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HIGH-TEMPERATURE PROPERTIES IN RELATION TO DESIGN

(This paper was presented by J. R. Weir and R. V. Meghreblian at the Third Sagamore Ordance Materials Research Conference at Duke University, December, 1956.)

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A. Introduction

Interest in high-temperature properties of metals has been greatly stimulated by the continually advancing objectives of high-performance engineering devices. These include jet and rocket motors, gas turbines, high-speed aircraft and missile structures, and nuclear reactor components. The structural problems arising in high-temperature design involve the creep, relaxation, thermal shock and strain-cycling properties of materials. These phenomena are intimately related to certain material properties of the structure and the imposed environmental conditions. Some of these factors are (1) the coefficient of thermal expansion (higher coefficient means higher stress), (2) the thermal conductivity (lower conductivity means higher stress), (3) stress-strain characteristics (higher modulus of elasticity means higher stress), (4) geometry (more constraint means higher stress), (5) time-rate of change of temperature (faster change means higher stress), and (6) time at temperature (longer time means lower stress, due to relaxation, but greater plastic strain). The concept of stress is used here only as a convenience since this is the principal variable in conventional problems of elasticity. Properly, one should think in terms of strain when dealing with high-temperature problems. This is especially important in describing thermal effects in structures.

The present discussion deals primarily with the strain-cyling and relaxation characteristics of ductile metals. These phenomena arise principally from changes in operating conditions (accidental or intentional). Such changes generally involve adjustments in pressures, temperatures, fluid-flow conditions, radiation levels, etc. The effect of load transients which introduce cyclic strains in materials is, at best, poorly understood. In particular, the phenomean of fatigue (either mechanically or thermally induced) is not yet well established on a theoretical basis, although there is considerable literature on the subject. No attempt is made here to explain the effect of strain cycling on the internal structure of materials. The discussion is confined to observations and measurements on the behavior of certain materials subjected to this condition.

In attempting to design for cyclic conditions three basic types of information are required. First, the designer must establish the complete operating program of the system; second, he must obtain data on the strain cycling and relaxation properties of the materials to be used; and third, he must devise suitable analytical methods for appling these data to the design of complex structural members. A detailed discussion of these considerations follows.

B. High-Temperature Properties of Ductile Materials

Metallurgical Factors Affecting High-Temperature Behavior - In general, the major metallurgical factors which are known to affect the deformation and failure characteristics of metals at high-temperatures may be listed as follows:

1. Temperature
2. Strain
3. Strain rate
4. Stress
5. Metal surface conditions and environment
6. Ductility
7. Previous thermal and mechanical treatment of the material
8. Microsctructural instabilities and inhomogeneties

Strain-Cycling Properties - One of the most notable contributions to the knowledge of the effect of thermal strain cycling on the failure of metals is the work of L. F. Coffin.[1] The equipment with which he performed the tests consists, briefly, of a tubular specimen the ends of which are fixed to heavy end plates supported by columns such that the ends of the specimen may then be resistance heated and air-cooled through a controlled ΔT about some mean temperature so that the specimen undergoes compressive and tensile strains according

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[1] L. F. Coffin, "A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal", Trans. ASME, 1954, p. 931.

to the following relationship:

$$\varepsilon_{thermal} + \varepsilon_{elastic} + \varepsilon_{inelastic} = 0 \qquad (1)$$

Using this equipment, Coffin studies the effect of various metallurgical variables on the failure, by thermal cycling, of type 347 stainless steel at temperatures around 350°C. Some of the qualitative results of his experiments are as follows:

(1) A characteristic fatigue curve is produced when the ΔT, about a fixed mean temperature, is plotted versus the number of cycles to failure.

(2) The effect of prior cold work is to reduce the number of cycles to failure at high strains per cycle and to increase the number of cycles to failure at low strains per cycle.

(3) An increase in mean temperatures resulted in a decrease in the number of cycles to failure. This behavior probably reflects the effect of stress relaxation which may occur at the higher temperature.

(4) Increasing the hold time at temperature decreases the number of cycles to failure, but increases the total elapsed time to failure.

(5) It was found that when $\ln 2N\,\varepsilon_p$ (the total plastic strain) was plotted versus $\ln N$ (number of cycles to failure) a straight line resulted if the ultimate tensile ductility was plotted at 1/4 cycle. This implies that an equation of the form $N^{\alpha}\varepsilon_p = C$ fits the experimental data.

At the Oak Ridge National Laboratory equipment has been developed which permits strain cycling of a metal specimen alternating in tension and compression at elevated temperatures in controlled environments.

For simplicity in descriptions a somewhat schematic drawing of this apparatus is shown in Fig. 1. In this case the specimen is a 3/4-in.-dia tube with a 1-in. long reduced section which serves as the test gauge length. The top shoulder of the specimen is welded to the casement and the rod is welded to the bottom shoulder of the specimen. The specimen is then loaded in tension or compression by means of controlled gas pressure on top of the piston. The total strain is sensed through the small rod which is connected to the top of the large rod and extends through a pressure seal in the top of the pressure chamber. The total strain in each of the tension and compression cycles is monitored by means of a dial indicator placed in contact with the top of the sensing rod. The total strain at which the stress in the specimen is to be reversed in direction is controlled by a motion transmitter which changes small linear movements into pressure changes. These pressure changes are then sensed by pressure switches which actuate solenoid valves in the gas pressure lines leading to the top and bottom sides of the piston, thereby changing the axial direction of the stress in the specimen. The specimen is pressurized internally at a very low gas pressure which is monitored for failure of the specimen. In order to test the solid rod specimens the rod and casement have been adapted to accommodate a threaded connection. The ends of a 0.250-in.-dia round specimen with a 1-in. long gauge length are then screwed into the bottom of the casement and rod.

Some preliminary data have been obtained on Inconel, a commonly used high temperature Ni - Cr - Fe alloy, at 1500°F. The effect of the magnitude of the strain per cycle on the number of cycles to failure of fine and coarse grained rod is shown in Fig. 2. The $\ln \varepsilon_p$ is plotted versus $\ln N$, where ε_p is the total plastic strain per cycle in percent (2 x the double amplitude of the strain-time wave), and N is the number of cycles to failure. The coarse grained material exhibits fewer cycles to failure at all strain amplitudes, the effect being more pronounced at the lower strains. Metallographic examination of specimens of the coarse and fine grained material disclosed that the failures were initiated at the intersection of grain boundaries with the surface and that the cracks propagated in an intergranular manner.

The effect of strain cycling on the failure of fine and coarse grained Inconel tubing at 1500°F is shown in Fig. 3. A grain size effect similar to that seen in the case of the rod is exhibited by the tubing. If a comparison is made between the properties of the fine grained rod and tubing it is seen that the tubing fails in a fewer number of cycles at similar strains. The reason for this behavior has not been determined but it seems probably that it may be attributed to (1) material differences between rod and tubing, (2) the difference in the method of sensing failure, or (3) the specimen surface to volume ratio.

The variation in the "total plastic strain" ($N \epsilon_p$), with the number of cycles to failure (N) for the fine grained rod is shown in Figure 4. The $\ln N \epsilon_p$ is plotted versus $\ln N$.

It is seen that the strain-cycling results may be correlated with the fracture ductility in simple tension ($N = 1/4$ cycle) and that the experimental data may be represented by an equation of the form $N^{\alpha} \epsilon_p = C$ suggested by Coffin.

In order to determine analytically the plastic strain per cycle in actual structures subjected to the conditions described in this discussion, information on the stress relaxation properties of the structural material is necessary. If the material is subjected to very large strains with each cycle (greater than 0.1%) the elastic component is a negligible fraction of the total deformation so that the measured or computed deformations are essentially plastic. At the lower values of strain, the elastic component becomes increasingly important and the fraction of the total strain which is plastic is determined by the "hold-time", or period, of the cycle. Thus, for very small strains per cycle the initial deformation is elastic, but due to the relaxation phenomenon, this deformation is rapidly transformed into plastic strain. Since the stress is proportional to the elastic strain, the stress in the member will decrease with time as more and more plastic strain is developed.

The stress relaxation characteristics of Inconel at 1500°F are shown in Figure 5. Stress is plotted versus time for various total strains. For high total strains (stresses) the stress is seen to decay quite rapidly, initially, and a limiting value is approached in a few hours. The data indicates that the limiting stress is independent of the initial stress.

C. Application to Design

High-Temperature Design Criteria- An essential difference in structural design for high-temperature operation (temperatures above 1000°F) as compared to design for more modest conditions is due to the appreciably shorter life-time of the high-temperature systems. The design life of such systems may be measured in minutes, hours, or at most, thousands of hours, in contrast to conventional systems wherein life-times may be given in decades. Although in both cases the requirements of design are given in terms of a specified program of operation, the application of these requirements to high-temperature systems introduces some difficulty due to the fact that the design requirements may be very close to the limits of the material properties, thus, so-called margins of safety may be markedly reduced over those presently acceptable. In many instances the limitations of material strengths may dictate the program of operation of a particular engineering device. For instance, in the design of some high-temperature power-plants, the most severe conditions imposed on the system arise from changes in the power level. In these cases, variations in power level must be limited in number, and frequently the ideal approach is to operate the plant at "steady-state" for its entire life. Thus, the details of the operating program are extremely important and must be selected with considerable care.

The first task of the designer is to spell-out this program, taking into account as best he can any unexpected variations arising from secondary failures or accidents and unprogrammed demands on the system. Herein lies the only real margin on which the designer can rely. If in the course of operation this margin is consumed prematurely, then the life of the system must be regarded as having "expired". This philosophy of design is entirely analogous to the requirements imposed on aircraft structures.

Several of the important physical properties of materials which can influence the structural design features of high-temperature systems were discussed in the preceding sections. Of these the phenomena of creep and thermal stress are perhaps best known. The phenomenon of strain-cycling has received serious attention only recently since operation under cyclic conditions at high temperatures has become an important facet of structural design only with the advent of jet propulsion machinery and nuclear reactors. Even during operation at "steady-state", structural members in these devices are subjected to cyclic loads, both thermal and mechanical, due to local variations and instabilities in environmental fluids. Although these conditions give rise to relatively high-frequency strain-cycling effects, the internal structure of the materials is subjected to much the same sort of physical pehnomena as in the case of slower, deliberate power variations. Whatever the source of these cyclic variations in strain, the determination of the magnitude, frequency and number of such cycles constitute an essential step in the preliminary analysis required of the designer. Thus, in order to construct a complete picture of the strain-cycling conditions imposed on the structure, the designer must couple the requirements arising from the specified operating program with those due to the "fine-structure" of the temperature and pressure profiles expected within the interior of the device.

Design Analysis- Having determined the strain-cycling requirements for the various structural members, the designer must next obtain information on the available cycle-life of the structure. This may be accomplished with the aid of labroatory measurements on the materials to be used, coupled, when necessary, with component tests under simulated operating conditions. The final task confronting the designer, then, is the application of laboratory measurements of physical and mechanical properties to the design of detailed structure. The numerous problems encountered in the design of structure exposed to cyclic conditions may be conveniently classified in two groups, those due to cyclic mechanical loads (e.g., pressures) and those due to changes in the temperature of the structure. The latter (thermal strain-cycling) may be further classified under two sub-headings, those due to gross constraint of a member subjected to differential thermal expansions, and those due to variations in the temperature profiles through the member.

Structures subjected to variations in temperature profiles are perhaps best handled by component test, although some elementary geometries can be treated by analytical methods. A good example of such structure are the pressure shells and heat exchanger tubes in a power-plant. It is clear that whenever the over-all power level of the system is changed, there will be a corresponding change in the temperature drop through the walls of these members. This change, of course, introduces certain strains within the walls, and in many cases these are well into the plastic range.

The problems of strain cycling arising from differential thermal expansion and mechanical loads are somewhat more amenable to analytical treatment. In these cases, it is possible to apply laboratory measurements of strain-cycling properties directly to the design analysis of particular structures.

From the viewpoint of the designer, the primary information required is a knowledge of life-time (in cycles) versus strain per cycle. Data of this type have been obtained by Coffin and some recent results for Inconel are reported in this paper. The final problem confronting the designer, then is the calculation of the plastic strain per cycle, given the operating program of the structure. As a simple illustration of how onemight approach this problem, consider the following situation. In designing a certain high-temperature molten-metal heat exchanger it was found that due to external constraints on the header sheets, the individual tubes in the bundle are subjected to an appreciable differential thermal expansion relative to the tube header sheets whenever the system was power-cycled. The tubes consist of long straight sections with short 90° bends at each end. When the temperature levels in the heat exchanger change due to an adjustment in operating conditions, the tubes experience an extension or compression which produces bending at the roots of the short stems. The critical areas of the design proved to be at these roots, and an analysis was undertaken to determine the plastic strain induced at these points. For this purpose it was assumed that the material behaved according to the idealized stress-strain curve shown in Figure 6.

The structural analysis was based on the simplified model of a cantilever beam to represent the tube stems, as shown in Figure 7. When the force, F, at the end of the beam (or the deflection y_o) is relatively small, the stress distribution at each station is entirely elastic (see Figure 8). As the force increases, some sections eventually deform plastically, starting with the root (see Figure 8b). The immediate problem was to determine the maximum plastic deformation, ε_1, at the root for a given end deflection y_o corresponding to the growth of the tubes relative to the surrounding structure. The analysis consisted of computing the deflection curve of the beam for an arbitrary value of y_o. This expression was then used to relate the maximum strain at the root ε_1 to y_o, and it was found that the result could be conveniently expressed in the form:

$$\beta = \frac{8}{3^{3/2}} \left[\frac{1 - \alpha^{3/2} - \frac{3}{2} \alpha^{1/2}}{(1 - \alpha)^2}\right] \tag{2}$$

$$\alpha = \frac{1}{3} \left(\frac{\varepsilon_o}{\varepsilon_1}\right)^2 \qquad \beta = \frac{y_o h}{\varepsilon_o \ell^2} \tag{3}$$

The function, α, which is given in terms of the maximum strain ε_1, is plotted in Figure 9 for various values of the parameter, β. The values of ε_1 obtained in this way were used to predict the number of cycles to failure with the aid of strain-cycling data of the type shown in Figure 4. Actual tests on the heat exchanger showed that the predicted life agreed to within 40% of the test value. Since the analytical model used here is relatively crude, this surprisingly good agreement is perhaps fortuitous. The present practice in fatigue design is to use factors of safety on life of several orders of magnitude. There is reason to expect, however, that with greater experience and more sophisticated analyses one should be able to predict strain-cycling fatigue failure times in complex structures to within a factor of 2 or 3.

The designer's interest in relaxation phenomenon arises from his concern with strain-cycling problems and the relationship between strain-cycling and relaxation was mentioned previously. As pointed out, relaxation effects are especially important in cases of small strains per cycle. These situations are very interesting from the designers's viewpoint since small strains per cycle correspond to large numbers of cycles to failure, and if a reliable estimate is to be made of fatigue life, an accurate measure of the plastic strain developed per cycle is required. This information can only be obtained from a detailed knowledge of the relaxation characteristics of the material.

In the absence of relaxation measurements, it is possible to synthesize these data from creep properties. This problem has received much attention and considerable literature is available on the subject[2]. One method which has been found to be convenient and reliable is based on the "strain-hardening" postulate suggested by Soderberg and Popov. Computations of relaxation curves from creep data for Inconel using this approach agreed well with measurements (see Figure 5). The computational procedure involved in this method is straight forward and begins with the general strain relation:

$$\epsilon_{total} = \epsilon_e + \epsilon_i + \epsilon_c \qquad (4)$$

Where ϵ_{total} is the total (fixed) initial strain on the specimen. This may be divided into ϵ_e, the elastic portion, ϵ_i, the initial plastic deformation (if any) and ϵ_c, the deformation resulting from creep. The differentiation of (4) with respect to time yields:

$$\frac{d\epsilon_c}{dt} = -\frac{1}{E}\frac{d\sigma}{dt} \qquad (5)$$

Where we have used $\epsilon_e = \sigma/E$, and σ is the stress, and E is the modulus of elasticity. The left hand side of this equation is simply the slope of the creep curves, and values for this term may be obtained directly from measurements. The following relation has proven to be useful for obtaining analytical expressions for creep in Inconel:

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[2] See for example, E. P. Popov, J. Applied Mech., 14, A135-A-142 (1947)

$$\varepsilon_c = K(e^{\sigma/s} - 1)\, t^m \qquad (6)$$

Where K, s, and m are constants to be determined from the creep curves.

The relaxation curves, which give stress as a function of time, may be obtained from the integration of (5); thus,

$$t = \frac{1}{E} \int_{\sigma_0}^{\sigma} \frac{d\sigma}{(d\varepsilon_c/dt)} \qquad (7)$$

Where σ_0 is the initial stress in the relaxation specimen. As mentioned above, the integration is based on the strain-hardening rule.

D. Summary

The essential physical and mechanical properties of materials which enter into the design considerations of high-temperature systems have been outlined, and the relationship of these factors to the detailed design of structural members noted. Particular attention is given to the phenomenon of strain-cycling and relaxation, and several engineering devices wherein these effects can markedly influence design are mentioned.

Techniques and apparatus for the measurement of strain-cycling and relaxation properties are described and some recent data on Inconel at 1500°F is reported.

A brief discussion is presented on design-criteria for high-temperature applications, and it is pointed out that in some high-performance devices the considerations of the strain-cycling phenomenon may impose the design philosophy of "steady-state" operation.

Some elementary applications of strain-cycling data to design are described, and test experience indicates that analytical techniques can be developed for predicting with reasonable reliability the fatigue life of structures.

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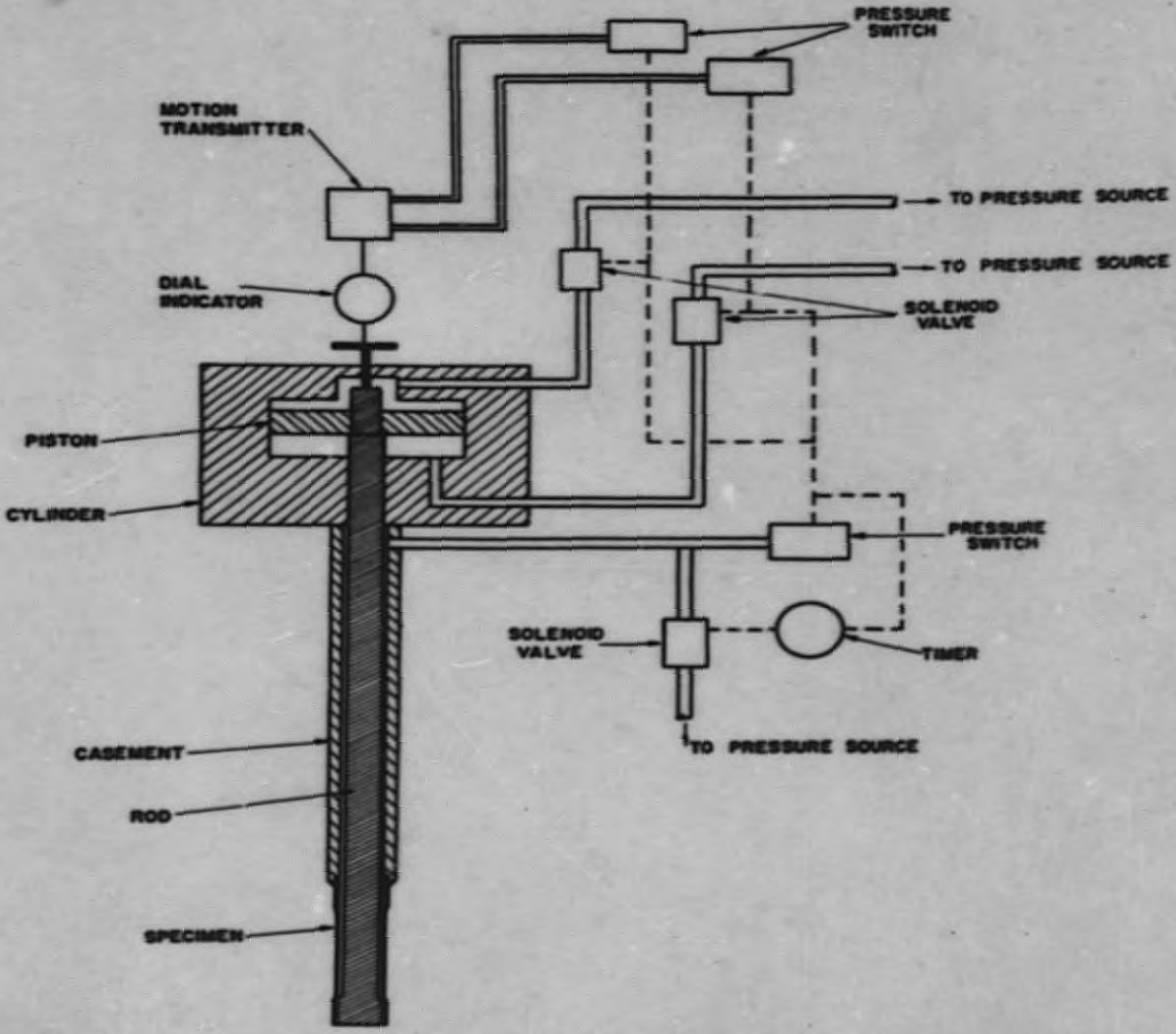

STRAIN CYCLE
APPARATUS

Figure 1. Strain Cycling Apparatus

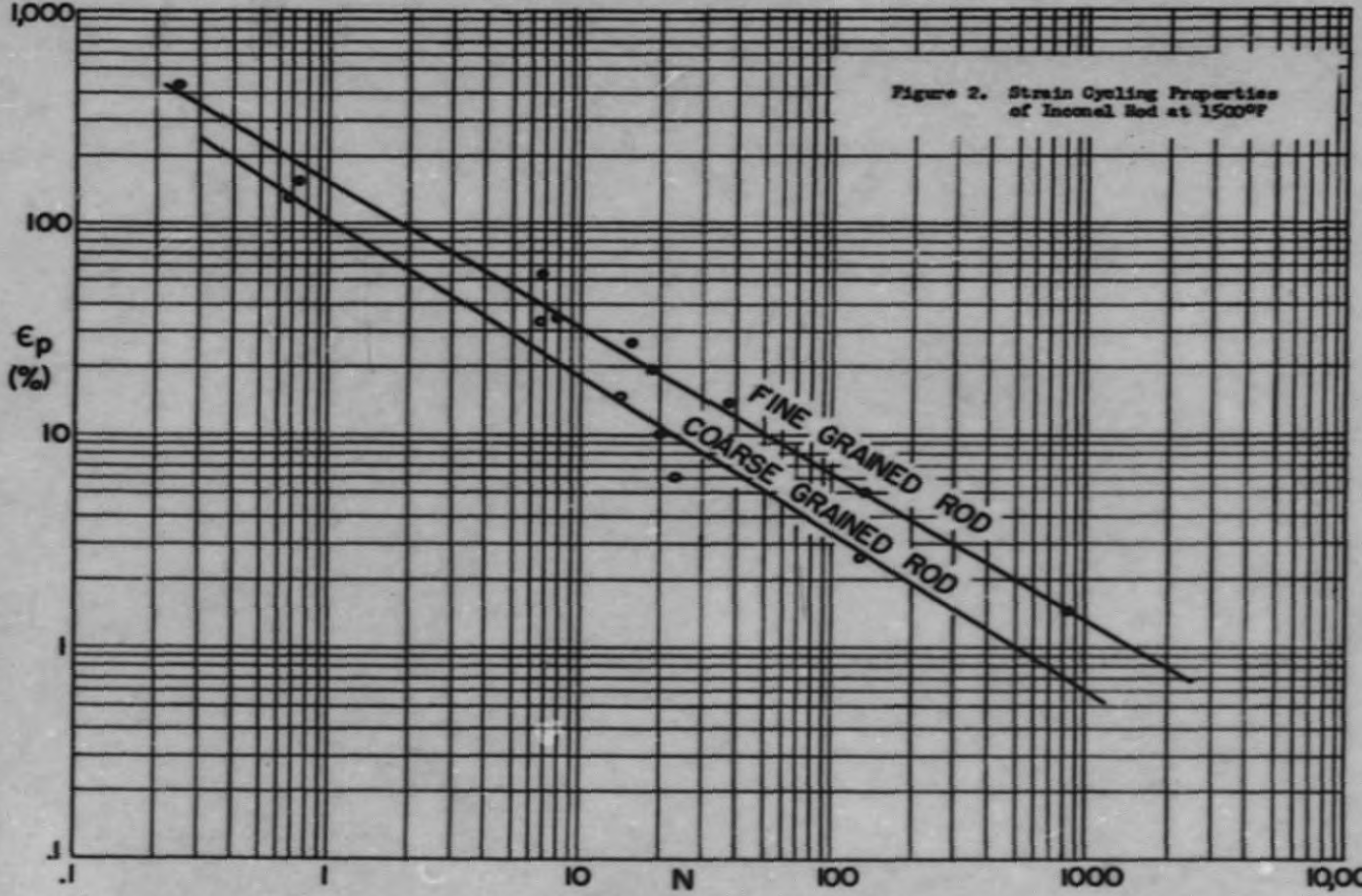

Figure 2. Strain Cycling Properties of Inconel Rod at 1500°F

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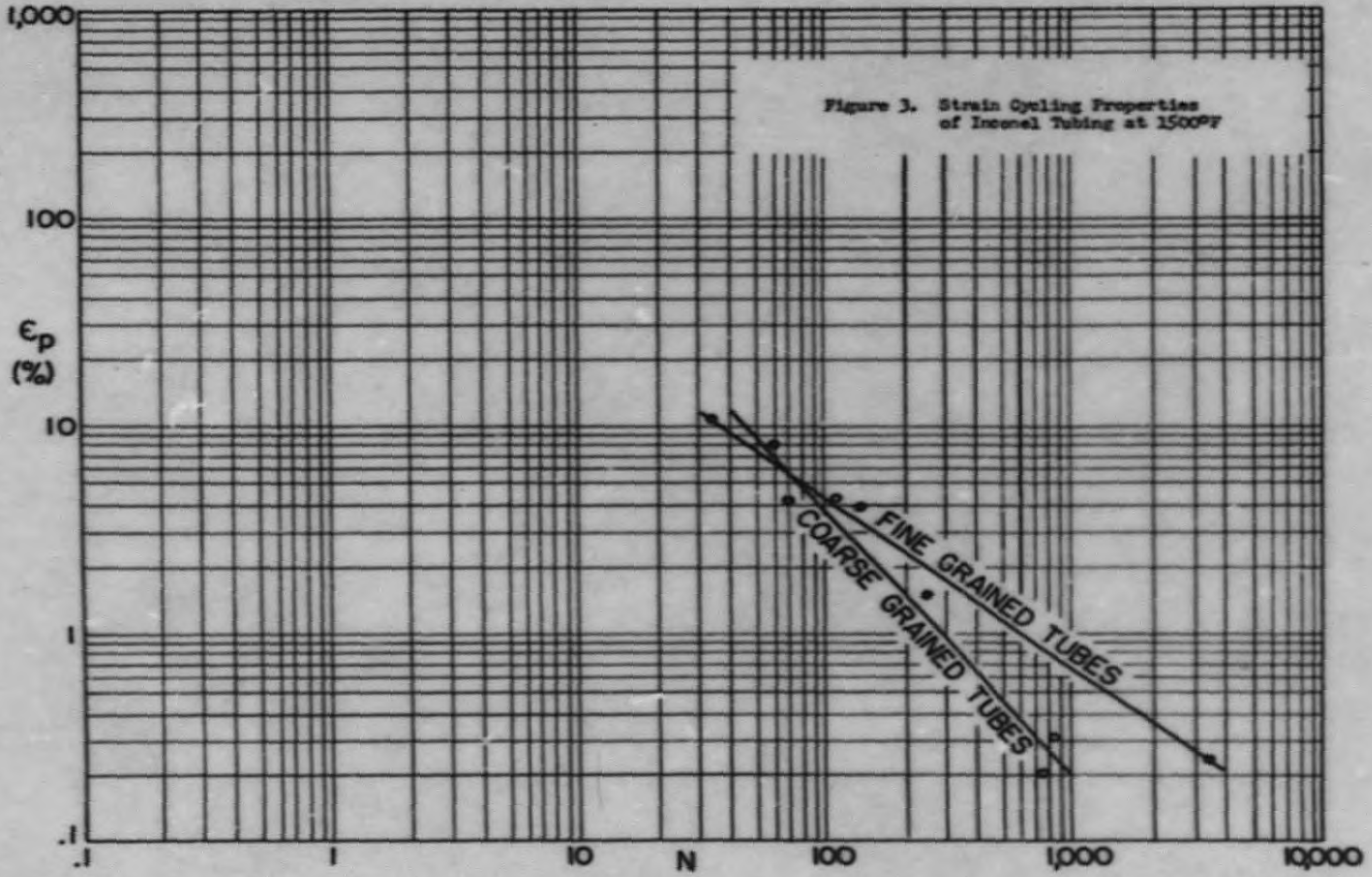

Figure 3. Strain Cycling Properties of Inconel Tubing at 1500°F

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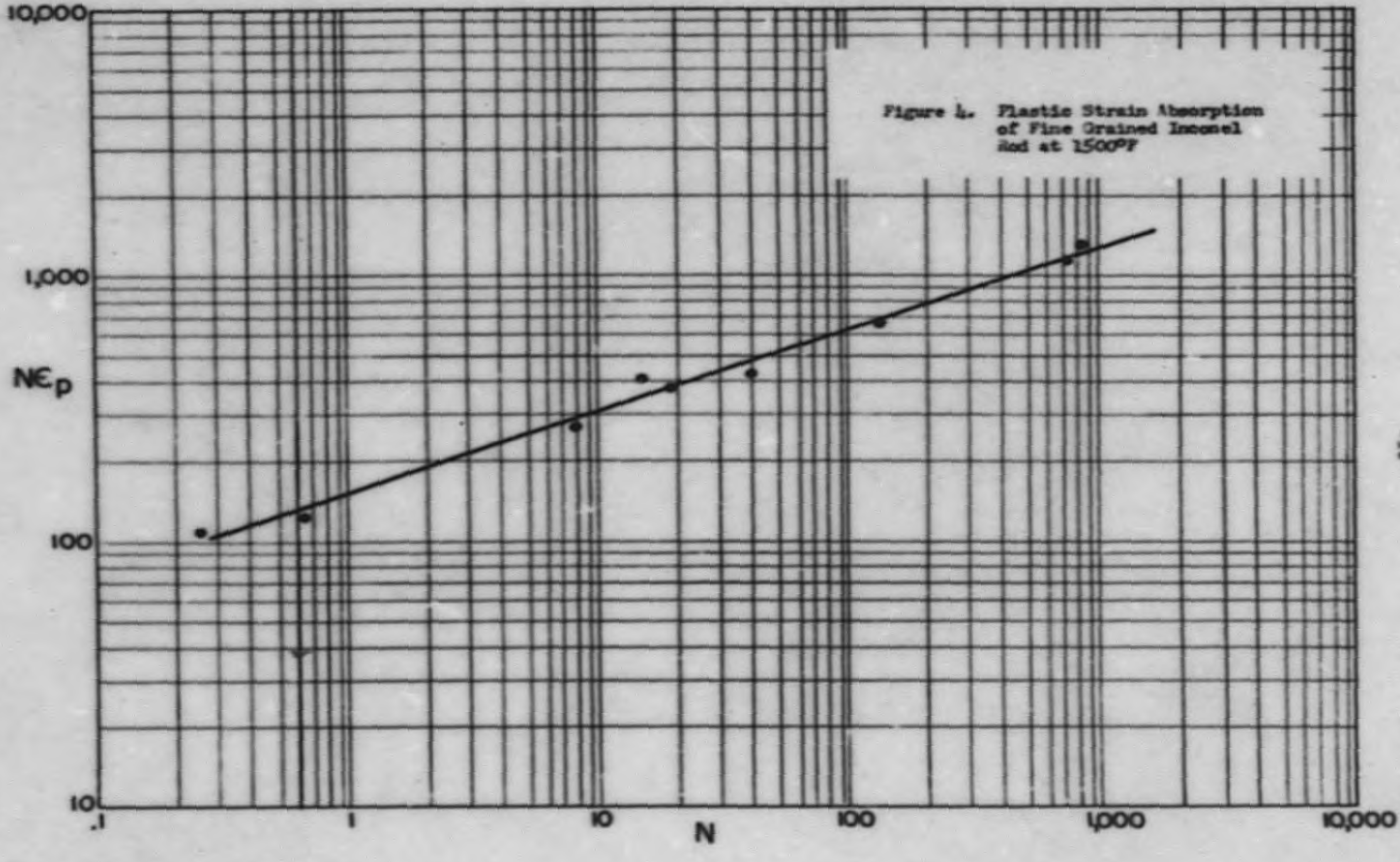

Figure 4. Plastic Strain Absorption of Fine Grained Inconel Rod at 1500°F

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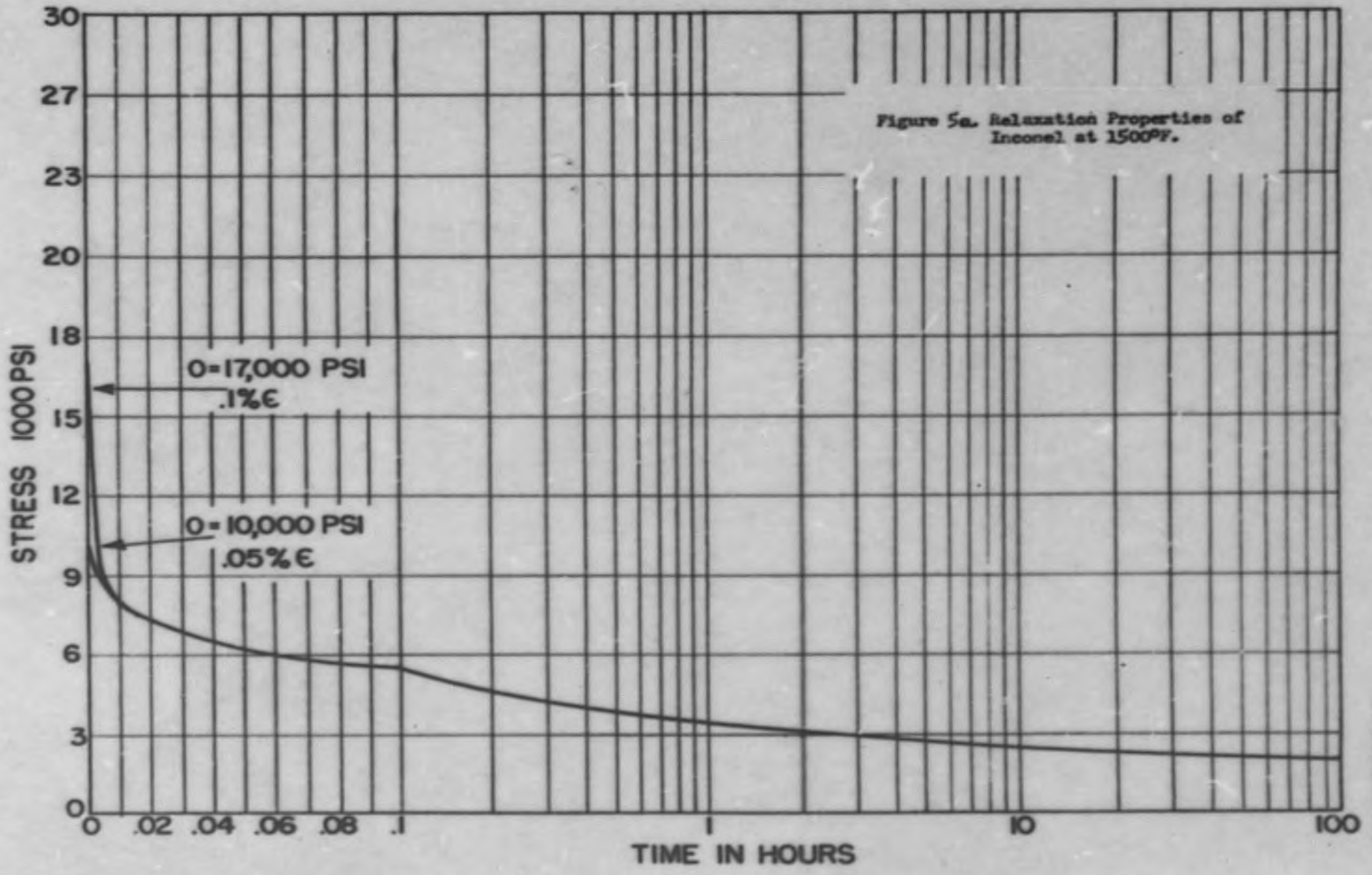

Figure 5a. Relaxation Properties of Inconel at 1500°F.

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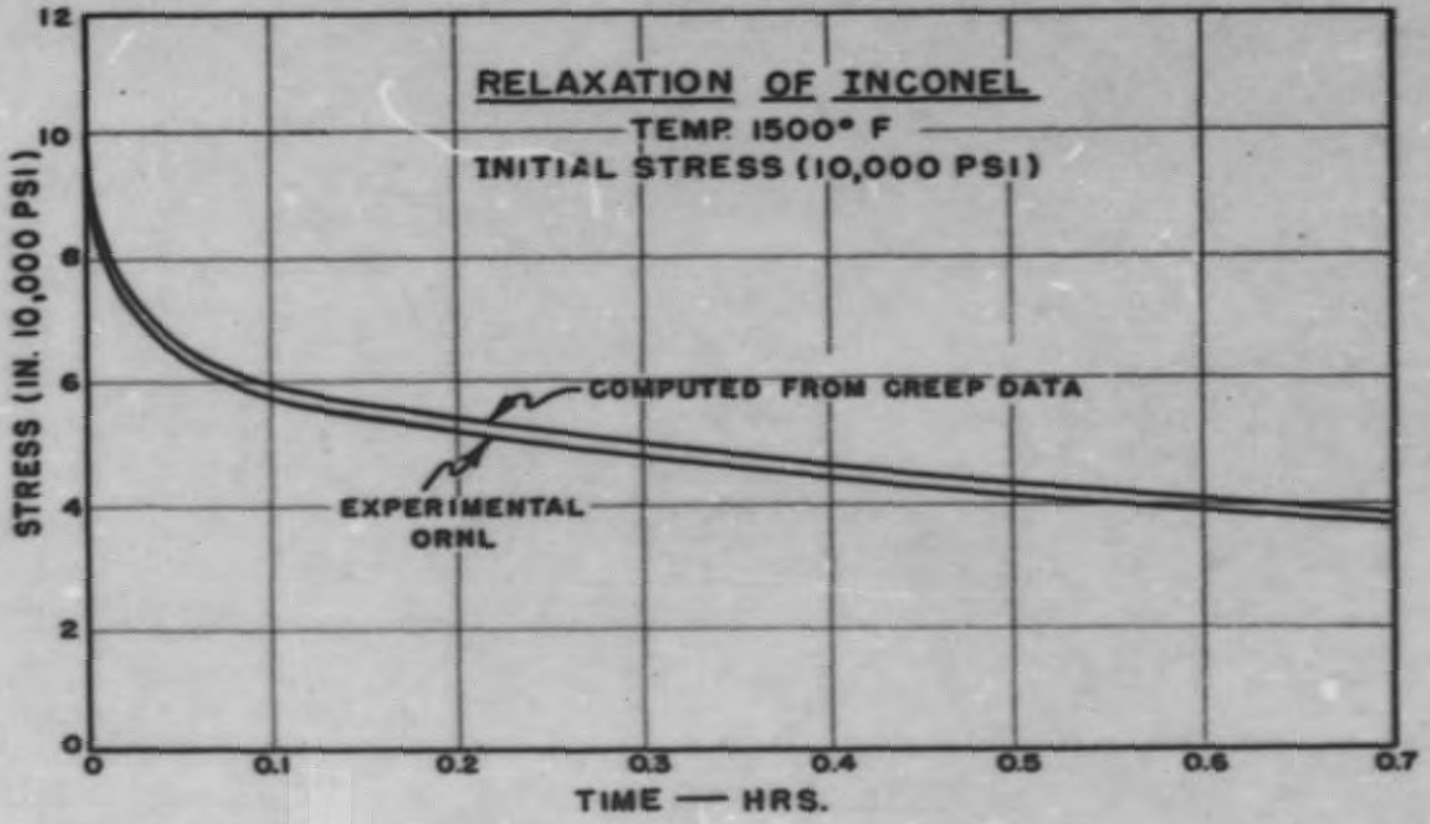
FIGURE 5b



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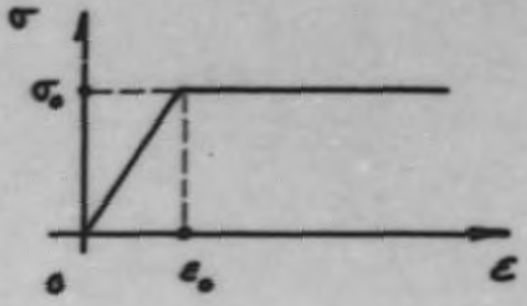

Figure 6

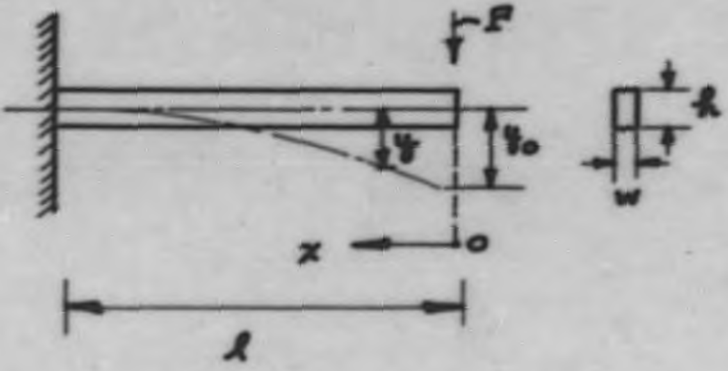

Figure 7

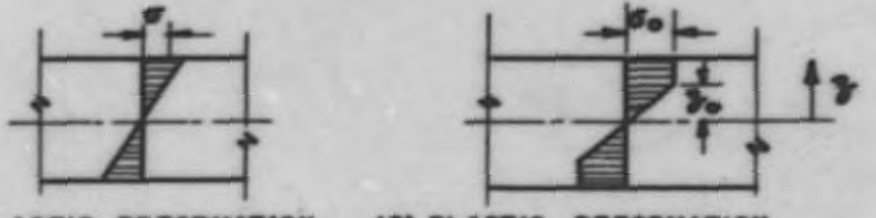

Figure 8

(A) ELASTIC DEFORMATION (B) PLASTIC DEFORMATION

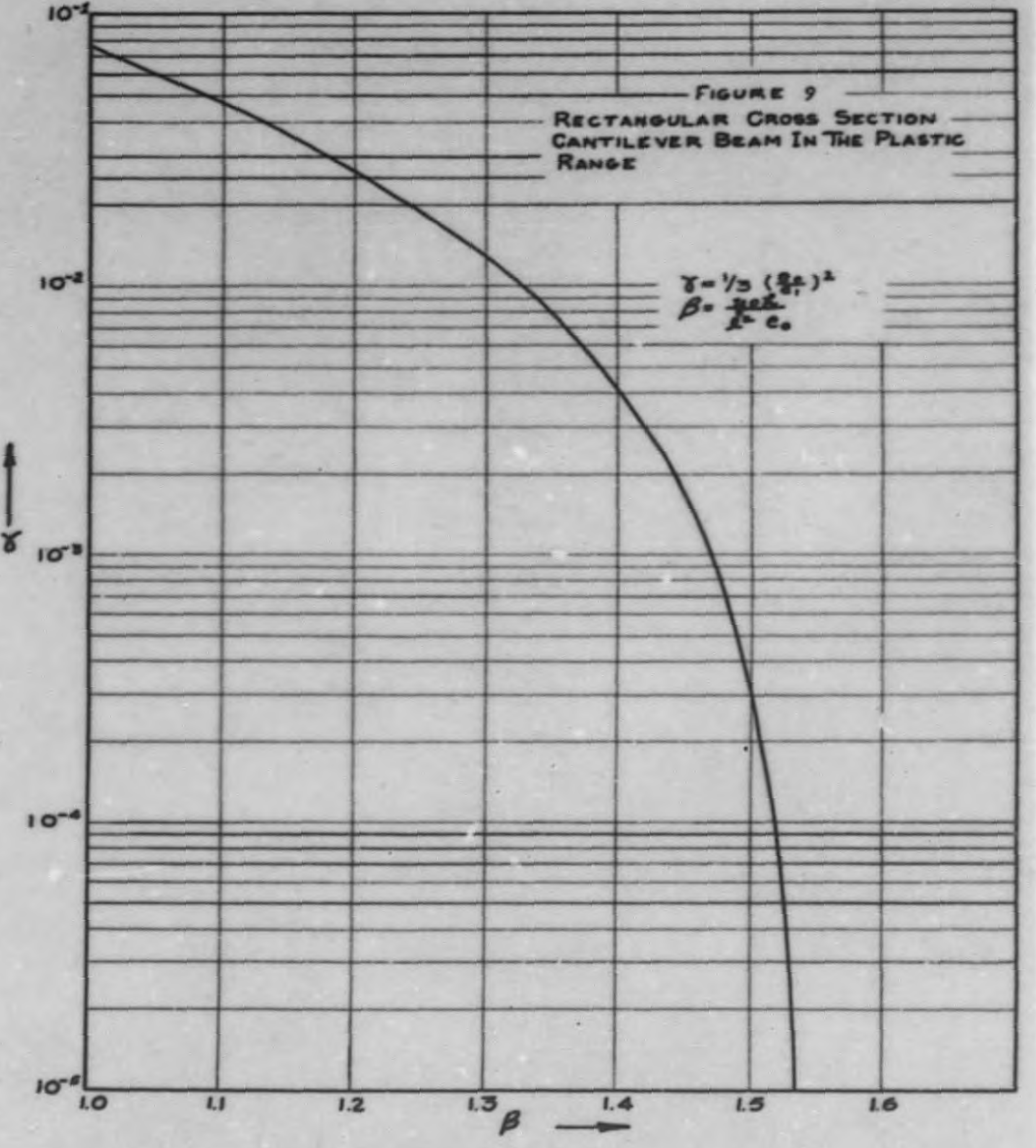

FIGURE 9
RECTANGULAR CROSS SECTION CANTILEVER BEAM IN THE PLASTIC RANGE