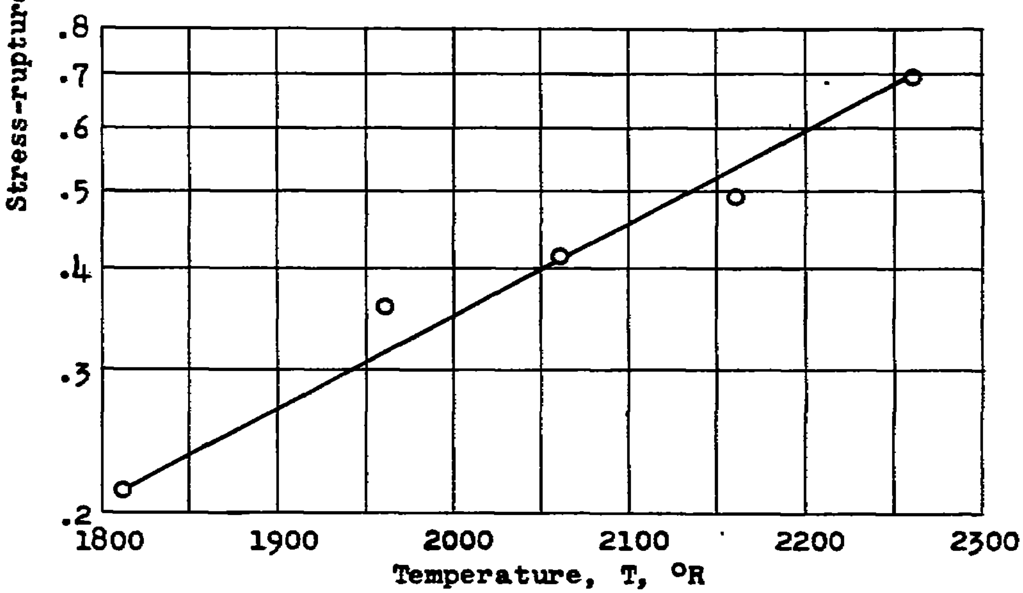


(d) Cast Vitallium.

Figure 1. - Concluded. Variation of rupture time t_r with tensile stress σ.

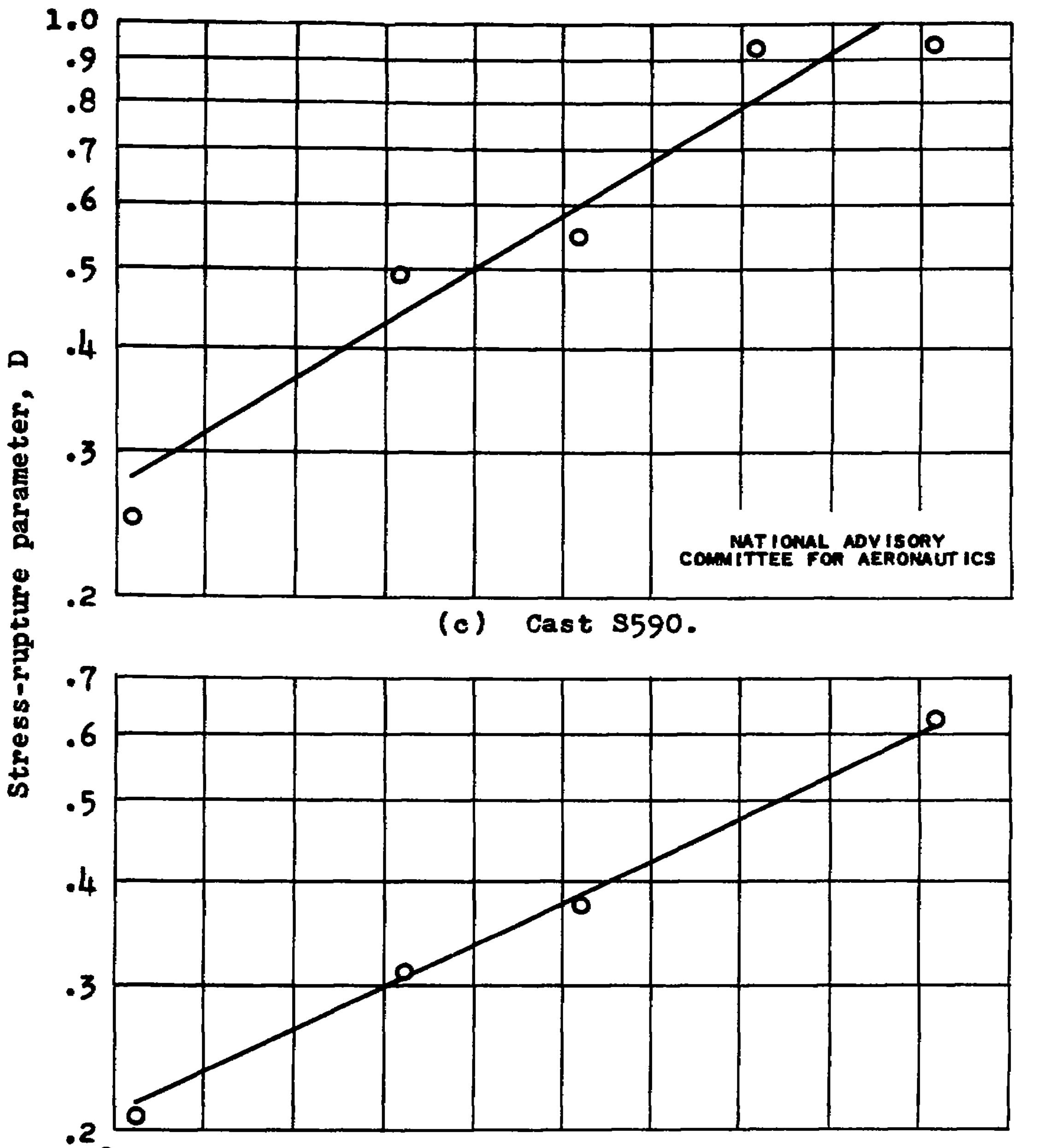


(a) Forged S816.



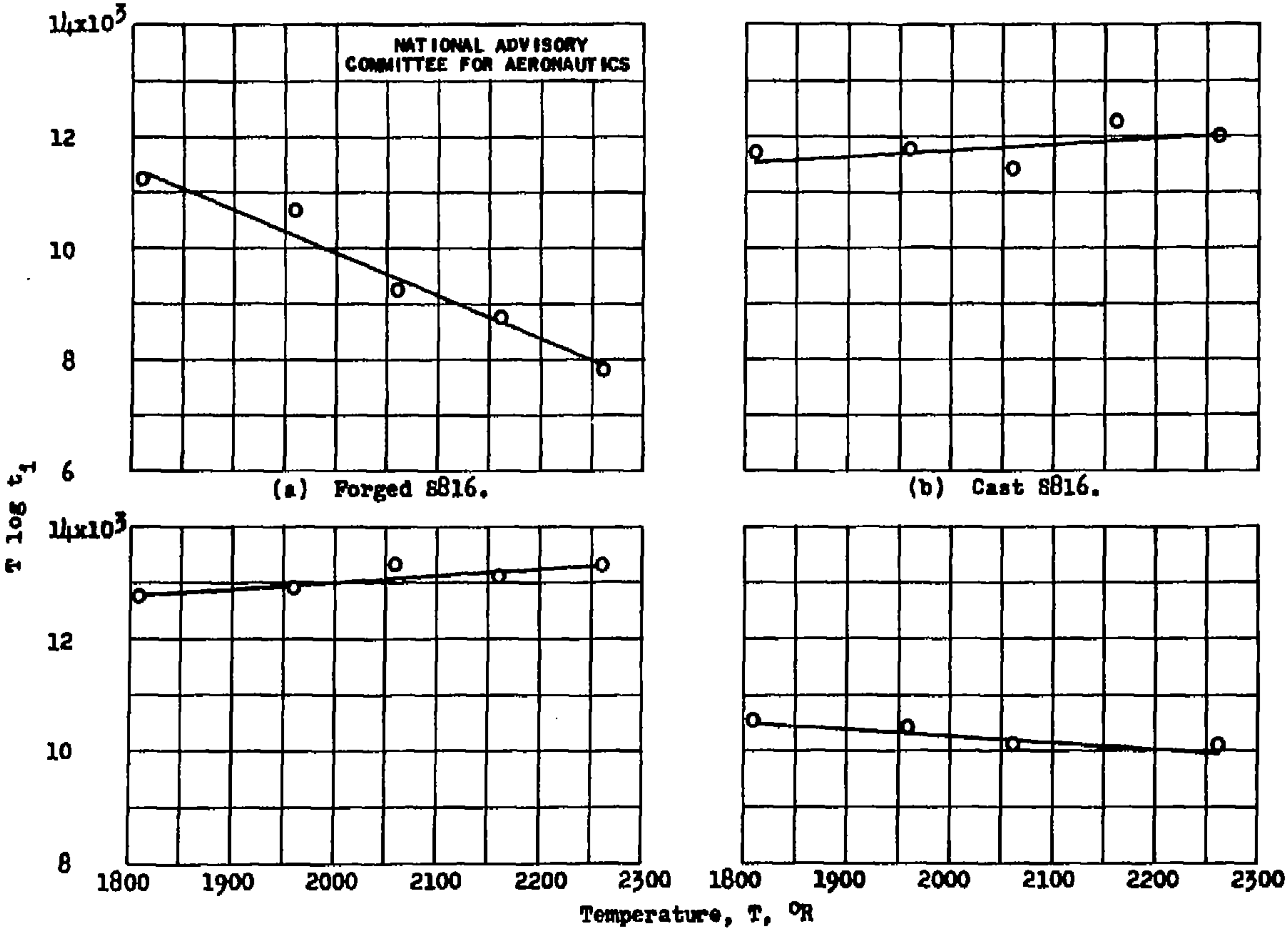
(b) Cast S816.

Figure 2. - Variation of log of stress-rupture parameter D with temperature T.



(d) Cast Vitallium.

Figure 2. - Concluded. Variation of log of stress-rupture parameter D with temperature T.



(a) Forged S816.

(b) Cast S816.

(c) Cast S590.

(d) Cast Vitallium.

Figure 3. - Variation of T log t_i with temperature T.

Metal - Fracture