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ORNL-2619
Metallurgy and Ceramics

THE FAILURE OF STRUCTURAL METALS SUBJECTED TO STRAIN-CYCLING CONDITIONS

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OAK RIDGE NATIONAL LABORATORY
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ORNL-2619
Metallurgy and Ceramics
TID-4500 (14th ed.)

Contract No. W-7405-eng-26

METALLURGY DIVISION

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DATE ISSUED

OCT 23 1958

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R. W. Swindeman and D. A. Douglas

Abstract

Data showing the isothermal strain-cycling capacity of three metals, Inconel, Hastelloy "B", and beryllium, are presented. It is noted that at frequencies of 0.5 cycles per minute the data satisfied an equation of the form $N^{\alpha}\epsilon_p = K$, where N is the number of cycles to failure, ϵ_p is the plastic strain per cycle, and α and K are constants whose values depend on the structure and test conditions. Data on Inconel are given to establish the effect of grain size, specimen geometry, temperature, and frequency. It is found that at temperatures above 1300°F, grain size and frequency exert a pronounced effect on the rupture life. Fine-grained metal survives more cycles before failure than coarse-grained material. Long time cycles shorten the number of cycles to failure when the strain per cycle is low.

Thermal strain cycling data for Inconel are compared to strain cycling data at the same mean temperature. Good correlation is found to exist between the two types of data.

Introduction

Many of the failures encountered in engineering devices result from dynamic loads which are imposed on the structure either mechanically or thermally. Most often, fatigue failures are considered to be the result of rapidly fluctuating stresses which introduce damage in the material on a very microscopic scale. Thus in low temperature fatigue, no bulk plastic straining of the metal can be discerned. However, at elevated temperatures, where relaxation of stress can occur, measurable amounts of plastic strain may be induced during each stress reversal. This is particularly true in the case of restrained structures when they are subjected to large thermal fluctuations. Quite often, under such conditions, the thermally induced stresses occur over relatively long time cycles and are large enough to exceed the elastic limit of the metal. Thus, in studying the behavior of materials loaded in this manner it is more meaningful to

think of the metal as experiencing a number of strain reversals which ultimately lead to failure, rather than to attempt to base such failures on an indeterminate stress state. It is this problem of thermal strain fatigue which will be discussed in this paper.

Recent studies have revealed that the plastic strain history of a metal under dynamic load conditions provides extremely useful data for calculating the metal life consumed and the service life remaining under expected operating conditions. This idea was conceived by Manson[1] and then demonstrated experimentally by Coffin[2] by thermally cycling stainless steel under conditions of restraint until failure occurred. The relationship between plastic strain and cycles to failure was found to be of the form $N^{\alpha}\epsilon_p = K$ where N is the cycles to failure, ϵ_p is the strain per cycle, and α and K are constants which depend on the material and test conditions.

Most of the subsequent work has been within the temperature range where the rate of work hardening was appreciably greater than the recovery rate. The work to be discussed in this presentation concerns metals at temperatures where creep and relaxation are the dominant factors.

Equipment

The fact that creep and relaxation are dominant in the temperature range of interest made it both feasible and attractive to substitute mechanical loads for thermal fluctuations as a means of producing strain cycles. The apparatus used at the Oak Ridge National Laboratory has been previously described in detail[3,4] and is represented by the schematic drawing in Fig. 1. By use of pneumatic pressure on the piston, strain in

[1] S. S. Manson, "Behavior of Materials Under Conditions of Thermal Stress," Nat. Adv. Comm. Aeronautics, Tech. Note No. 2933 (1953).

[2] L. F. Coffin, "A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal," Trans. Am. Soc. Mech. Engrs., 76, 931 (1954).

[3] J. R. Weir, R. V. Meghreblian, and D. A. Douglas, "High Temperature Properties in Relation to Design," Proc. Third Sagamore Conference, p 441 (1956).

[4] C. R. Kennedy, "Plastic Strain Absorption as a Criterion for High Temperature Design," Proc. Fourth Sagamore Conference, p 193 (1957).

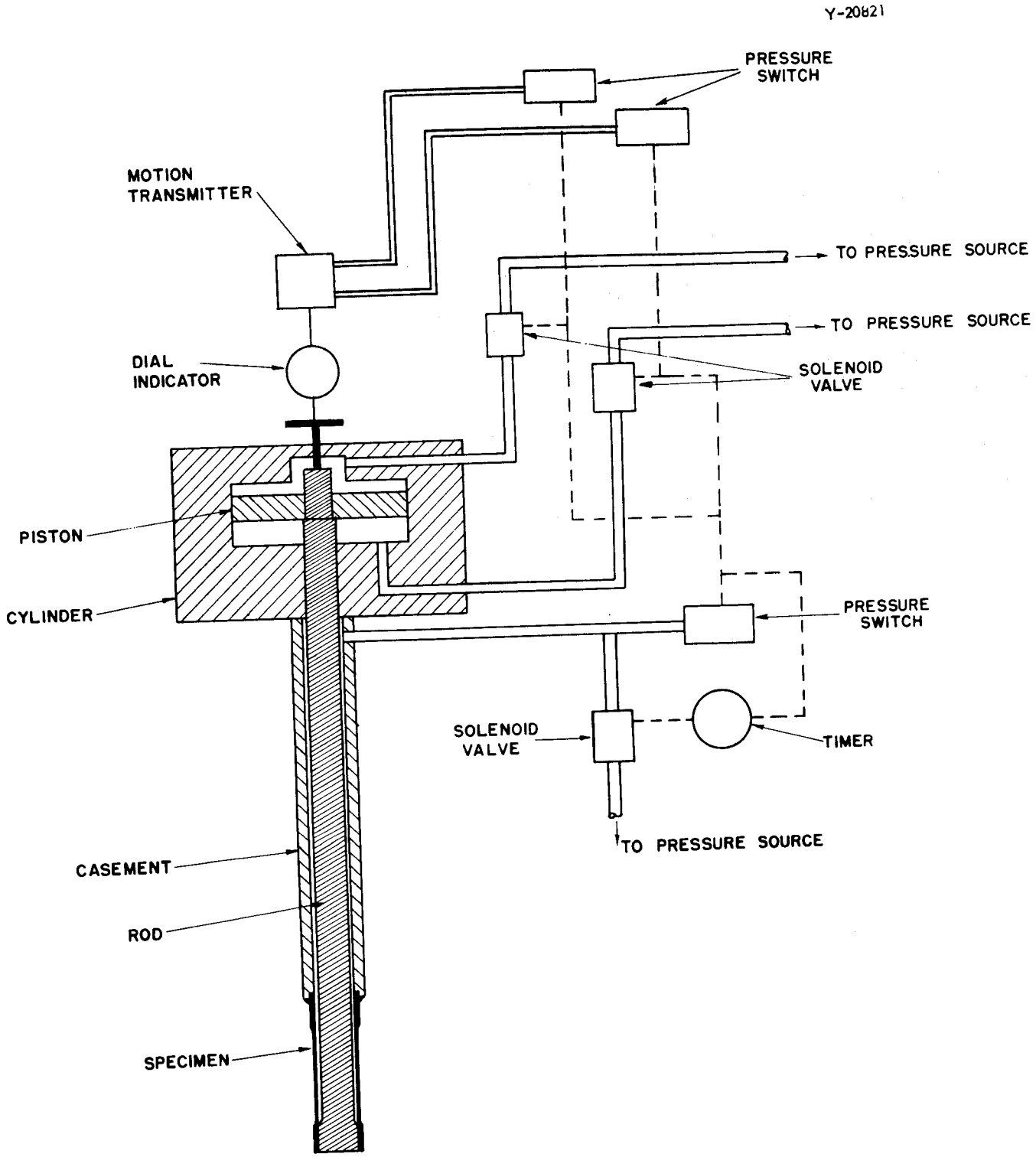

Figure 1. Strain Cycle Apparatus

tension and compression can be imposed on both rod and tubular specimens. The strain amplitude is controlled either by a rigid reference member or by a motion transmitter device which actuates solenoid valves, when the strain reaches a preset value. The plastic strain can be measured in any desired cycle by bleeding off all pressure in the piston chamber, and directly reading the displacement from the zero position of the dial gage. As part of this investigation, additional testing of specimens is being carried out at the University of Alabama under the direction of Dr. W. D. Jordan of the Engineering Mechanical Department. In this program, which is sponsored by ORNL, tubular specimens are thermally cycled in test devices which are modifications of the one described by Coffin[5] in his original work. Thus, by utilizing each of these types of test apparatus it is possible to explore separately the effects of material variables, thermally and mechanically produced strains, geometry of specimen, temperature, and frequency.

Results and Discussion

Most of this investigation has been conducted with Inconel as the test material; however, a few tests were made using Hastelloy "B" and beryllium. Thus, representative data can be compared between metals of quite widely different degrees of strength, ductility, and fabrication history. In Fig. 2 are conventional plots of the plastic strain per cycle, ϵ_p, versus N, the number of cycles to failure. The co-ordinates are plotted on logarithmic scales so that if Manson's relationship $N^{\alpha}\epsilon_p = K$ is satisfied, the data points should define a straight line. It is apparent that this condition is satisfied for each material, but it is also evident that there is a variation in the slope of the line from one metal to another. These slopes are approximately -0.58 for Hastelloy "B", -0.76 for Inconel, and -0.81 for beryllium. Such values are in contrast to the findings of Coffin[6] who shows α to be very nearly -0.5 for several different metals all tested at temperatures below 1200°F.

[5] L. F. Coffin and R. P. Wesley, "Apparatus for Study of Effects of Cyclic Thermal Stresses on Ductile Metals," Trans. Am. Soc. Mech. Engrs., 76, 923 (1954).

[6] L. F. Coffin, "Strain Cycling and Thermal Stress Fatigue," Proc. Fourth Sagamore Conference, p 219 (1957).

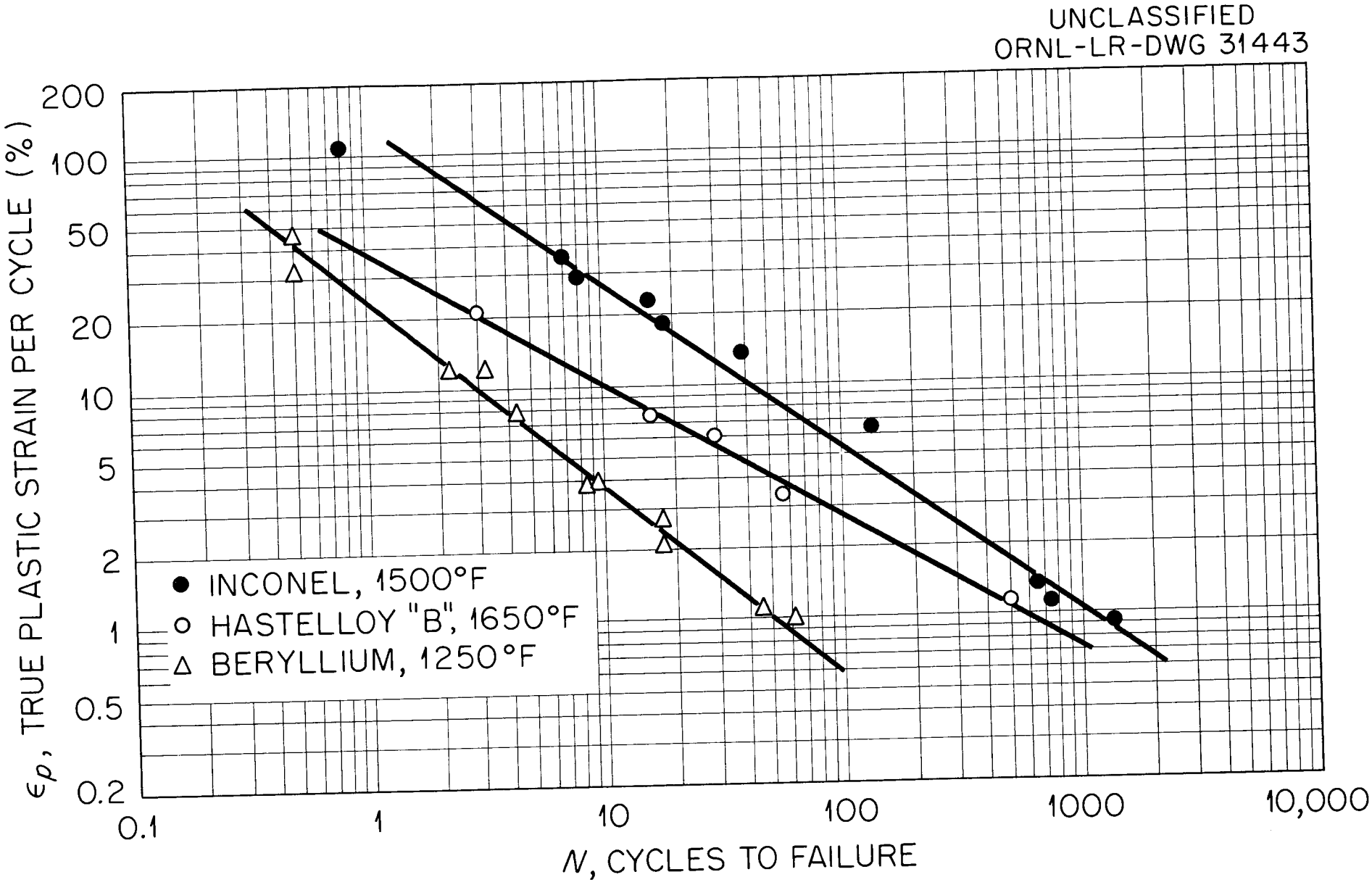

Fig. 2. Comparison of the Strain Cycling Properties of Inconel, Hastelloy "B", and Beryllium.

It has also been noted that for any given material K can be varied by changes in the metallurgical structure. Figure 3 is a plot of the strain-cycling properties of Inconel rod specimens machined from the same heat but differing in the annealing treatment before test. The specimens given an anneal of 1650°F had a finer grain size and were much more resistant to fracture than the specimens given a 2050°F anneal prior to test. Comparative data for rod material at 1300, 1500, and 1600°F, which has been previously reported in the literature,[7] indicates that grain size effects are most pronounced at 1500 and 1600°F. At 1300°F, however, coarse- and fine-grained material have nearly identical strain-cycling properties. Inconel is a solid solution type alloy which is not subject to phase changes or aging reactions so that this difference in behavior seems clearly dependent on the relative grain size. It is also noteworthy that the slopes of the two lines are parallel and thus the α value is consistent for both types of specimens.

The question of whether specimen geometry seriously affects the strain-cycling properties also merits consideration. In Fig. 4 the strain-cycling properties at 1500°F of rod and tube specimens are compared. Tube data fall slightly short of the rod curve but this may be attributed to two factors: (1) There is a difference in the method of sensing failure inasmuch as the tubes are considered to fail when the first crack propagates through the wall whereas rods are tested to complete failure; (2) The rod specimens possess a slightly finer grain size than the tube specimens. The tube data shown include test results from two different heats of metal and the agreement indicates that the cycling properties are not particularly sensitive to small variations in alloy composition.

Naturally one of the most important considerations in regard to test variables is the influence of temperature on the number of cycles to failure. This is particularly important where it is desired to apply isothermal mechanical strain cycling data to design problems where thermal cycling is involved. In Fig. 5 are plotted the results for tests at 1300, 1500, and 1600°F. The band represents the scatter of points obtained

[7] Kennedy, op. cit.

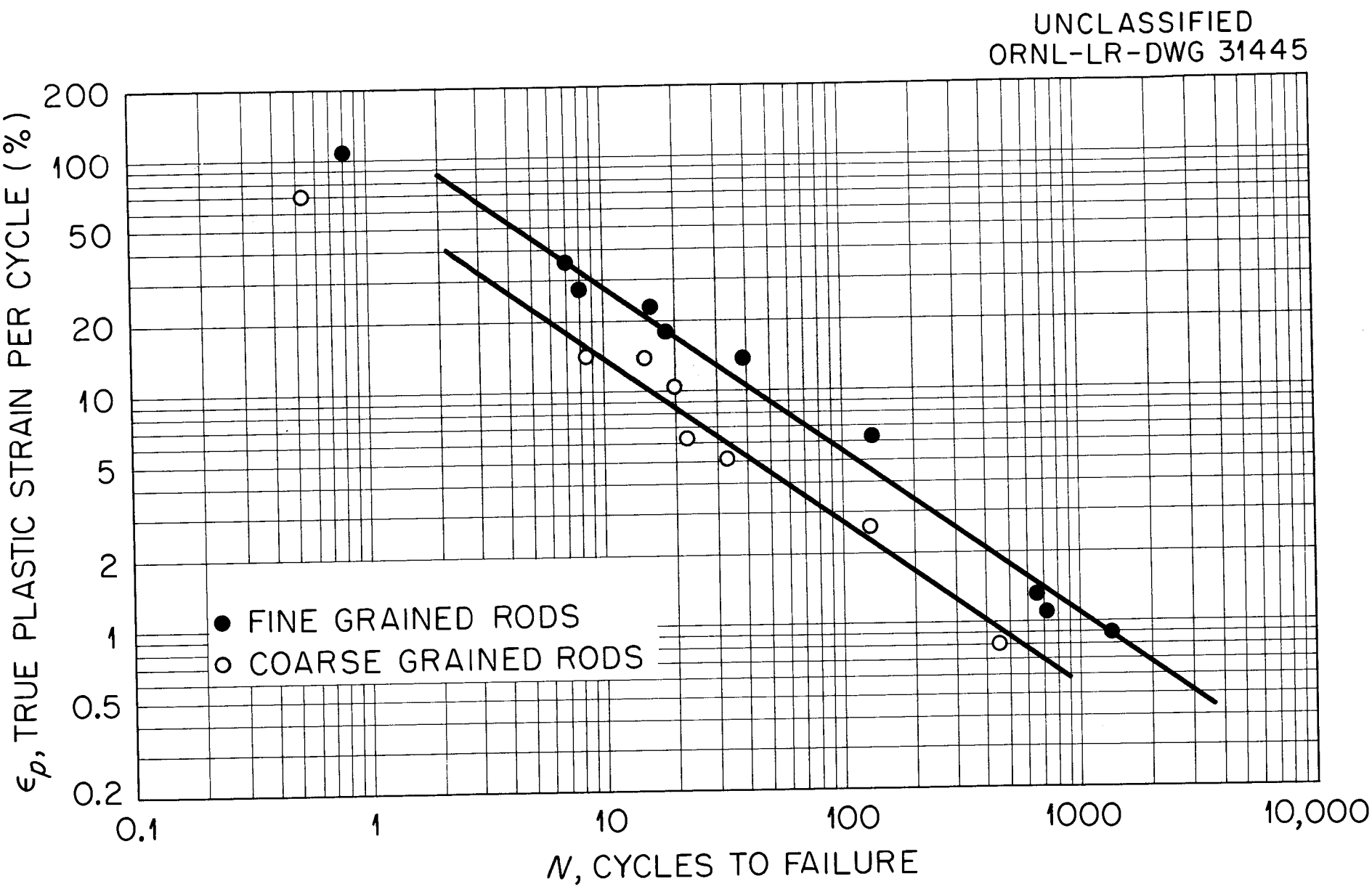

Fig. 3. Effect of Grain Size on the Strain Cycling Properties of Inconel at 1500°F.

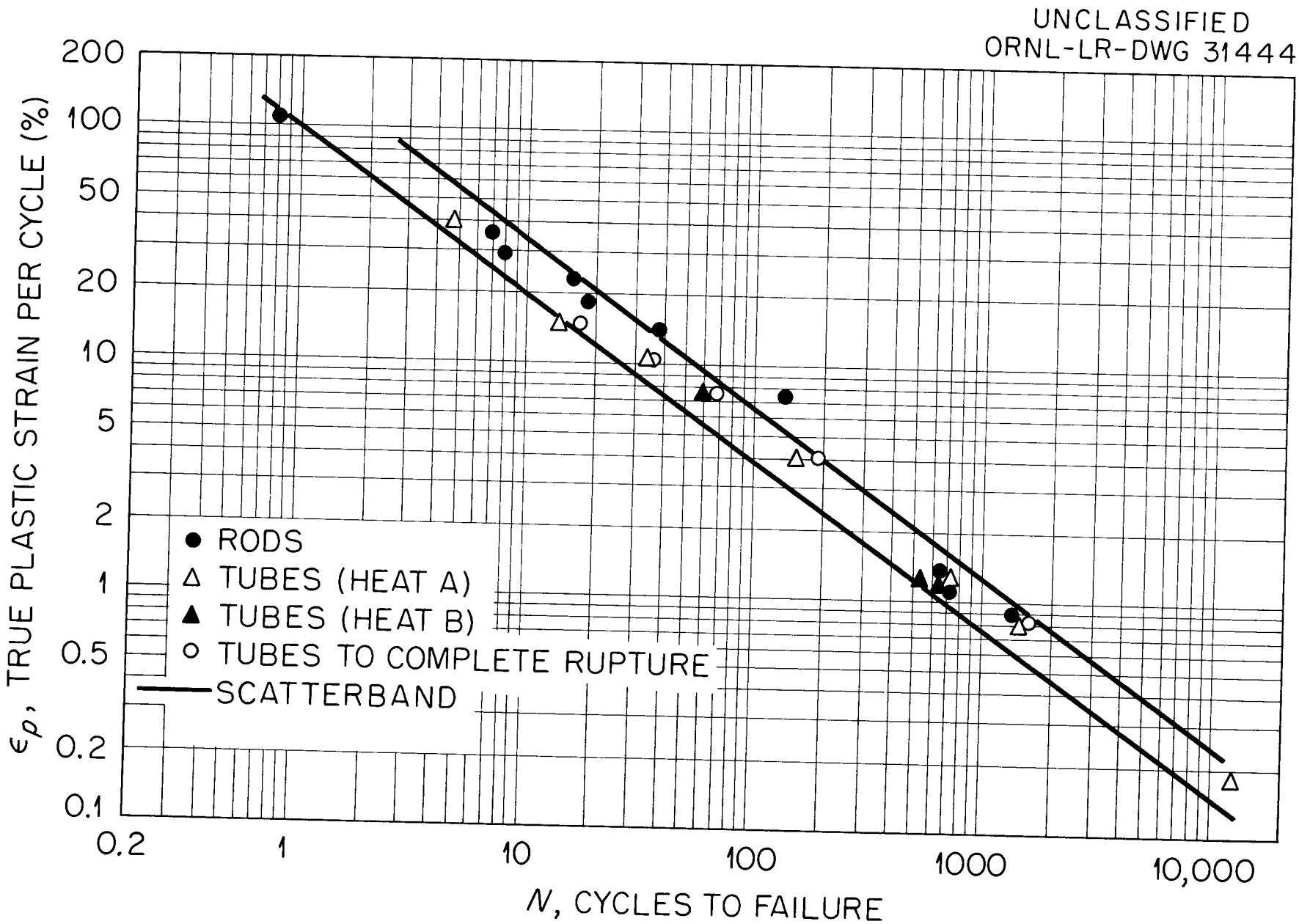

Fig. 4. Strain Cycling Properties of Inconel Tubes and Rods at 1500°F.

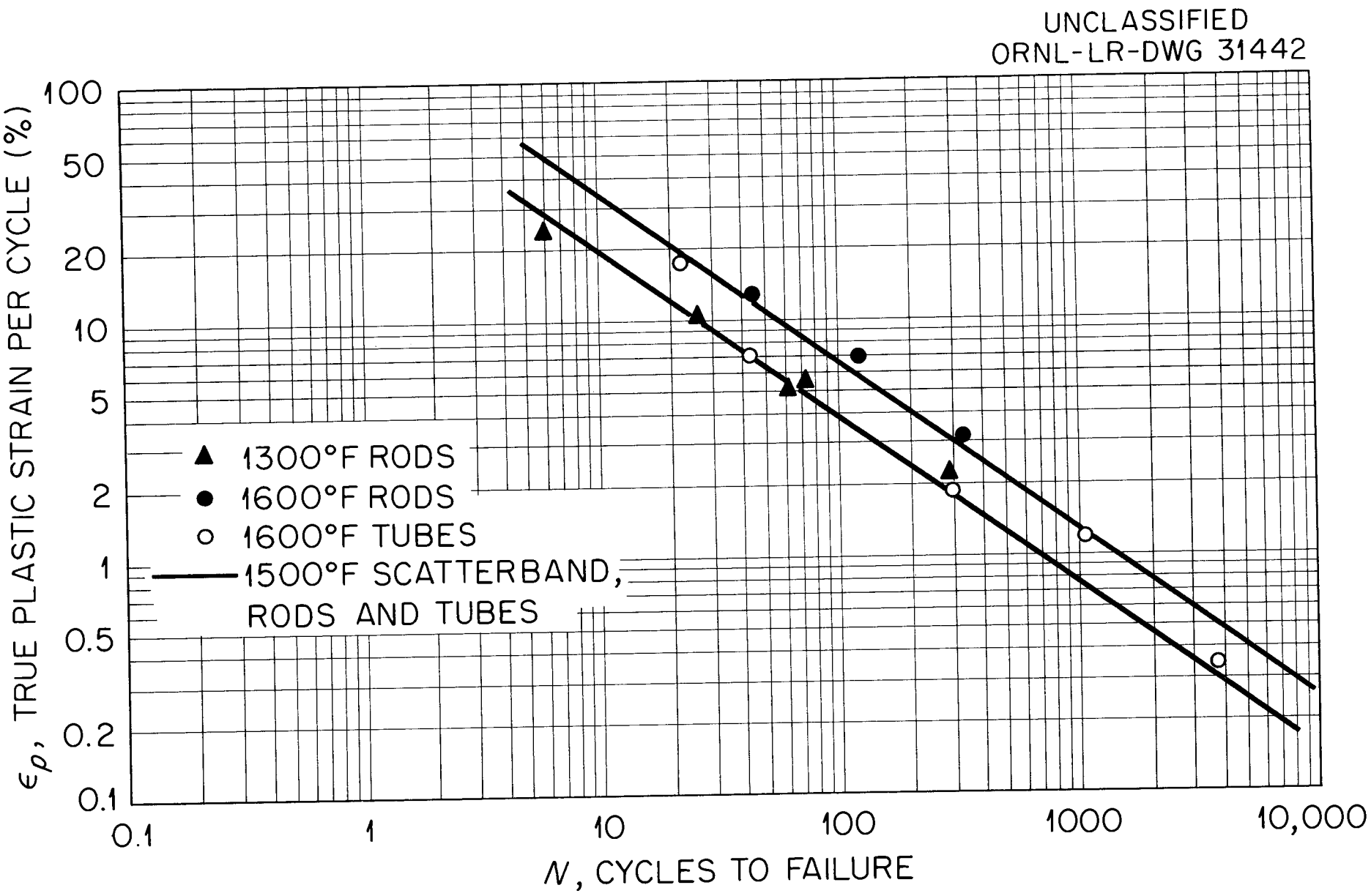

Fig. 5. Effect of Temperature on the Strain Cycling Properties of Inconel.

on an extensive test program of tubes and rods at 1500°F. Nearly all of the data for rods at 1300°F and tubes at 1600°F fall inside this band. The 1600°F rod data fall consistently above the band but is due to the grain size effect previously mentioned. It appears, therefore, that within this particular range there is no major change in fracture behavior as a function of temperature. The fact that Inconel is metallurgically stable, that no grain growth occurs, and that the deformation mechanism is uniform throughout this span are important points to bear in mind when considering these results.

Since temperature appears to have no major influence on the number of cycles to fracture from 1300 to 1600°F, it would appear reasonable to expect mechanical strain cycle results under isothermal conditions to correlate with those obtained by thermally cycling about a corresponding mean temperature. In Fig. 6 are data illustrating the validity of this assumption. The thermal excursions about the 1300°F mean covered the range from 1000 to 1600°F. At the 1500°F mean the temperature extremes were 1400 and 1600°F. It is evident that in the absence of metallurgical instabilities a metal responds to the mechanically produced strain in the same manner as to one thermally induced.

One very important variable to be considered in studying the effect of dynamic loads on the behavior of metals at elevated temperatures is that of frequency. It is well known that the test frequency can be changed over a wide range without producing a marked effect on the S-N curve in low temperature fatigue tests. On the other hand, several investigators have found that frequency does exert an influence on the cycles to rupture at high temperatures. This is especially true at lower frequencies where creep or relaxation may become active. Moore and Alleman[8] have conducted fatigue studies for 0.17% carbon steel at 1200°F employing two frequencies: 200 and 2500 stress cycles per minute. Specimens cycled at the high frequency, 2500 cpm, outlasted the low frequency test by a factor of ten.

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[8] H. F. Moore and N. J. Alleman, Proc. Am. Soc. Testing Mat., 31(1), 114 (1931).

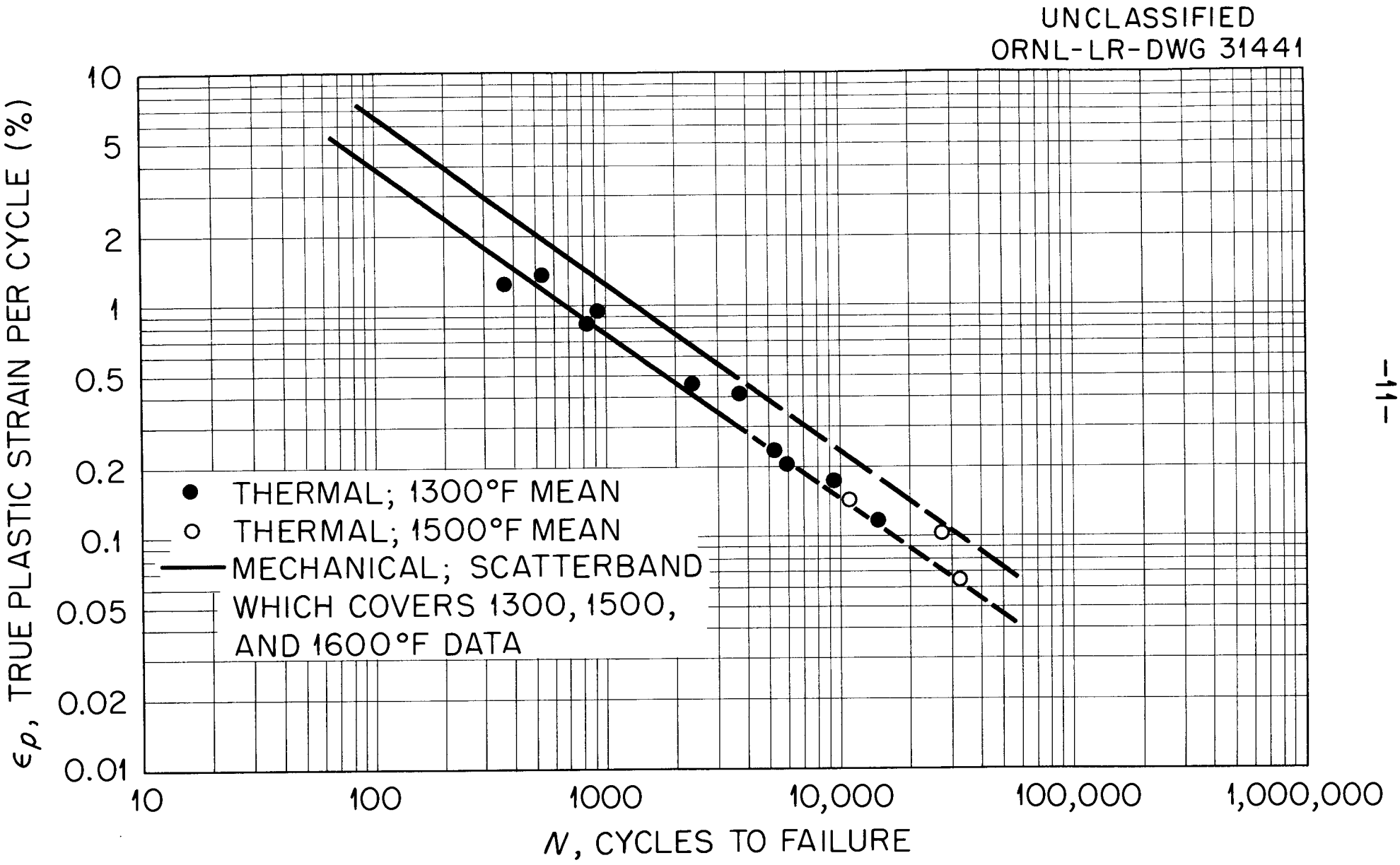

Fig. 6. Comparison of the Thermal and Mechanical Strain Cycling Properties of Inconel.

Hyler[9] has conducted fatigue studies on Inconel at 1200 and 1600°F, using frequencies of 60 and 600 cycles per minute. He observed essentially no difference in the S-N diagram at 1200°F but an appreciable frequency effect was seen at 1600°F. Specimens cycled at 600 cpm endured 10 times more cycles than those at the lower frequency. Fatigue studies on lead have yielded similar results. Dolan[10] reports data for reversed flexure fatigue tests on lead at room temperature for frequencies of 1, 6, 44, and 248 cycles per minute. Curves relating the strain per cycle and the number of cycles to rupture were determined for each frequency. A comparison of the curves revealed that the cycles to rupture increase with increasing frequency. Unfortunately the strain values range only from 0.1 to 1% and the reported strains include both elastic and plastic components. Since plastic strain per cycle was not determined in any of these studies, the direct use of these data for studying the frequency effect on the strain-cycling behavior is not possible. The results, however, raise the question of whether or not the difference in the plastic strain absorbed could explain the variation in properties with frequency. Since plastic strain is generally considered a reliable measure of damage to a structure, it would appear that specimens strained within the same limits of plastic deformation should survive an equivalent number of cycles before fracture, regardless of the rate at which the strain is introduced. However, since design problems involving temperature fluctuations are often concerned with slow thermal cycles, a series of tests to investigate frequency effects was initiated.

The majority of the data previously discussed was obtained using a constant load, thus the specimen creeps until the limiting strain condition is reached in the desired time interval. This type of test is quite easy to regulate for short time cycles, but the prescribed load required to produce specific strains in 10 or 30 min is difficult to obtain. Thus, a slight modification of the equipment was made to provide adjustable but rigid reference limits as shown in Fig. 7. In this test the specimen

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[9] W. S. Hyler, Battelle Memorial Institute, Unpublished Work.

[10] T. J. Dolan, "How Can We Appraise Metals for High-Temperature Service?" Metals Progress, 61(3) 55 (1952).

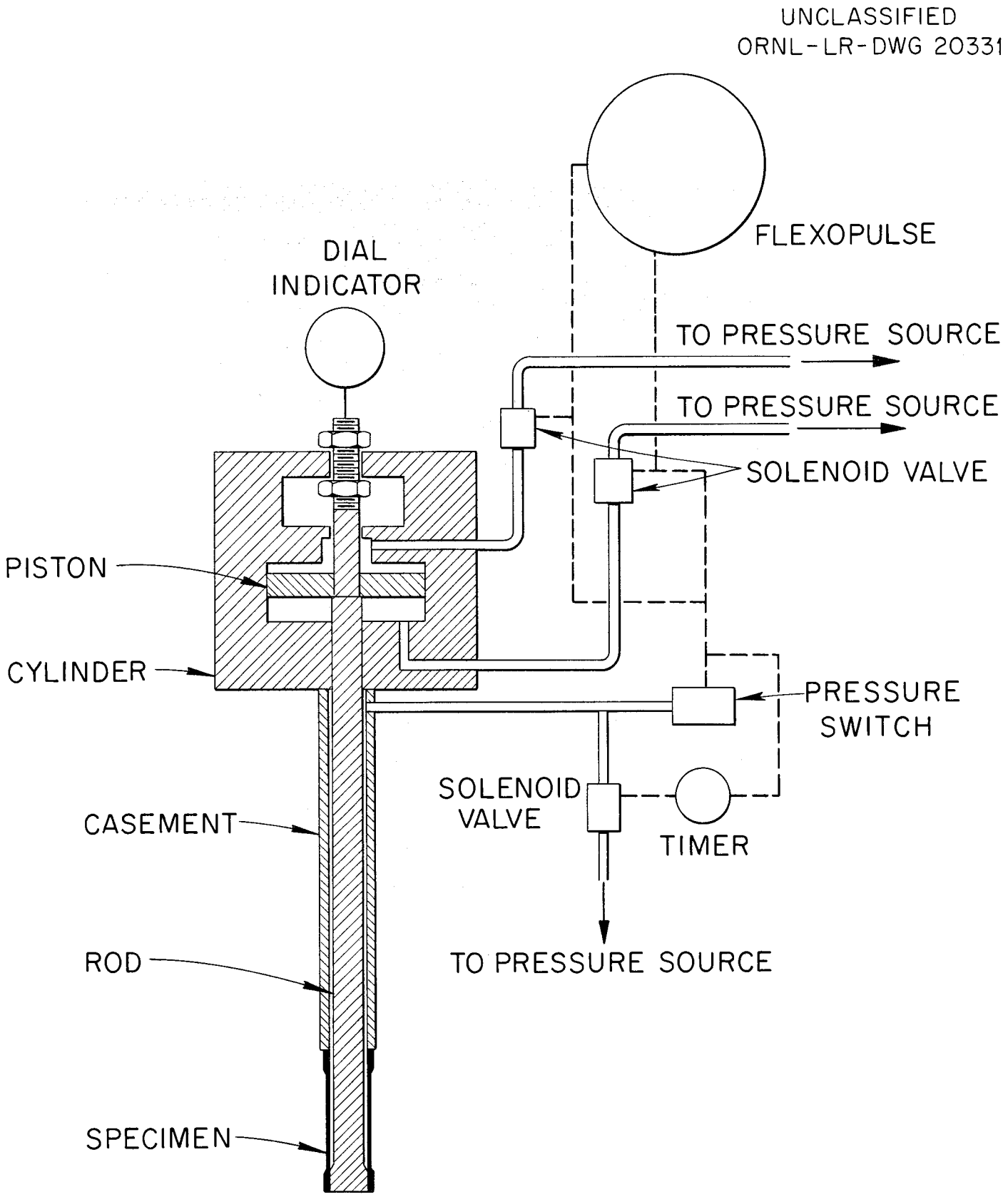

Fig. 7. Strain Cycle Apparatus (Modified).

is strained to the selected limit very rapidly and held at this strain for the selected time interval. During this period, the elastic strain is gradually converted into plastic strain by the relaxation process. It is therefore quite simple to control frequency and vary it from times as short as one-half minute per cycle up to whatever time cycle seems practical. The plastic strain in any given cycle can be measured as before by releasing the load so that specific values are obtained. In Fig. 8 is a comparison of results obtained by the creep method and the relaxation method. Since creep and relaxation are manifestations of the same deformation phenomena, the excellent correlation shown between the two types of tests was expected.

Figure 9 presents the data from a series of tests at 1500°F using the standard 2 min per cycle period in comparison with results when a 30-min time cycle was used. At the high percentages of plastic strain per cycle, good correlation exists, but a significant deviation is clearly shown for the low strain values. The data for 1650°F at 30 min per cycle follow a trend similar to that at 1500°F, but at 1300°F, as shown in Fig. 10, the only test point which falls outside of the 2 min per cycle data occurs below 1% strain and even here the deviation is not appreciable.

There is, of course, considerable engineering interest in the fact that for the same amount of repeated plastic deformation, a metal subjected to slowly fluctuating loads will survive for only a fraction of the cycles of a specimen cycled more rapidly. This is especially important since the frequency appears to exert the greatest influence for values of strain below 2% which are also equivalent to the thermal strains most often encountered during service. There is no evidence to indicate that the longer thermal exposure encountered in the low frequency tests is detrimental so it must be concluded that the mechanisms controlling fracture at high temperatures are strongly influenced by time as well as plastic flow.

Conclusions

This investigation into the high-temperature behavior of metals under dynamic loads reveals the following significant points:

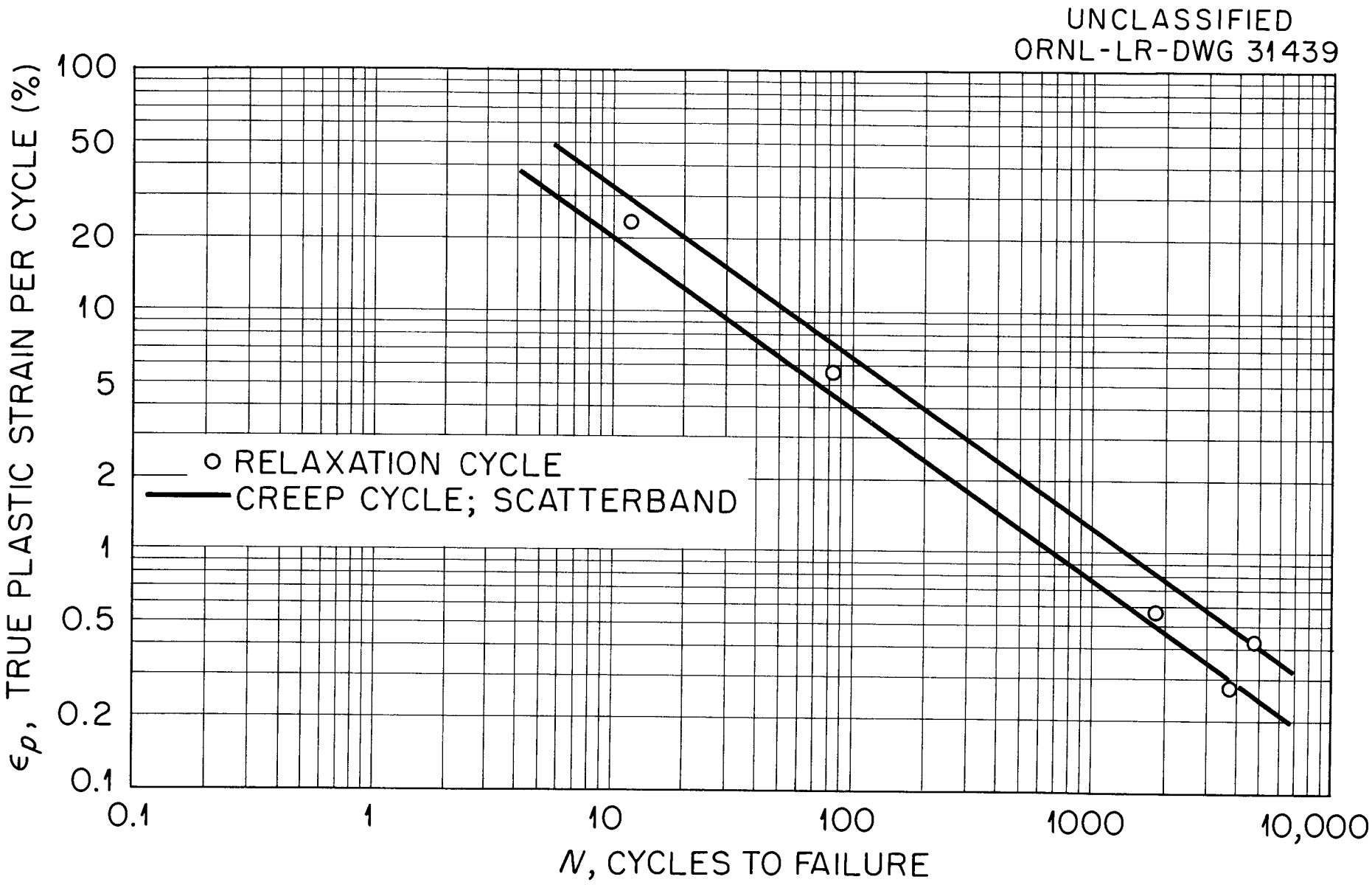

Fig. 8. Comparison of the Strain Cycling Properties of Inconel Subjected to Creep and Relaxation Cycles at 1500°F.

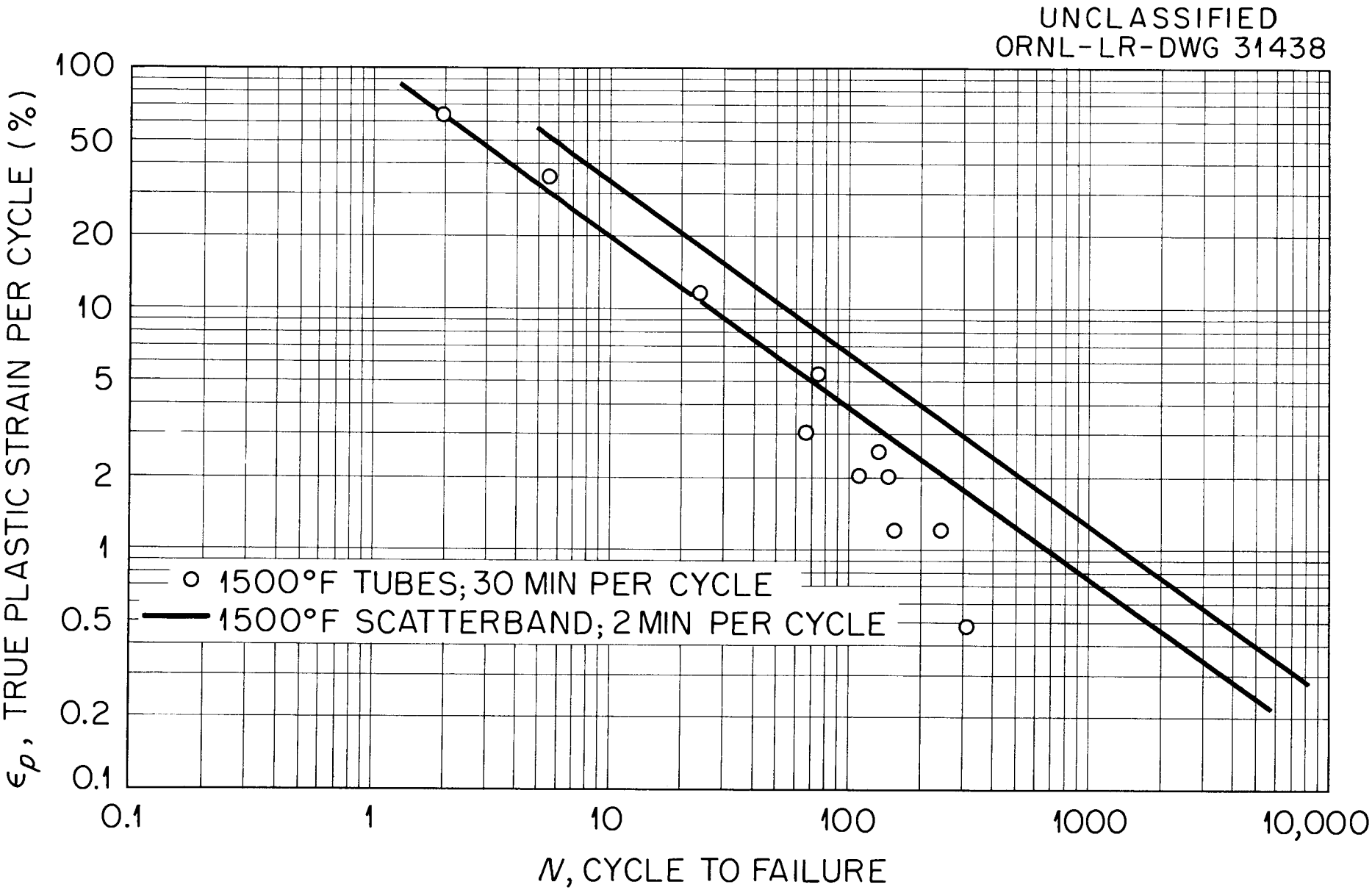

Fig. 9. Effect of Frequency on the Strain Cycling Properties of Inconel at 1500°F.

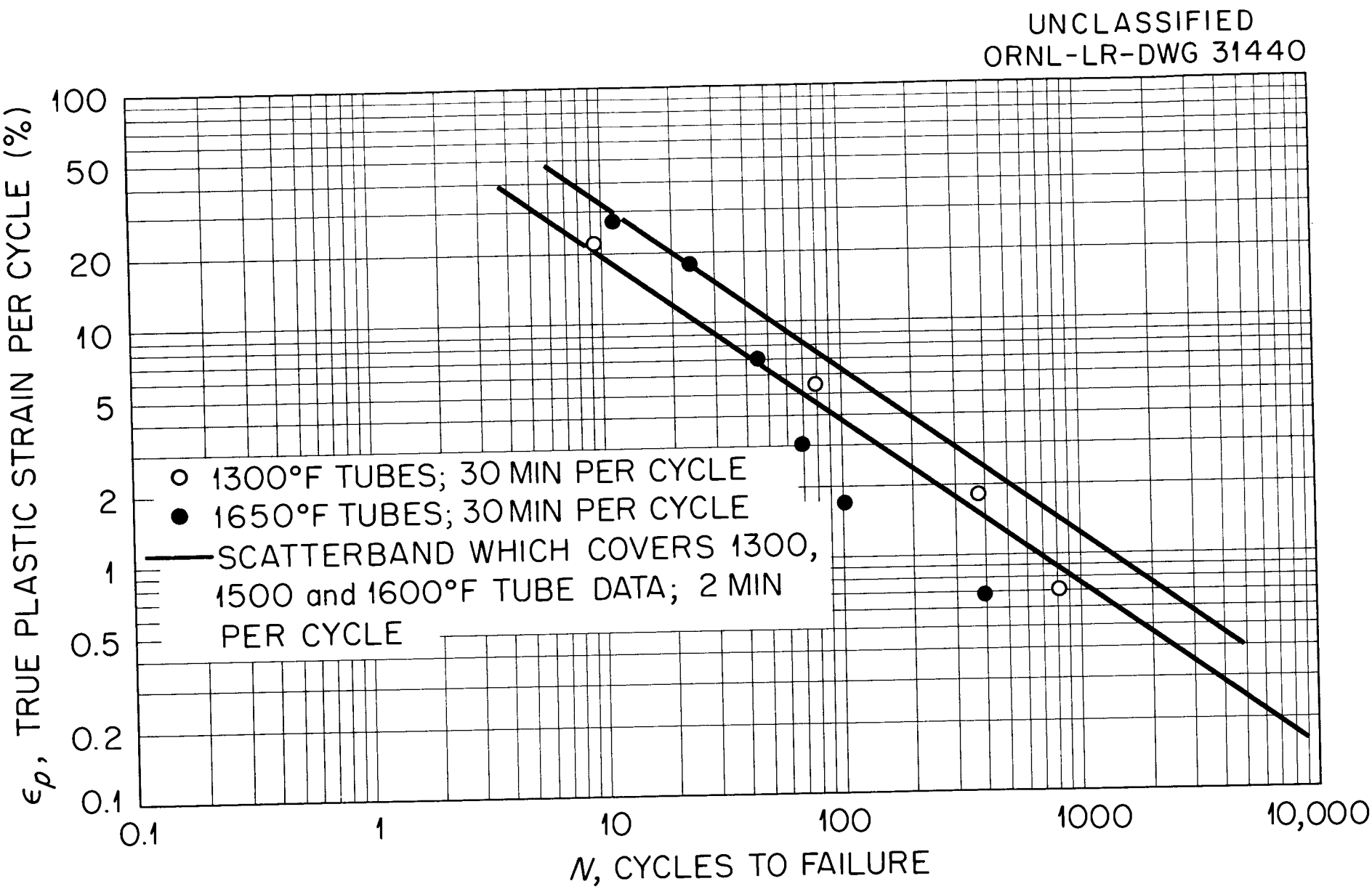

Fig. 10. Effect of Temperature on the Strain Cycling Properties of Inconel Tested at 30 Min per Cycle.

(1) The relationship, $N^{\alpha}\epsilon_p = K$, is verified for several metals at elevated temperatures providing that the cycle time is relatively short. The exponent, α, is found to be dependent on the material and to vary from -0.58 to -0.81. Since many metals have exhibited a slope of -0.5 in low-temperature tests, the greater slopes seen at the high temperatures indicate a dependence on temperature or deformation mechanism rather than directly on material composition. In this study Inconel is shown to have no significant variation in α over a 300°F range which suggests that the deformation mechanism is the major factor affecting the slope. Thus, there may be a break in the strain-cycling curve similar to the one observed for the equicohesive temperature in creep. The K factor is found to be changed significantly by changes in grain size; thus, it is believed that the displacement of the rupture curve can be attributed to metallurgical changes.

(2) Metals respond in the same manner to plastic strain whether it is introduced by thermal changes or mechanically imposed loads. This statement must be qualified to the extent that the deformation mechanism and metallurgical structure must not be altered by the temperature fluctuations.

(3) There is a marked changed in the number of equivalent strain cycles a metal can survive as a function of the rate at which the strains are reversed. These phenomena are apparently confined to the high-temperature region and establish the fact that plastic deformation is not the sole mechanism controlling the fracture life of a metal.

Acknowledgments

The authors would like to acknowledge the contributions of K. W. Boling, E. Bolling, and E. B. Patton of the Mechanical Properties Group in the performing of the tests.

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