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SENSITIVITY OF THE CREEP-RUPTURE PROPERTIES OF NICKEL-BASE SUPERALLOY SHEET TO SHARP EDGE-NOTCHES IN THE TEMPERATURE RANGE OF 1000°-1400°F

by

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SUMMARY

Investigations are now in progress to evaluate the severe, time-dependent edge-notch sensitivity known to occur in thin sheet, nickel-base superalloys exposed at 1000° and 1200°F. Studies of René 41, Waspaloy, and Inconel 718, over a wide range of heat-treated conditions, has served to define the scope of this problem in 0.026-inch thick sheet. In addition, exploratory data have been obtained on the influence of notch acuity and sheet thickness on notch sensitivity.

Both smooth and edge-notched specimens fractured by the initiation and growth of intergranular cracks, followed by abrupt transgranular fracture due to the increase in stress caused by creep cracking. Analysis of these processes showed that the degree of notch sensitivity was strongly dependent upon the effect of the notches on the time for the initiation of the creep crack and early stages of its growth. There were some differences among alloys and within an alloy with heat treatment and test temperature. The notch sensitvity was not exhibited for the testing time periods considered when sheet thickness was increased from 0.026- to 0.050-inch thick. This, together with other considerations, suggests that the stress and strain state is a major factor; until this is understood, it is not possible to correlate notch sensitive behavior with precise microstructural features or mechanical properties.

SENSITIVITY OF THE CREEP-RUPTURE PROPERTIES OF NICKEL-BASE SUPERALLOY SHEET TO SHARP EDGE-NOTCHES IN THE TEMPERATURE RANGE OF 1000°-1400°F*

By D. J. Wilson*, J. W. Freeman**, and P. D. Goodell*

INTRODUCTION

The results presented have been derived from current research being carried out at the University of Michigan, Ann Arbor, Michigan, under the direction of the National Aeronautics and Space Administration, Washington, D. C. These studies are directed towards the determination of the scope and cause of the severe time-dependent notch sensitivity known to occur in several superalloys in the temperature range of 1000° to 1200°F.

During a study of the influence of stressed exposure in the intermediate temperature range on the superalloys, René 41, Waspaloy, and Inconel 718 (refs. 1, 2), some of the heat-treated materials failed unexpectedly in 1000 hours at 40 ksi at 1000°F. Under these conditions, the life had been expected to be practically infinite; the temperatures were sufficiently low that the design strengths would normally be be based on short-time tensile strengths or yield strengths, rather than on creep-rupture properties. Subsequent determinations of the stress-rupture time curves (fig. 1) showed that the notched to smooth specimen rupture strength ratios can fall from about 0.8 to as low as 0.45 for 1000 hours at 1000°F.

From the results obtained at the University to date, it has not been possible to establish the basic cause of notch sensitivity; therefore, the results presented in this paper will be concerned primarily with the scope and general description of this behavior.

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EXPERIMENTAL DETAILS

Materials

The information presented was based on studies of commercially-produced René 41, Waspaloy and Inconel 718 alloys. There is no reason to expect, however, that other superalloys would not be subject, in varying degrees, to similar notch sensitivity problems.

The compositional differences of the three alloys under consideration can be tabulated as follows:

	C	Cr	Ni	Co	Mo	Ti	Al	Cb	Fe	Minor Elements
René 41	0.09	19	55	11	10	3.2	1.5	-		B
Waspaloy	0.08	19.5	56	13.5	4.3	3.0	1.4	-	2.0	B,Zr
Inc. 718	0.04	18.5	52	----	3.1	1.0	0.3	5	19	

Due to these compositional differences, these alloys in the heat-treated condition exhibit a wide range of microstructural features and mechanical characteristics.

1. René 41 and Waspaloy are high-strength, γ', $Ni_3(Al, Ti)$ precipitation hardened alloys which differ in metallurgical characteristics imparted by high and low molybdenum contents. In René 41, the high molybdenum promotes the formation of an M_6C carbide. $M_{23}C_6$ is the main carbide in Waspaloy. Both contain the relatively inert Ti(C, N) carbides.

2. Principally due to the presence of columbium, Inconel 718 differs appreciably from the other two alloys. The γ'-precipitation is more sluggish, and there are considerable differences in compositional aspects of the matrices and γ' phases. In addition, the carbide phases can differ in type, amount, and morphology.

These materials have been studied in the cold-worked and aged condition, as well as in a number of solution-treated and aged conditions.

Testing Procedures

The heat-treating practices and testing methods used in various investigations have been described in depth elsewhere (refs. 1, 2, 3). The sheet materials were received in either the cold-worked or annealed condition, and were subsequently aged. Waspaloy material in the cold-worked condition was also studied after a number of solution and aging treatments (in an argon atmosphere).

The dimensions of the smooth and notched specimens used in the investigation (fig. 2) conformed to an ASTM specification which was being used when the research began, but which is now out-dated.

The creep-rupture tests were conducted in beam-loaded machines in accordance with ASTM Recommended Procedures. Specimen rupture times were recorded automatically. Creep extension was measured by an optical extension system, which has a sensitivity of five-millionths of an inch.

EXPERIMENTAL OBSERVATIONS

The experimental programs have provided data on short-time tensile and creep-rupture properties of superalloy sheet material. In the initial investigation, the time-dependent notch sensitivity of 0.026-inch thick René 41, Waspaloy, and Inconel 718 sheet was evaluated for cold-worked and aged material, and for materials in standard conditions of heat treatment (annealed and aged)(refs. 1, 2). In the current research to determine the scope and cause of notch sensitivity, Waspaloy and Inconel 718 are being utilized. Extensive variations of microstructural features (and, hence, the mechanical characteristics) of these alloys have been generated by appropriate solution and aging treatments. The creep-rupture properties (and, therefore, the notch sensitivity) of these heat treated materials at 1000°, 1200°, and 1400°F, are being evaluated, to varying extents, for 0.026-inch thick material.

In the following sections, results selected from the programs described above are presented which characterize the behavior of 0.026-inch thick sheet materials, creep-rupture tested in the intermediate temperature range. Limited results on the influence of notch acuity and sheet thickness are also presented.

Fracture Process

When creep-rupture tested in the temperature range of from 1000° to 1400°F, both notched and smooth specimens failed by creep-induced intergranular crack initiation and growth, followed by transgranular failure. The transition to transgranular fracture apparently results from the increase in stress on the load-bearing section due to the development of the intergranular crack. The rupture time is therefore governed by both of these fracture mechanisms.

The initiation and growth of the intergranular cracks consume most of the time-to-rupture. Optical examination of the fractures showed that the intergranular cracks were oxidized, while the transgranular cracks were not. In addition, intergranular cracks were found in several of the specimens which had been discontinued before rupture, particularly in those which had nearly attained the expected rupture time. In no case, however, was a specimen found before rupture which exhibited transgranular cracking.

Although transgranular fracture occurs relatively rapidly, the transgranular strength influences the rupture time because it controls the amount of intergranular cracking required to induce transgranular fracture, and therefore influences the time period of intergranular crack growth. An exploratory test in which the reate of crack growth was measured, indicates that this rate increases as the crack develops--presumably due to the increase in stress on the load-bearing section (fig. 3).

Thus, at least in the cases where the intergranular cracks are relatively long, only a small time period is required for extensive growth just prior to transgranular crack initiation. This should have the effect of limiting the influence of changes in intergranular crack length on the rupture time. It should be noted that variations in intergranular crack length, produced by changes in the transgranular strength (through heat treatment variations, etc.), will almost certainly be accompanied by changes in the creep-induced intergranular cracking characteristics, and will thus be reflected in the rupture times.

The notch sensitivity of the material can be considered to be: 1) the difference in rupture strengths of a material for a given rupture time, or, 2) the difference in rupture times for a given stress level. For the latter case, the notch sensitivity can be considered to be the difference in the time period for intergranular crack initiation and growth in notched and smooth specimens at a given stress.

At the present time, crack growth rate studies are still not at a stage where it would be possible to reach any conclusions with regard to the relative importance of these processes in the two specimen types. Measurements of the intergranular crack lengths at transgranular crack initiation do, however, allow some insight into their behavior relative to each type of specimen. Transgranular crack initiation for a given material is presumably dependent upon the nature of the stress and strain state existing at the intergranular crack tip. Transgranular crack initiation which occurs with similar intergranular crack lengths in the two specimens must reflect, to a great degree, similarity of stress and strain states. Measurements of the intergranular crack lengths of Inconel 718 specimens, rupture-tested at 1000° and 1200°F (see fig. 4), exhibit the following:

1. Small amounts of intergranular cracking occurred in specimens tested at the high load levels. For crack lengths up to 5 to 10 per cent, smooth specimens required higher loading stresses than notched ones.

2. At intermediate loading-stress levels, intergranular cracking was approximately the same for both types of specimens.
3. At "relatively" low loading-stress levels, where the amount of intergranular cracking is high, the amount of cracking tended to be greater in smooth specimens.

For a given material, intergranular crack growth will be governed by the stress and strain states at the intergranular crack tip. Thus, from the data (fig. 4), the stress and strain states apparently became similar enough that the intergranular crack growth rates in the two specimen types (for a given loading stress) were similar when the cracks developed to from 5 to 10 per cent of the specimen width. It is apparent, therefore, that for a given loading stress and test temperature, the difference between rupture times for notched and smooth specimens (i. e., the notch sensitivity) is determined primarily by the first stages of intergranular cracking. Thus, metallurgical variables that influence intergranular crack initiation (and growth) can be expected to have the most influence on the notch sensitivity.

Scope and General Description of Notch Sensitive Behavior

Time-Temperature Notch Sensitive Region

The time-dependent notch sensitivity of René 41, Waspaloy and Inconel 718 thin sheet is apparently limited to the intermediate temperature range (apparently somewhat below 1000°F to somewhat above 1200°F). At these temperatures, high stresses are required for creep to occur, and, consequently, design strengths are based on short-time tensile strengths or yield strengths, rather than on the time-dependent, creep-rupture strengths. On the other hand, at the higher temperatures creep processes are predominant in rupture and, in fact, little or no notch senstivity occurs. The extent of the notch sensitivity, and the time-temperature range in which it is most pronounced, vary somewhat with the alloy composition and heat treatment. This is demonstrated by the following examples.

1. Waspaloy in the standard condition of heat treatment (solution treated 1/2-hour at 1975°F and aged 16 hours at 1400°F) exhibited increasing notch sensitivity in tests at 1000° and 1200°F; the N/S rupture strength ratio decreased to a value as low as 0.56 (see fig. 5). In the tests at 1400°F, notch sensitivity decreased with time, from an N/S ratio of 0.78 at 1 hour, to 1.0 at 1000 hours.

During the study of changes in the rupture strengths of this type with time and temperature, it became apparent that the results could best be represented as a graph of logσ versus a time-temperature parameter (see fig. 6). Most evident was that the N/S rupture strength ratio exhibited a minimum, or "trough", with increasing parameter values. It should be noted here that, although the parameter T(Constant + Log t) was convenient for presenting and understanding the results of this investigation, it is not known at the present time if it has any additional use. In particular, the results should not be utilized either to interpolate or to extrapolate to time and temperature values, even within the range of parameter values used, i.e., without further verification.

2. Inconel 718 exhibited variations in notch sensitivity which were similar to those described above. For the cold-worked and aged material (see figs. 7, 8), for example, the notch sensitivity increased at 1000°F, but decreased in tests at 1200°F. In this case, therefore, the time or temperature at which the maximum in notch sensitivity occurs is lower than for the Waspaloy material presented earlier.

3. Heat treatment can also markedly influence the extent of the notch sensitivity and the parameter range in which it occurs. For Waspaloy, aged 16 hours at 1400°F (see fig. 9), increasing the solution temperature from 1825°F to 1975°F has the effect of shifting the trough in

the N/S values to higher parameter values. For a given solution treatment, aging for 10 hours at 1700°F markedly increases the minimum value of the N/S ratios when compared with the 1400°F aging treatment.

Influence of Cold Work Fabrication

The original survey of superalloys for the SST showed that the short-time tensile and yield strengths could be increased markedly by cold working. It should also be noted that the yield strength was raised more than the tensile strength, and, consequently, the YS/TS ratio was increased. Rupture testing (see fig. 10) resulted in the following:

1. Cold-worked and aged material exhibited an extreme sensitivity to sharp edge-notches in the temperature range of 1000°-1200°F.
2. Transverse notched specimens exhibited much lower strengths than longitudinal ones. On the other hand, smooth specimen strengths exhibited little dependence upon specimen direction.
3. When compared to annealed and aged material, the smooth specimens of the cold-worked material exhibited higher strength levels, whereas the notch strength tended to be lower (especially in transverse specimens).
4. For the cold-worked and for the annealed materials, the notched specimen rupture curves exhibited drastic changes in slope, both increasing and decreasing. This is in marked contrast to the smooth specimen rupture curves, which are apparently linear.

Notched Specimen Rupture Curves

At least for the majority of the materials and heat treatments studied, the changes in notch sensitivity with time and temperature primarily reflect changes in the notched specimen rupture curves:

a. The decrease in notch sensitivity at high parameter values is reflective of the convergence of notched and smooth specimen rupture curves. In the cold-worked materials (see figs. 7,8), it was clear that this results from an upward break (decrease in slope) that occurred in the notched specimen rupture curves. This upward break was also observed for a number of materials in the annealed conditions (see. fig. 11). The number of data points available from research to date, however, is too limited to establish the general applicability of the above tendencies.

b. At low parameter values, the notched specimen rupture curves diverge markedly from the curves for smooth specimens (see fig. 12), resulting in the drastic increase in notch sensitivity. Within the limits of the data available, it is apparent that the increase in slope in the notched specimen rupture curves occurs when the loading stress, based on the net section at the base of the notch, is reduced below the 0.2 per cent offset yield strength, as determined in the smooth specimen tensile tests.

Ductility-Notch Sensitivity

There is a rather general belief that ductility values in rupture tests are related to notch sensitivity. However, in only a limited number of heat treatments for the alloys studied did notch sensitivity appear to vary directly with ductility.

1. For Waspaloy (annealed at 1975° and aged 16 hours at 1400°F) there was a correlation between ductility of smooth specimens and notch sensitivity (see fig. 13). The ductility trough for this material occurred

because most of the deformation occurred on loading at low P-values, and in third stage creep at high P-values. The elongation on loading decreased rapidly as the load to yield strength ratio decreased, i.e., with increasing values of P. In contrast, the elongation in third stage creep was small for low values of P, but increased at high values. The result was a minimum in deformation at intermediate parameter values.

2. For Inconel 718 (cold-worked and aged) the N/S rupture strength ratio formed a trough (see fig. 14) with increasing parameter. There was not a similar variation in total elongation; however, the elongation did decrease with increasing parameter for the lower parameter values.

Notch sensitivity is dependent upon the relative behavior of notched and smooth specimens, and can be expressed as a rupture strength (or rupture time) ratio. Ductility itself seldom correlates directly with the rupture strengths of smooth specimens. Frequently, increasing the creep resistance by heat treatment results in increased rupture strength levels and decreased ductility. Yet, if the ductility is reduced too much, although the creep resistance is increased, the rupture strength may be decreased. Such effects can be altered by the presence of notches or cracks. Consequently, it is not surprising that there is no direct correlation between the notched to smooth specimen rupture strength ratio and the ductility.

Because of the apparent importance of intergranular crack initiation on notch sensitivity, flow characteristics that influence crack initiation must also affect it.

1. The notch sensitivity apparently increased markedly when the loads were reduced below the net section yield strength. Yielding in these cases could only be extensive in the area of the notches where the initial stress is the highest. Presumably, the deformation on loading (time-independent, or "tensile" type deformation) resulted in the relaxation of stresses at the notches and/or introduced cold work into these areas. Subsequent creep processes, which led to intergranular crack initiation, occurred under this pre-established stress and strain state. It is of

interest to note that in an exploratory test (on René 41 at 1000°F), in which a notched specimen was pre-loaded above the yield strength, the rupture life at a stress below the yield stress was extended. Evidently, loading above the yield strength, i.e., causing yielding over the complete cross section at the base of the notch, reduced the notch sensitivity.

2. At low loading levels, yielding was presumably restricted to the areas of stress concentration at the notches. Relaxation of the stresses at the notches can also occur by creep; this process must be achieved without the introduction of creep cracks. High amounts of local creep due to high local stresses, or low creep resistance, can be expected to accelerate the creep cracking process.

3. The deformation characteristics listed above must be considered within the context of a third major factor, namely specimen geometry. Specimen geometry will be considered in the following section.

Influence of Notch Specimen Geometry on Notch Sensitivity

The results which reflect the relationships between the notch sensitivity and notched specimen geometry were obtained by variations in thickness and notch acuity of sheet specimens and in the testing of round specimens.

Exploratory tests have shown that sheet thickness has a very marked influence on the degree of notch sensitivity. The extent of the effect has not been completely defined.

1. When 0.050-inch thick Waspaloy sheet was tested at 1000° and 1200°F in two conditions of heat treatment (solution treated 1/2-hour at 1975°F and aged either 16 hours at 1400°F, or 10 hours at 1700°F), it did not exhibit a time-dependent notch sensitivity. These results are in contrast to those obtained from 0.026-inch thick material in identical heat treated conditions. The difference was most evident for the material aged at 1400°F, where the sensitivity of the 0.026-inch thick material was quite marked.(fig. 15). Although the two materials had slightly different compositions, the fact that the smooth specimen properties were similar suggests that the very large differences in the rupture strengths of the notched

specimens were a real effect of thickness.

2. Results for René 41 sheet materials tested at 1000°F showed a similar influence of sheet thickness in that 0.04-inch thick sheet was considerably less notch sensitive that 0.026-inch thick sheet (fig. 16). It should also be noted that testing round bars at 1200°F resulted in a slight degree of notch strengthening, whereas the 0.026-inch thick sheet showed very marked notch sensitivity.

The variation of rupture strength with sheet thickness must reflect changes in the rates of intergranular crack initiation and/or growth. These rate changes are especially reduced in notched specimens by increasing the sheet thickness; smooth specimens exhibited little or no increase in rupture life with increasing sheet thickness and, hence, the notch sensitivity decreased with increasing sheet thickness. Although the cause of the variations of rupture strength with sheet thickness has not been definitely established, future research will consider two possible contributing factors:

a. The stress and/or strain states vary significantly with sheet thickness, thus influencing the deformation behavior at notches sufficiently to result in the observed change in notch sensitivity.

b. Surface effects could have a marked influence on the mechanical properties of the sheet, and, hence, on notch sensitivity. Element losses, e.g., B or Al, and other environmental effects, which may or may not be evident as microstructural changes, could be expected to have an increasing influence on the properties of sheet materials, the thinner the sheet. In this case, however, it would also be necessary to explain the apparent invariance of smooth specimen strengths with sheet thickness.

The stress and strain state at the notch can also be varied by varying the degree of notch acuity. Measurements of the degree of notch sensitivity as a function of notch acuity for 0.026-inch thick sheet material pointed toward an apparent critical K_t effect. At this K_t, which is dependent upon alloy composition and heat treatment, apparently a drastic increase in the notch sensitivity can occur.

a. For Waspaloy in the cold-worked and aged condition, when tested at 1200°F, a K_t of 3.0 was found to be nearly as detrimental to the rupture strength as a K_t of 20 (fig. 17).

b. Inconel 718, annealed at 1750°F and aged, was extremely notch sensitive at 1000°F and much less so at 1200°F for a K_t of 20 (see fig. 18). However, for K_t's of 2.3 and 6.0, very little notch sensitivity was observed at either temperature. In this case, therefore, the critical K_t at 1000°F was somewhat greater than 6.0.

DISCUSSION

Considerable research has been conducted on the notch sensitivity of superalloys. Generally, these studies have been conducted utilizing round specimens to obtain the rupture properties at temperatures no lower than 1200°F. It is not known if the relationships established between the notch sensitivity and metallurgical characteristics in these studies can be applied to edge-notched, thin sheet specimens tested at 1000° and 1200°F. It is apparent, however, that the presence of edge notches in sheet specimens results in a more extreme stress and/or strain state than in notched round specimens. In any event, the results show that the notch sensitivity can be many magnitudes more severe in sheet materials than has been reported for round specimens.

Due to the intimate association of microstructural features and mechanical characteristics, it is extremely difficult to evaluate notch sensitivity in terms of particular factors within one of these classifications. For example, intergranular crack initiation (and growth), which apparently controls the notch sensitivity, will depend upon plastic deformation processes (yielding on loading and subsequent creep), which in turn are directly related to microstructural features (e. g., γ' distribution, grain boundary characteristics, etc.).

The results of a study of the influence of the heat treatment of Waspaloy sheet on the microstructure, mechanical characteristics, and notch sensitivity, have been reported in detail in an unpublished report to NASA (ref. 3). However, it is useful, at this point, to present a brief summary of some of the effects of variation in solution treatments from 1825° to 2150°F (1/2-hour), and aging treatments from 16 hours at 1400°F to 10 hours at 1700°F.

1. Aging at 1700°F, as compared with 1400°F (for a solution treatment of 1900° and 1975°F), resulted in a marked increase in γ' size, but little variation in other microstructural features. Corresponding to these changes, tests at 1000° and 1200°F showed a small decrease in creep resistance, an increase in rupture ductility, and a decrease in the extent of time-dependent notch sensitivity (fig. 9).

2. For a given aging treatment, increasing the solution temperature resulted in a marked variation in grain boundary characteristics. The grain boundaries were partially filled with $M_{23}C_6$ for the lower-temperature heat treatments; with the higher-temperature heat treatments, grain growth occurred, and extensive precipitation of $M_{23}C_6$ and γ' occurred in the grain boundaries; also, regions depleted of γ' were observed adjacent to the boundaries. Increasing the solution temperature also resulted in lower creep resistance and tensile strengths, and in similar changes of rupture ductility with time and temperature. However, although the maximum notch sensitivity occurred for heat treated material at longer times and higher temperatures, the higher the solution temperature, the minimum in N/S ratio was about the same. (Data for some of these heat treatments were presented in fig. 9.)

In a study of the effect of microstructural features on the notch sensitivity of two Inconel alloys (X-750 and 718) (ref. 4), Raymond concluded that the primary effect of heat treatment in rendering these alloys notch-ductile was the elimination of any γ' denuded zone adjacent to the grain boundaries. Eiselstein (ref. 5) showed that round, notched bars were notch strengthened (at 1300°F/75 ksi) when annealed in the 1700° to 1850°F range and aged, whereas annealing at 1975°F or above, and aging resulted in notch sensitive material. Raymond concluded that this increase in notch sensitivity with increasing annealing temperature was associated with the formation of a denuded zone.

Inconel 718 (ref. 2) cold-worked, 0.026-inch thick material has been tested after the following heat treatments, the annealing temperatures of which lie in the two ranges described by Raymond.

a. Annealed one hour at 1750°, aged 8 hours at 1325°F, F.C., to 1150°F in 10 hours, A.C.

b. Annealed one hour at 1950°, aged 8 hours at 1350°F, F.C., to 1200°F in 12 hours, A.C.

The stress-rupture time curves and the N/S ratios are presented in figures 7, 11, and 19. From these the following is evident.

1. Both of the heat treated sheet materials exhibit a very pronounced time-dependent notch sensitivity in the intermediate temperature range. The variations in microstructural features of the two materials did not result, in this case, in a marked difference in the maximum notch sensitivity exhibited, but only in the time and temperature at which it occurred.
2. It should be noted that for the sheet material annealed at 1750°F, little or no notch sensitivity was exhibited until the notch acuity was increased above 6.0. In contrast, the material annealed at 1950°F was almost as notch sensitive with a K_t of 3.0 as with one of 20.
3. Results reported from testing round bars in heat treated conditions similar to the above (refs. 4, 5), showed a minimum notch to smooth specimen rupture time ratio (for the material annealed at the higher temperature) of the order of 1:10. In contrast, the minimum ratio for the sheet material (for either heat treatment), being $\sim 1:10^6$, was many orders of

magnitude lower. It is evident, therefore, that the results being reported in this paper for edge-notched, thin sheet involve a much more extreme effect.

For Inconel 718, the heat treatment (and, hence, the microstructure and mechanical characteristics) has an influence on the extent of the notch sensitivity for notched round bars or sheet specimens with low notch acuities. However, a high degree of notch sensitivity (for annealing at 1750° and 1950°F) occurred for sheet specimens with very sharp notches. Results presented previously for René 41 at 1200°F (fig. 16) showed that round bars exhibited slight notch strengthening, while sheet specimens (K_t=20) were extremely notch sensitive. Together with the data for Waspaloy sheet, these results indicate that the extreme edge-notch sensitivity of thin sheet materials to temperatures as low as 1000°F, at least, involves factors in addition to most of the data reported in the literature.

CONCLUSIONS

The results obtained to date from a study of the scope and cause of time-dependent notch sensitivity shown to occur in superalloy sheet materials at temperatures of 1000° and 1200°F, have been presented. Creep rupture testing of René 41, Waspaloy, and Inconel 718 in a wide range of heat-treated conditions has served as a means of providing a general description of the notch sensitive behavior of 0.026-inch thick material. In addition, the influence of sheet thickness and notch acuity on notch sensitivity has been evaluated to further define the scope of the problem.

1. The results show that rupture occurs by intergranular crack initiation and growth, apparently by creep, until abrupt shear occurs due to the increase in stress on the reduced load-carrying area. The time-to-rupture for both smooth and notched specimens is determined by all of these fracture processes. For a given stress and temperature, the difference between rupture times for the notched and smooth specimens

(i.e., the notch sensitivity) is determined primarily by the first stages of intergranular cracking.

2. The notch sensitivity of 0.026-inch thick sheet is apparently limited to an intermediate temperature range (from slightly below 1000° to slightly above 1200°F) within the testing times considered. The extent of the notch sensitivity exhibited is dependent upon the composition and thermal treatment of the alloy, i.e., the microstructural features and mechanical characteristics. The notch to smooth specimen rupture strength ratios commonly fall as low as 0.5, which corresponds to the extremely low rupture time ratio of nearly $1{:}10^6$.

3. The evidence indicates that relaxation of the stresses around the notches is a critical factor affecting the intergranular fracture processes, and thus the notch sensitivity. The relaxation can be the result of deformation by yielding and/or by subsequent creep. On the other hand, excessive creep deformation can promote intergranular cracking. The interaction of these two effects apparently results in the notch sensitivity being more dependent upon the processes contributing to the ductility than upon the actual level of ductility itself.

4. Limited data indicate that specimen geometry has an important effect on notch sensitivity. Round, notched specimens (triaxial stress) are not known to exhibit the time-dependent notch sensitivity in the temperature being considered in this investigation. In addition, in limited testing, 0.050-inch thick specimens have not shown time-dependent notch sensitivity. The influence of notch acuity (K_t) on the degree of notch sensitivity (for 0.026-inch thick sheet) is apparently related to a critical K_t. Below this critical K_t, which is dependent upon the alloy, test temperature, and heat treatment, the material exhibits little or no notch sensitivity, whereas above it, the material exhibits extensive notch sensitivity.

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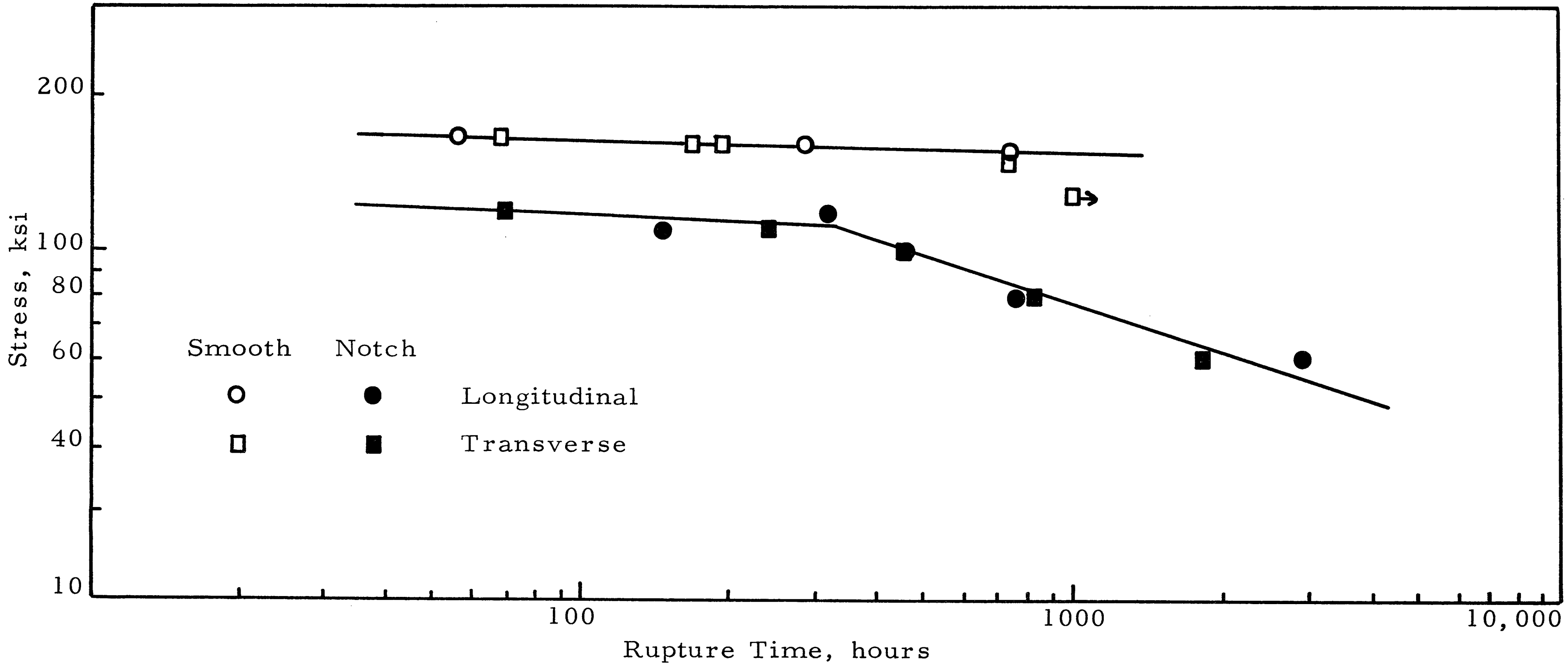
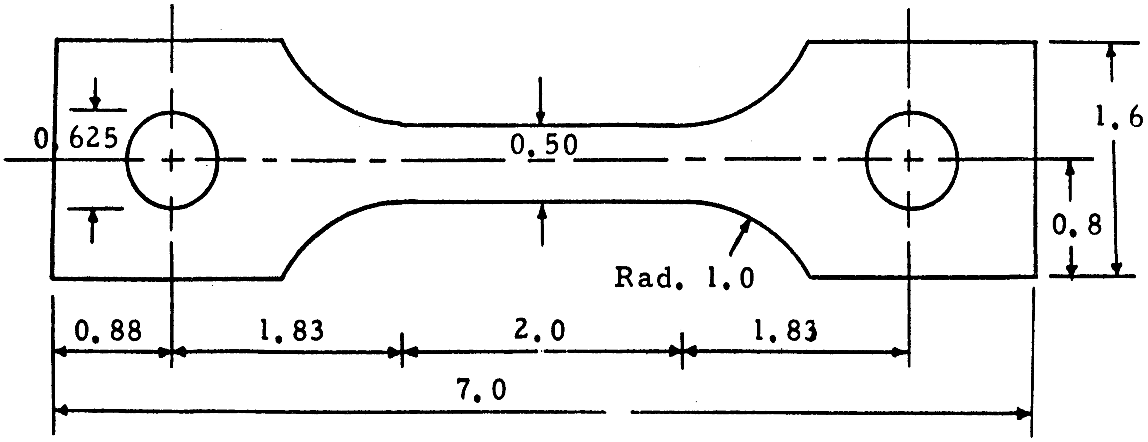
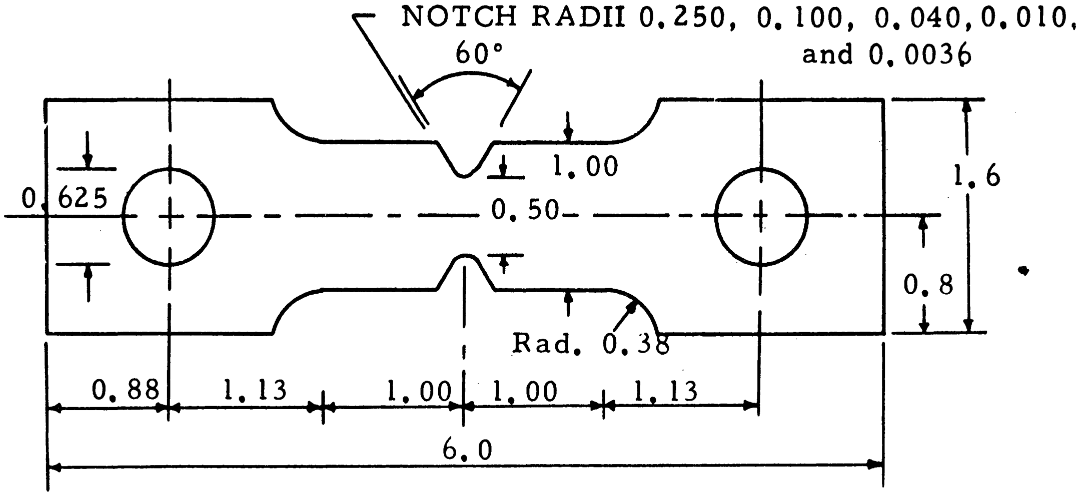


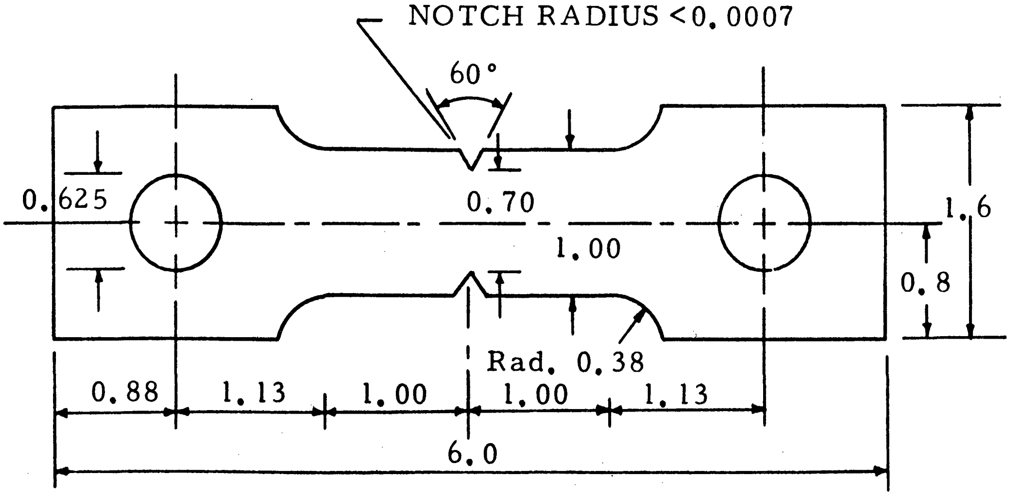
Figure 1. Stress versus rupture time data at 1000°F, obtained from smooth and notched (K_t = 20) specimens of 0.026-inch thick René 41, annealed at 1975°F and aged 16 hours at 1400°F.



Smooth (unnotched) Specimen (K_t=1.0)



Notched Specimen for K_t=2.3 and 6.0



Sharp Edge notched Specimen (K_t> 20)

Figure 2. Types of test specimens (all dimensions in inches).

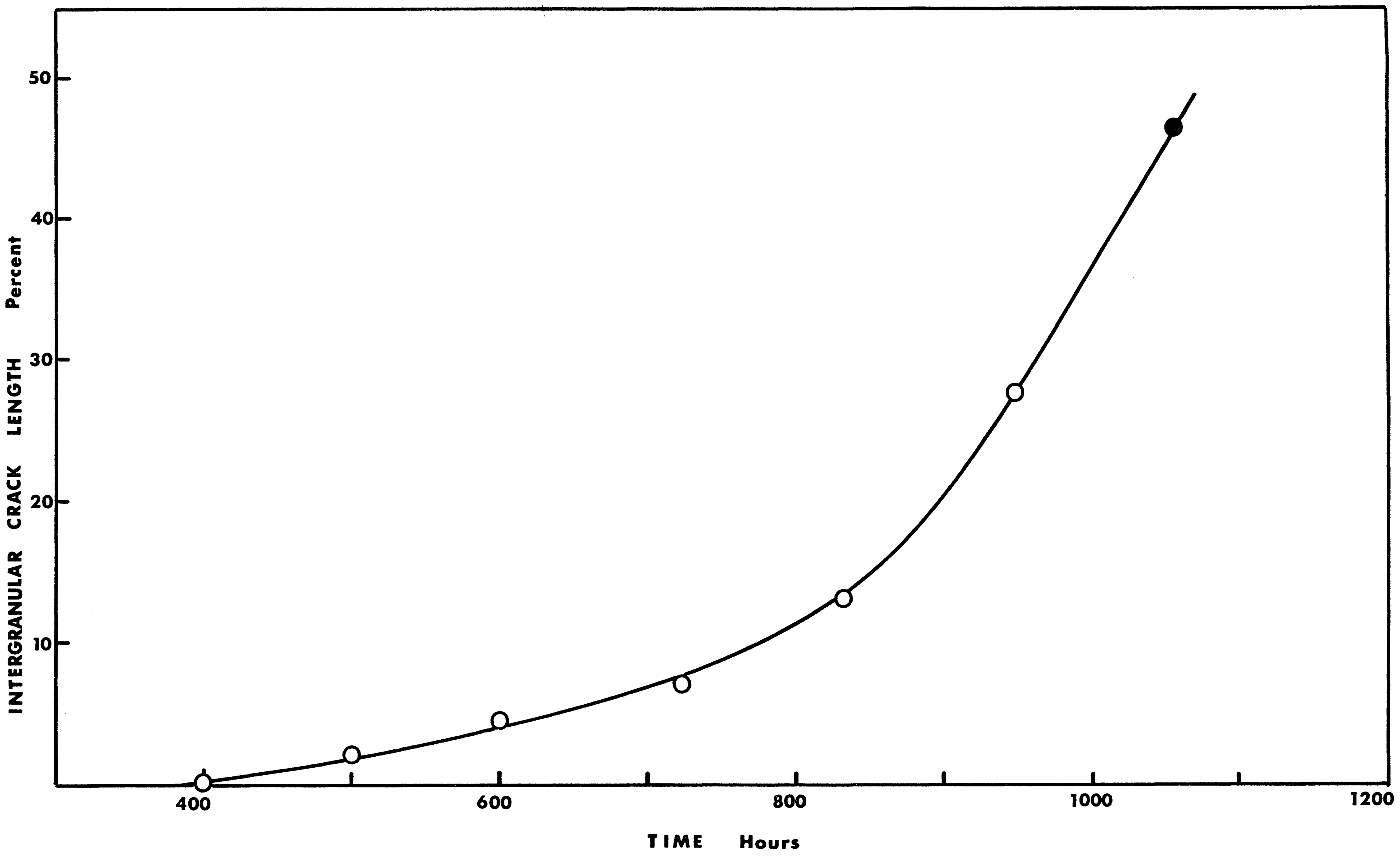


Figure 3. Intergranular crack growth obtained from a notched specimen (K_t=20) of 0.026-inch thick Waspaloy sheet, annealed at 1825°F and aged 16 hours at 1400°F; tested at 1000°F at 100 ksi.

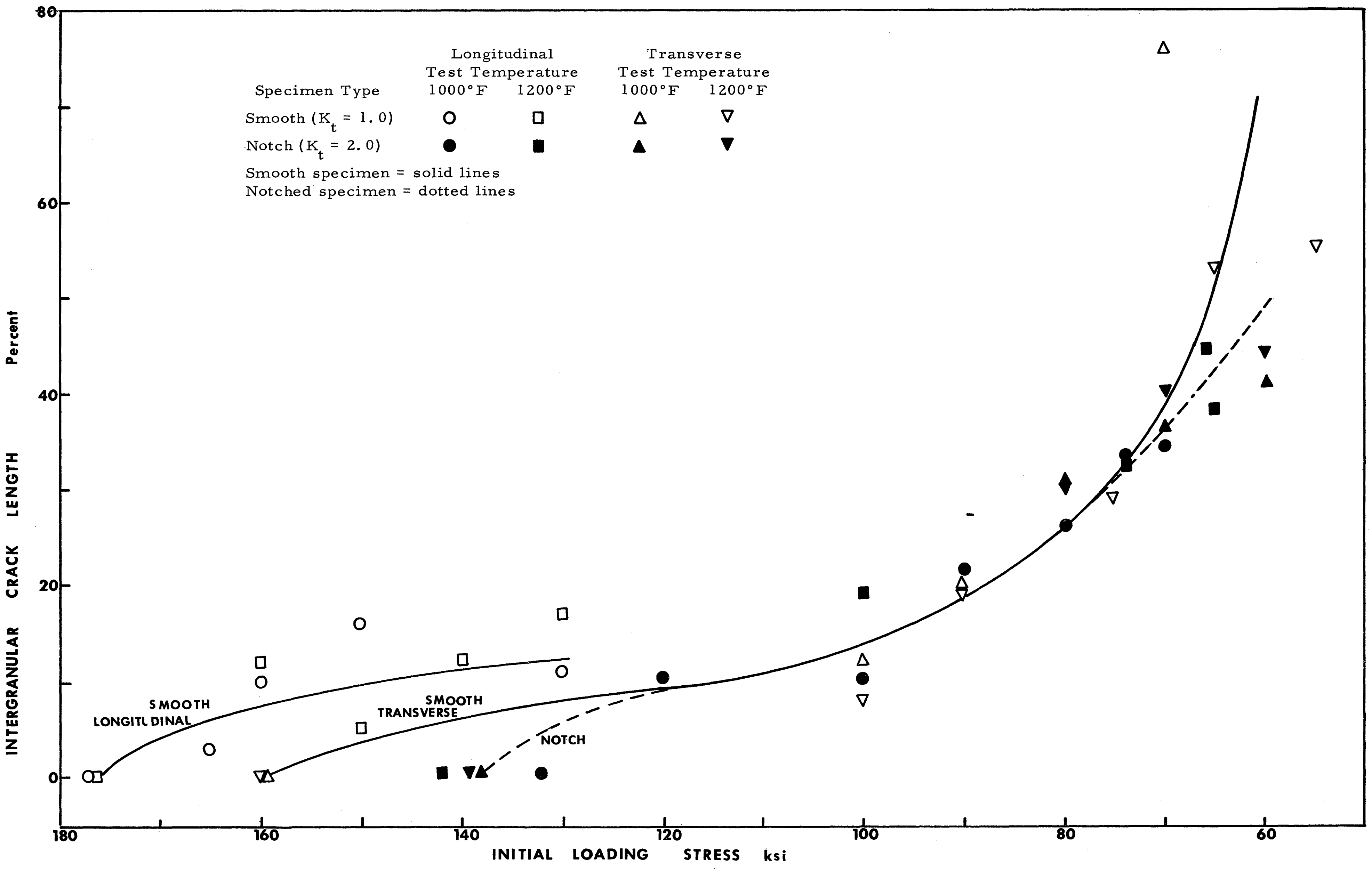


Figure 4. Intergranular crack length versus initial loading stress at 1000° and 1200°F, obtained from smooth and notched ($K_t = 20$) specimens of 0.026-inch thick Inconel 718 sheet, annealed at 1750°F and aged (1325°F/8 hours, F. C., to 1150°F in 10 hours, A. C.).

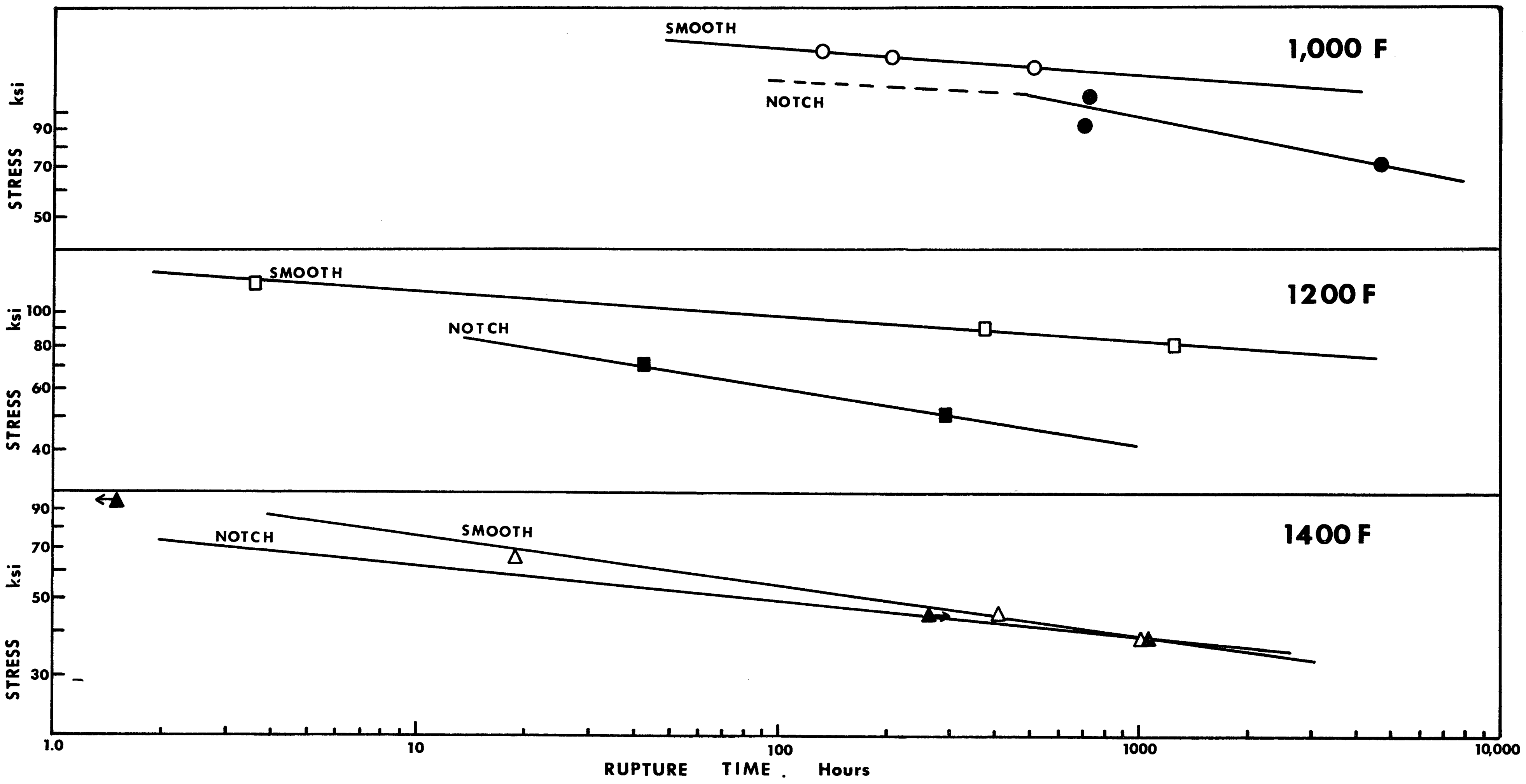


Figure 5. Stress versus rupture time data obtained from smooth and notched ($K_t = 20$) specimens of 0.026-inch thick Waspaloy sheet, annealed at 1975°F and aged 16 hours at 1400°F, and tested at 1000°, 1200°, and 1400°F.

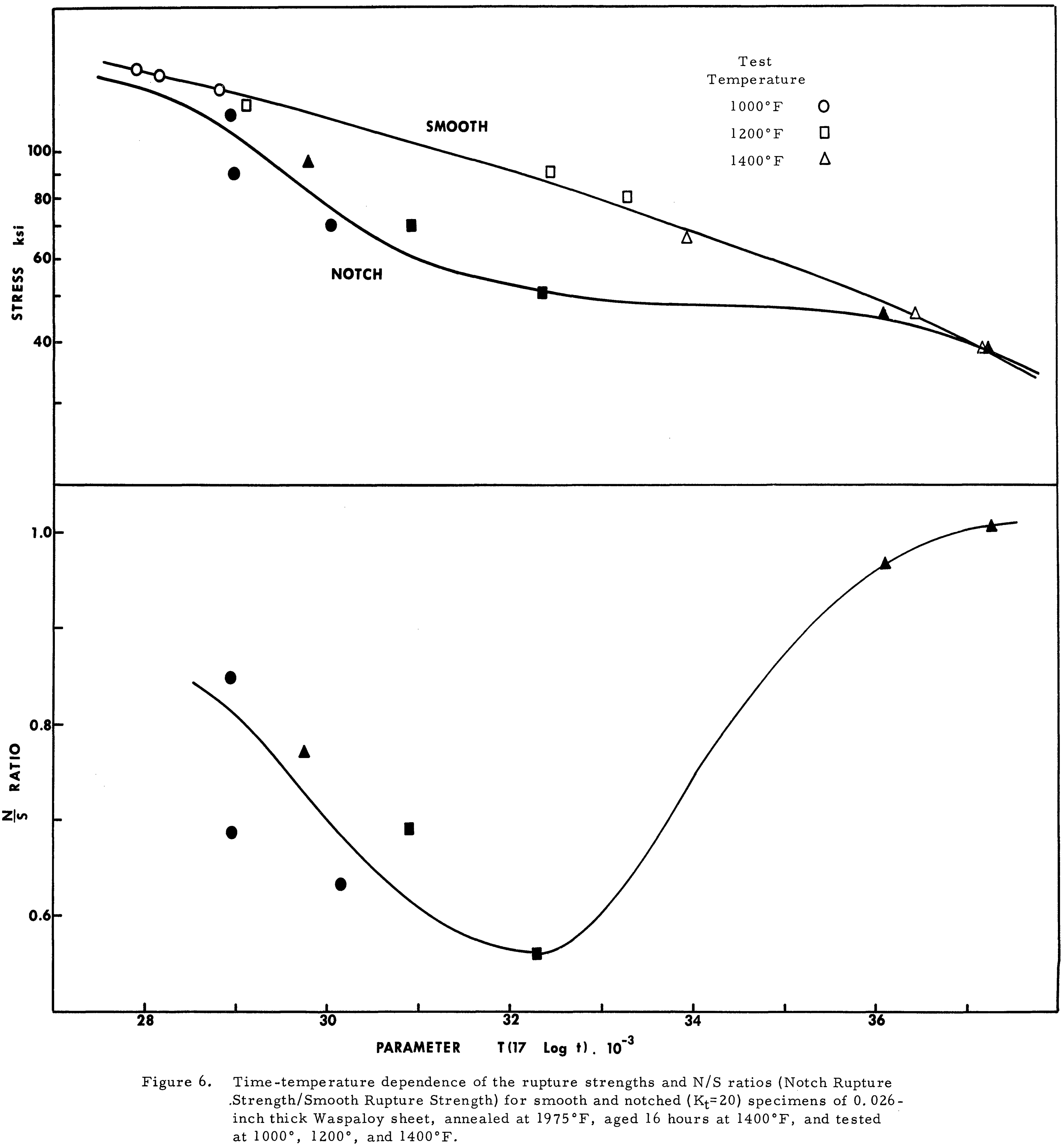


Figure 6. Time-temperature dependence of the rupture strengths and N/S ratios (Notch Rupture Strength/Smooth Rupture Strength) for smooth and notched (K_t=20) specimens of 0.026-inch thick Waspaloy sheet, annealed at 1975°F, aged 16 hours at 1400°F, and tested at 1000°, 1200°, and 1400°F.

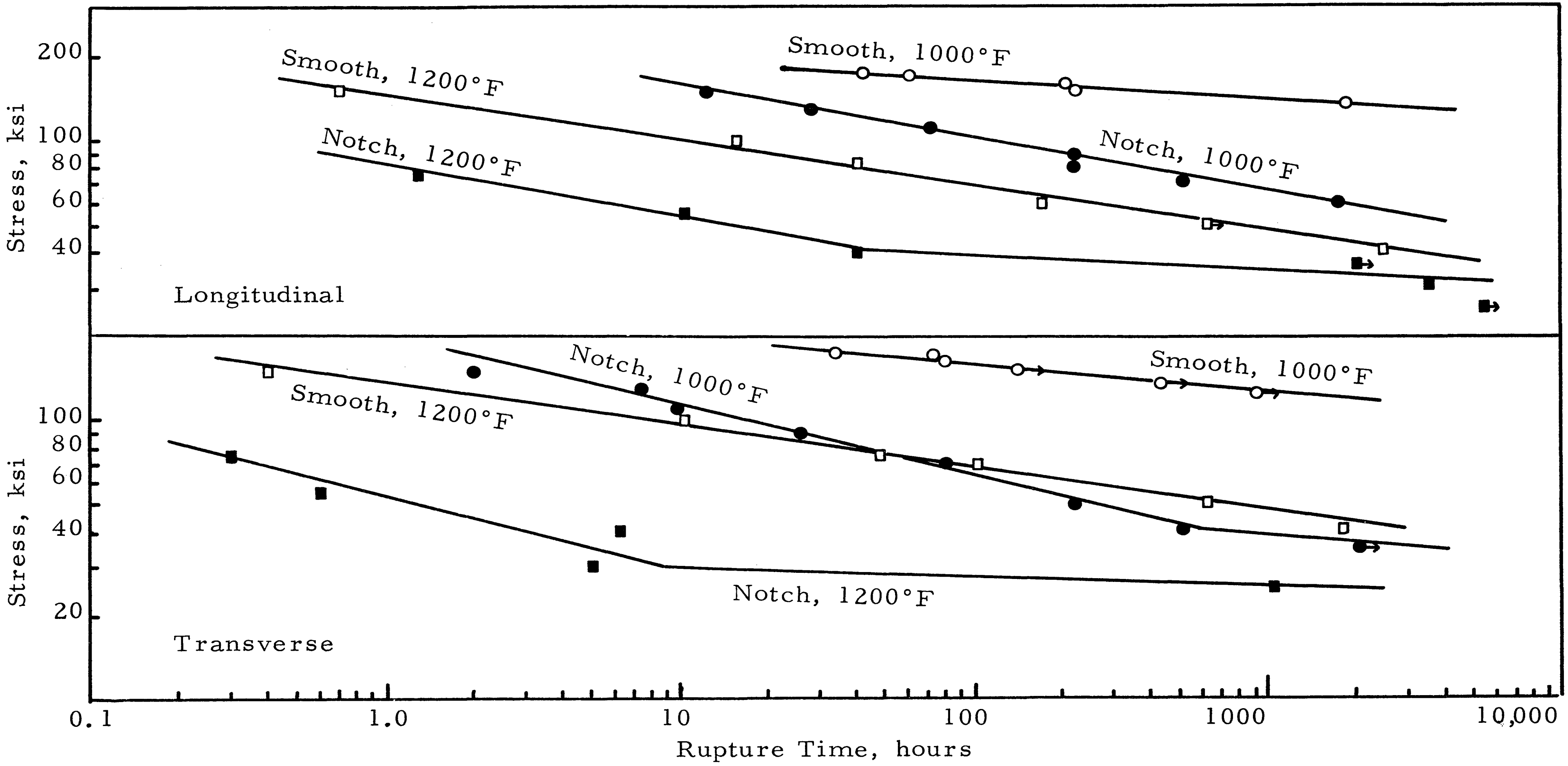


Figure 7. Stress versus rupture data at 1000° and 1200°F, obtained from smooth and notched (K_t=20) specimens of 0.026-inch thick Inconel 718 in the cold worked and aged condition (1325°F/ 8 hours, F. C., to 1150°F in 10 hours, A. C.).

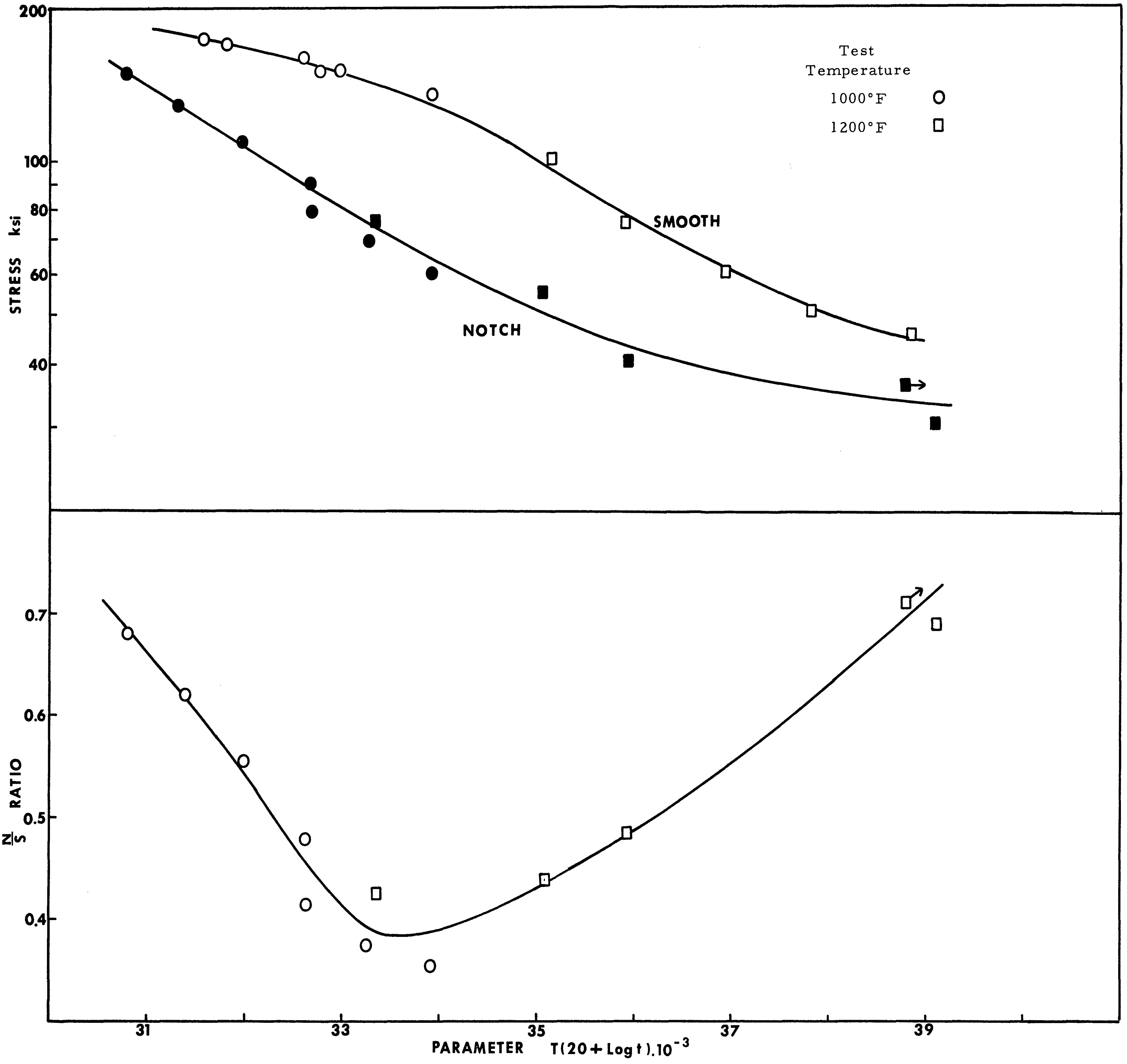


Figure 8. Time-temperature dependence of the rupture strengths and N/S ratios (Notch Rupture Strength/Smooth Rupture Strength) for smooth and notched (K_t=20) specimens of 0.026-inch thick Inconel 718 in the cold worked and aged condition; tested at 1000° and 1200°F.

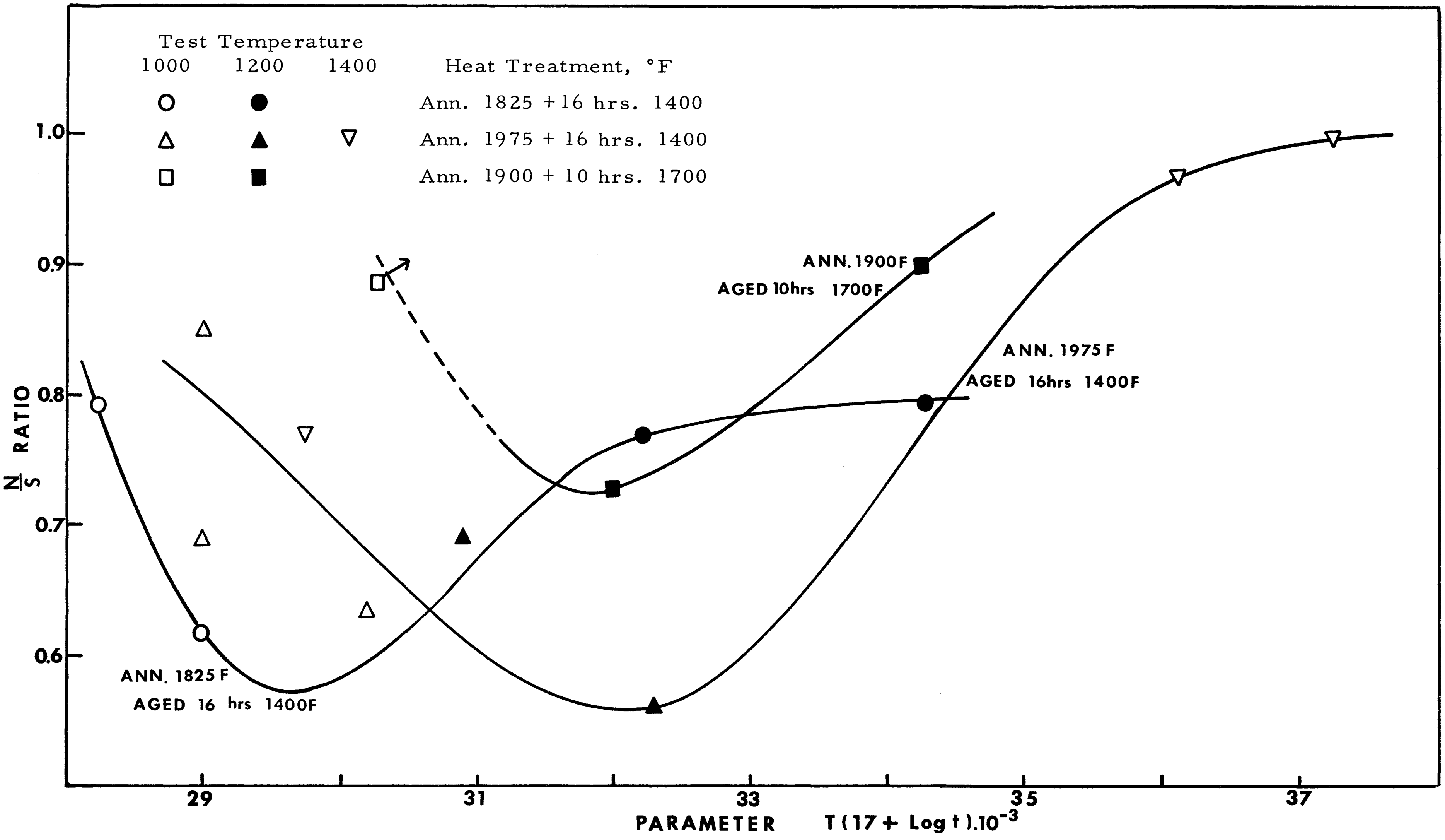


Figure 9. Time-temperature dependence of the N/S ratios (Notch Rupture Strength/Smooth Rupture Strength) obtained from smooth and notched (K_t=20) specimens of 0.026-inch thick Waspaloy sheet in the heat treated conditions.

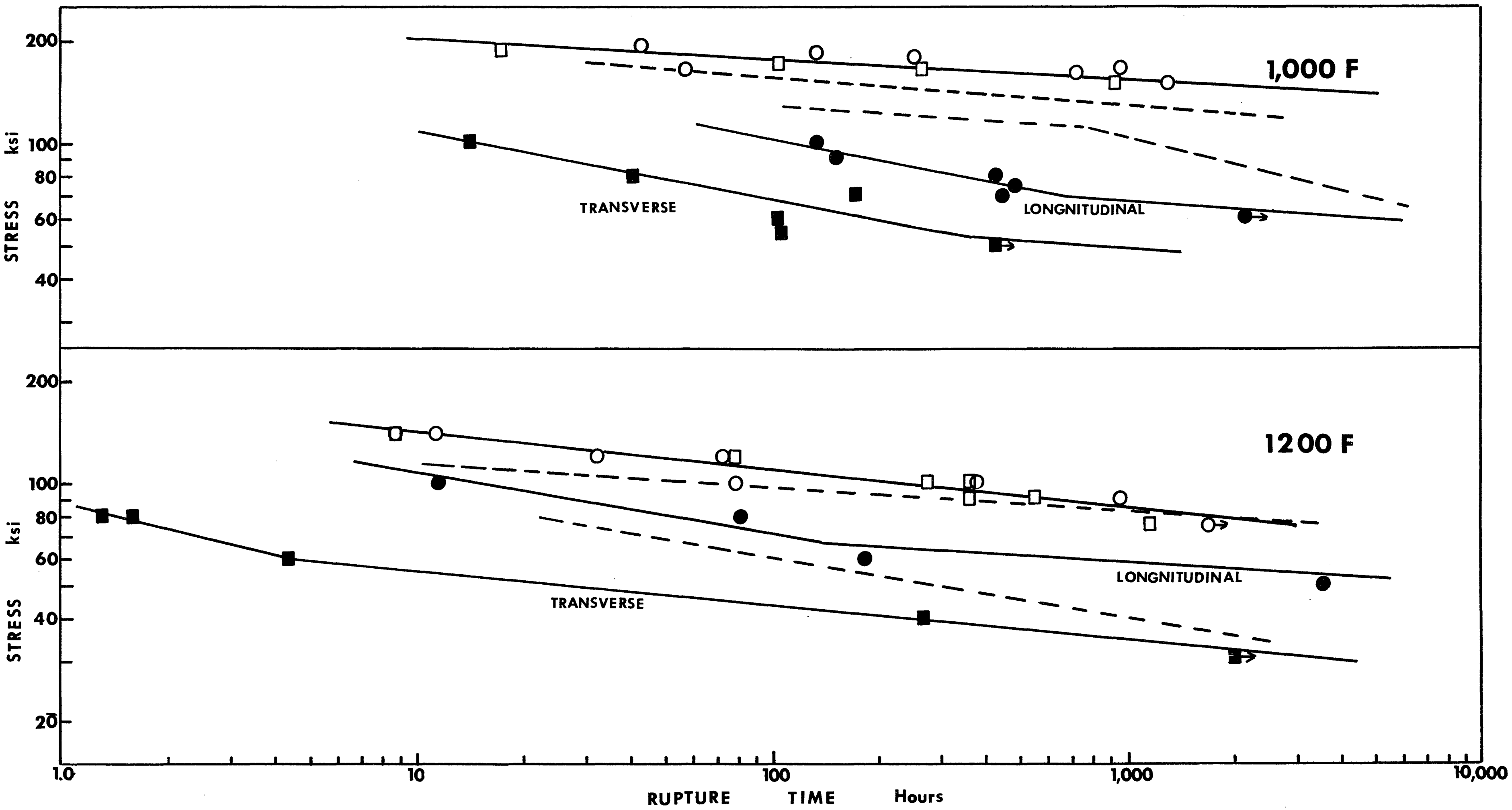


Figure 10. Stress versus rupture data at 1000° and 1200°F, obtained from smooth and notched specimens of 0.026-inch thick Waspaloy, cold worked and aged 2 hours at 1500°F; dotted rupture curves were obtained from material annealed at 1975°F and aged 16 hours at 1400°F.

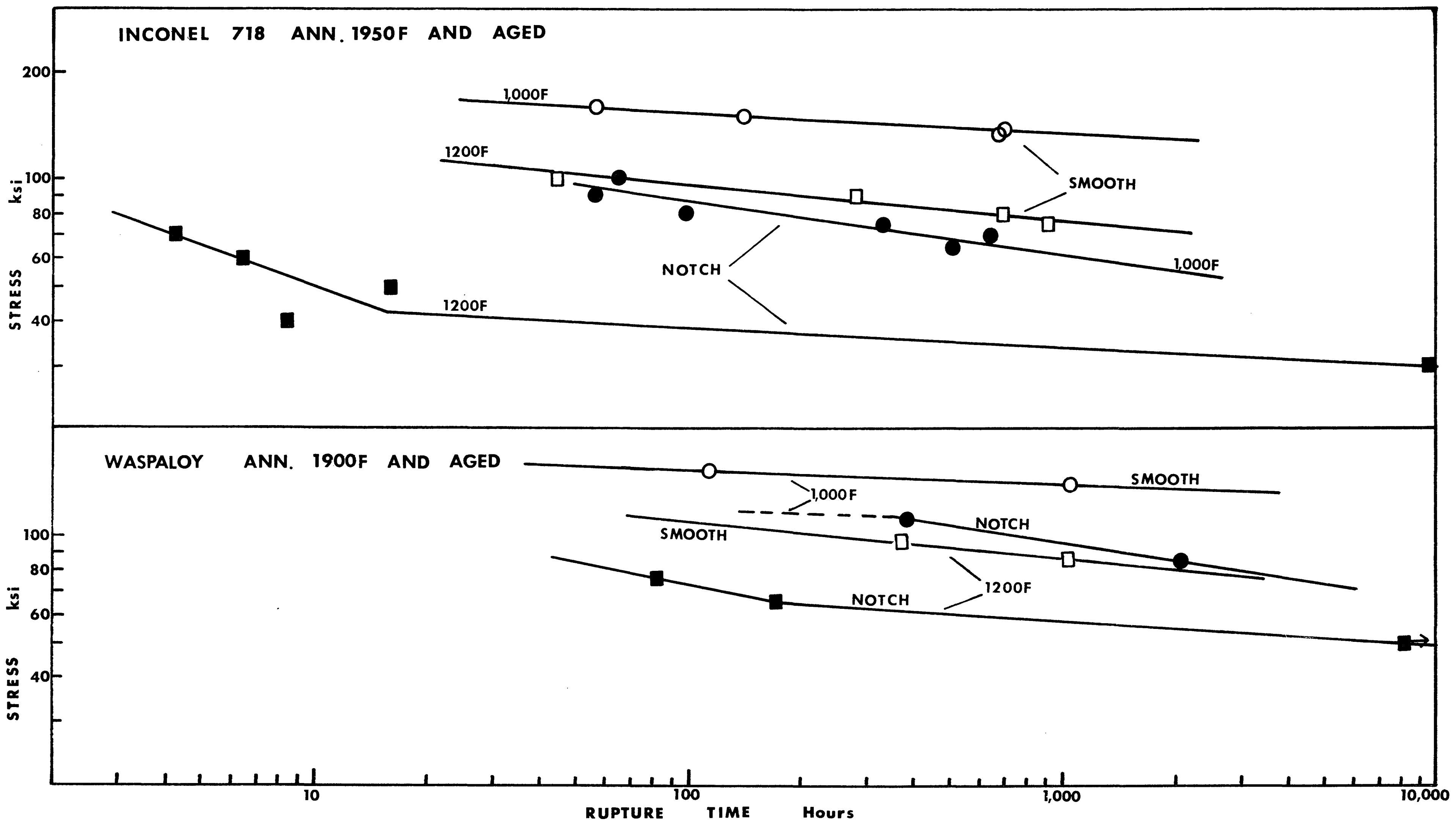


Figure 11. Stress versus rupture data at 1000° and 1200°F, obtained from smooth and notched (K_t = 20) specimens of 0.026-inch thick Inconel 718 and Waspaloy sheet in the heat treated conditions. (Inconel 718: ann. at 1950°F, aged 1350°F/8 hours, F.C., to 1200°F in 12 hours, A.C.; Waspaloy: ann. at 1900°F and aged 16 hours at 1400°F.)

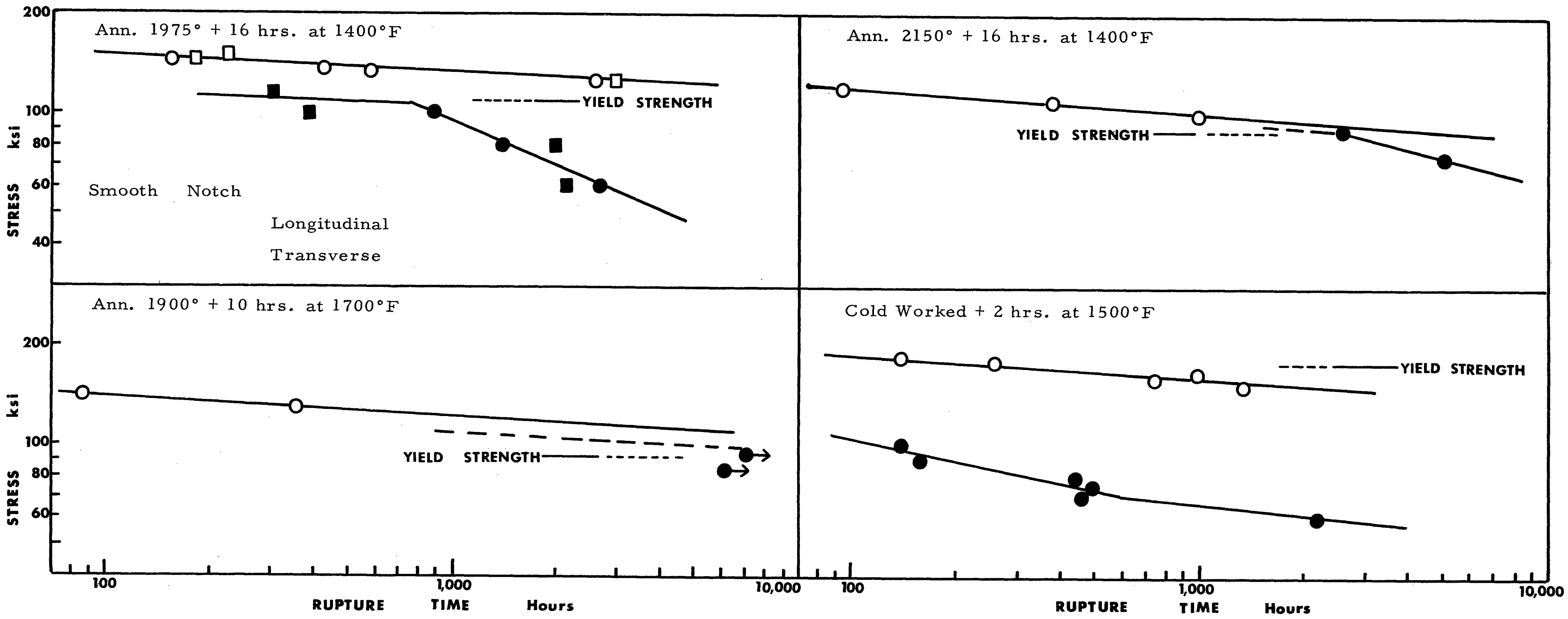


Figure 12. Stress versus rupture data at 1000°F, obtained from smooth and notched specimens of 0.026-inch thick Waspaloy sheet in the heat treated conditions.

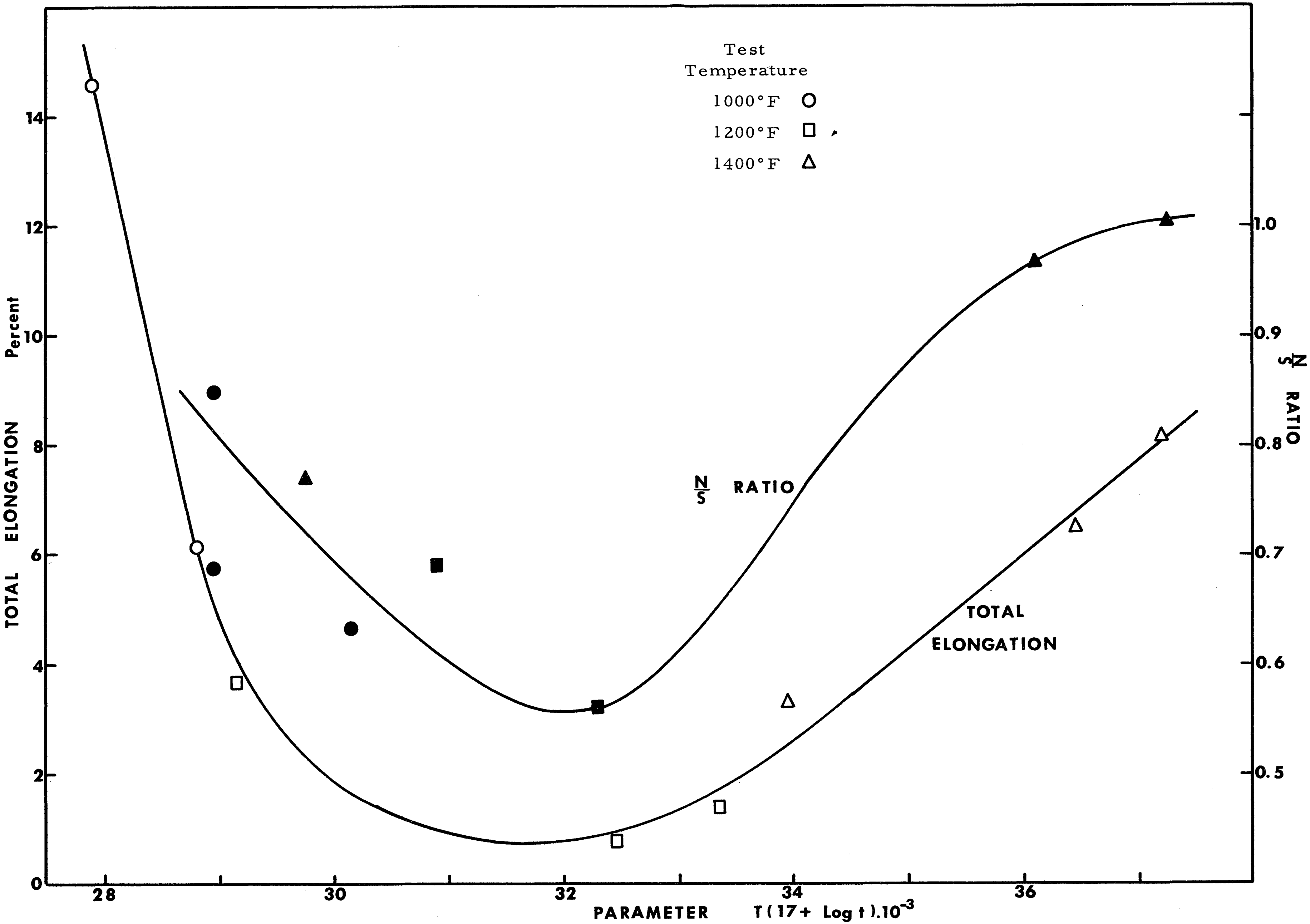


Figure 13. Time-temperature dependence of total elongation and N/S ratios (Notch Rupture Strength/Smooth Rupture Strength), obtained from smooth and notched ($K_t = 20$) specimens of 0.026-inch thick Waspaloy sheet, annealed at 1975°F and aged at 1400°F; tested at 1000°, 1200°, and 1400°F.

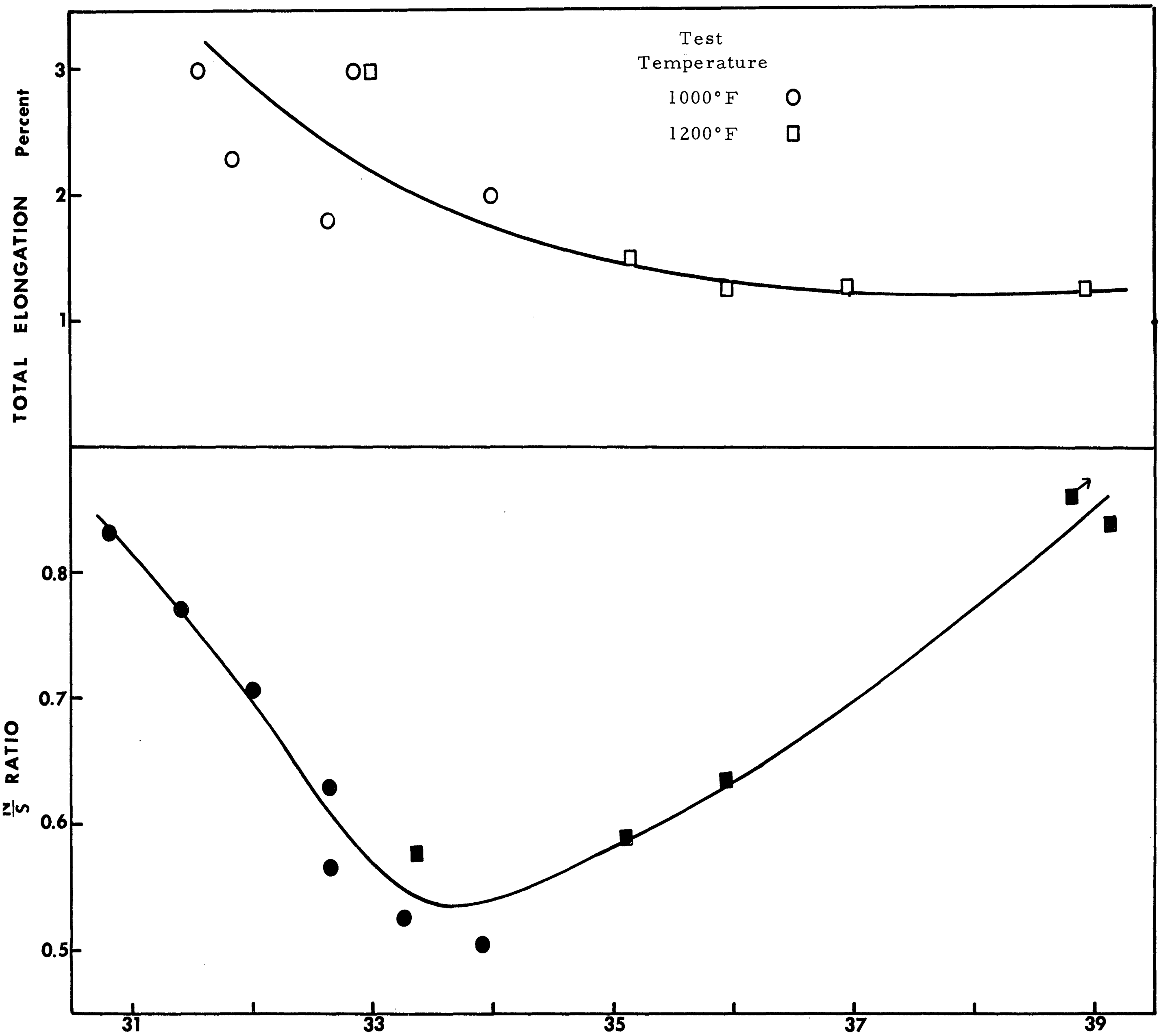


Figure 14. Time-temperature dependence of total elongation and N/S ratios (Notch Rupture Strength/Smooth Rupture Strength) at 1000° and 1200°F, obtained from smooth and notched (K_t=20) specimens of 0.026-inch thick Inconel 718 in the cold worked and aged condition (1325°F/8 hours, F.C., to 1150°F in 10 hours, A.C.).

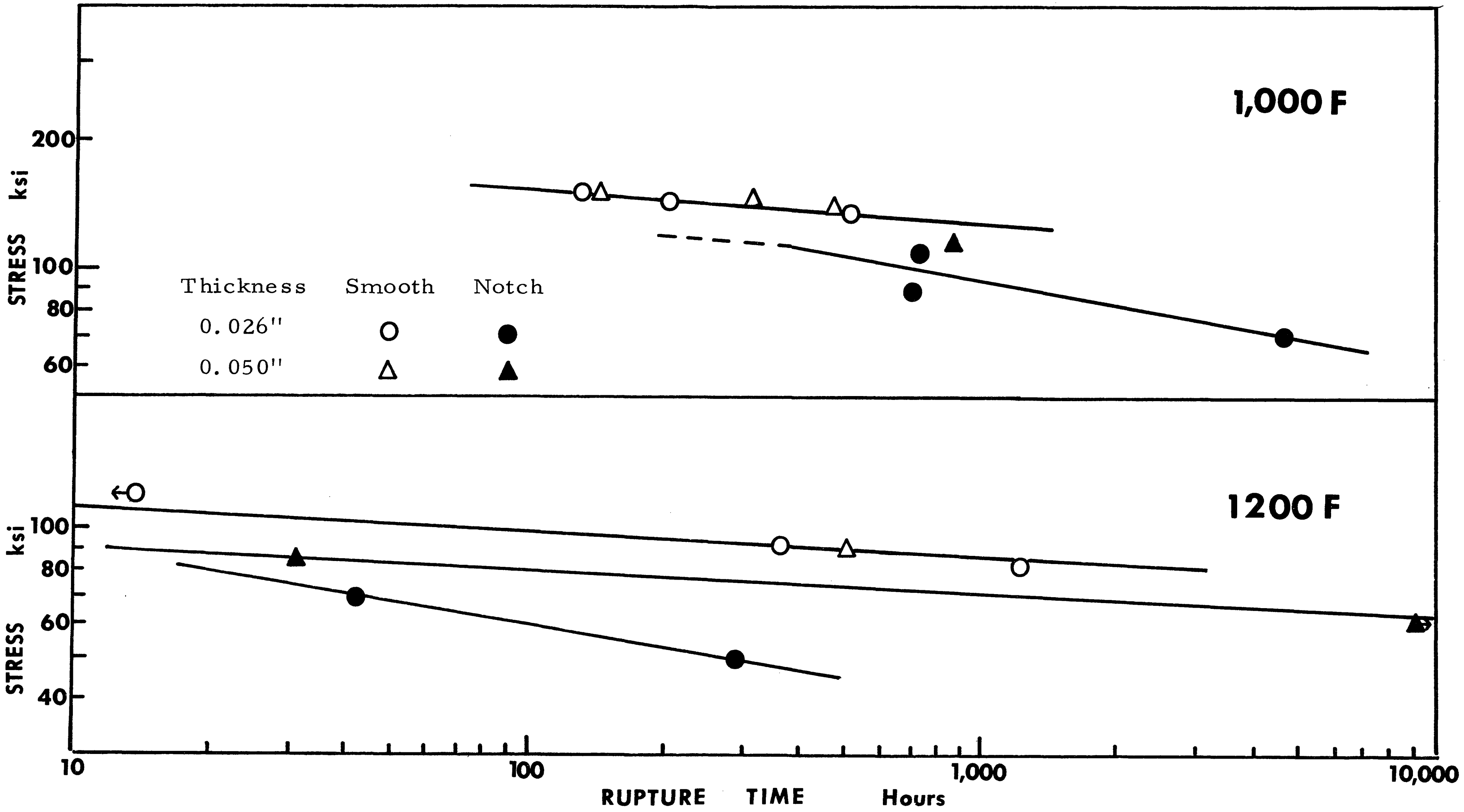


Figure 15. Stress versus rupture data at 1000° and 1200°F, obtained from smooth and notched ($K_t = 20$) specimens of 0.026- and 0.050-inch thick Waspaloy sheet annealed at 1975°F and aged 16 hours at 1400°F.

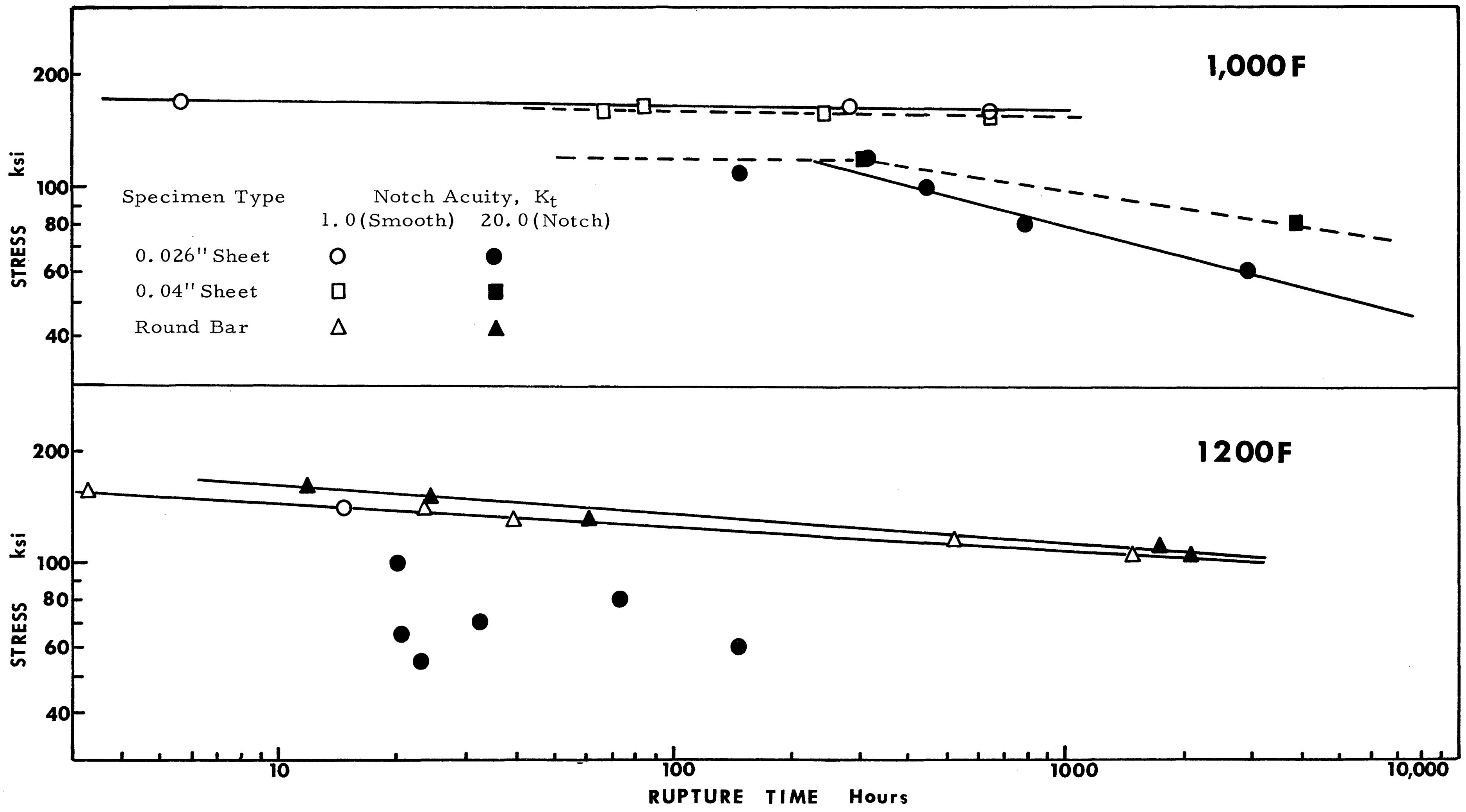


Figure 16. Stress versus rupture data at 1000° and 1200°F, obtained from smooth and notched (K_t=20) specimens of René 41 sheet and round bar, annealed at 1975°F and aged 16 hours at 1400°F.

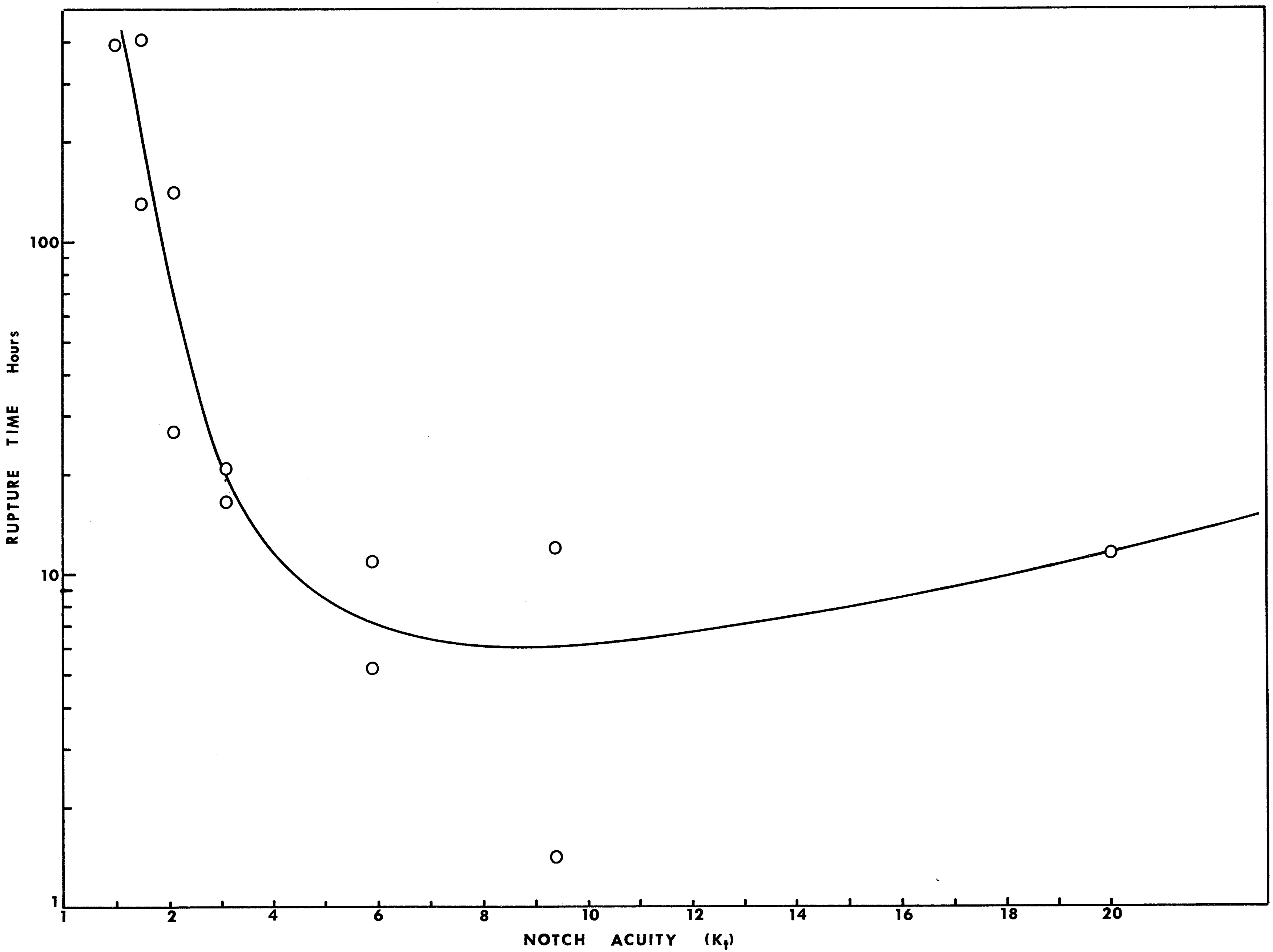


Figure 17. Influence of notch acuity on the rupture life of 0.026-inch thick Waspaloy sheet, cold worked and aged 2 hours at 1500°F; tested at 1000°F at 100 ksi.

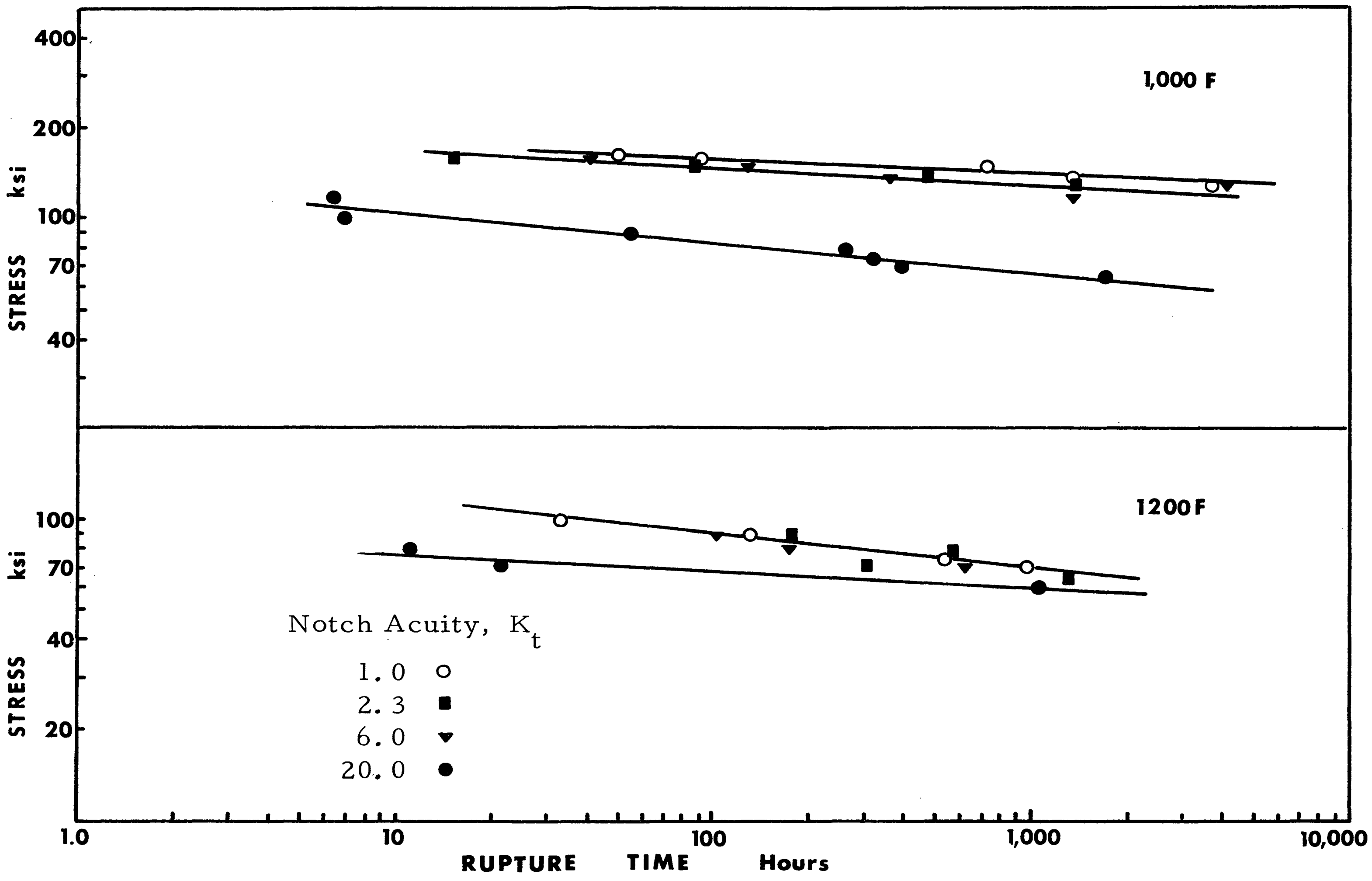


Figure 18. Effect of notch acuity at 1000° and 1200°F on the stress-rupture properties of 0.026-inch thick Inconel 718 sheet, annealed at 1750°F and aged (1325°F for 8 hours, F.C., to 1150°F in 10 hours, A.C.).

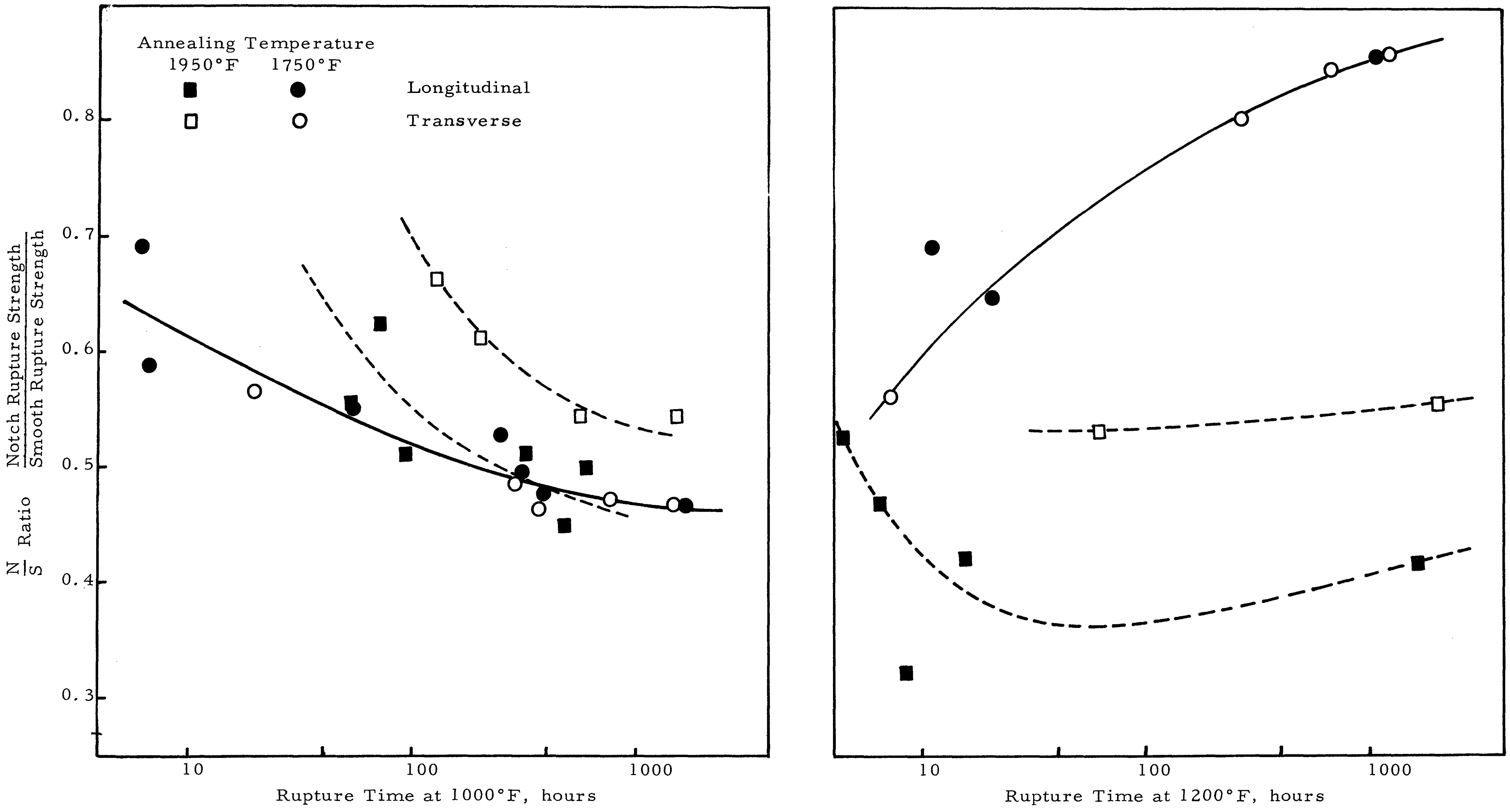


Figure 19. Time-temperature dependence of notch sensitivity at 1000° and 1200°F, obtained from smooth and notched (K_t=20) specimens of 0.026-inch thick Inconel 718 sheet in two conditions of heat treatment (1950°F ann., aged 1350°F/8 hrs., F.C., to 1200°F in 12 hrs., A.C.; 1750°F ann., aged 1325°F/8 hrs., F.C., to 1150°F in 10 hrs., A.C.).