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ON

NOTCH SENSITIVITY OF HEAT RESISTANT ALLOYS AT ELEVATED TEMPERATURE

By

H. P. Voorhees
J. W. Freeman

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SUMMARY

This report covers progress to date of a program aimed at the accumulation and analysis of data on the significance of notched-bar rupture tests of alloys for high-temperature service. For its part of the joint research by two contractors, the University is to study the role of relaxation of stress concentrations by creep relaxation, together with influence of metallurgical variables on the notched-bar rupture test.

Data from the literature have been combined with results obtained in a canvass of four other laboratories doing this type of testing. These results have been presented in graphical form, with separate identification for different forms of test bar or for different prior treatments.

Examination of the compiled data reveals that notch sensitivity is a complex function of notch geometry, physical properties and microstructures. Though no quantitative generalities are apparent for the notches employed in the tests reviewed, sharper notches gave lower notched-bar rupture strength. With fixed notch geometry, sensitivity to notch effects appears to be related to ductility of the conventional smooth rupture bars, but no one minimum value of elongation marks onset of notch sensitivity for different alloys or for different conditions of heat treatment.

Data on metallurgical factors are too sparse to permit any sound generalization at present.

Examination of probable effects of notches on rupture life indicates that the notch should lead to strengthening if rupture life depends on an effective stress related to differences in principal stresses and if high initial stresses can be reduced sufficiently by a combination of plastic strain during loading and stress relieval by creep relaxation during the test.

After detailed consideration of the probable role of creep and relaxation in notch-bar rupture testing, a stepwise procedure has been devised whereby the simultaneous creep strain and pure stress relaxation are evaluated as separate alternate processes. Preliminary calculations for two quite different assumed patterns of initial stress showed that exact knowledge of starting stress was not critical for the arbitrary set of data used. An experimental program has been devised to prove or disprove the analysis for actual data on an alloy and conditions of interest.

Relaxation tests have been started with an advance shipment of a small portion of S-816 stock received before prolonged strikes at plants of the supplier delayed delivery of the balance of the material.

General outlines of a suitable experimental program have been drawn and a tentative notch configuration chosen, so that tests may now be initiated with 16-25-6 to study changes in notch sensitivity of this alloy resulting from metallurgical variables. If stocks of Waspaloy or Inconel-550 are received in the coming quarter, preliminary runs will be started to determine conditions for notch sensitivity.

In all tests, results are to be integrated with those to be obtained by the second contractor in the program.

INTRODUCTION

The work under Contract AF 18(600)-62 dated December 11, 1951, was initiated for the purpose of clarifying the significance of notch-bar rupture test data as applied to types of alloys commonly used in the gas turbines of jet engines. Engineers generally are concerned over the problem of providing for the effects of stress concentrations in structures. This is most commonly accomplished by specifying minimum ductility for the materials.

At high temperatures where creep occurs during service, the significance of ductility is unsettled. Alloys are evaluated by short-time tensile, creep, and rupture tests. The measured elongation and reduction of area usually decrease with increasing time for fracture as the testing time shifts from the tensile test to the rupture test. Opinion of engineers seems to be divided regarding the applicability of elongation and reduction of area values from such tests as a guide in establishing provisions for avoiding premature failures from stress concentrations during service at high temperatures.

Increasing recourse has been made by engineers to rupture tests conducted on notched specimens, the claim being made that such tests are necessary to evaluate ability of alloys to withstand the stress concentrations of service. A number of problems still face engineers.

1. Data from notched tests are scarce and somewhat more difficult to obtain than data for smooth bar tests. The determination of the existence of a relationship between elongation or reduction of area in the rupture test and sensitivity to stress concentration would be useful.

2. Data from notched specimens are difficult to interpret except as a direct comparison with unnotched bars. The notch sensitivity for alloys varies with the time for rupture as well as with the testing temperature. The problem would be greatly simplified if data from smooth specimens could be properly evaluated to predict behavior in structures with stress concentration present.

3. The mechanism by which notch sensitivity develops with increasing time for fracture, and in some cases disappears at longer testing times, is not understood. It would seem that the opportunity for creep to occur and relieve stress concentrations ought to reduce the possibility of notch sensitivity. The relaxation-creep characteristics of alloys would certainly seem to be related to the proper interpretation of data.

4. Notch specimens generally utilize a very severe notch. This presents the problem of interpreting the results in terms of the less severe stress concentrations usually encountered in service. It is well known that certain alloys which are notch sensitive by present test methods have performed satisfactorily in service.

5. The influence of notch geometry in rupture tests is controversial. Varying notches result in varying test results. The information available seems inadequate to standarize the specimens. Also the method of preparing the notch has uncertain effects.

6. Metallurgical factors are sure to be important. The influence of varying microstructures produced by varying the prior history of specimens can have profound effects on elongation and reduction of area in the rupture test. Even greater effects on notch-bar testing are certain.

The answer desired by a designer of a jet-engine turbine blade is the life expectancy for a blade of given alloy when subjected to a given history of temperature under expected variable operating stresses. This situation contains three basic differences from the ordinary creep or rupture tests performed on materials for high-temperature service.

(1) The stress pattern is a complex of twisting, bending, centrifugal and thermal stresses rather than a pure axial tension.

(2) The stress pattern may change with time and with temperature.

(3) Temperature of operation is not constant over the operating life.

(4) Certain metallurgical variables may be present, such as the tendency to crack set up by surface finish conditions or lack of control of grain structures.

With these factors present, conventional tests cannot give more than a general indication of strength under the actual conditions of service. One rather direct approach to the problem is afforded by the expedient of testing notched-bars in the usual tensile stress-rupture equipment. A given notch develops a unique initial stress concentration composed of three component principal tensile stresses. If these principal stresses at the critical point in a turbine blade are all tensile, it might be possible to approximate the stress distribution at that point by a suitable choice of notch geometry in a tensile specimen. Alternately, comparative rupture strengths of smooth bars versus bars with variable notch configuration might allow qualitative prediction of behavior in an actual installation operated at steady-state conditions. In any structure where one or more compressive stress acts in conjuntion with tensile stresses, it is questionable whether any combination of notched-bar tensile-rupture tests would supply the desired answer.

A second approach to the ultimate prediction of behavior under tri-axial loading involves analysis of stress-rupture tests under a variety of stress combinations in search of a general law for all cases. This process is sure to take considerable time and much careful testing, but should be of the greatest ultimate value. Even if one were to overlook the shortcomings of the first or more direct approach, above, he would still require the more general analysis if he is to include effects of variable operating conditions.

A first step would be to establish for the alloy under consideration a firm method to predict total life until rupture for a specimen operated at different discrete levels of pure tension and/or of temperature over different portions of the test. A further requirement is formulation of a law to predict rupture life at fixed temperature and constant stress distribution, but with several stresses acting simultaneously at a point to give a multi-axial stress condition.

Comparison of smooth versus notched bars of variable configuration might then give a tentative law which can be confirmed or disproved only by future experimenters conducting tests where widely-differing types of stress exist. The final result to be hoped for is a method of combining these individual findings for steady multi-axial stresses, for variable simple stress and for variable temperature in such a manner that a minimum of tests with smooth and notched bars would supply sufficient information to design a structure for any set of conditions that might be outlined.

Fundamentals of Notch Effects

Before the details of notch-bar tests are considered, it might be well to review along general lines the effects of a notch on a rupture specimen and how these effects alter with time.

A circumferential notch in a tensile specimen introduces at the root of the notch a high axial stress (S_a) and a hoop stress (S_h) which is smaller but still higher than the nominal stress (axial load/minimum cross section of the bar). A radial stress (S_r) is also created, starting with a value of zero at the base of the notch and always remaining smaller than the nominal axial stress for radii nearer the axis of the specimen. For small strains, the average axial stress over the section of the notch remains constant for a constant load. Consequently, the fibers at the notch root with high axial stress support proportionately more of the load than do those nearer the interior of the bar. The stress near the specimen axis thus is lower than is the uniform stress of a smooth bar.

When stresses in different directions are present in a material they interact. Forces in different directions tend to cancel each other's effect when both are tensile or both are compressive. According to the maximum shear-strain energy theory of yielding, for ductile materials the stress ($\overline{S}$) which is effective in causing plastic yielding to take place may be computed by the expression

$$2\,\overline{S}^2 = (S_a - S_h)^2 + (S_a - S_r)^2 + (S_h - S_r)^2$$

For elastic conditions the effective stress over much of the bar will exceed the nominal because S_a is so much higher than S_h and because S_r is small. The maximum stress concentration occurs at the root of the notch. Towards the axis of the bar each of the stresses becomes smaller, the stress differences even smaller, and the effective stress becomes a small fraction of the nominal stress of the entire bar.

When yielding occurs, the high axial stress near the notch root is relieved, shifting a greater portion of the total axial load to portions of the test bar farther in from the notch. The hoop stress and radial stress also tend to become more uniform, but still remain as finite tensions. The effective stress at points near the axis never is able to rise above the nominal axial stress while the effective stress near the notch root steadily drops. Soon the effective stress of all points approaches that for a uniform smooth bar in simple tension, where the effective stress starts the same for all points and remains very nearly constant. The tendency for stresses to level is less marked for materials which have high work-hardening ability.

At elevated temperatures, stresses present in a restrained portion of metal tend to decrease with time by a process of stress relaxation, where elastic strains are replaced by plastic strains without gross dimensional change. The rate of such relaxation is non-linear in stress, so that high stresses show a much faster rate of fall than do stresses of slightly lower initial value. It is expected that the extreme stress concentration found at the base of a sharp notch upon loading a notched bar should relax rapidly, again shifting more of the total load to fibers nearer the axis of the specimen. The different rates of relaxation for the three principal stresses of a fiber near the root of the notch should cause a progressive reduction in the differences between these principal stresses. And it should be remembered that it is these differences which determine the effective stress.

Since the effective stress defined above has been verified as a satisfactory combination of the individual stresses in correlations of yielding and plastic flow of ductile metals at room temperature and of creep of metals at elevated temperatures when constant multiple stresses are acting, it appears reasonable to use this same effective stress in the first attempts to correlate rate of relaxation of variable multi-axial stresses. If this assumption holds, the effective stress acting at any point across the minimum section of a notched bar should gradually be reduced so that a significant portion of the test life of such a bar could be at a level of effective stress below that for a smooth bar, providing the rate of this stress relaxation had been sufficiently rapid.

OUTLINE OF INVESTIGATION

An Air Force representative notified the University at the time the contract was awarded that the work on the problem was to be divided with another contractor. Subsequent discussion followed, and during a meeting at Wright-Patterson Air Force Base on January 24, 1952, it was established that the work at the University would consist of the following:

1. Participate in a canvass of the literature and testing laboratoreies to accumulate and analyze available data from rupture tests on notched-bar specimens.

2. Study the role of stress concentration relaxation by creep in the notched-bar rupture test.

3. Study the influence of metallurgical variables on notched-bar rupture test results.

During the above meeting it was agreed upon by all concerned that the investigation would be conducted to establish fundamental principles. "Design Data" accumulation would be avoided unless the survey of available data indicated certain tests to be desirable.

The other contractor would participate in the accumulation and analysis of available data. It was understood that the two groups would contact different ones of the laboratories doing such testing. The University was to request data from Allegheny Ludlum Steel Corporation, Crucible Steel Company, Lewis Laboratory of the NACA, and the International Nickel company.

The relaxation work was to be correlated with the notched-bar testing work of the other contractor to avoid duplication of effort. The correlation of effort in general was to involve agreement on the test to be made and which laboratory was to conduct the needed tests.

Choice of test materials was discussed at some length. Castings were eliminated on the basis that they were too variable for fundamental work. S-816 alloy was agreed upon as one test material and the University was delegated to procure the 80 feet of test stock. One-half of the stock was to be furnished to the other contractor.

It was agreed that other materials should include typical alloys hardened with Ti + Al. However, no definite choice was made largely because the characteristics of the various alloys were uncertain. It was presumed that the survey would enable a choice to be made. Selection of all materials was rendered difficult by the fact that the alloys of most future interest were understood not to be notch sensitive when properly prepared. One of the most influential factors in establishing practical heat treatments was that the alloys would not be notch sensitive.

A fundamental study of behavior of these alloys in the notch-sensitive state will probably involve either the use of non-standard heat treatments or testing under conditions different from those usually found in service. In either case, care would have to be exercised to avoid misinterpretation, while any test results obtained under these conditions would have little value as design data.

The University was assigned the problem of investigating the effects of processing variables on the notch sensitivity of 16-25-6 alloy. In so far as possible the work was to supplement work on smooth bars carried out at the University in other investigations. It was also understood that the University would investigate the influence of abnormal structures in the other alloys to be included in the program. Such abnormal structures would be designed to approximate the ranges sometimes encountered in commercial production so as to demonstrate what their effect might be on notch sensitivity under creep rupture conditions.

The contract also specified that the work should be coordinated with related activities of the Gas-Turbine Panel of the ASME-ASTM Joint Committee on the Effects of Temperature on the Properties of Metals. Their recent activities centered around a "Symposium on Notches and Metallurgical Changes on Strength and Ductility of Metals at Elevated Temperatures", held in connection with the Fifty-fifth Annual Meeting of the ASTM the week of June 22, 1952. Close association with the program made it appear that the present investigation should benefit considerably from information to be made available by this symposium. In particular, it had been indicated that considerable data would be forthcoming on the subjects of notch geometry and of the relationship of rupture-test elongation and reduction of area to notch sensitivity.

CURRENT STATUS OF THE INVESTIGATION

The status of the phases of the work in progress may be summarized as follows:

1. Compilation of Data

The next section of the report summarizes the data obtained. As yet the specific information collected by the other contractors has not been made available so that it is impossible to judge the completeness of the available data.

2. Role of Relaxation in Notched-Bar Rupture Testing

An exhaustive analysis of the expected behavior of metal in the vicinity of a notch during rupture testing has been made. The analysis developed requires a starting point of known or assumed stress pattern. Since the actual distribution of stress at the moment of loading a notched bar is difficult to establish exactly a check was made to see how serious an error in initial stress should be in determining the final result. A complete set of calculations extending to over 1000 hours was made for each of two extreme conditions. For both analyses the same arbitrary data used assumed the 1000 hour time to be well short of third-stage creep at the highest stress involved. For elastic loading as predicted for a hyperbolic notch and for uniform axial stress combined with hoop and radial stress assumed to vary linearly with the radius, stepwise calculations of stress relations indicated approach to a common final stress condition. On the basis of this, an experimental program has been devised to prove or disprove the analysis. This subject is treated in more detail in a subsequent section.

3. Influence of Prior Treatment on the Notch Sensitivity of 16-25-6

This phase of the work is about to be started with stock on hand previously used for tests on smooth bars. Data obtained during the survey indicate that a notch-root radius of 0.025 inch will not cause notch sensitivity at 1200°F. This notch gives a rather low stress concentration. The work to be done will include a range of solution, aging and hot-cold working conditions so as to develop the influence of structural variation on notch sensitivity for this alloy.

4. Procurement of S-816 stock

Eighty feet of S-816 stock was ordered from the Allegheny Ludlum Steel Corporation. This material was ready to be shipped when the strike occured in the steel industry. Shipment has been delayed until about one week after the mill reopens. Information available at the writing of this report indicated the strike had not yet been settled.

COMPILATION OF DATA ON NOTCH SENSITIVITY FOR ALLOYS OF INTEREST

Detailed tabulations are being prepared of notched-bar rupture data for alloys which might serve as blade materials for jet engines or for which available data include notch geometry information or metallurgical principles useful to this investigation. In this survey the listed organizations were contacted to supplement information found in a search of published literature and of reports in files of the University:

Allegheny Ludlum Steel Corporation (Dr. G. Mohling)
Crucible Steel Company (Mr. D. W. Kaufmann)
International Nickel Company (Mr. C. A. Crawford)
National Advisory Committee for Aeronautics (Lewis Laboratory)

Allegheny Ludlum and the International Nickel Company supplied limited data for alloys of the type under consideration. Crucible Steel Company data were limited to alloys of no interest to this investigation and their representative stated that they did not have data on any of the fundamental principles involved. The NACA data were included in papers presented before the ASTM in June 1952.

NOTCHED BAR RUPTURE PROPERTIES OF ALLOYS

Rupture data for smooth and notched bars have been assembled for S-816, S-816-Cb+Ta, M-252, and Inconel-X as alloys of special interest in the present project. Also included are plots for three alloys tested after varying prior treatments: Refractaloy 26, K-42-B, and Timken alloy 16-25-6. Numbers adjacent to points for smooth bars indicate percent elongation at rupture.

Data points for a given alloy are distinguished for different heat treatments or for different types of specimen by a letter code identified in the summary below. Reference numbers relate to the bibliography at the end of this report. Descriptions of the notched bars are given in terms of the diameter (D) before notching, the diameter (d) at the base of the notch, and the radius of curvature (r) of the notch root (all given in inches), plus the notch angle in degrees.

S-816 (See Fig. 1)

Heat Treatment	Notched Specimen Design D	d	r	r/d	d/D	Angle	Ref.
2150°F, 1 hr, WQ + 1400°F, 12 hr, AC	0.177	0.125	0.005	0.04	0.707	60°	1

In the original reference, data for all temperatures were presented on a single curve for the notched bars. A single curve for smooth bars was also drawn so as to give the average of these and other tests with S-816. This method of plotting master rupture curves has been shown to give good correlation of smooth-bar tests (2), but examination of the separate points for different test temperatures with notched bars leaves some doubt as to its desirability in presenting results to show areas of notch sensitivity. Pending further verification of such parameter curves for notched-bar tests, all results plotted in that manner have been replotted for this report.

Though the data indicate no notch sensitivity for the conditions tested for rupture lives up to 1000 hours, the limited number of tests at 1200°F suggest that S-816 might exhibit sensitivity to the notch used for runs extending slightly more than 1000 hours, while at 1350°F there appears to be little difference between smooth and notched specimens for the notch acuity used.

S-816-Cb+Ta (See Fig. 2)

Data for three different heats have been assembled on the same plot for alloy of nominal composition with 3.5-4 percent of added columbium plus tantalum:

Code	Heat Treatment	Notched Specimen Design						Ref.
		D	d	r	r/d	d/D	Angle	
A	2150°F, 1 hr, WQ+ 1400°F, 12 hr, AC	0.177	0.125	0.005	0.04	0.707	60°	1
B (Heat U-732)	2250°F, 1 hr, WQ+ 1400°F, 16 hr, AC	0.275	0.1955	0.005	0.0256	0.71	45°	3
C (Heat U-871)	2250°F, 1 hr, WQ+ 1400°F, 16 hr, AC	0.275	0.1955	0.005	0.0256	0.71	45°	3

The number of tests reported are too few to allow differentiation between effects of variable solution temperature and those due to notch configuration.

Very limited data at 1200°F suggest notch sensitivity at about 200 hours rupture life where smooth bar elongations are still approximately 10-20 percent.

M-252 (See Fig. 3)

All results for this alloy are for tests of rather short duration used for correlation with the G. E. parameter. Some data reported for very short tests at 1650°F have not been included on the plots of this report.

Heat Treatment	Notched Specimen Design						Ref.
	D	d	r	r/d	d/D	Angle	
Forged from 2050°F + 1950°F, 4 hr, AC + 1650°F, 1 hr, FC to 1000°F at 90°F/hr.	0.177	0.125	0.005	0.040	0.707	60°	1

M-252 (concluded)

For the conditions examined, no evidence of notch embrittlement was apparent.

Inconel-X (See Fig. 4)

Code	Heat Treatment	Notched Specimen Design						Ref.
		D	d	r	r/d	d/D	Angle	
A	2100°F, 4 hr + 1550°F, 24 hr + 1300°F, 20 hr	0.370	0.250	0.005	0.02	0.675	60°	4
B	Same as A	Same as A, then ground flat on opposite sides to form a bar 0.100-inch thick						4
C	2100°F, 4 hr, Oil + 1550°F, 24 hr, AC + 1300°F, 20 hr, AC	0.424	0.300	not over 0.002	≤ 0.0067	0.707	60°	5

For the very limited tests reported, a bar made by grinding flats on opposite sides of a notched cylindrical bar showed greater sensitivity than did the original round bar with the same notch.

At the two temperatures where data were available for notches with 0.005-inch root radius and also for a sharp notch ($r \leqq 0.002$-inch), the sharp notch had the lower strength in both instances. At 1350°F, the sharper of the two notches exhibited notch weakening while the bar with 0.005-inch root radius was strengthened by this notch.

Refractaloy 26 (See Fig. 5)

Material of constant composition was treated so as to give rather different diamond pyramid hardness at constant small grain size and to give coarse versus fine ASTM grain size at roughly the same hardnesses. A wide range of root radii were employed for constant bar diameter, notch depth and notch angle (Ref. 6). Only part of the data of the original plots are given here, with curves for several intermediate (r/d) values omitted in each figure.

Code	Heat Treatment	Hardness DPH	A. S. T. M. grain size
A	1800°F, 20 min, oil + 1500°F, 20 hr, air + 1200°F, 20 hr, air + 1500°F, 20 hr, air + 1200°F, 20 hr, air	330	7-8
B	1800°F, 20 min, oil + 1350°F, 44 hr, air + 1200°F, 20 hr, air	375	7-8
C	2100°F, 1 hr, oil + 1500°F, 20 hr, air + 1350°F, 20 hr, air + 1200°F, 20 hr, air	325	2-3

All notched bars had a 60° notch angle and diameter (d) at the base of the notch of 15/32-inch, with d/D = 0.75. The radius at the notch root varied to give r/d ratios for most tests between 0.01 and 0.27.

Effects of notch acuity are strongly evident from the rupture curves. For all three prior treatments it was found possible to produce bars with either higher or lower strength than for the smooth bars by suitable choice of root radius alone.

Comparison of the three sets of curves shows that the onset of notch sensitivity is not a function of a single universal value of ductility for unnotched bars. Thus, alloy A for r/d = 0.02 is strengthened for rupture times where smooth-bar elongations are only about 7 percent, whereas alloy C with slightly better unnotched ductility is definitely notch brittle at like time periods to failure.

K-42-B (See Fig. 6)

Again bars with like analysis are compared for different prior heat treatments:

Code	Heat Treatment	Hardness DPH	A. S. T. M. grain size	Reference
A	1750°F, 1 hr, WQ + 1200°F, 24 hr, AC	330	6-7	6
B	1950°F, 1 hr, WQ + 1350°F, 20 hr, AC	280	3-4	6

All notched bars were made with a root radius of 0.005-inch and with constant notch depth, but with variation in diameter of the specimens.

For both conditions, the points for all diameters appear to lie on the same curves. Ductilities are very low (0.4-3.4%) with rather severe notch sensitivity apparent at all stresses employed.

16-25-6 (See Fig. 7)

Code	Treatment	Hardness (BHN)	Reference
A	Forged at 1950°F + 2000°F, 1/4 hr, AC	187/200	1
B	Forged at 1950°F + cold worked 20% at 1350°F + 1200°F, 8 hr, AC	245/265	1
C	Forged at 1950°F + cold worked 30% at 1300°F + 1200°F, 8 hr, AC	280/320	1

The notch used in these particular tests is not so sharp as most others mentioned in the present report:

D	d	r	r/d	d/D	Angle
0.177	0.125	0.025	0.20	0.707	60°

When the notched bar results are all plotted together, as in Fig. 7(d), it appears that cold working had little effect on strength of notched bars, even though there was a pronounced rise in strength of the smooth bars upon cold working.

When smooth and notched bars with like amounts of cold working are compared with other pairs, it is found that the notch sensitivity becomes more severe for the condition with highest elongation in the ordinary rupture test.

DISCUSSION OF COMPILED DATA

The data available are too sparse for any conclusive generalities. The most evident conclusion is that notch sensitivity is a complex function of notch geometry, physical properties, and microstructure. Thus, a material having elongations in the rupture test in the range from about 2 to 15 or 20 percent may or may not show notch sensitivity depending on the notch geometry and metallurgical characteristics. For commonly used notches materials with more elongation will not show sensitivity. Those with less elongation will show sensitivity.

Elastic stress concentration factors alone apparently cannot be used to compare results from different notches for a given material. Certainly they cannot be used to compare different materials. For any given material it appears that there is at least a qualitative relationship between elastic concentration factor and strength when the variation in the factor is obtained by varying the root radius of the notch alone.

When the notch depth is varied at constant root radius under conditions giving nearly constant stress concentration factors, apparently wide variations in effects on strength can be obtained. For one material Davis and Manjoine(6) found that the maximum effect was obtained for d/D = 0.5. The elastic concentration factor is a maximum at a d/D of approximately 0.75. There is, however, no evidence that this holds for other materials or even for other root radii.

It appears that for a given notch geometry (constant angle, d and D) varying the root radius to change stress concentration factors has a consistent pattern of effect on strength. As the notch increases in sharpness from a very dull to a very sharp notch, the strength increases to a maximum and then decreases to a point where the rupture time is reduced more and more as the sharpness increases. The notch radius at which strength starts to decrease is a function of ductility and metallurgical characteristics. The lower the ductitlity the larger the root radius which will show sensitivity. The ductility values for sensitivity also vary with materials. This latter holds for different treatments of the same alloy as well as for different alloys.

The influence of notch geometry cannot be left without recognizing that notches in the edge of thin strip specimens apparently reduce strength more severely than the same notch in a round bar.(4)

Consideration of the influence of notch geometry makes it difficult to generalize other factors involved in notched bar rupture testing. The following summaries appear to be pertinent.

Structural Stability

From the work of Davis and Manjoine it is indicated that a given notch will give a rupture curve varying from the smooth bar curve by a constant value of notched to unnotched strength provided the specimens are structurally stable during the tests. In this case structural stability apparently means nearly constant elongation at rupture.

In those cases where ductility changes with time for fracture, it appears that notch sensitivity effects will qualitatively follow the ductility changes. If ductility falls below a certain value, then notch sensitivity will appear. If the ductility increases sufficiently at more prolonged times, then recovery from notch sensitivity results. According to the data of Brown and co-workers(5, 7) these effects can occur at a rather wide variation in ductilities. Particularly significant was their finding that for sharp notches, sensitivity could develop at surprisingly high ductilities when structural changes occurred during the tests.

Metallurgical Factors

It is practically impossible to generalize regarding metallurgical factors. Apparently for a given solution treatment, varying ductility by varying aging conditions will vary the strengthening or weakening of a given notch. In general, decreasing the ductility will increase the notch sensitivity.

If the solution treatment is changed then the effects of the notches are changed. Apparently the change in ductility is not an adequate measure of the effect of the change in structure. Certain materials heat treated to coarsen the grain size had much greater notch sensitivity at the same ductility than the fine grained condition. The available results show that change in grain size alone is not a perfect indicator.

Limited data on cold working of 16-25-6 indicated that cold working increased the strength of smooth bars with very little effect on notched strength. This may or may not be general. Certainly more data would be needed to verify this finding. Cold working of solution treated 16-25-6 is known to produce very low ductility at 1200°F. Consequently cold working would be expected to greatly increase the notch sensitivity of solution treated 16-25-6.

It would seem that the influence of metallurgical variables is so complex in the intermediate ranges of ductility that some other approach than routine testing would be necessary to arrive at practical answers. Otherwise the testing required would be too extensive for consideration. It is presumed that the answers must lie in the details of the influence of the treatments on physical properties, creep characteristics, and fracture mechanisms.

THE ROLE OF CREEP AND RELAXATION IN NOTCHED BAR RUPTURE TESTING

Preparatory to experimental investigation of effects of notches on rupture life at high temperature, an attempt has been made to analyze the probable contribution of creep and stress relaxation. At the outset it was reasoned that a notch introduces nothing inherently new into properties of the material. If one were to follow the history of a given small fiber of metal in the notched bar, the life of this fiber should be exactly the same as any fiber for which the temperature and stress history was the same.

In this portion of the over-all problem it is not sought to explain why a rupture specimen in pure tension behaves as it does. Rather, it is hoped that given the properties of the alloy as ordinarily tested in tension, it might be possible to extend these results to any other case where stress conditions are not uniform, but may be estimated with reasonable accuracy.

Tentatively it will be assumed that the significant factor determining time until rupture of any fiber at constant temperature is the variable effective stress existing during its life. The general method of analysis outlined below may still, however, be adapted to any more applicable combination of the principal stresses which may be suggested at a later date. For a notched bar to have a longer rupture life under given nominal axial stress than does a smooth bar, the assumption is that the notch reduces the effective stress below the nominal value during a major portion of the test. It appears that this can occur by one or more of the following ways:

(1) Plastic yielding upon application of the load.

(2) Relaxation of high stresses by change of elastic deformation to creep deformation with no significant change in dimensions (similar to the behavior of a tightened bolt at high temperature).

(3) The normal creep process which occurs under high stresses with progressive change in notch geometry by plastic deformation.

For the presence of a notch to shorten rupture life, the notch apparently raises the effective stress. This would occur whenever the combination of stated mechanisms still does not reduce the effective stress below the nominal stress early enough in the test.

Brown and associates(5, 7) have presented data for rupture of notched and smooth bars where the alloy under study is notch sensitive only over limited range of stresses, as is indicated in Fig. 8.

At least for the materials studied, it was found that elongation of the smooth bars at rupture seems to be related to the presence or absence of notch sensitivity.

For short times to rupture where the elongation values are high, the notched bar was stronger. As elongation fell off the notched-bar strength dropped below that of the smooth bars but rose above it again when the elongation increased at very long testing times.

Despite this apparent relation between notch effect and final elongation of rupture bars, no general ductility criterion for notch sensitivity has been published to date. The present investigation attempts to examine the effects of a notch in terms of a race between failure and redistribution of high initial stresses to a more favorable condition. It is hoped that the final results may help to clarify whether ductility per se is a controlling factor or whether it is but a qualitative manifestation of resistance to relaxation which often accompanies notch embrittlement.

The region (1) of Fig. 8 involves nominal stresses above the proportional limit for the alloy considered. As the specimen is loaded, local yielding occurs at the region of high stress at the root of a notch and builds up the radial and hoop stresses, thus lowering the effective stress. Even in regions where the effective stress fails to quite reach the proportional limit, a certain amount of stress redistribution is effected by relaxation of high initial effective stresses through a creep mechanism.

For smaller applied load (slightly below the proportional limit) a rather high local stress exists near the notch. The metal never reaches yield condition while the specimen may not last long enough for the relaxation process to take place before the life of the notched bar has been used up.

At still lower loads it is postulated that life to rupture is sufficiently prolonged so that even the slow relaxation proceeds to a more favorable distribution of effective stress than would be present in a bar without a notch.

In those cases where yielding occurs at the root of the notch, the material's characteristics can be expected to alter. Working may strengthen or weaken an alloy depending on the particular alloy, the temperature, and the time period, as has been well demonstrated by tests with smooth bars. Working can also alter the amount of deformation which can occur before fracture initiates. Since initial fracture appears to start near the base of the notch, possible alteration of properties by yielding at the start of the test should be considered. Again, however, it is postulated that any fiber from any bar, smooth or notched, will still exhibit the same rupture lives for identical histories of temperature and stress.

Such considerations furnish a qualitative explanation of observed behavior regardless of the exact law of rupture life under variable stress. This theory also permits of the special cases where the notched-bar curves lie either above or below those for the unnotched bars at all stress levels. The particular properties of the alloy at the stress and temperature, and in the metallurgical state used, are considered to be the controlling factors. In all cases the balance is between ability to relieve concentrations of effective stress before the life of the specimen has expired. Any prior metallurgical treatment which changes the proportional limit and work-hardening characteristics, the creep rates or the rupture life under constant load will be reflected in the relative behavior of notched bars versus unnotched bars under stress-rupture conditions.

A general stepwise method of calculation has been developed to follow representative fibers of the notched test specimen from loading to rupture. In rough outline the treatment is as follows:

1. For a fixed notch geometry, determine for each of several fibers the magnitude of the stress increments in the axial, radial and hoop directions resulting from elastic addition of one pound of axial load. An exact solution of Neuber(8) for deep hyperbolic notches appears to approximate closely the results to be used for the common V-notch with small root radius. From the increments of principal stress, compute the effective stress added per pound of axial load.

2. (a) If the total load to be added to obtain the desired nominal stress (axial load/initial minimum cross section) gives no fiber an effective stress greater than the proportional limit, the elastic stress distribution is used as a starting point.

(b) When the effective stress at the root of the notch exceeds the proportional limit, the course of the resulting plastic deformation and the final stress pattern after loading may be found by application of accepted methods used to treat problems of plastic flow. Details are to be found in texts on the subject.(9)

3. Though relaxation and creep occur simultaneously, the two will be separated into alternate processes to permit of easier analysis. It is reasoned that the original plane of the notch remains plane in view of the symmetry present. Moreover, at a distance from the notch the stresses across the entire bar should be essentially uniform. Under these restrictions, all fibers are expected to show the same total axial strain at any time in the test. Moreover, after any step in the process if the axial stress for each fiber is multiplied by its cross sectional area and all these products are added, the sum must equal the actual axial load applied.

(a) For the effective stress present in each fiber at the start of the period and for the accumulated plastic strain of the fiber to date, one can determine the stress relaxation which would occur neglecting creep deformation during the time interval; i. e. , if plastic strain were only to replace elastic strain present at the start of the interval.

For this fictitious relaxed state, the individual principal stresses can be found. The values for the different fibers can now be brought to their actual levels by raising all the individual values in proportion to the elastic-stress distribution appropriate to the notch configuration of the moment, until the average stress in the axial direction has been raised to the known value of axial load/cross section at base of notch.

(b) While the above relaxation process has been occurring, the bar has undergone a simultaneous general creep deformation. Rigorous analysis should probably allow for the gradual changes in effective stress over the time interval, but it seems a reasonable simplification to use the average of all the initial and final effective stresses over the section as the acting stress. The creep rate chosen is that for the average plastic strain of all fibers up to the start of the interval.

4. The cycle of calculations may be repeated starting with the new effective stresses and new total plastic strains found after the combined relaxation-creep process. In this fashion the history of representative fibers may be followed from loading to incipient fracture.

It may appear that the validity of this approach is limited by ability to predict with accuracy the stresses present after loading. Though errors in initial stress distribution were believed not to be critical, check calculations were made using a hypothetical set of data. Two quite different assumed stress conditions were found to approach rather similar stress distribution in a time well short of that when rupture should occur. Final confirmation of this tentative finding awaits the assembly of actual test data for an actual case.

REQUIREMENTS OF AN EXPERIMENTAL PROGRAM

A. The Significance of Notched-Bar Rupture Tests

A satisfactory experimental program designed to clarify the significance of notched-bar rupture tests must seek to isolate the separate effects of plastic yielding, creep relaxation of stresses, and ductility on notch sensitivity.

1. Any plastic deformation on loading will affect the stresses present at the start of a test. Analysis of such plastic flow requires knowledge of the complete stress-strain curves for each alloy at each temperature considered.

2. Assuming that a stress concentration will remain after the load is applied, then the time to rupture should depend on the rate at which this stress concentration is reduced by creep and relaxation. Relaxation properties over the range of stresses expected to remain after loading, as well as conventional creep data, are requisite to the proposed analysis of creep and relaxation effects. Despite continual change with time of the actual stresses present in a notched rupture bar, it is believed that several ordinary constant-load creep tests plus three or four constant-strain relaxation tests should supply sufficient information if short time intervals are considered in using the data.

A few tests should be made to determine the effect of prior strain on relaxation. That is, it now appears that it will be necessary to allow creep to occur for various times and then carry out relaxation tests to determine if prior strain greatly alters relaxation characteristics. This information is deemed necessary because there should be a shifting of maximum stress from one fiber to another as relaxation occurs and the relaxation characteristics may be altered.

A quantitative answer, rather than qualitative, is sought in an attempt to establish a general analysis which should be valid for any system of known initial stress distribution.

3. Before such an analysis as that suggested can be carried to the ultimate goal of explaining notched-bar test results in terms of commonly measured material properties, it is necessary to know how increments of life at varying stress influence total time for rupture; i. e., how to add portions of rupture life. Possible correlations to be examined include simple addition of fractions of rupture life or fractions of rupture elongation. Thus if a conventional rupture test under certain constant conditions would give 100 hours elapsed time and 10 percent elongation to rupture, and if the sojourn under these conditions was 20 hours, during which time 1 percent

elongation occurred, the two methods suggested should indicate expenditure during this interval of 20 hours/100 hours = 20 percent and 1%/10% = 10%, respectively. of the potential life of the alloy.

A suitable answer to the problem is to be sought by conducting tests with smooth bars for one constant stress over part of the run with later change to a higher or lower constant stress for the remainder of the test.

4. The role of ductility has been given secondary consideration in the above analysis. This is only because the separate effects of ductility on the several other factors are sought so that the time significance of each may possibly be more easily classified:

(a) During application of the load, the material must possess a suitable combination of yield point and ductility to prevent the stress concentration from exceeding the tensile strength. Ability to deform and relieve high stresses is intimately tied up with work-hardening characteristics as exhibited by the shape of the stress-strain curve. Even when the stress concentration in the immediate vicinity of the notch root is relieved by very localized yielding, the stress pattern just after loading should be quite different for a bar which yields deeply as compared with one which yields only to a very slight depth. These differences may reflect changes in ductility or strength brought about by the cold working which has taken place.

(b) The role of relaxation and creep as related to ductility has not yet been clarified. It is expected that analysis of relaxation effects using actual data will lead to an answer to the question of whether or not changes in the gross shape of the notch by creep are necessary to reduce effective stresses to levels below the nominal stress. This should furnish an indication of the importance of creep ductility to absence of notch sensitivity.

(c) The apparent dependence of notch sensitivity on final ductility seems to require further clarification. It is anticipated that being able to analyze changes in stress pattern in terms of relaxation and creep is a necessary preliminary to clearing up the situation. In all tests the elongation and reduction of area should be noted to examine for effects of localized versus general elongation, as was suggested in Siegfried's writings.(10)

B. Effects of Metallurgical Variables

Just as notched bars are but one special means of examining the more general case of multi-axial stressing, so the study of how different metallurgical treatments alter notched-bar rupture properties is to be considered but one suitable starting point to the investigation of the over-all problem of predicting comparable effects on the life of any structure of any alloy in any desired state.

Detailed listing of tests and conditions to be employed cannot be presented until a sufficient number of preliminary tests have been completed to define conditions of notch sensitivity of the 16-25-6 alloy to be used. However, the type of research to be conducted may be seen from the following examples:

1. Specimens of the same alloy may often be treated to have similar short-time tensile properties at a given temperature, but to have different creep characteristics or different elongations at rupture under like stresses. Notched bars with different treatments should now have nearly identical stress patterns when subjected to equal loadings. Only the two remaining major variables of creep relaxation and ductility need be examined.

Further insight into the involved interdependence of notch sensitivity on the several factors considered might be gained if it is found possible also to change the relative relaxation properties of the alloy in two conditions differently from the corresponding relative changes in ductility brought about by the treatments.

2. The General Electric Company tests on 16-25-6 summarized in the Data section of this report indicate nearly identical rupture life for notched bars with 0, 20, and 30 percent "cold" working at 1300°F, whereas

smooth bars exhibited considerable variation in rupture strengths for the same three treatments. It may be significant that for the range of cold working tested, the smooth bars for equal times to rupture all elongated about the same amount. A similar series of tests with different amounts of cold working, but after previous solution treatment, should prove to be enlightening.

3. Tests of notched bars after abnormal heat treatments which alter the properties from those normally found for the alloy would be useful as a guide in rejection or use of parts for multi-component stress service. This will be done for all the alloys to be included in the joint program: S-816, Waspaloy, Inconel-550, and 16-25-6.

C. Tentative Specifications for Notch-Rupture Test Bars

A variety of notch configurations has been used in recent investigations of notch sensitivities in cylindrical bars under stress-rupture conditions. Many early testers used a cross section at the root of the notch equal to half the area of the original bar, so that the ratio (d/D) of minimum diameter to original diameter was 0.707. This choice was established to give maximum stress concentration under elastic loading.

Some early experimenters employed a 45° or 90° notch angle, but 60° is nearly universal in current work on circumferentially-notched bars.

A few groups, notably the Lewis Laboratory of the NACA, prefer the sharpest obtainable notch root radius (0.002-inch max.) to obtain high stress concentration. Other investigators have used root radii varying from 0.005-inch to as much as 0.200-inch, with the lower range predominating. The lower value of 0.005-inch ($\pm$ 0.001) has been established by workers at Westinghouse Research Laboratory to be about as sharp a notch as can be ground reproducibly in the super alloys.

Notch-root radius alone is not the only factor in stress concentration. Careful tests by Davis and Manjoine(6) indicate the ratio (r/d) of notch root radius to diameter of the bar at the root of the notch and the ratio (d/D) both to be important. Maximum effect of a given notch was found at (d/D) of about 0.5. Detailed review of all available data shows that some alloys of interest are notch sensitive for (r/d) as high as 0.2, while other alloys are still notch ductile for (r/d) as low as 0.02. An intermediate value of r/d = 0.04 appears a reasonable compromise to give a practical comparison of alloys for jet-engine turbine-blade application.

Bar stock as small as 1/4-inch original diameter could still be ground with the 0.005-inch root radius at the adopted stress concentration.

The following dimensions are proposed for notched bars to be used in the testing program involving metallurgical variables:

Notch angle	Diam. at root of notch (d)	Diam. of rest of bar D	Notch-root radius r	(r/d)
60°	0.125	0.250	0.005 ± 0.001	0.04
60°	0.250	0.500	0.010 ± 0.001	0.04

Some variations in specimen size will be involved due to limitations of test material and in order that results may be compared with those for unnotched bars previously run for other work. Since such variation in specimen size is anticipated, it appears that the use of a constant (r/d) ratio is advisable to allow the best comparison of data.

FUTURE WORK

Stress-relaxation tests have been started on a small advance shipment of the S-816 alloy. As soon as the balance of the material from the order is received, the experimental work will be expanded in an effort to accumulate all necessary data in time to compare with notch-bar tests scheduled to be run by the other contractor cooperating in this program.

During the next quarter, work will be started with 16-25-6 alloy to study changes in its notch sensitivity resulting from metallurgical variables.

If the Waspaloy or Inconel-550 stock is received in the coming period, preliminary tests will be initiated to determine regions of notch sensitivity.

In all these tests, results of heat-treating variables and data on smooth bars will be integrated with results on notched bars to be obtained by the other contractor.

It is hoped that by the time of the next report the separate data compilations of the two contractors will have been combined and evaluated so that gaps in the available data on alloys of interest may become apparent and efforts directed toward running tests under conditions for which results are needed.

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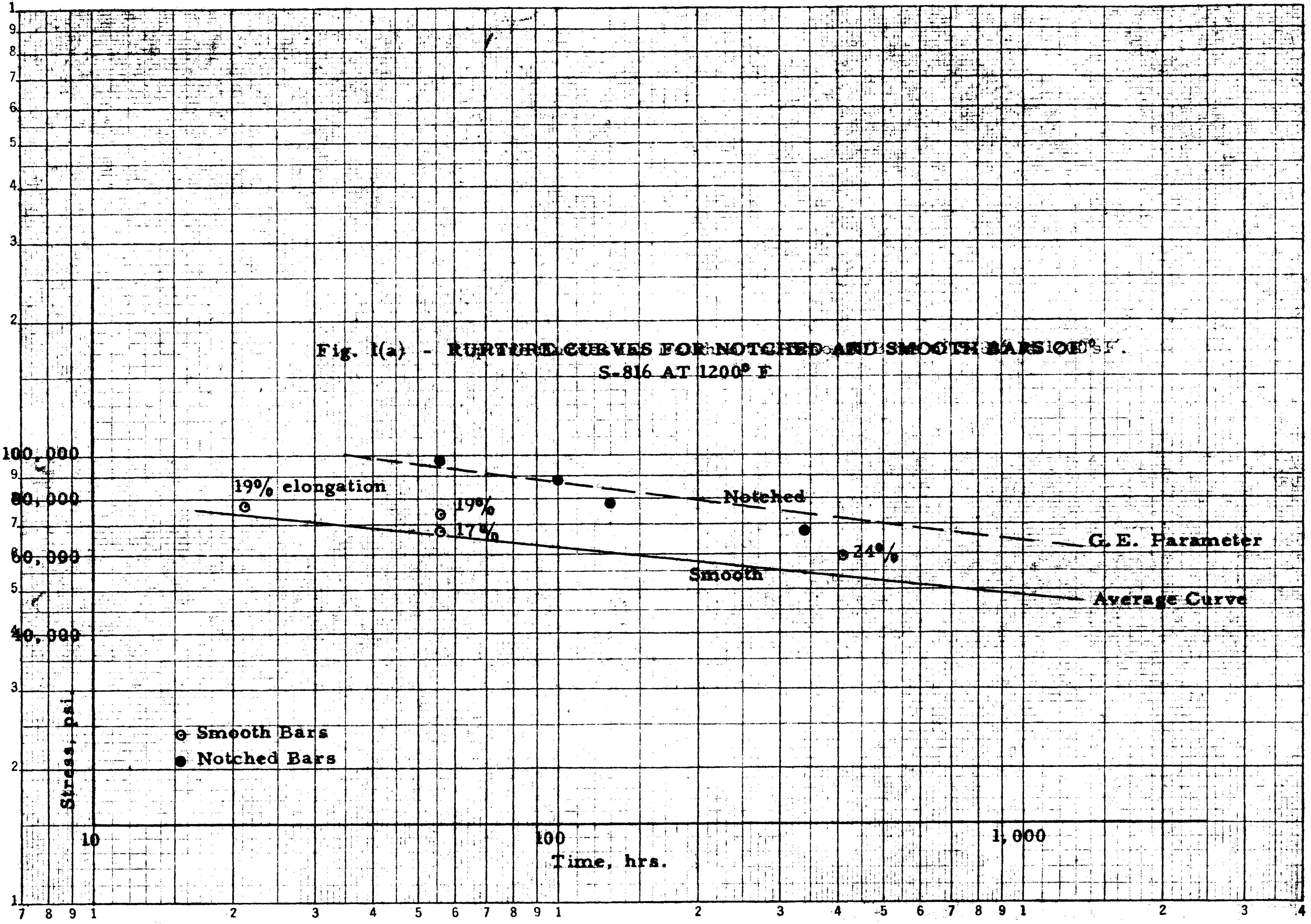


Fig. 1(a) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF S-816 AT 1200° F

Fig. 1(b) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF S-816 AT 1350° F.

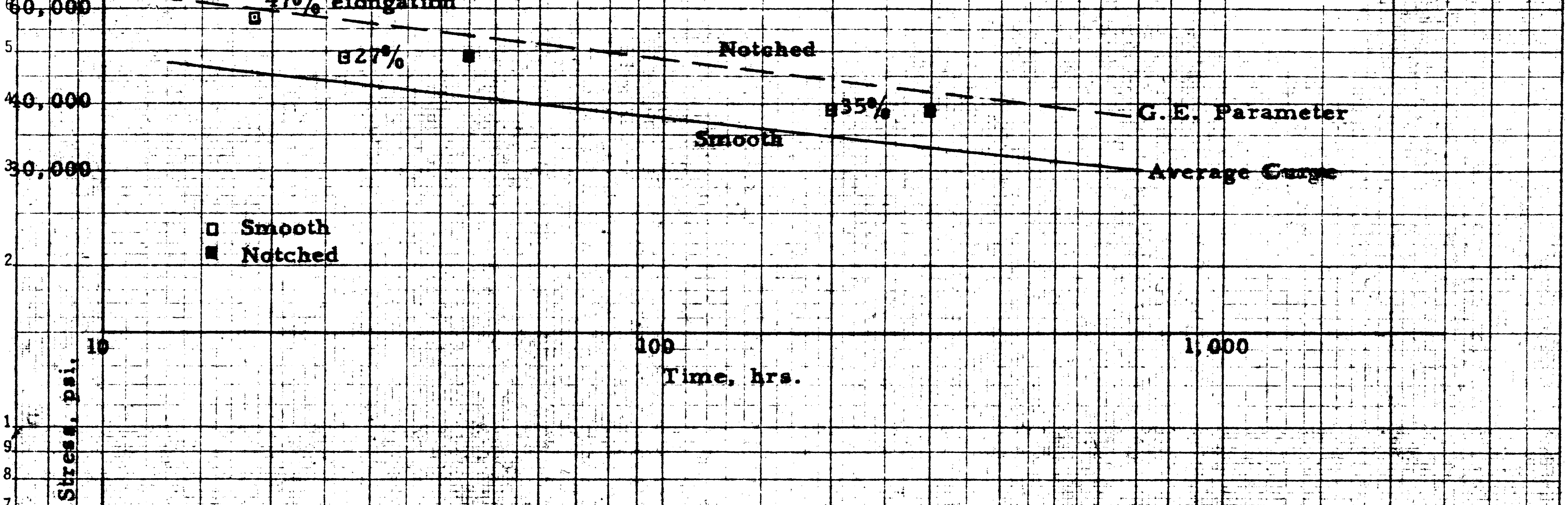
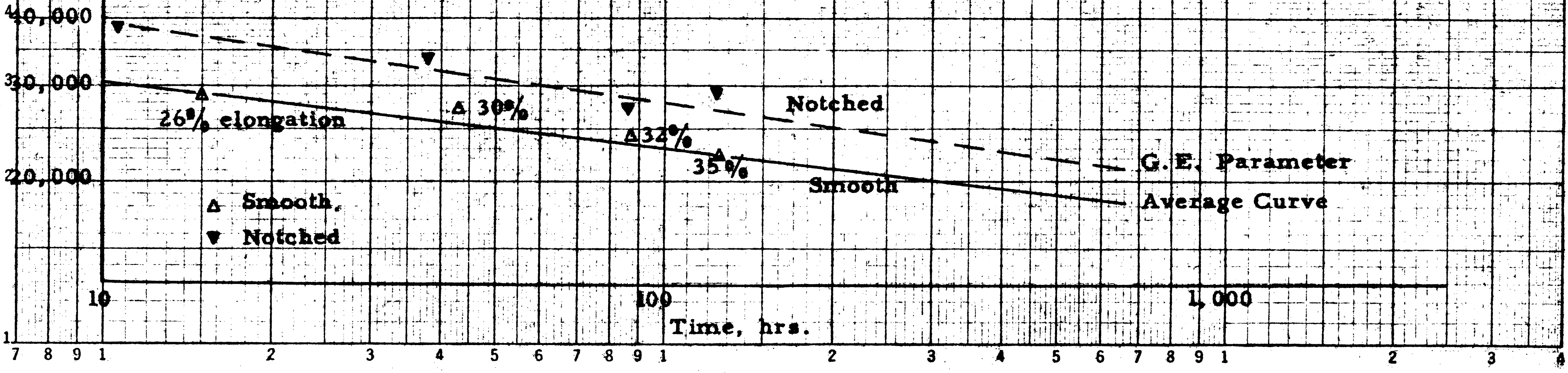


Fig. 1(c) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF S-816 AT 1500° F.



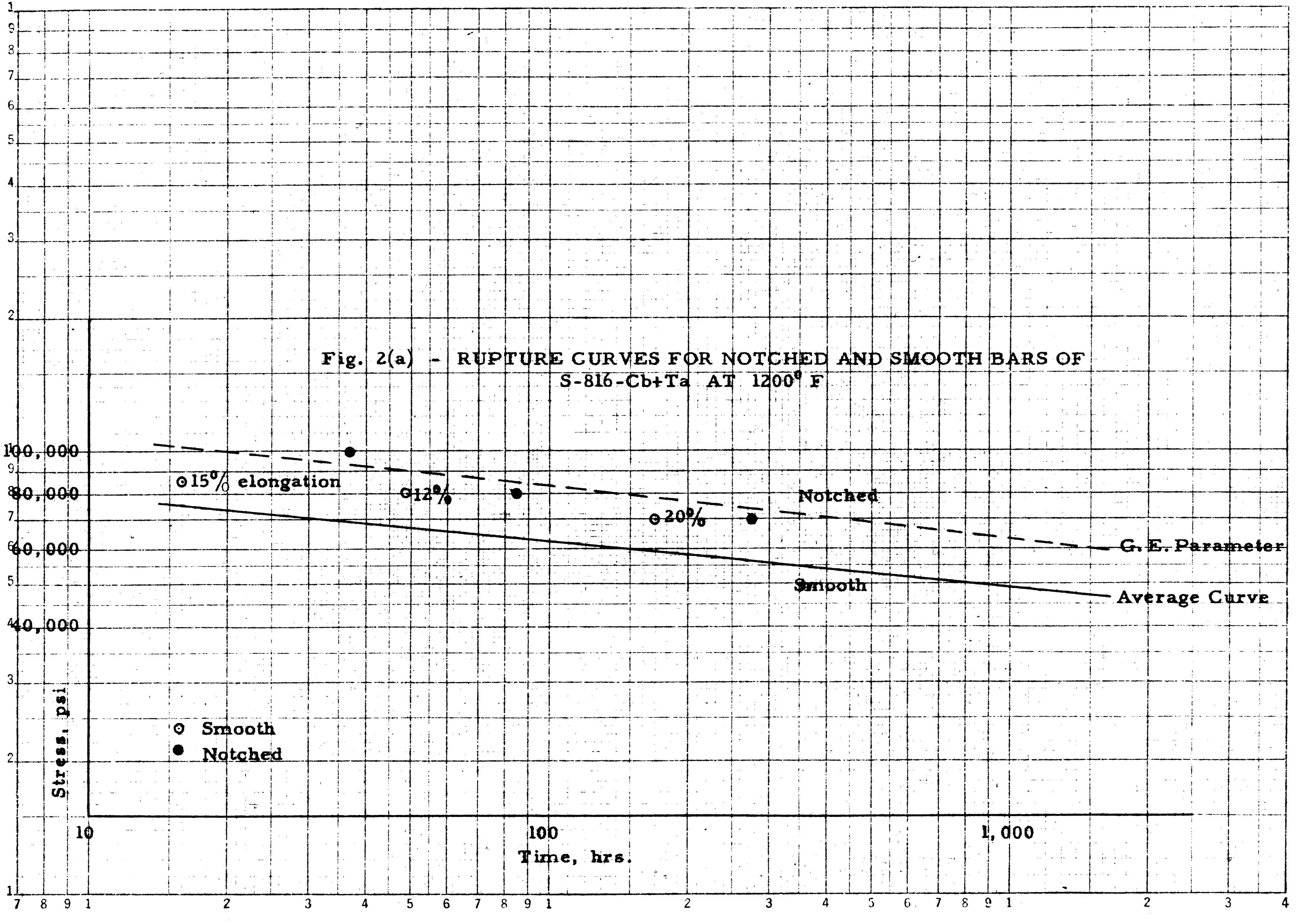


Fig. 2(a) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF S-816-Cb+Ta AT 1200° F

Fig. 2(b) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF S-816-Cb+Ta AT 1350° F

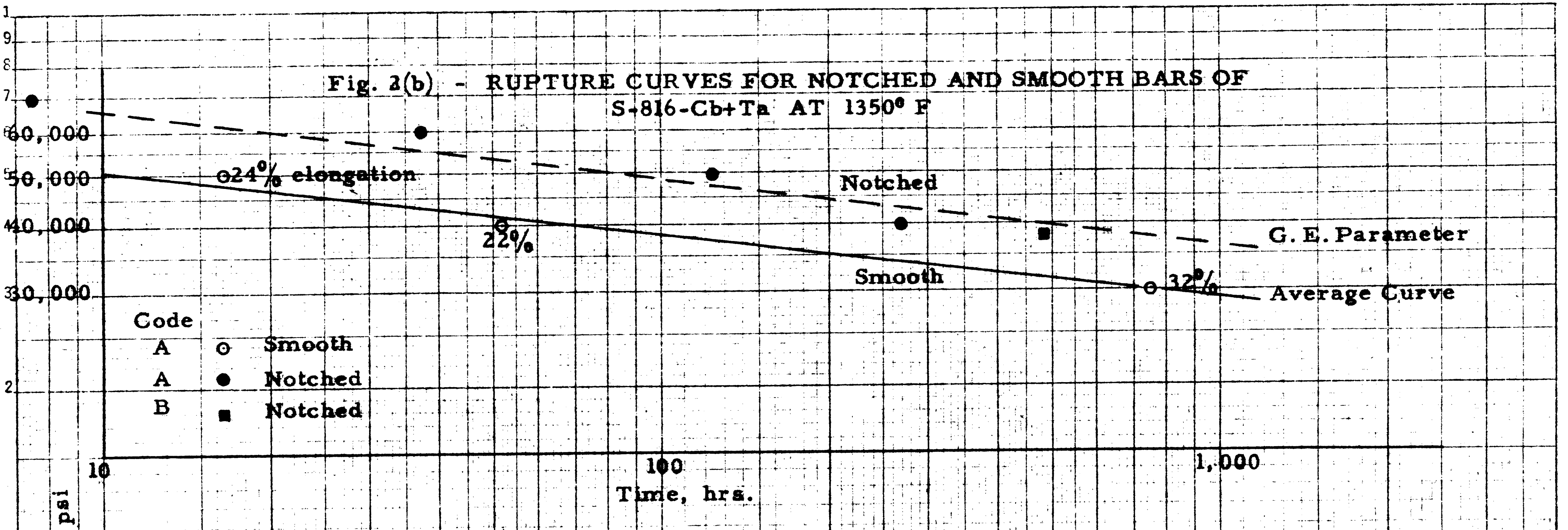
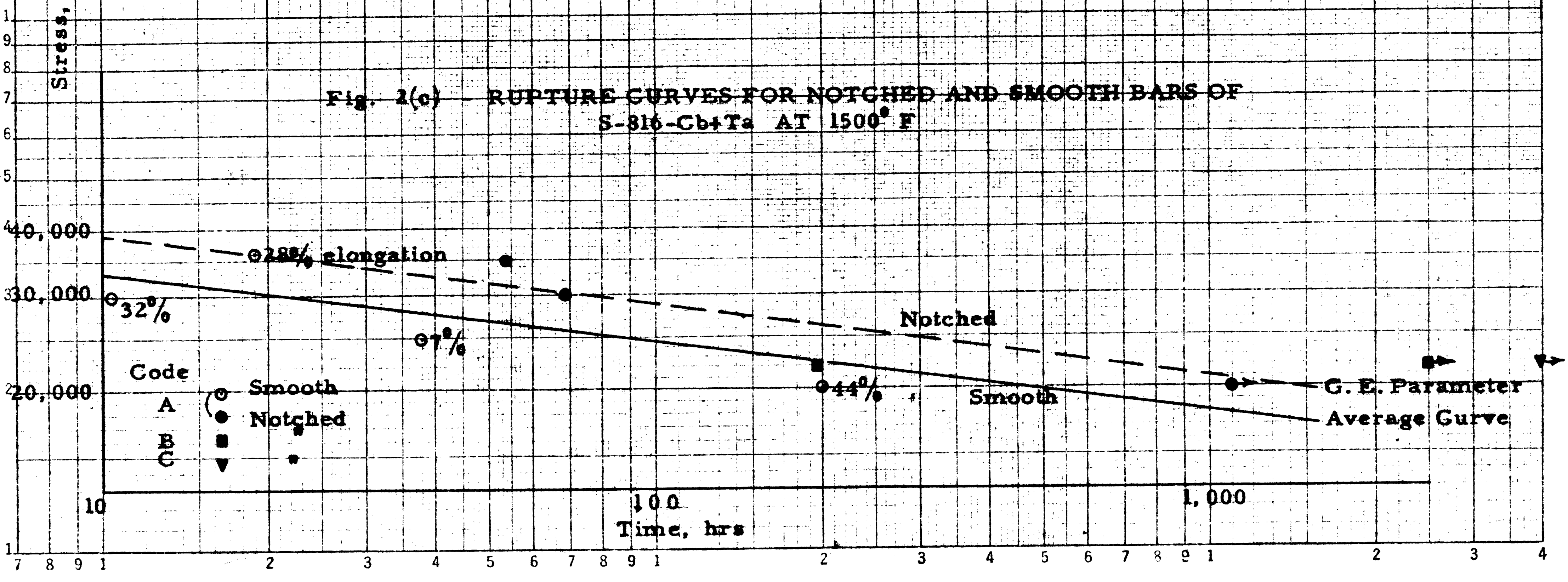


Fig. 2(c) - ~~RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF~~ S-816-Cb+Ta AT 1500° F



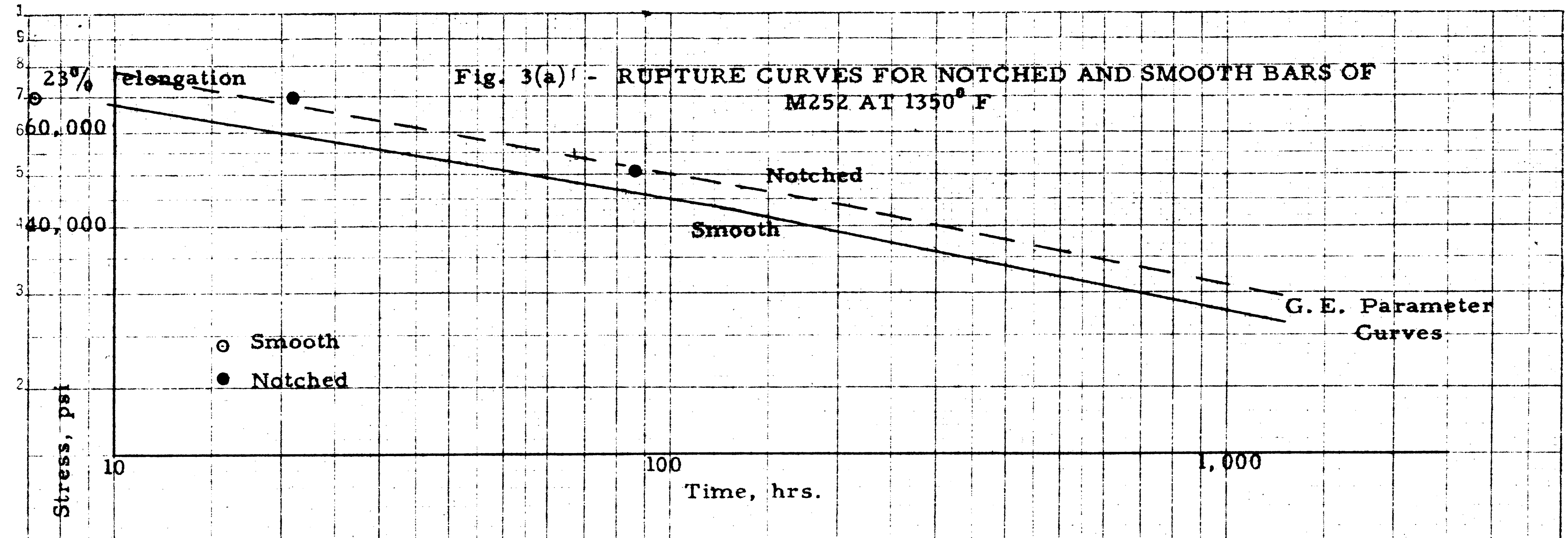


Fig. 3(a) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF M252 AT 1350° F

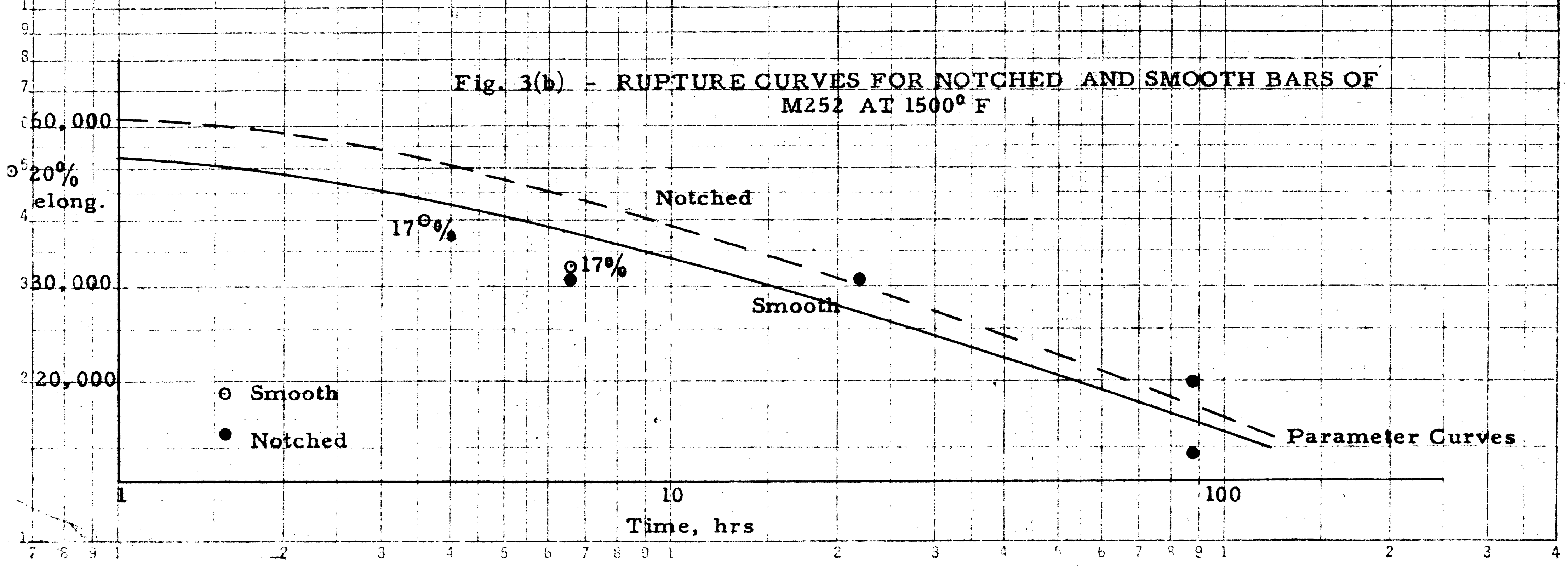


Fig. 3(b) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF M252 AT 1500° F

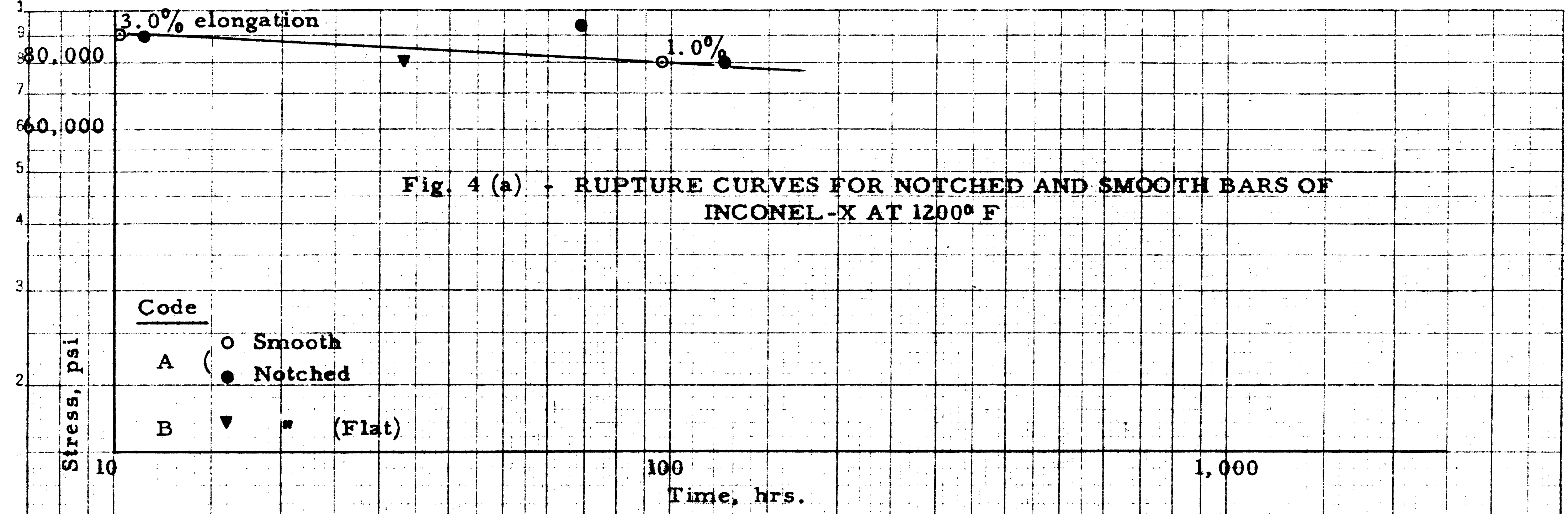


Fig. 4 (a) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF INCONEL-X AT 1200° F

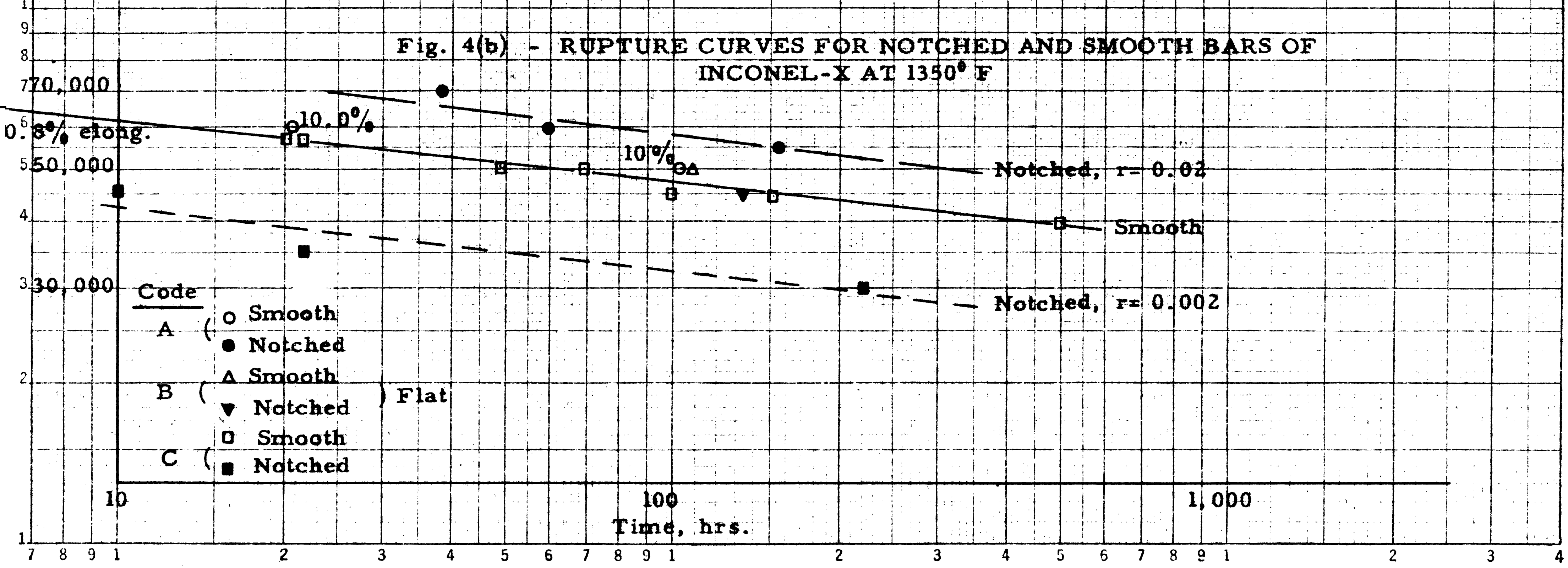


Fig. 4(b) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF INCONEL-X AT 1350° F

Fig. 4(c) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF INCONEL-X AT 1425° F

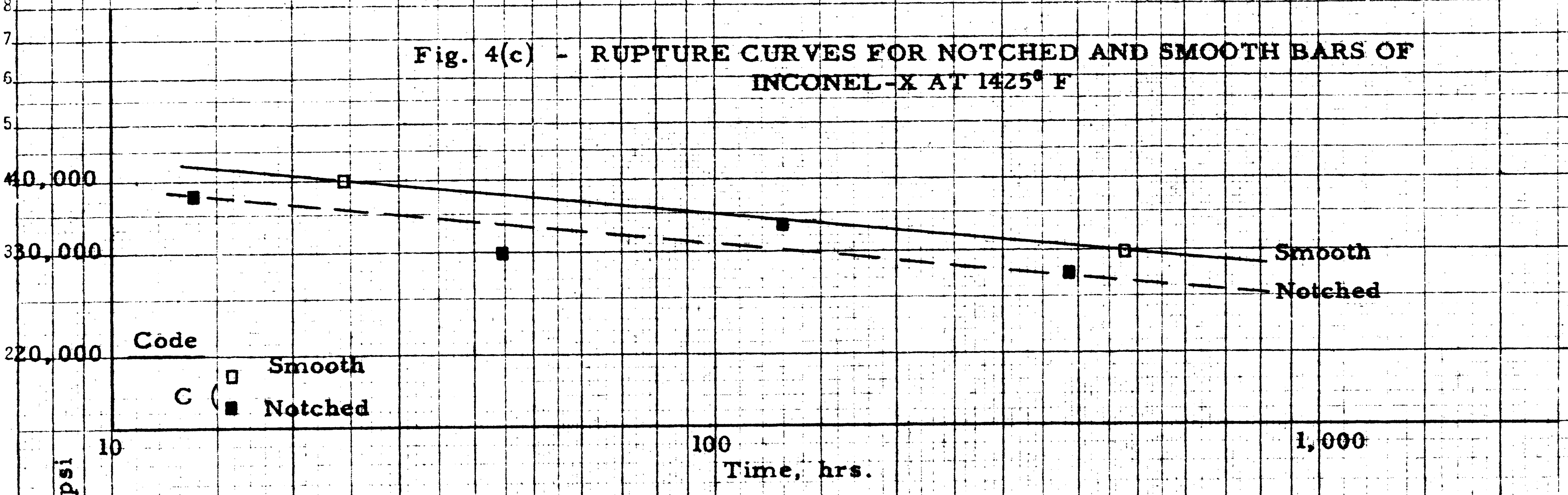
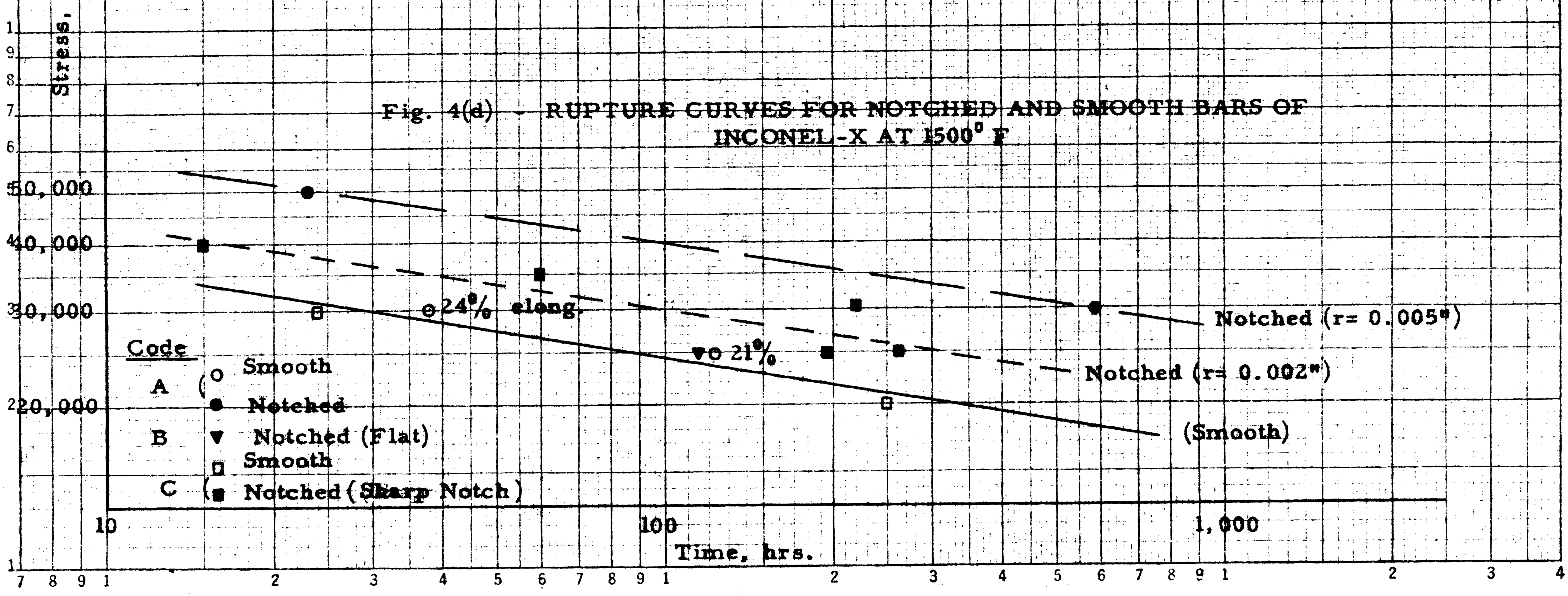


Fig. 4(d) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF INCONEL-X AT 1500° F



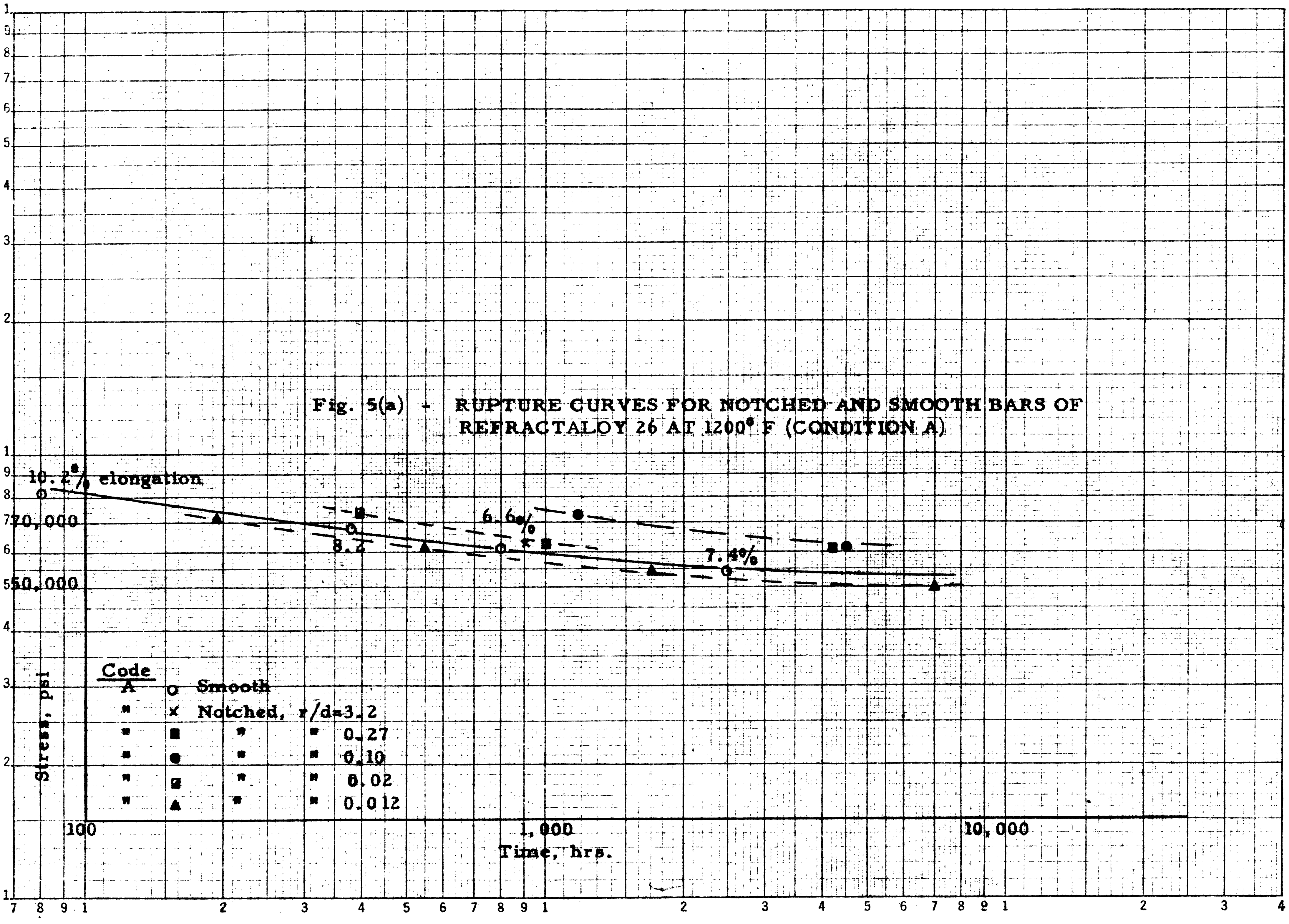


Fig. 5(a) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF REFRACTALOY 26 AT 1200° F (CONDITION A)

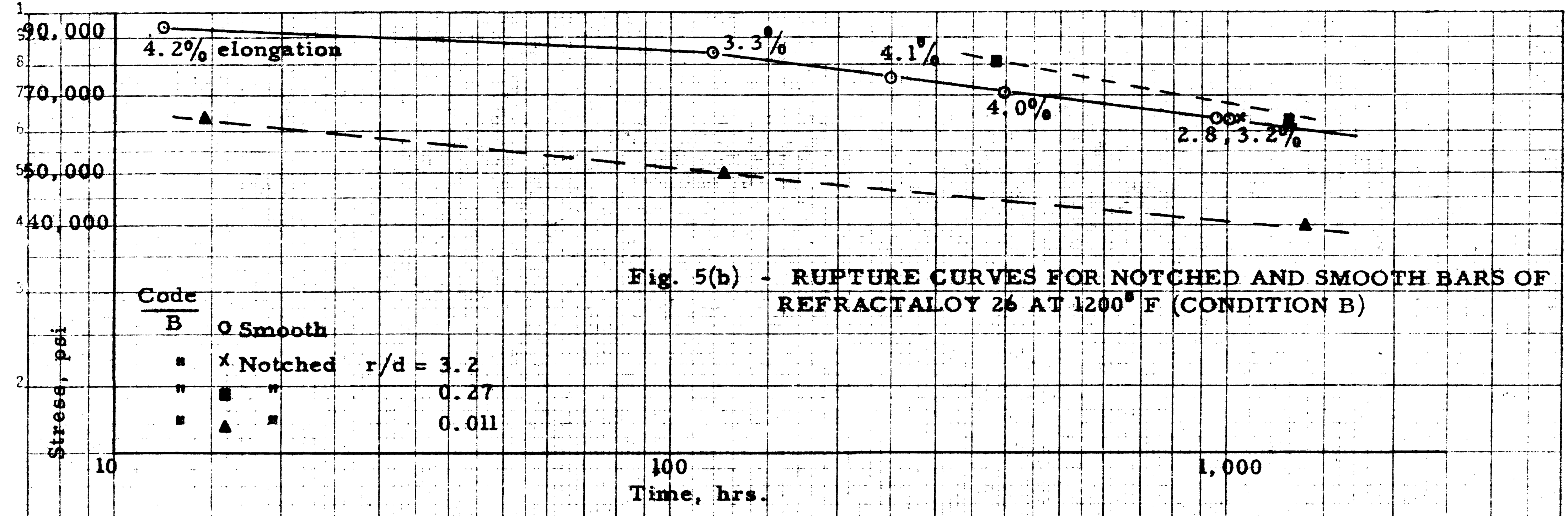


Fig. 5(b) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF REFRACTALOY 26 AT 1200° F (CONDITION B)

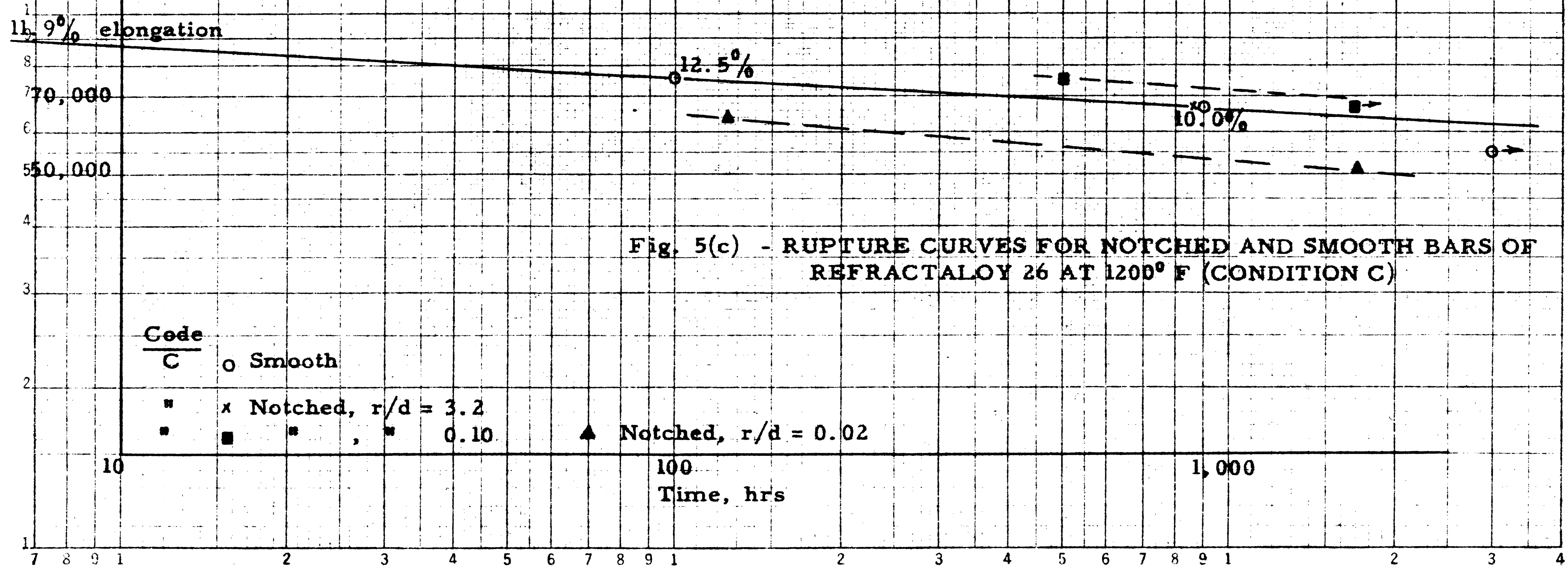


Fig. 5(c) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF REFRACTALOY 26 AT 1200° F (CONDITION C)

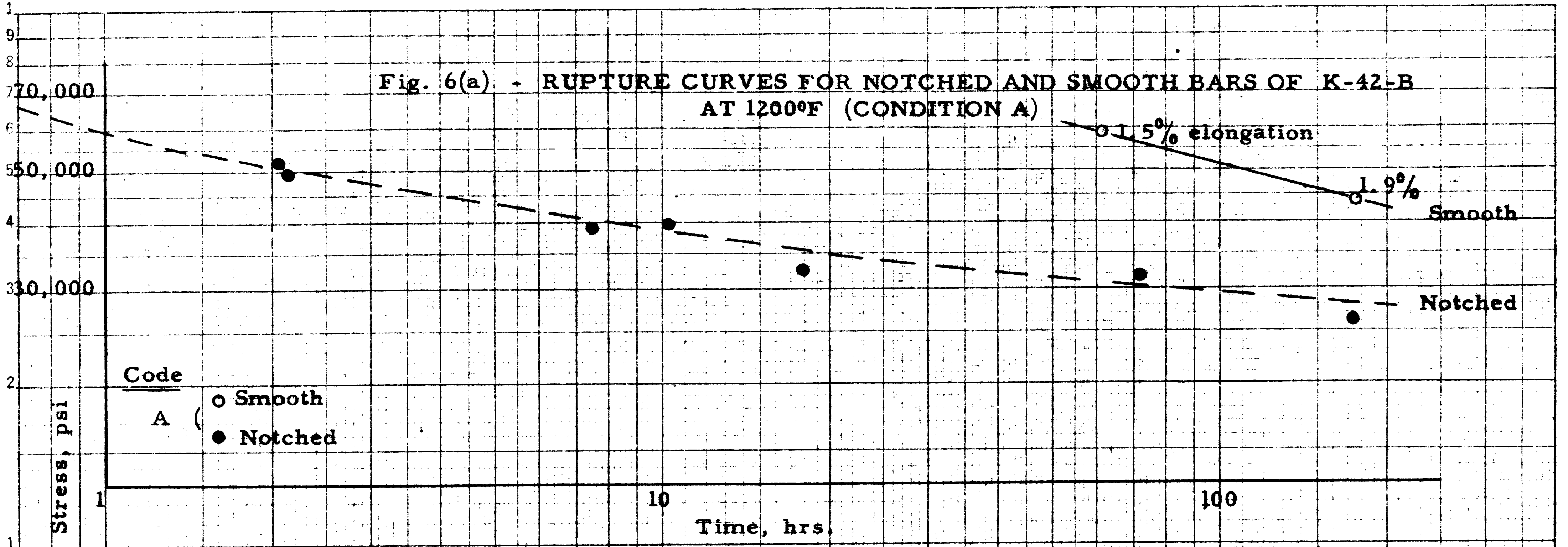


Fig. 6(a) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF K-42-B AT 1200°F (CONDITION A)

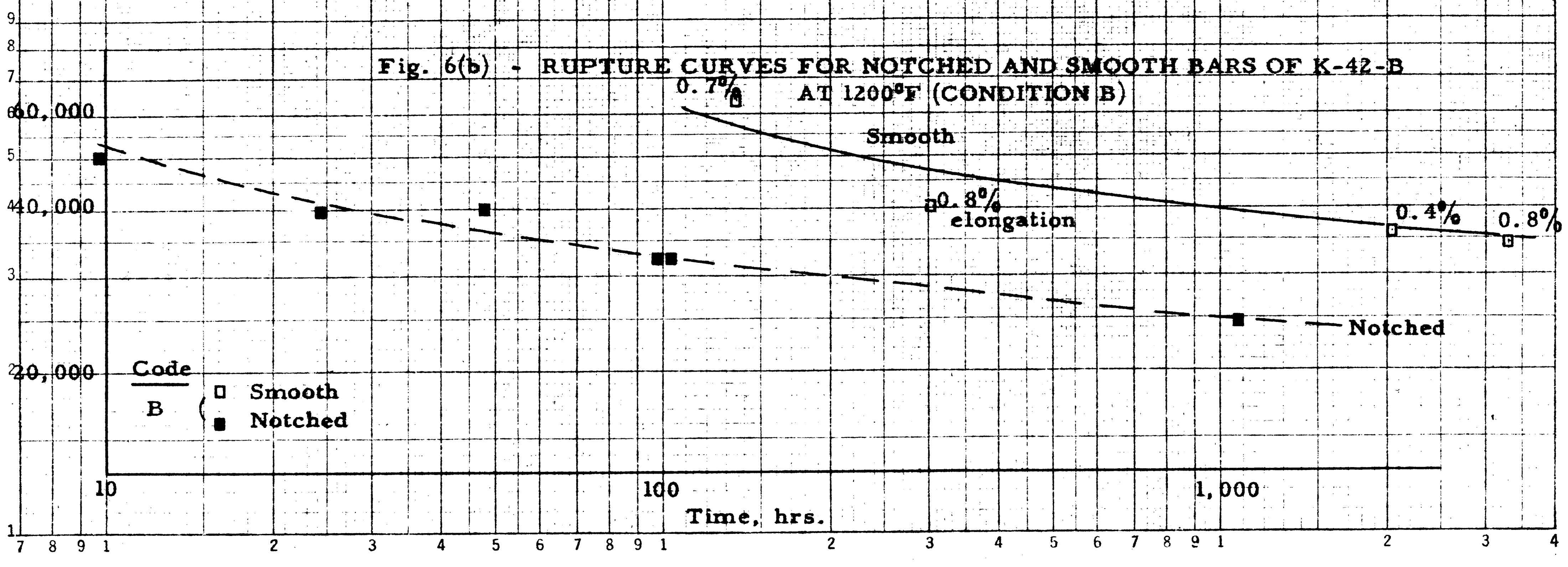


Fig. 6(b) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF K-42-B AT 1200°F (CONDITION B)

Fig. 7(a) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF 16-25-6 AT 1200° F (CONDITION A)

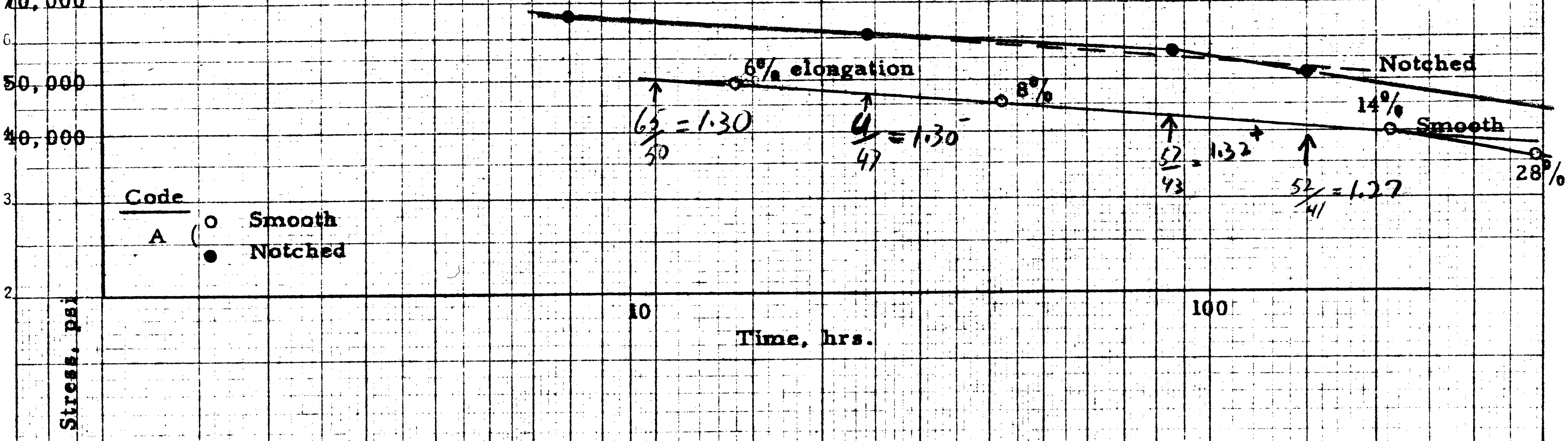


Fig. 7(b) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF 16-25-6 AT 1200° F (CONDITION B)

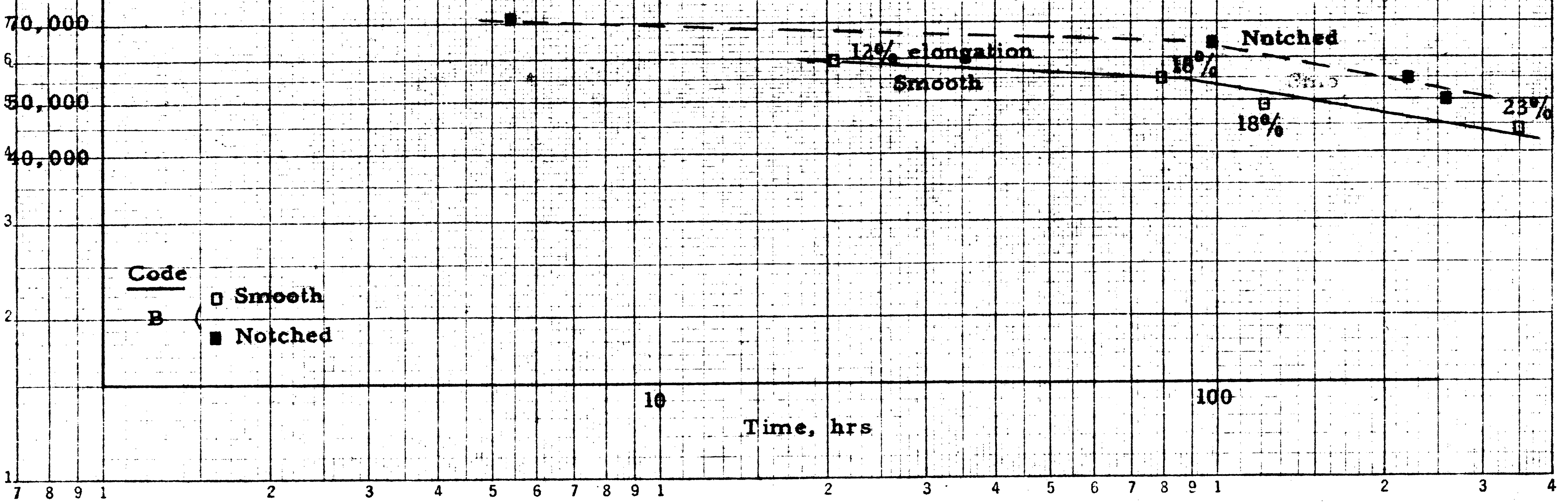


Fig. 7 (c) - RUPTURE CURVES FOR NOTCHED AND SMOOTH BARS OF 16-25-6 AT 1200° F (CONDITION C)

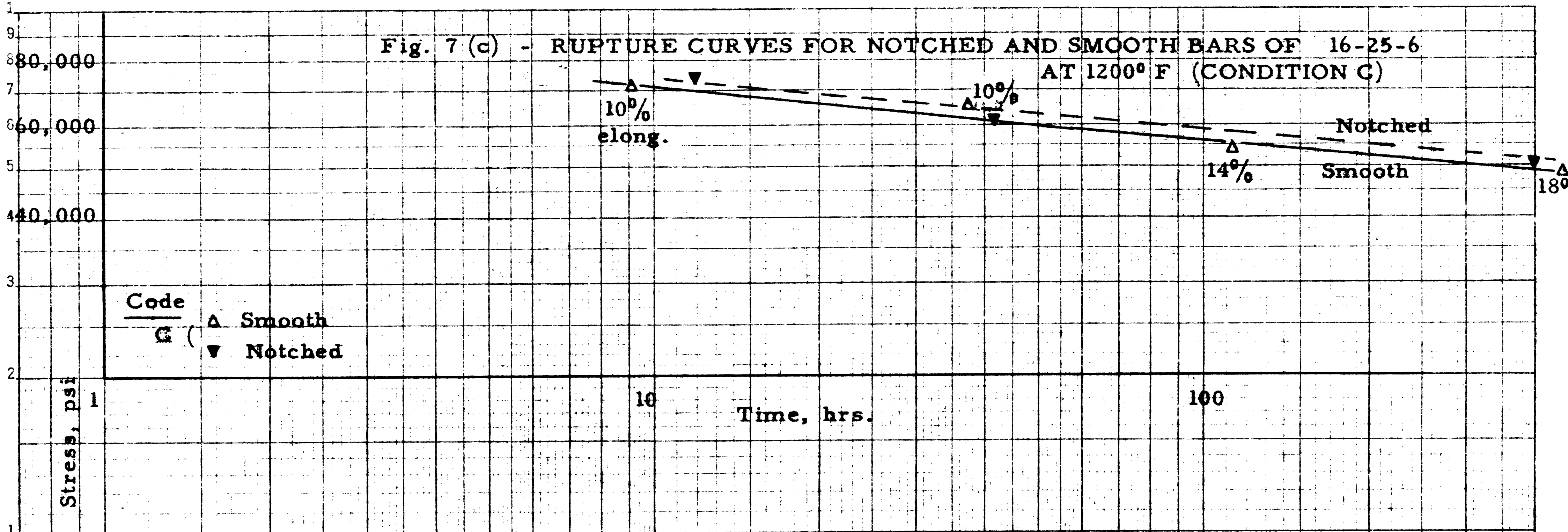
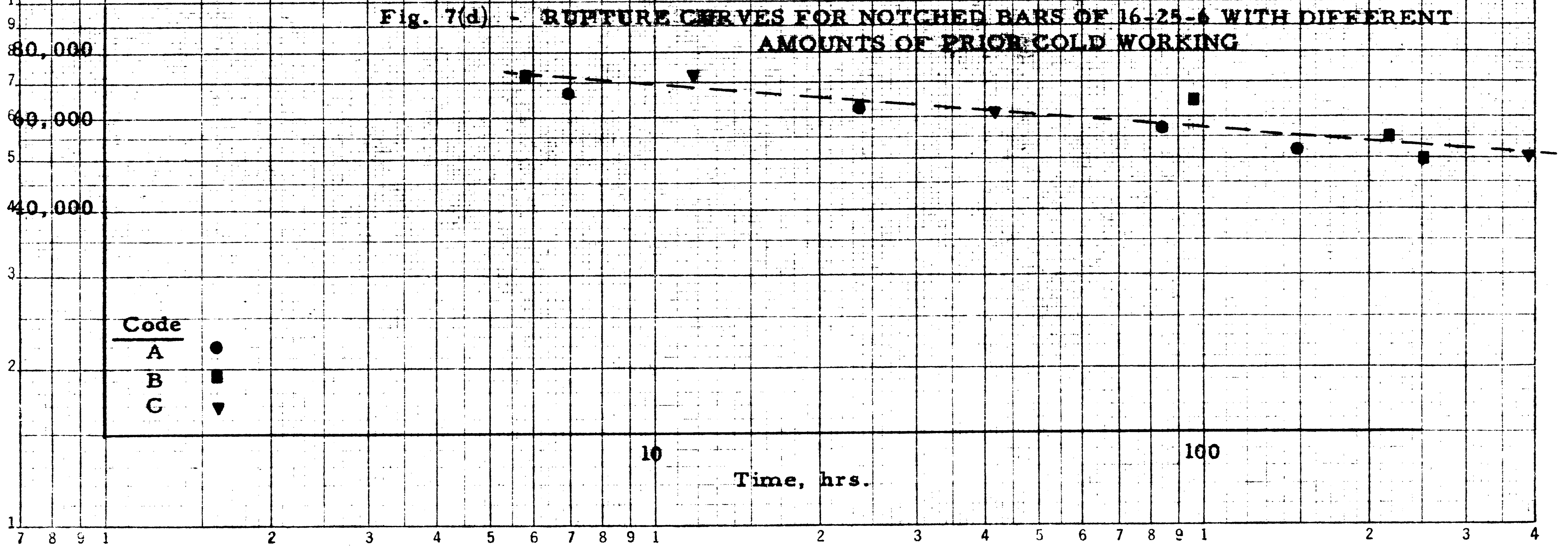


Fig. 7(d) - RUPTURE CURVES FOR NOTCHED BARS OF 16-25-6 WITH DIFFERENT AMOUNTS OF PRIOR COLD WORKING



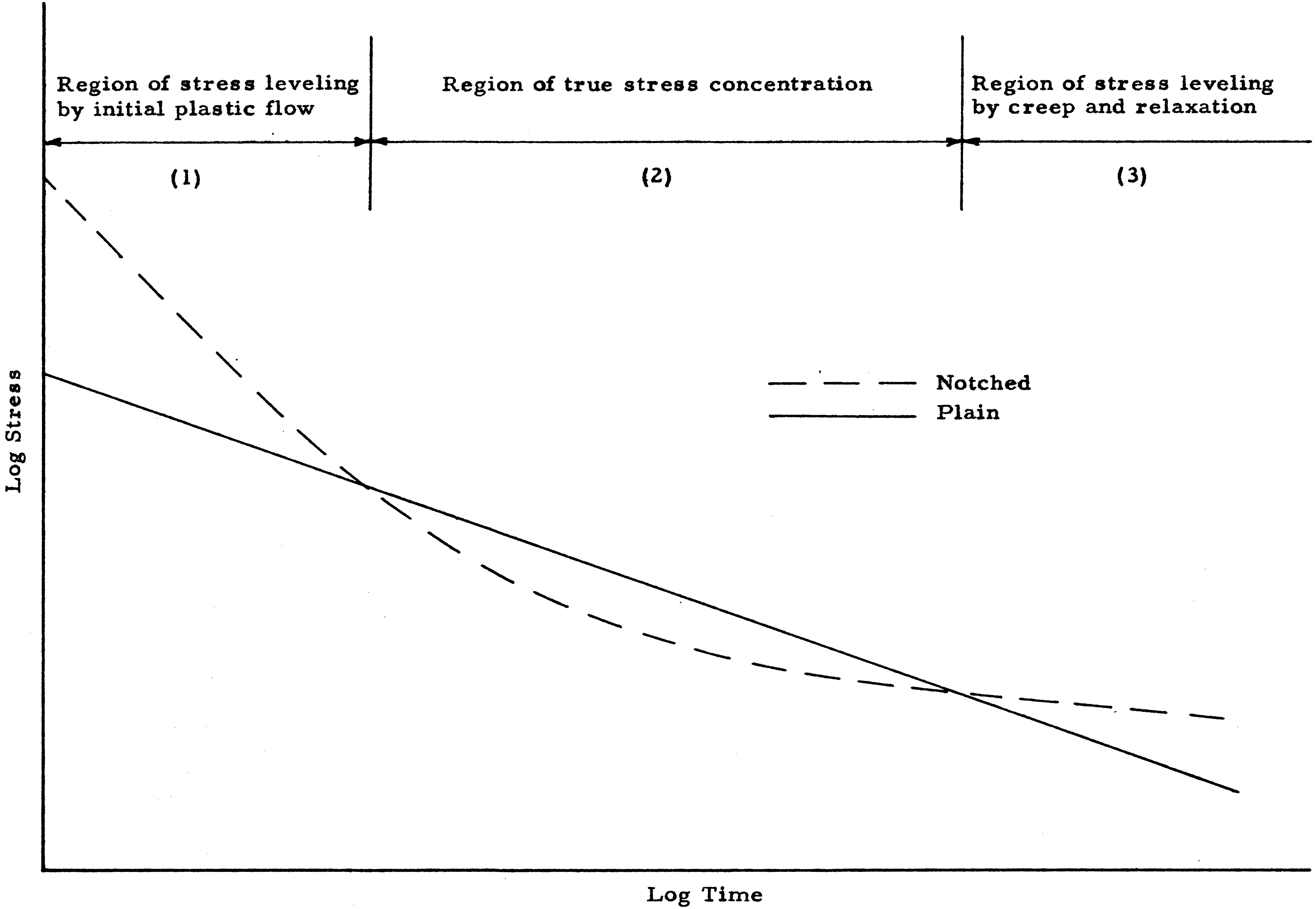


Fig. 8. - AVERAGE AXIAL STRESS VERSUS RUPTURE TIME FOR A TYPICAL NOTCH SENSITIVE ALLOY.