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ON

INTERMEDIATE TEMPERATURE CREEP AND RUPTURE BEHAVIOR OF TITANIUM AND TITANIUM ALLOYS

By

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SUMMARY

This report, the fourth under contract AF 33(616)-244, covers the period from April 16, 1953 to July 15, 1953.

The object of the investigation is to establish general principles relating types of microstructures of typical titanium base alloys to rupture and creep resistance in the range from 600° to 1000°F.

Rupture testing is now complete at 600°, 800° and 1000°F on Ti 75A and Ti 150A. Rupture testing at 600° and 1000°F is complete on three conditions of the experimental alpha alloy (6% Al) and three conditions of the experimental beta alloy (30% Mo). Creep tests on all materials are in progress.

Metallographic and x-ray studies have revealed changes in microstructure as a result of testing.

The meta-stable beta alloy (10% Mo) has not yet been received.

INTRODUCTION

The present report, covering the period from April 16, 1953, to July 16, 1953, is the fourth to be issued under Contract AF 33(616)-244. The investigation is sponsored by the Materials Laboratory, Wright Air Development Center.

The purpose of the investigation is to study creep and rupture behavior of titanium and its alloys in the range from 600° to 1000°F. Five alloys are included in the study. They were selected to be representative structural types. They include:

1. Commercially pure titanium (Ti 75A)
2. Commercial martensite-forming alloy (Ti 150A)
3. Stable alpha alloy (6% Al)
4. Meta-stable beta alloy (10% Mo)
5. Stable beta alloy (30% Mo)

The latter three alloys are being obtained in the form of small experimental heats from the Armour Research Foundation. All materials have been received, save the meta-stable beta alloy.

Treatments were selected so as to explore as fully as possible the microstructural conditions appropriate to each alloy. The number of tests has been limited so that as many as possible of the conditions of heat treatment of interest may be surveyed in the period covered by the present contract. Thus, for each condition and at each temperature, are run a tensile test, two rupture tests (up to 100-150 hours), and a creep test. Data from each test are utilized in planning the succeeding one, the long-time creep test being the last one run.

Microstructural examination is made of specimens after testing in order that changes, if any, can be correlated with creep and rupture behavior.

By taking as much data as possible during each test, it is possible to make a limited analysis on the basis of total deformation criteria.

RESULTS AND DISCUSSION

A detailed discussion of the aims and method of attack of this investigation was presented in the First and Second Progress Reports (dated October 15, 1952, and January 15, 1953, respectively). The Third Progress Report (dated April 15, 1953) presented considerable tensile data and some rupture data for all materials. No comparison was made between materials.

Sufficient data have now been accumulated to permit some comparison between the alloys under investigation. Each alloy is discussed separately and appropriate comparisons are made where possible. Following the discussion of the alloys, there has been tabulated, on the basis of creep and rupture criteria, a very tentative quantitative comparison.

Commercially Pure Titanium (Ti 75A)

Rupture and tensile tests at 600°, 800° and 1000°F are now nearly complete for the seven conditions of commercially pure titanium (Ti 75A) chosen for study in the initial phase of the investigation. In addition, two-thirds of the creep tests at these temperatures have been completed and the others are in progress. The conditions studied include as-received (hot rolled and annealed), re-annealed at either 1500° or

1700°F, and 10.9% and 31.3% cold work for each of the re-annealing temperatures.

Metallographic and x-ray techniques have been used to study completed rupture and tensile specimens.

Rupture Properties of Ti 75A

Rupture test results at 800° and 1000°F for seven conditions of Ti 75A were presented previously in both tabular and graph form.* The present report extends these results to 600°F (see Table I). The data are also plotted on Figures 1, 2, 3 and 4. At 600°F, as-received or annealed Ti 75A possess an extremely flat rupture curve. A change in stress of only 1,000 psi may extend rupture life by over 1000 hours. Consequently, selection of test stresses has been difficult. To further complicate the matter, cold worked conditions of Ti 75A are somewhat more stress dependent for rupture life. Thus, the criteria for choosing rupture stresses for the annealed material could not be successfully applied to the cold worked case. Table I thus presents the best estimate that could be made under the circumstances of 100-hour rupture strength.

In conjunction with previously reported data from the higher temperatures, these results have been plotted as a function of the amount of cold work on Figure 5. Here it will be seen that the strengthening effect of cold work is considerably diminishing in going from 600° to 800°F and eliminated almost completely at 1000°F.

To further emphasize this result, a plot was presented in the previous report** which showed a linear decrease of the quotient

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* Third Progress Report, Contract AF 33(616)-244, April 15, 1953, Table I and Figure 4.

** Third Progress Report, Figure 5.

$\frac{\text{100-hour Rupture Strength}}{\text{Ultimate Tensiel Strength}}$ with increasing temperature. Thus, at 600°F the quotient was about 0.94, and at 1000°F it fell to 0.21. It is believed that the quotient approaches 1.0 asymptotically for decreasing temperatures. This effect is shown to have some generality for titanium and its alloys in Figure 6. Here data obtained for Ti 150A, a ferro-chrome ternary alloy, show good agreement with the Ti 75A data. This will be discussed in a succeeding section.

The inference to be drawn is that, barring reduction of strength by extreme brittleness (a condition encountered in room temperature tests of Ti 150A strip specimens in another investigation*), the rupture strength at temperatures up to 600°F is approximately equal to the ultimate tensile strength, i.e., between 95 to 98% of it. Yet, appreciable deformation does occur at stresses immediately below the rupture strength without leading to rupture, as will be shown later. At 600°F, tests on Ti 75A at stresses only very slightly below the tensile strength were characterized by a high initial deformation on loading and immediately thereafter, and then a very small second stage component with no indication of third stage creep. (Duration of longest test was 1500 hours.) The question of deformation will be covered more fully in a later section of this report. A consideration of rupture strength alone shows with increasing temperature both a greatly increased stress dependency and a lowered cold-working dependency.

Creep and Total Deformation Studies of Ti 75A

Creep testing of Ti 75A at 800° and 1000°F has progressed to the point where some indication of the relationship can be presented

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* Under Contract AF 33(038)-14111.

(Figure 7). Of interest is the extremely high stress dependency of creep rate at these temperatures. Little difference, if any, was found between the annealed and cold worked conditions -- cold working did decrease creep rate somewhat. At 600°F it is noted that annealed and as-received conditions showed very low second stage creep rates even after appreciable deformation during loading and during first-stage creep. This was found for stresses about 98% of the ultimate tensile strength. It is believed that creep tests at 600°F now in progress on cold worked material will show a definite second stage since stress dependency of rupture results for these materials appears to be increased.

In Table II are presented a tabulation of all creep data on Ti 75A to date together with an estimate of the stress to cause a minimum rate of 5 x 10^{-6} in. /in. /hr. (roughly equivalent to the 1000-hour rupture strength). For this criterion, the stress at 800°F ranged from only 5,000 to 10,000 psi and at 1000°F is between 1,500 and 3,500 psi. The ranges resulted from varying treatments. It will also be noted that the ratio of the rupture strengths to the creep resistance increases with increasing temperature.

Total deformation characteristics have been determined (as far as the available data permits) for all conditions at 800° and 1000°F and for only the annealed condition at 600°F. These are presented in Figures 1, 2, 3 and 4. Salient points to be noted are the large amounts of total deformation at 600°F on annealed or as-received stock without lowering of rupture life. Also to be noted are the high elongations in rupture tests at 1000°F. One-per cent total deformation was reached at 1000°F in one-hundredth to one-tenth of the rupture life at that stress. This is also emphasized by the low stresses for a given minimum creep rate--discussed in the preceeding paragraph.

A correlation with lower temperature creep test results* is shown in Figure 8. Here the stress for a minimum creep rate of 3 x 10^{-6} in. /in. /hr. (0.3%/1000 hours) has been determined over a range from 76° to 1000°F. A strengthening, characteristic of a strain aging reaction, is noted at 400°F following which the relationship drops off rapidly. Above 800°F, the indications are that the stress for the creep rate correlated approaches zero.

Metallographic Studies of Ti 75A

Metallographic studies have been made on several completed tensile and rupture specimens. Some difficulty has been experienced in the prevention of pitting of electro-polished samples. Little change, if any, has been noted on micro-structure as an effect of stress and/or temperature. Figure 21 is representative of the type of structure obtained. It shows a sample originally annealed from 1700°F after testing at 1000°F and 6,500 psi. When correlated with Figure 20, the same structure previous to testing, little effect is noticeable.

X-Ray Studies of Ti 75A

Several x-ray diffraction traverses have been made on representative conditions of Ti 75A before or after testing, employing a Norelco Hi Angle geiger tube spectrometer equipped with a Brown recorder. Studies to date have been confined merely to identification of diffracted lines.

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* Obtained with strip specimens under Contract AF 33(038)-14111.

Commercial Martensite-Forming Alloy (Ti 150A)

Although described as a martensite-forming alloy, Ti 150A, a ferro-chrome ternary alloy of titanium, shows very poor properties when such structures are tested. It can also be characterized as an alloy undergoing eutectoid decomposition. In either case, structures most appropriate to creep and rupture testing (reasonable room temperature tensile ductility) were only found for conditions of treatment solely within the $\alpha + \beta$ phase region, or solution treated in the β region followed by isothermal transformation in the $\alpha + \beta$ region. Accelerated cooling from the β region (producing the martensite structure) results in excessive brittleness.

Hence, treatments under investigation in the present study represent different methods of approach to variation of $\alpha + \beta$ proportions. Employing two solution temperatures, 1350° and 1500°F, either furnace cooling, air cooling, or water quenching was used from each temperature. In addition, subsequent re-heating to lower temperatures of the above treated material was used, and full isothermal transformation at 1000° and 1300°F after solution treatment at 1800°F was also studied.

Rupture tests are almost complete at 600°, 800°, and 1000°F for most of these conditions. In addition, tensile test results were obtained for several conditions not reported previously. Some creep test results have also been obtained. Metallographic and x-ray studies are also reported.

Tensile Properties of Ti 150A

A complete presentation of tensile properties of Ti 150A at 600°, 800° and 1000°F was given in a preceding report for conditions of single heat treatment and isothermal treatment.*

Additional data have now been obtained at 75°, 800° and 1000°F on two conditions of double heat treatment: 1500°F water quench + 1350°F anneal, and 1350°F water quench + 900°F anneal. These are presented in Table III.

The annealing at 1350°F of material originally water quenched from 1500°F produces properties at 75° and 1000°F identical to a 1350°F anneal alone. This is a case of reheating into the $\alpha + \beta$ region (lower boundary approximately 1050°F.)

If, however, re-heating is done to a temperature below the $\alpha + \beta$ region, then a different effect is to be noted. Material reheated to 900°F after a 1350°F water quench shows a tendency to be embrittled. Thus, brittle failure in the threads at 193,000 psi was found in contrast to 18% elongation and a 170,000 psi tensile strength for the stock water quenched only and not reheated. While less marked at higher test temperatures, nevertheless there exists a tendency for the doubly heat treated material to show less elongation at comparable tensile strengths. The as-quenched and 900°F re-heated structure, Figure 42, shows nothing to differentiate it from the merely as-quenched structure, Figure 30. On re-heating to 1350°F after a 1500°F water quench, a structure of large α grains similar to a 1350°F anneal alone (Figure 40) is found. However, a dark etching precipitate is noted in the matrix of the doubly treated sample.

Rupture Properties of Ti 150A

Results of all rupture testing to date at 600°, 800° and 1000°F on eleven conditions of Ti 150A are summarized in Table IV and plotted in Figure 9. One-hundred hour rupture strengths were determined indi-

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* Third Progress Report, Table II and Figures 7 and 8

vidually for each condition at each temperature and are summarized graphically in Figure 10. In conjunction with Figure 9 it will be noted that a rather narrow band encompasses all results at 1000°F. Little variation from prior treatment was found in 100-hour rupture strengths. At 600° and 800°F, the results separated into three bands. The as-received or annealed structures--save that for a 1500°F water quench--can be lumped together; and the 1500°F water quench stands alone.

No breaks in the rupture curve such as were found at 800°F in the case of Ti 75A were found for Ti 150A.

From the bar graph, Figure 10, it was then possible to plot on Figure 11 the 100-hour rupture strength for the three "grouped" treatments as a function of test temperature. Tensile strengths at these temperatures were similarly plotted on the same figure. The quotient, $\frac{\text{100-hour rupture strength}}{\text{ultimate tensile strength}}$, for each group for each temperature was plotted in Figure 6, showing an extremely good agreement with those previously obtained and discussed for Ti 75A. Thus, some generality of this ratio appears to be the case.

The effect of alloying is to almost double or triple the rupture strength at each temperature over that of Ti 75A. Nevertheless, the absolute level of the strengths for Ti 150A were not high at 800° and 1000°F. In particular, at 1000°F the 100-hour rupture strength was only about 12,500 psi.

Creep Properties of Ti 150A

All available creep data from this investigation for Ti 150A at 600°, 800° and 1000°F are tabulated in Table V and plotted in Figure 12. At 1000°F variations from heat treatment to heat treatment was so slight based on available data that one line has been deemed satisfactory to correlate the data. At 800°F the influence of heat treatment required the data be broken down to "groups" similar to the case of rupture strengths discussed previously. Data at this temperature are still extremely limited.

The only points available at 600°F are shown in Figure 13 in relation to 600°F tests of similarly treated strip specimens. Indeed, it is quite surprising to find such close adherence to the same straight line. (Incidentally, strip specimens could not be tested satisfactorily above about 65,000 psi due to brittleness.) In relation to these results it will be noted that a considerable increase in stress dependence of creep rate occurs in going to 800°F and even more so at 1000°F.

A relationship over the entire range from 76° to 1000°F is plotted in Figure 8 of the stress to cause a creep rate of 3 x 10^{-6} in./in./hr. in as-received Ti 150A with a similar relation plotted for Ti 75A. The lower temperature data was taken on strip specimens.* The general features of both plots are the strengthening at 400°F from strain aging and the rapid drop with increasing temperature at 600°F and above.

Metallographic Examination of Ti 150A

A number of samples of Ti 150A have been examined metallographically to study the effects of temperature, stress and/or time on microstructure occurring as a result of testing. Changes involving a decomposition of β have been found in a number of conditions whose treatment was solely within the $\alpha + \beta$ region. Similar results had previously been noted at lower temperatures on strip specimens of Ti 150A.*

Beginning with the as-received material, a progressive type of precipitation in the β matrix was observed. That this is dependent on

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* Under Contract AF 33(038)-14111.

temperature is shown in Figures 22 and 23. Thus, 979 hours at 600°F and 80,000 psi did not result in a significant microstructural change, yet, only 150 hours at 1000°F and 12,000 psi did show a change.

A similar effect was found with 1500°F annealed material. All tests at 600° and 800°F had structures as shown in Figure 24 (an 800°F tensile test), while exposure at 1000°F and 111,000 psi for 116 hours showed a deterioration of the β similar to the as-received material tested at 1000°F (Figure 25).

When the material is given an original accelerated cooling treatment, then structural alterations are greatly increased. The as-cooled structures show decreased amounts of α depending on solution temperatures in the two phase region and cooling rate. Upon testing, changes in microstructure occur. For instance, Figure 26 shows a sample air-cooled from 1500°F and then tensile tested at 800°F. No change over the as-treated structure was noted. Similarly, 100.5 hours at 800°F and 52,000 psi, Figure 27, was not sufficient to produce any noticeable change. However, a tensile test at 1000°F was sufficient to result in considerable precipitation in the matrix (Figure 28). Similarly, 16 hours at 1000°F and 16,000 psi, Figure 29, resulted in greater precipitation. A longer time at a lower stress produced somewhat different results. Figure 30 (188.8 hours at 1000°F and 11,000 psi) is anomalous. It shows what could be the beginning of a precipitation reaction or the end of an agglomerating process. Because of the different character of the precipitate between the tensile test and 16 hour test on one hand, and the 188.8 hour test on the other, it is difficult to make a clear cut statement as to its nature at this time.

After water quenching from 1500°F, the structural changes are still more extensive. Figure 31 shows the result of 2.3 hours at 800°F and 85,000 psi. No change in the as-quenched structure was noted. Apparently the time at 800°F was too short since 1000-hour creep tests at 600°F of this condition on strip samples did show precipitation.* When tensile tested at 1000°F (Figure 32) considerable precipitation occurred. Extension of 1000°F test time to 348.8 hours (Figure 33) at 9,000 psi showed progression of the reaction.

Figures 34 and 35 show respectively the result of a tensile test at 800°F and 34 hours at 1000°F and 14,000 psi on material annealed from 1350°F. Results were similar to those noted for 1500°F annealing.

Figure 36 shows a 1350°F air cooled specimen after 43.5 hours at 800°F and 55,000 psi. Figure 37 shows the same original treatment after 194.3 hours at 1000°F and 11,000 psi. Matrix precipitation is noted in the case of the latter. Similarly, Figures 38 and 39 show a 1350°F water quench after a 600°F tensile test and 16.7 hours at 1000°F and 15,000 psi respectively. A matrix effect is again noted.

When a specimen rapidly cooled from the $\alpha + \beta$ region is then annealed in the $\alpha + \beta$ region, microstructural changes follow to a degree the effect on properties. For instance, a 1500°F water quenched plus 1350°F annealed treatment was shown previously to have properties quite close to those of the 1350°F annealed treatment alone. Figure 40, a 1000°F tensile test of this condition, shows large α grains in a dark etching matrix very similar to a 1350°F anneal (also very similar to 1500°F anneal). Figure 41 shows the progression of this reaction after a rupture test for 43 hours at 1000°F and 13,000 psi.

If, however, re-annealing is carried out below the $\alpha + \beta$ region the results are quite different. Not only is strength retained, but the microstructural effects are different.

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* Under Contract AF 33(038)-14111.

Figure 42 shows the structure of a 1350°F water quench plus 900°F annealing treatment essentially as treated (tested at 75°F). Figure 43 shows the same structure after an 800°F tensile test. Here, matrix precipitation has occurred. A longer time at a lower stress appears to show a different effect. Thus, 37 hours at 800°F and 58,000 psi result in a structure (Figure 44) showing only the barest beginnings of any reaction or perhaps the end of the reaction with the product going to the grain boundaries.

It is, therefore, possible to characterize microstructural changes in Ti 150A in the following manner:

1. They are favored by higher temperatures.
2. Times are short at 1000°F and considerably longer at 800° and 600°F (up to 1000°F).

The nature of this dark etching product has not been positively determined. There is a further possibility that it may be the result of hydride formation.* Enough evidence does exist from this and other investigations**, ***, to substantiate the conclusion that it is the result of a eutectoid decomposition reaction. The composition of this alloy is such as to favor precipitation of $Ti\ Cr_2$ from non-equilibrium beta structures. The eutectoid is then formed from α and $Ti\ Cr_2$.

Further study of these and other effects is to be made. Examination of isothermally transformed structures after testing has not yet revealed any clear cut results.

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* Battelle Memorial Institute, Second Progress Report on Development of Improved Titanium Base Alloys, April 20, 1953/

** Contact AF 33(038)-14111.

*** "Constitution of Titanium Alloy Systems," WADC Tech. Report 53-41, (Hansen et al.), pp. 185-194 (Feb. 1953.)

X-Ray Study of Ti 150A

X-ray diffraction traverses have been made on a limited number of representative conditions of Ti 150A after testing. The results are briefly summarized in Table XI. Because of difference in sample size, it was impossible to obtain a correlation by line intensities. This was dictated because the actual specimens, representing different reductions of area, were used. Rather, the number of discrete α lines and β lines observed has been recorded. As expected, conditions of accelerated cooling tend to have a fairly high number of β lines. These, in turn, disappear under conditions of testing. Since non-equilibrium β is retained under fast cooling, it is only reasonable that the material should seek equilibrium and is thus aided by stress, time and temperature. Hence the reduction in the number of β lines is to be expected.

Experimental Alpha Alloy (6% Al)

Rupture testing of the experimental alpha alloy, a binary containing 6% Al, has been confined, in the period covered by this report, to completion of the study of the treatments outlined in the previous period. Results are now complete at 600° and 1000°F for one quenched condition and two cold worked conditions. Some creep data are also available. Metallographic examination has been made on a number of specimens after testing. Exploratory x-ray work was also started.

Rupture Properties of Alpha Alloy (6% Al)

Rupture tests are now complete at 600° and 1000°F for three conditions of the experimental 6% Al alpha alloy. The conditions are: water quenched from 2025°F, and 10% and 17% cold work respectively. The data are summarized in Table VI and plotted on Figure 14.

Several points are evident from examination of the data. The relationships at 600°F is a very flat one. Very slight changes in stress (1000 to 2000 psi) may change rupture life by over 1000 hours. In this respect, the behavior of the aluminum alloy is even more sensitive than that of Ti 75A. Very little improvement from cold working up to 17-per cent reduction resulted. At 1000°F the 100-hour rupture strengths are fairly high, 26,000 to 39,000 psi. The deleterious effect of an increased amount of cold work on rupture strength at 1000°F should be noted. If the condition of water quenching from 2025°F can be regarded as the unstressed, uncold-worked alpha condition, then the effect is quite striking and consists of a progressive decrease in rupture properties with increased cold work. This will be checked by testing material which has not been rapidly cooled from as high a temperature as 2050°F.

Some metallographic evidence exists to support the possibility of recrystallization as being the reason for this effect. It will be discussed subsequently.

Creep Properties of Alpha Alloy (6% Al)

All creep data available for the experimental alpha alloy are summarized in Table VII and plotted on Figure 15. The results are still limited, expecially at 600°F.

As was noted in the case of rupture properties, creep properties, too, show a decrease with greater amounts of cold work. This seems to be greater at 1000°F than at 600°F. The stress for a minimum creep rate of 5 x 10^{-6} in./in./hr. was estimated from extremely sparse data and appears to be surprisingly low in comparison with the seemingly favorable rupture properties at 1000°F. At 1000°F it was found to be in the range from 5,000 to 10,000 psi in relation to a 100-hour rupture strength of about 35,000 psi. Yet, in the case of Ti 150A, the stress for 5 x 10^{-6} in./in./hr. minimum creep strength is about 11,000 psi. Since the strength for a given minimum creep rate is about the same for both the 6% Al alloy and Ti 150A, and Ti 150A shows much lower rupture properties, it appears that the difference between first stage or third stage creep deformations are the controlling factors in these alloys.

Metallographic Examination of Alpha Alloy (6% Al)

A number of completed tensile and rupture specimens of the experimental alpha alloy were examined metallographically. Some significant changes could be noted as a result of test conditions.

Figure 45 shows a sample (at 100X magnification) after a tensile test at 1000°F. Although not as well definied, the structure is very similar to the as-quenched structure.* An example of the type of structural alteration possible in this material is shown in Figure 46, giving the effect of an accidental overheat of a test of the same structure after a long time at 600°F. After 1443.9 hours at 600°F and 96,000 psi the test was accidentally overheated to at least 1600°F and, of course, ruptured long before 1600°F was reached. The effect on the structure is to grossly exaggerate it. At 50X magnification the individual grains, although still bearing evidence of definite crystallographic orientation, are much enlarged.

A different effect was noted for the cold work conditions. This is the effect of recrystallization occurring during testing. Figure 47 shows material given 17% cold work and tested 1172.2 hours at 600°F and 101,000 psi. Little difference was noted between this and the as-treated structure.** Figure 48 shows the effect of a tensile test on this

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* Third Progress Report, April 15, 1953, Figure 30.

** Ibid., Figure 29.

structure at 1000°F. Some slight changes are in evidence. Quite a different effect is noted for a rupture test. Figure 49 shows the same material (17% cold work) after 13.4 hours at 1000°F and 37,000 psi. Here it appears that some sort of recrystallization process has taken place. The structure seems to consist of small equiaxed grains in contrast to the elongated, as-forged structure of the proceeding conditions.

A somewhat confusing picture is obtained from a study of the structures from the 10% cold worked condition. This is most probably due to non-homogeneous deformation. Figure 50 shows a structure after a 600°F tensile test. It shows little change over the as-treated structure.* Figure 51 shows the same structure after 1216 hours at 600°F and 96,500 si. Again, little change is evident. Figure 52, after a 1000°F tensile test, suggested that a seeming recrystallization has occurred under conditions of stress and temperature. Figure 53, after 20.5 hours at 1000°F and 40,000 psi, shows no such effect, although the as-forged and cold worked structure appears diffuse and may be on the verge of recrystallization. Figure 54 lends credence to this possibility. After 176.4 hours at 1000°F and 26,800 psi, it does seem to be in progress.

The foregoing facts of the recrystallization may be summarized as follows:

Condition	Temp (°F)	Type Test, Stress, Time	Progress of Recrystallization
10% Cold Work	600	Tensile - 97,800 psi	none
	600	1216 hr - 96,500 psi	none
	1000	Tensile - 83,300 psi	fairly complete
	1000	20.5 hr - 40,000 psi	on verge
	1000	176.5 hr - 26,800 psi	in progress
17% Cold Work	600	1172 hr - 101,000 psi	none
	1000	Tensile - 82,400 psi	doubtful
	1000	13.4 hr - 37,000 psi	complete

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* Third Progress Report, April 15, 1953, Figure 28.

The existance of anomalies in the data at 600°F is recognized and being investigated. Quite possibly these are due, as mentioned before, to non-homogeneous deformation. In any case, recrystallization appears to be favored by high stress or long time and occurs in time periods under 1200 hours only at 1000°F.

X-Ray Study of Experimental Alpha Alloy (6% Al)

One complete diffraction traverse was run for exploratory purposes on the experimental alpha alloy after testing at 1000°F. The specimen investigated was the condition of 10% cold work after testing at 1000°F for 176.4 hours at 26,800 psi (Figure 54). Thirteen α lines were identified out of a possible twenty in the range covered by the high angle spectrometer. No beta lines were found.

Experimental Stable Beta Alloy (30% Mo)

Study of the experimental stable beta alloy, a binary containing 30% Mo, has continued with exploratory tensile testing of heat treated conditions and continuation of rupture and creep testing of conditions outlined previously. Metallographic examination revealed formation of a precipitate in this material at 1000°F. X-ray studies suggest this may be α phase.

Tensile Properties of Stable Beta Alloy (30% Mo)

Several additional conditions of the experimental stable beta alloy were tensile tested in order to establish conditions promising for creep and rupture testing. In addition, testing of the as-forged material was initiated.

In Table VIII the results of the tensile testing performed in this period are summarized. Data at two temperatures for material water quenched after 1 hour at 1325°F was included for comparison purposes. The as-forged material was found to have only a very slight difference in tensile properties at 75° over the 1325°F water quenched stock.

To explore the effect of a different solution treatment, stock was heated to 1500°F for 2 hours and then water quenched. Properties are almost identical with the 1325°F treatment.

One test at 75°F is available for a "double" heat treatment. Material was held at 1500°F for 2 hours and water quenched. It was then reheated to 1375°F for 24 hours and water quenched. The effect of this treatment was to lower the 75°F tensile properties slightly.

In addition to the above, a cold working treatment was attempted on this alloy. Four bars were solution treated at 1325°F for 1 hour and then water quenched. An attempt was then made to cold reduce the bars. Two of the bars were reduced about 3 to 3.5 per cent. Both the other bars split on attempts to obtain reductions only slightly greater than 3.5%. In view of the 12% reduction on tensile testing, it was expected that more cold work than 3.5% could be put into the material.

Thus far, it appears that the 30% Mo alloy is relatively insensitive to heat treatment and not amenable to cold work.

Rupture Properties of Stable Beta Alloy (30% Mo)

Rupture testing at 600° and 1000°F was continued on the as-forged and 1325°F water quenched conditions of the experimental stable beta alloy. The data are summarized in Table IX and plotted in Figure 16.

The relationship at 600°F is extremely flat, as is characteristic of other alloys at this temperature. At 1000°F the points for all conditions of testing fall on the same line. A check test at 1000°F was run on a sample water quenched after 2 hours at 1500°F. It was run at 37,500 psi, the estimated 100-hour rupture strength for this material. The slightly short rupture time of 83.4 hours appears to be in good agreement with the other treatments.

For the heat treatments tested to date, no essential differences in rupture properties exist.

Creep Properties of Stable Beta Alloy (30% Mo)

Only very limited creep data are available for the experimental stable beta alloy. The data are summarized in Table X and plotted in Figure 17.

At 600°F the results of one test at 90,000 psi are all that presently are available for the 1325°F water quenched condition. The test duration was 1485 hours and, following a short period of first stage creep, the minimum creep rate was very low.

At 1000°F the results from the as-forged and 1325°F water quenched conditions were found to be correlated by the same line. The estimated stress for a minimum creep rate of 5×10^{-6} in./in./hr. was 10,000 psi for the 30% Mo alloy. This indicates a higher ratio of creep to rupture strength than has been obtained for other alloys tested. This may be of considerable importance because the creep strength in the other alloys has appeared to be abnormally low in relation to rupture strength with the implication that excessive deformation by creep at stresses well below the rupture strength would severely limit load carrying ability.

Metallographic Examination of Stable Beta Alloy (30% Mo)

Several conditions of the experimental stable beta alloy have been examined after tensile and rupture testing in order to ascertain if changes occurred in the microstructure.

Very conclusive evidences of a precipitation reaction have been found for tests at 1000°F and long times.

Figure 55 shows the as-forged structure after testing for 77 hours at 1000°F and 40,000 psi. No change can be noted over the untested structure.* However, the same condition after 133 hours at 1000°F and 35,000 psi (Figure 56) shows a fine, dark precipitate within the β grains.

The 1325°F water quenched material exhibits the same behavior. Figure 57 shows the structure after 836 hours at 600°F and 100,000 psi. Slight precipitation, if any, is visible. Figure 58 shows the same condition after 141.2 hours at 1000°F and 35,000 psi. The precipitate is finer, but more widely dispersed than that noted in the as-forged condition.

Specimens were also examined for the condition of 2 hours at 1500°F plus a water quench. Figure 59 is the structure after a tensile test at 1000°F. No evidence of precipitation is visible. However, 83.4 hours at 1000°F and 37,500 psi (Figure 60) was sufficient to cause the initiation of precipitation within the β grains. It appears to form in lines along crystallographic planes as dispersed particles.

The nature of this precipitate is not clear; however, evidence does exist from x-ray data to suggest α phase as a component. This will be discussed in the next section. The formation of the precipitate is favored by a temperature of 1000°F and time periods of about 100 hours. The stress condition (35,000 to 40,000 psi) undoubtedly has some effect.

X-Ray Study of Stable Beta Alloy (30% Mo)

The specimen whose microstructure appears in Figure 58 was examined by x-ray diffraction analysis in an effort to discern the nature

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* Third Progress Report, April 15, 1953, Figure 31.

of the observed precipitate. The specimen was given the 1325°F water quench treatment and tested 141.2 hours at 1000°F and 35,000 psi. A complete traverse with a high angle geiger tube x-ray spectrometer was made on the sample.

Although the material is supposed to have an allβ structure, the α 100 and 102 lines were definitely identified. In addition, the appearance of the α 002 and 103 was also suspected, although they were not strong enough for a positive identification. It thus appears likely that the precipitate in this sample at least contains α.

Comparison between Alloys

Sufficient data have now been accumulated to premit some comparison between the various alloy types to be made. This has been done in Table XII on the basis of two criteria, 100-hour rupture strength and stress to give a minimum creep rate of 5×10^{-6} in. /in. /hr. The data are also plotted in Figures 18 and 19.

Several points appear worthy of mention at present. First, both Ti 75A and Ti 150A show relatively poor properties above 800°F and little difference in properties exists between treatments at 1000°F. The experimental binary alloys show moderate tensile and rupture strength properties at temperatures up to 600°F, yet retain considerably greater strength at 1000°F than do the commercial alloys. In addition, all alloys have the common characteristic of permitting relatively large amounts of loading and first stage creep deformation. In addition, rupture life appears to be quite high in relation to the amount of deformation that has occurred.

The next report will explore these points more fully.

TABLE I

Rupture Results at 600°F for Ti 75A

Treatment	Test Temp (°F)	Stress (psi)	Time (hrs)	Elongation (% in 1 in.)	Reduction of Area (%)	Minimum Creep Rate (in/in/hr)	100-Hour Rupture Strength (psi)
As Received	600	37,600	0.1	34.9	68.6	--	--
		37,000	0.15	45.0	65.5	--	--
		35,000	>911.0	(5.5)*	--	4.7×10^{-7}	--
		33,000	>1313.6	(2.8)*	--	$<10^{-8}$	36,000
1500°F An-	600	34,900	0.1	41.5	67.0	--	--
nealed (1 hr at		33,000	0.3	43.5	71.5	--	--
temp + furnace		32,000	>977.7	(7.4)*	--	$<10^{-8}$	--
cool)		28,000	>1512.0	(3.7)*	--	$<10^{-8}$	32,500
1700°F An-	600	33,600	0.1	40.7	69.6	--	--
nealed		31,500	0.2	34.0	55.4	--	--
		30,000	>975.1	(7.8)*	--	$<10^{-8}$	--
		25,000	>1002.9	(1.9)*	--	$<10^{-8}$	31,000
1500°F An-	600	53,300	0.1	14.6	57.5	--	--
nealed + 10.9%		51,000	0.3	14.7	45.0	--	--
cold work		48,500	1.0	14.7	57.0	--	45,000+
1500°F An-	600	67,000	0.1	13.3	51.1	--	--
nealed + 31.3%		64,000	0.2	16.5	52.0	--	--
cold work		61,000	0.2	15.4	46.6	--	55,000+
1700°F An-	600	53,700	0.1	14.8	55.2	--	--
nealed + 10.9%		51,000	0.1	13.1	53.5	--	--
cold work		45,000	54.4	not available yet		--	44,000
1700°F An-	600	66,500	0.1	14.0	57.5	--	--
nealed + 31.3%		62,000	0.1	15.5	56.2	--	--
cold work		59,000	0.3	14.4	59.5	--	55,000+

* Permanent deformation after test - did not rupture.

\> Greater than, i.e., did not rupture, test stopped.

NOTE: Tensile test used as 0.1-hour rupture.

TABLE II

Creep Rates at 600°, 800° and 1000°F for Ti 75A

Treatment	Test Temp (°F)	Stress (psi)	Minimum Creep Rate (in/in/hr)	Test Time (hrs)	Est. Stress for Rate of 5×10^{-6} in/in/hr
As Received	600	35,000	4.7×10^{-7}	911.0	
		33,000	$<10^{-8}$	1313.6	
	800	16,000	8.6×10^{-4}	156.0	
		7,000	1.8×10^{-5}	736.0	5,000
	1000	5,000	6.0×10^{-3}	54.4	
		2,000	5.0×10^{-5}	575.0	1,500
1500°F Annealed (1 hr at temp + furnace cooled)	600	32,000	$<10^{-8}$	977.7	
	800	20,000	1.9×10^{-3}	54.1	
		16,000	8.3×10^{-4}	126.6	
		6,000	1.8×10^{-5}	779.5	5,000
	1000	5,000	3.4×10^{-3}	92.5	
		2,500	1.6×10^{-4}	1126.4	1,500
1700°F Annealed	600	30,000	$<10^{-8}$	957.1	
	800	15,000	8.0×10^{-4}	184.3	
		6,000	3.8×10^{-6}	*	5,000
	1000	5,500	6.0×10^{-3}	65.2	
		2,500	1.4×10^{-5}	766.0	1,500
1500°F Annealed + 10.9% cold work	600	40,000	not available	*	
	800	19,000	2.8×10^{-4}	159.4	
		12,000	5.0×10^{-5}	1052.4	8,000
	1000	6,500	1.9×10^{-3}	88.4	
		4,000	8.0×10^{-4}	259.8	3,500
1500°F Annealed + 31.3% cold work	600	50,000	not yet available	*	
	800	22,000	4.2×10^{-4}	69.9	
		15,000	not available	*	10,000
	1000	4,200	1.6×10^{-3}	120.1	
		2,500	1.3×10^{-4}	1200.0	<1,000
1700°F Annealed + 10.9% cold work	600	not available		*	
	800	22,000	2.2×10^{-3}	63.0	
		14,000	not available	*	
	1000	7,000	3.6×10^{-3}	60.0	
		5,500	6.7×10^{-5}	220.2	
		4,200	2.1×10^{-5}	610.0	3,500
1700°F Annealed + 31.3% cold work	600	not available		*	
	800	20,000	7.6×10^{-4}	180.6	
		15,000	not available	*	10,000
	1000	6,500	8.0×10^{-3}	25.8	
		5,000	1.6×10^{-3}	80.5	
		3,000	3.5×10^{-4}	765.0	<1,000

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* Not Completed yet.

TABLE III

Tensile Test Data for Ti 150A (not reported previously)

Treatment	Test Temp (°F)	Ultimate Strength (psi)	Yield Strength (0.2% Offset)	Elongation (% in 1 in.)	Reduction of Area (%)	Elastic Modulus ($\times 10^{-6}$ psi)
1500°F Water Quench + 1350°F Anneal	75	156,900	152,800	14.6	15.2	16.6
	1000	39,500	32,300	123.0	98.4	8.2
1350°F Water Quench + 900°F Anneal	75	>193,000	Broke in threads	--	--	14.7
	800	98,800	59,000	31.8	76.0	9.5
	1000	43,500	25,800	91.5	99.0	6.8

TABLE IV

Rupture Test Results at 600°, 800° and 1000°F for Ti 150A

Treatment	Test Temp (°F)	Stress (psi)	Time (hrs)	Elongation (% in 1 in.)	Reduction of Area (%)	Minimum Creep Rate (in/in/hr)	100-Hour Rupture Strength (psi)	Estimated Elongation (%)
As Received	600	90,600	0.1	30.4	60.6	--	--	--
		89,000	5 min	30.6	60.0	--	--	--
		85,000	not yet available			--	--	--
		80,000	>979.3	5.7*	--	2.0×10^{-5}	85,000**	35
	800	69,900	0.1	36.2	75.5	--	--	--
		50,000	5.5	44.2	76.6	--	--	--
		38,000	142.7	***	***	1.1×10^{-4}	39,000	50
	1000	37,800	0.1	93.0	98.0	--	--	--
		20,000	3.2	65.3	87.8	LC	--	--
		12,000	150.2	55.3	92.6	5.4×10^{-4}	12,500	55
1500°F Annealed	600	85,300	0.1	29.5	61.0	--	--	--
		80,000	>791.6	11.6*	--	2.0×10^{-5}	82,000	35
	800	68,300	0.1	41.7	74.3	--	--	--
		45,000	94.6	53.4	78.4	2.5×10^{-3}	--	--
		42,000	118.1	44.8	76.0	***	43,000	50
	1000	37,400	0.1	68.0	93.5	--	--	--
		14,000	24.7	87.0	88.4	8.0×10^{-3}		
		11,000	116.0	82.0	92.0	1.4×10^{-3}	11,500	85
1500°F + Air Cool	600	115,000	0.1	19.6	70.4	--	--	--
		110,000	not completed			1.1×10^{-4}		
	800	96,100	0.1	36.5	80.9	--	--	--
		60,000	31.8	30.0	70.0	8.3×10^{-4}	--	--
		52,000	100.5	48.0	81.0	1.4×10^{-3}	52,000	48
	1000	46,000	0.1	91.5	97.0	--	--	--
		16,000	16.1	90.0	92.0	LC	--	--
		11,000	188.8	42.7	92.0	4.0×10^{-4}	12,000	50
1500°F + Water Quench	600	162,300	0.1	4.8	11.6	--	--	--
		155,000	125.4	***	***	***	154,000	--

TABLE IV, Continued

Treatment	Test Temp (°F)	Stress (psi)	Time (hrs)	Elongation (% in 1 in.)	Reduction of Area (%)	Minimum Creep Rate (in/in/hr)	100-Hour Rupture Strength (psi)	Estimated Elongation (%)
1500°F + Water Quench	800	138,700	0.1	36.9	76.9	--	--	--
		85,000	2.3	37.0	75.5	--	--	--
		48,000	659.2	***	***	7.4×10^{-5}	60,000	40
	1000	46,700	0.1	99.2	98.0	--	--	--
		16,000	7 ± 1	67.0	94.0	LC	--	--
		9,000	348.8	60.0	95.0	3.3×10^{-4}	11,000	65
1350°F Annealed	600	87,000	0.1	28.4	56.0	--	--	--
		84,000	4.7	28.0	58.4	--	--	--
		82,000	>979.1	--	--	3.3×10^{-6}	83,500	30
	800	70,200	0.1	41.1	76.5	--	--	--
		44,000	84.0	40.2	77.4	1.6×10^{-6}	--	--
		40,000	166.4	42.5	76.4	8.0×10^{-4}	43,000	40
	1000	39,500	0.1	105.6	84.0	--	--	--
		14,000	34.0	59.5	92.0	6.2×10^{-4}	--	--
		12,000	157 ± 4	62.0	96.0	***	13,500	60
1350°F + Air Cooled	600	107,000	0.1	16.4	54.3	--	--	--
		102,000	not yet complete					
	800	88,500	0.1	40.4	77.0	--	--	--
		55,000	43.6	42.0	76.5	***	--	--
		50,000	101.6	52.0	79.4	1.5×10^{-3}	50,000	52
	1000	41,700	0.1	115.4	98.0	--	--	--
		14,000	33.6	57.2	71.8	4.7×10^{-3}	--	--
		11,000	194.3	55.0	95.0	4.6×10^{-4}	12,500	55
1350°F + Water Quench	600	119,000	0.1	12.9	47.0	--	--	--
		114,000	368.8	7.6	1.6	***	115,000	10
	800	106,200	0.1	34.3	69.2	--	--	--
		65,000	26.4	41.0	66.5	LC		
		55,000	61.8	39.2	77.0	2.0×10^{-3}	54,000	40
	1000	41,500	0.1	98.0	98.0	--	--	--
		15,000	16.7 ± 2.5	69.2	89.4	LC	--	--
		10,000	160.6	44.4	90.6	1.4×10^{-3}	10,500	45

TABLE IV, Concluded

Treatment	Test Temp (°F)	Stress (psi)	Time (hrs)	Elongation (% in 1 in.)	Reduction of Area (%)	Minimum Creep Rate (in/in/hr)	100-Hour Rupture Strength (psi)	Estimated Elongation (%)
1500°F Water Quench + 1350°F Anneal	1000	39,500	0.1	123.0	98.4	--	--	--
		13,000	43.0	71.5	96.0	***	--	--
		10,500	247.7	172.0	94.0	4.6×10^{-4}	11,500	120
1350°F Water Quench + 900°F Anneal	800	98,000	0.1	31.8	76.0	--	--	--
		58,000	37 ± 5	37.4	76.0	***	--	--
		51,000	107.5	30.8	77.0	***	51,000	30
	1000	43,000	0.1	91.5	99.0	--	--	--
		14,000	48.9	57.5	93.5	LC	--	--
		11,500	127.0	67.0	96.5	***	12,500	65
1800°F Isoth. 1 hr 1300°F + Water Quench	600	113,600	0.1	15.0	35.5	--	--	--
		110,000	37.6	6.8	8.6	***	--	--
		108,000	not yet complete			***	--	--
	800	92,700	0.1	26.0	33.3	--	--	--
		55,000	55 ± 4	42.0	78.0	***	--	--
		45,000	320.4	26.4	76.0	2.9×10^{-4}	52,000	35
	1000	48,500	0.1	110.7	99.0	--	--	--
		17,500	16.0	51.5	91.0	LC	--	--
		11,000	582.0	45.5	93.0	8.3×10^{-5}	14,000	50
1800°F Isoth. 1 hr 1000°F + Water Quench	800	98,900	0.1	20.8	65.6	--	--	--
		60,000	8.4	30.4	73.7	--	--	--
		55,000	95.1	30.5	80.6	***	--	--
		45,000	>790.0	1.9*	--	1.8×10^{-5}	55,000	30
	1000	59,100	0.1	79.3	99.0	--	--	--
		20,000	7.5 ± 2.5	36.0	93.5	LC	--	--
		11,000	203.7	47.0	93.5	5.7×10^{-4}	12,000	45

---

* Permanent deformation after cooling.

** Approximately.

*** Not yet available.

LC Loading Curve only.

TABLE V

Available Creep Data at 600°, 800° and 1000°F for Ti 150A

Treatment	Test Temp (°F)	Stress (psi)	Minimum Creep Rate (in/in/hr)	Test Time (hrs)	Est. Stress for Rate of 5×10^{-6} in/in/hr
As Received	600	80,000	2.0×10^{-5}	979.3	50,000
	800	38,000	1.1×10^{-4}	142.7	29,000
	1000	12,000	5.4×10^{-4}	150.2	
		6,000	1.1×10^{-5}	768.6	5,000
1500°F Anneal	600	80,000	2.0×10^{-5}	791.6	*
	800	45,000	2.5×10^{-3}	94.6	29,000
	1000	14,000	8.0×10^{-3}	24.7	
		11,000	1.4×10^{-3}	116.0	
		5,000	4.8×10^{-6}	860.4	5,000
1500°F Air Cooled	600	110,000	1.1×10^{-4}	*	*
	800	80,000	8.3×10^{-4}	31.8	
		52,000	1.4×10^{-3}	100.5	35,000
	1000	11,000	4.0×10^{-4}	188.8	5,000
1500°F Water Quenched	800	48,000	7.4×10^{-5}	659.2	41,000
	1000	9,000	3.3×10^{-4}	348.8	
		5,000	1.5×10^{-5}	350 *	5,000
1350°F Anneal	600	82,000	3.3×10^{-6}	979.1	*
	800	44,000	1.6×10^{-3}	84.0	
		40,000	8.0×10^{-4}	166.4	29,000
	1000	14,000	6.2×10^{-4}	34.0	5,000
1350°F Air Cooled	800	50,000	1.5×10^{-3}	101.6	35,000
	1000	14,000	4.7×10^{-3}	33.6	
		11,000	4.6×10^{-4}	194.3	5,000
1350°F Water Quenched	800	55,000	2.0×10^{-3}	61.8	41,000
	1000	10,000	1.4×10^{-3}	160.6	5,000
1500°F Water Quench + 1350°F Anneal	1000	10,500	4.6×10^{-4}	247.7	5,000
1800°F Isoth. 1 hr 1300°F + Water Quench	800	45,000	2.9×10^{-4}	320.4	35,000
	1000	11,000	8.3×10^{-5}	582.0	5,000
1800°F Isoth. 1 hr 1000°F + Water Quench	800	45,000	1.8×10^{-5}	790.0	41,000
	1000	11,000	6.7×10^{-4}	203.7	5,000

* Not yet complete.

TABLE VI

Rupture - Test Results at 600°, 800° and 1000°F for Experimental 6% Al Alpha Alloy

Treatment	Test Temp (°F)	Stress (psi)	Time (hrs)	Elongation (% in 1 in.)	Reduction of Area (%)	Minimum Creep Rate (in/in/hr)	100-Hour Properties Rupture Strength (psi)	100-Hour Properties Est. Elongation (%)
2025°F Water Quench	600	97,900	0.1	17.6	34.1	--	--	--
		96,000	>1443.9	(overheated)			96,500	18
	1000	80,300	0.1	14.9	33.8	--	--	--
		35,000	361.0	30.6	34.2	2.3 x 10^{-4}	40,000	25
10% Cold Work	600	97,800	0.1	9.6	45.8	--	--	--
		96,500	>1216.0	1.0*	--	not yet available		--
		95,000	259.8	4.9	22.4	3.8 x 10^{-6}	96,000	7
	1000	83,300	0.1	18.6	38.1	--	--	--
		40,000	20.5	43.2	68.6	LC	--	--
		26,800	176.4	53.5	87.6	1.0 x 10^{-3}	30,000	45
17% Cold Work	600	105,100	0.1	10.0	34.7	--	--	--
		103,500	0.1	12.9	52.8	--	--	--
		101.000	>1172.2	1.0*	--	3.3 x 10^{-5}	102,000	15
	1000	83,400	0.1	14.6	32.8	--	--	--
		37,000	13.4	19.0	32.8	9.9 x 10^{-3}	--	--
		26,000	123.6	56.0	83.0	1.5 x 10^{-3}	27,000	50

* Permanent deformation on cooling.

\> Greater than, test discontinued without rupture.

NOTE: Tensile test used as 0.1-hour rupture stress.

TABLE VII

Creep Data at 600° and 1000°F For Experimental 6% Al Alpha Alloy

Treatment	Test Temp (°F)	Stress (psi)	Minimum Creep Rate (in/in/hr)	Test Time (hrs)	Estimated Stress for 5×10^{-6} in/in/hr
2025°F Water Quench	600	96,000	data erratic	1443.9	--
	1000	35,000	2.3×10^{-4}	361.0	--
		20,000	3.8×10^{-5}	*	5,000 - 10,000
10% Cold Work	600	95,000	3.8×10^{-6}	259.8	--
		96,500	*	*1216.0	95,000
	1000	26,800	1.0×10^{-3}	176.4	5,000 - 10,000
17% Cold Work	600	101,000	3.3×10^{-5}	1172.2	80,000
	1000	37,000	9.9×10^{-3}	13.4	--
		26,000	1.5×10^{-3}	123.6	5,000

* Not complete.

TABLE VIII

Tensile Results at 75°, 600° and 1000°F for Experimental 30 Per Cent Mo Stable Beta Alloy

Treatment	Test Temp (°F)	Ultimate Strength (psi)	Yield Strength (0.2% Offset)	Elongation (% in 1 in.)	Reduction of Area (%)	Elastic Modulus (x 10^{-6} psi)
As Forged	75	144,700	142,500	14.0	27.4	13.6
1325°F 1 hr + Water Quenched	75	145,800	142,200	12.6	28.0	14.6
	1000	82,500	74,400	22.1	40.5	13.0
1500°F 2 hr + Water Quenched	75	144,400	142,400	12.2	21.6	13.1
	600	106,000	95,600	19.4	47.5	11.7
	1000	83,200	73,700	21.3	62.0	12.0
1500°F 2 hr + Water Quench + 1375°F 24 hr + Water Quench	75	140,500	136,600	11.6	22.6	14.0

TABLE IX

Rupture Data at 600° and 1000°F for Experimental 30 Per Cent Mo Stable Beta Alloy

Treatment	Test Temp (°F)	Stress (psi)	Time (hrs)	Elongation (% in 1 in.)	Reduction of Area (%)	Minimum Creep Rate (in/in/hr)	100-Hour Rupture Properties: Rupture Strength (psi)	100-Hour Rupture Properties: Est. Elong. (%)
As Forged	600	90,000	>1158.0	(overheated -- too damaged)		*	--	--
	1000	40,000	77+2	54.8	49.4	8.8×10^{-4}	--	--
		35,000	133.0	62.8	70.0	2.0×10^{-4}	37,500	60
1325°F 1 hr + Water Quench	600	105,400	0.1	15.8	43.4	--	--	--
		100,000	>836.0	--	--	--	--	--
		90,000	>1485.0	--	--	--	102,000	15
	1000	82,500	0.1	22.1	40.5	--	--	--
		40,000	74.5	54.4	37.9	LC	--	--
		35,000	141.2	54.3	75.4	4.3×10^{-4}	--	--
		22,000	1143.9	84.0	82.1	2.5×10^{-5}	37,500	55
1500°F 2 hr + Water Quench	1000	37,500	83.4	66.6	71.2	LC	37,000	--

* Not yet available.
LC Loading curve only.

TABLE X

Creep Data at 600° and 1000°F for Experimental 30 Per Cent Mo Stable Beta Alloy

Treatment	Test Temp (°F)	Stress (psi)	Minimum Creep Rate (in/in/hr)	Test Time (hrs)	Est. Stress for 5 x 10^{-6} in/in/hr
As Forged	1000	40,000	8.8 x 10^{-4}	77±2	--
		35,000	2.0 x 10^{-4}	133.0	--
		20,000	4.6 x 10^{-5}	912.5	10,000
1325°F 1 hr +	600	90,000	$< 10^{-8}$	1485.0	?
Water Quench	1000	35,000	4.3 x 10^{-4}	141.2	--
		22,000	2.5 x 10^{-5}	1143.9	10,000

TABLE XI

Result of X-Ray Diffraction Traverse of Ti 150A

Treatment and Test Details	α Lines	β Lines
As Received - 979 hr - 80,000 psi - 600°F	11	5
As Received - 150 hr - 12,000 psi - 1000°F	14	1
1500°F Air Cooled - 1000°F Tensile Test	10	3
1500°F Air Cooled - 16 hr - 16,000 psi - 1000°F	8	1
1500°F Water Quench - 1000°F Tensile Test	11	5
1500°F Water Quench - 7 hr - 16,000 psi - 1000°F	11	3
1500°F Water Quench - 157 hr - 12,000 psi - 1000°F	11	4
1350°F Air Cooled - 33 hr - 14,000 psi - 1000°F	12	3
1350°F Water Quench - 26 hr - 65,000 psi - 800°F	4	0
1350°F Water Quench - 160 hr - 10,000 psi - 1000°F	10	4
1350°F Annealed - 84 hr - 44,000 psi - 800°F	7	1
1300°F Isothermal - 800°F Tensile Test	12	3
1000°F Isothermal - 8 hr - 60,000 psi - 800°F	10	0
1000°F Isothermal - 10 hr - 20,000 psi - 1000°F	12	0

NOTE: All heat treatment times 1 hour.
Isothermal Treatments: 1 hr 1800°F → 1 hr at temp (leadpot) → Water Quench.

TABLE XII

Alloy Comparison

Property	Temp	Ti 75A	Ti 150A	6% Al	30% Mo
100-Hour Rupture Strength	600°F	31,000-55,000	82,000-154,000	96,000-102,000	102,000
	800°F	17,000-20,000	39,000- 60,000	--	--
	1000°F	4,400- 6,200	11,500- 12,500	27,000- 40,000	37,500
Estimated Stress for Minimum Creep Rate of 5 x 10^{-6} in/in/hr	600°F	25,000-50,000	50,000 → ?	80,000- 95,000	>90,000
	800°F	5,000-10,000	29,000- 41,000	--	--
	1000°F	1,500- 3,500	5,000	5,000- 10,000	10,000

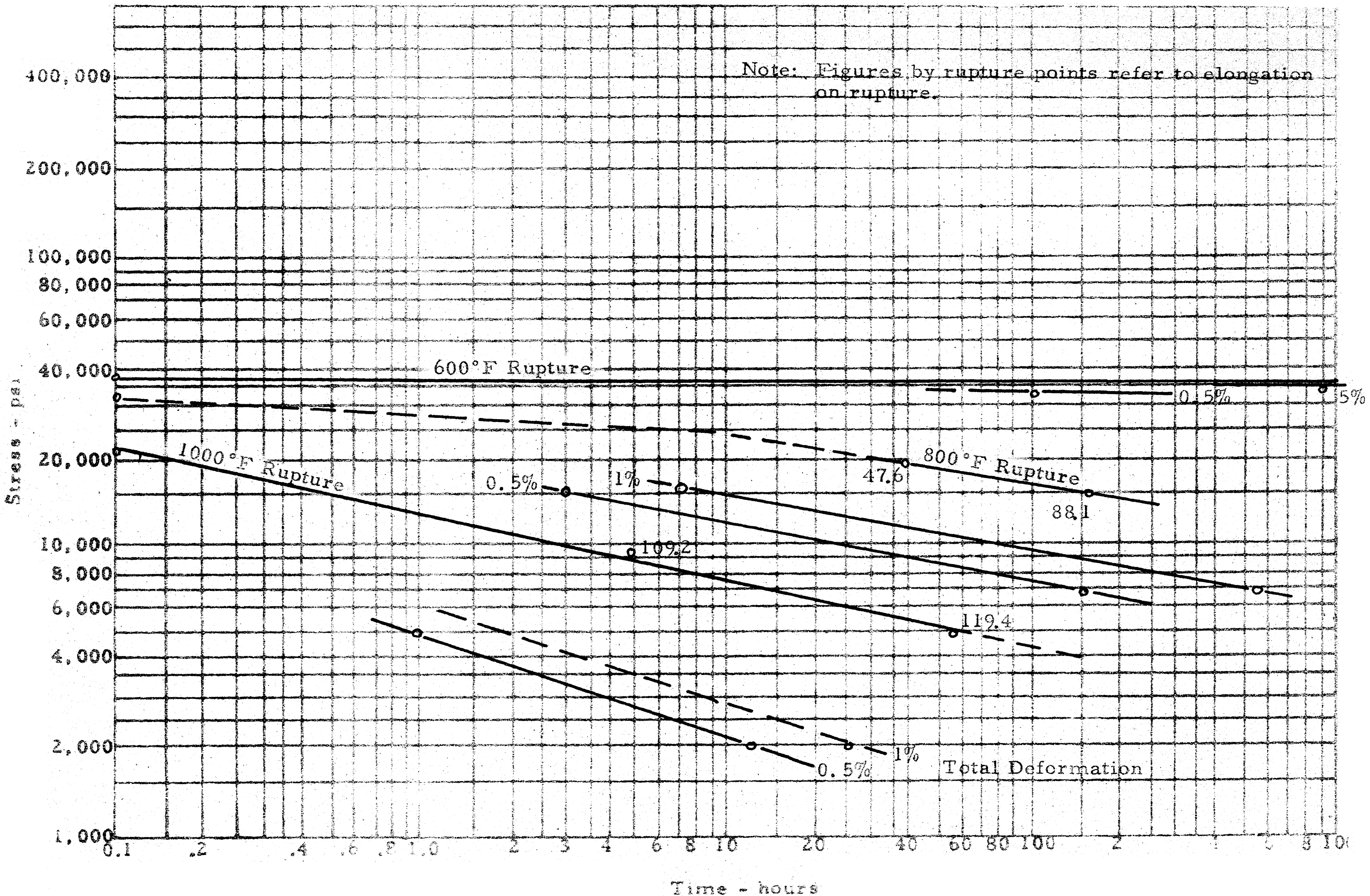


Figure 1. - Stress Versus Time at 600°, 800° and 1000°F for Rupture and Time for Specified Total Deformation for Ti 75A As-Received (Hot Rolled and Annealed).

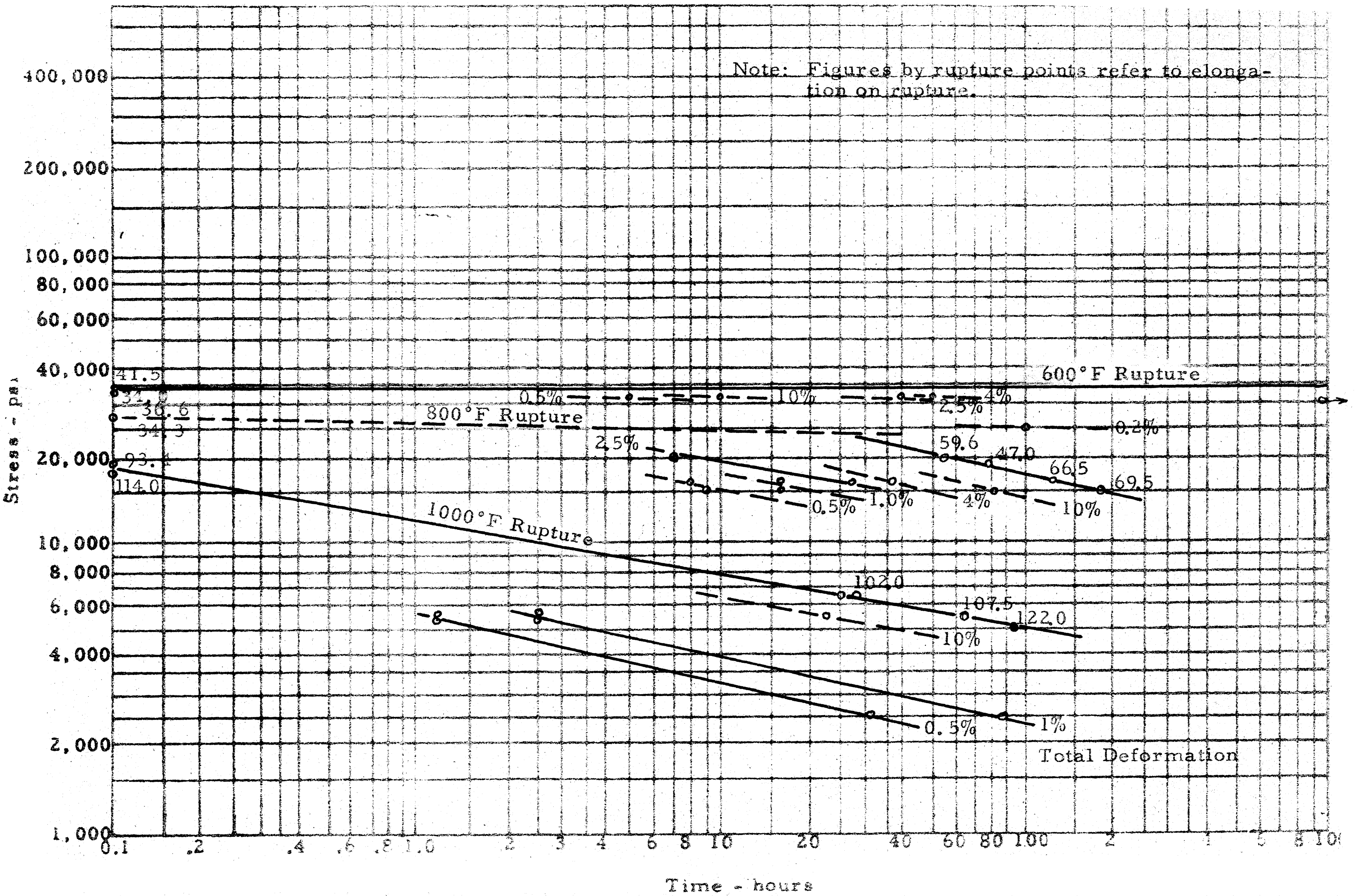


Figure 2. - Stress Versus Time at 600°, 800° and 1000°F for Rupture and Time To Reach Specified Total Deformation for Ti 75A Annealed at 1500° or 1700°F.

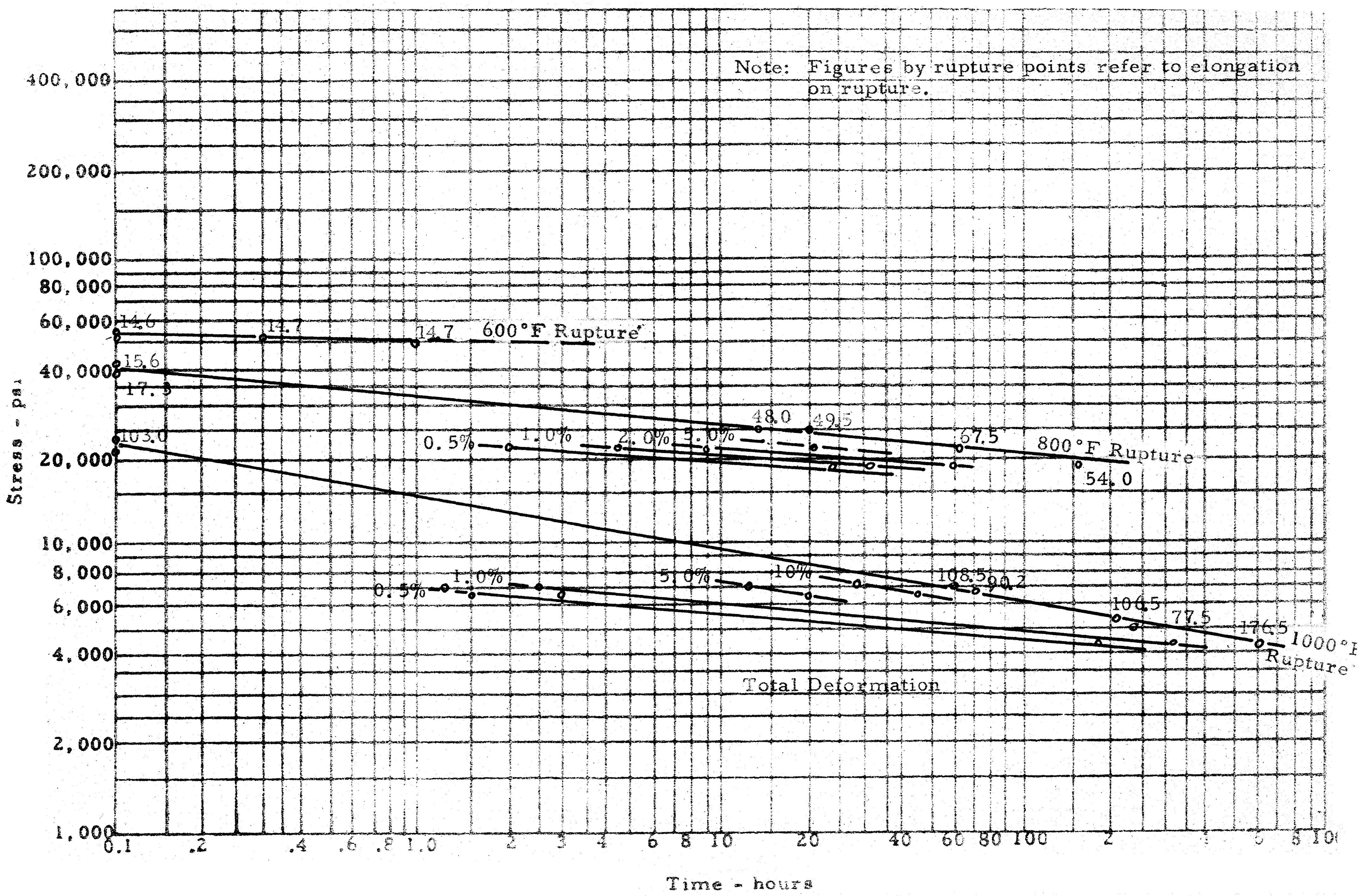


Figure 3. - Stress Versus Time at 600°, 800° and 1000°F for Rupture and to Reach Specified Total Deformation for Ti 75A Annealed at 1500° or 1700°F and Cold Worked 10.9%.

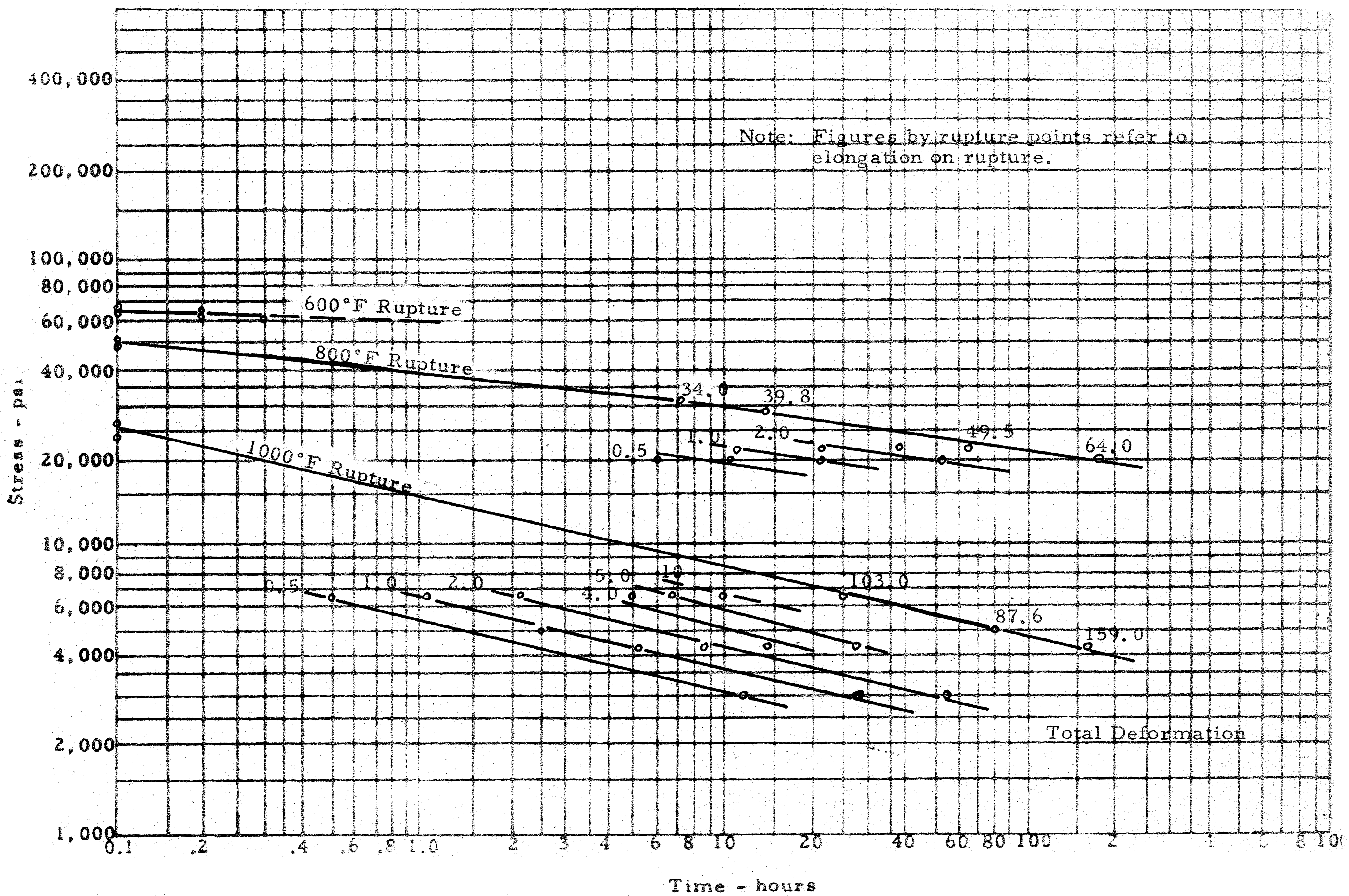


Figure 4. - Stress Versus Time at 600°, 800° and 1000°F for Rupture and Time to Reach Specified Total Deformation for Ti 75A Annealed at 1500° or 1700°F and Cold Worked 31.3%.

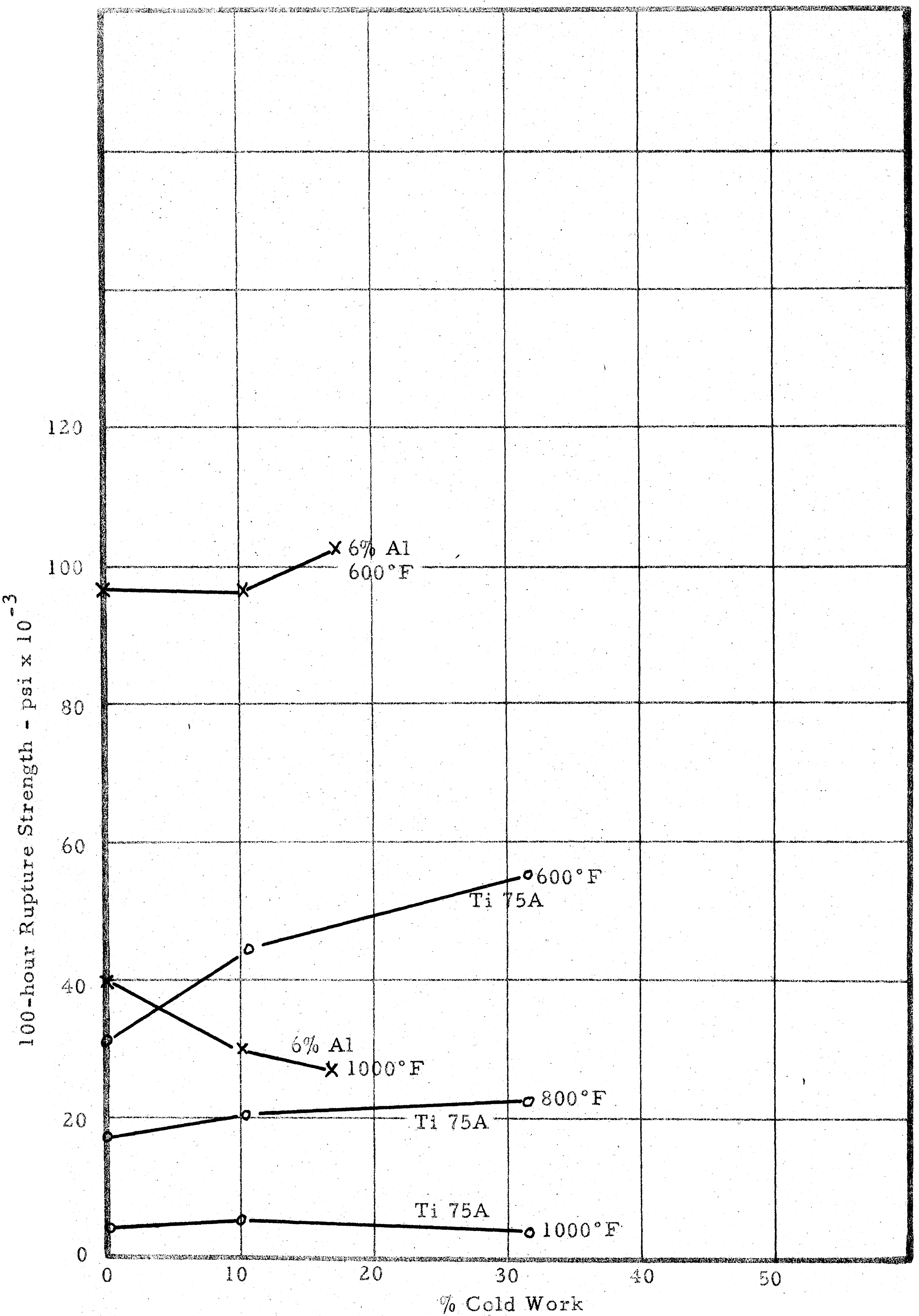


Figure 5. - Degree of Cold Work Versus 100-hour Rupture Strength at 600°, 800° and 1000°F for Ti 75A Annealed at 1500° or 1700°F and 6% Al-Ti Cold Worked as-Forged.

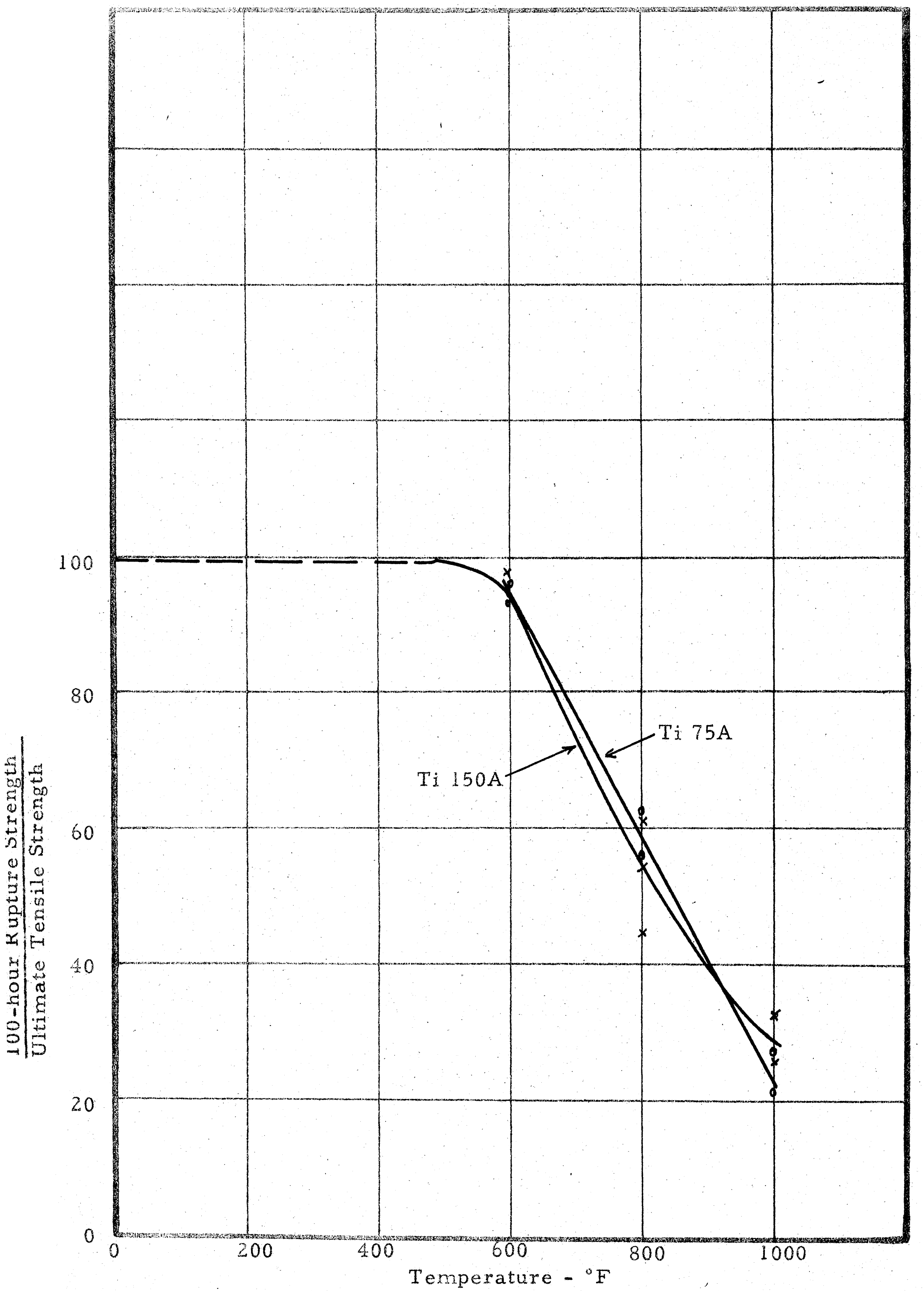


Figure 6. - Test Temperature Versus the Quotient $\frac{\text{100-hour Rupture Strength}}{\text{Ultimate Tensile Strength}}$ for Ti 75A and Ti 150A.

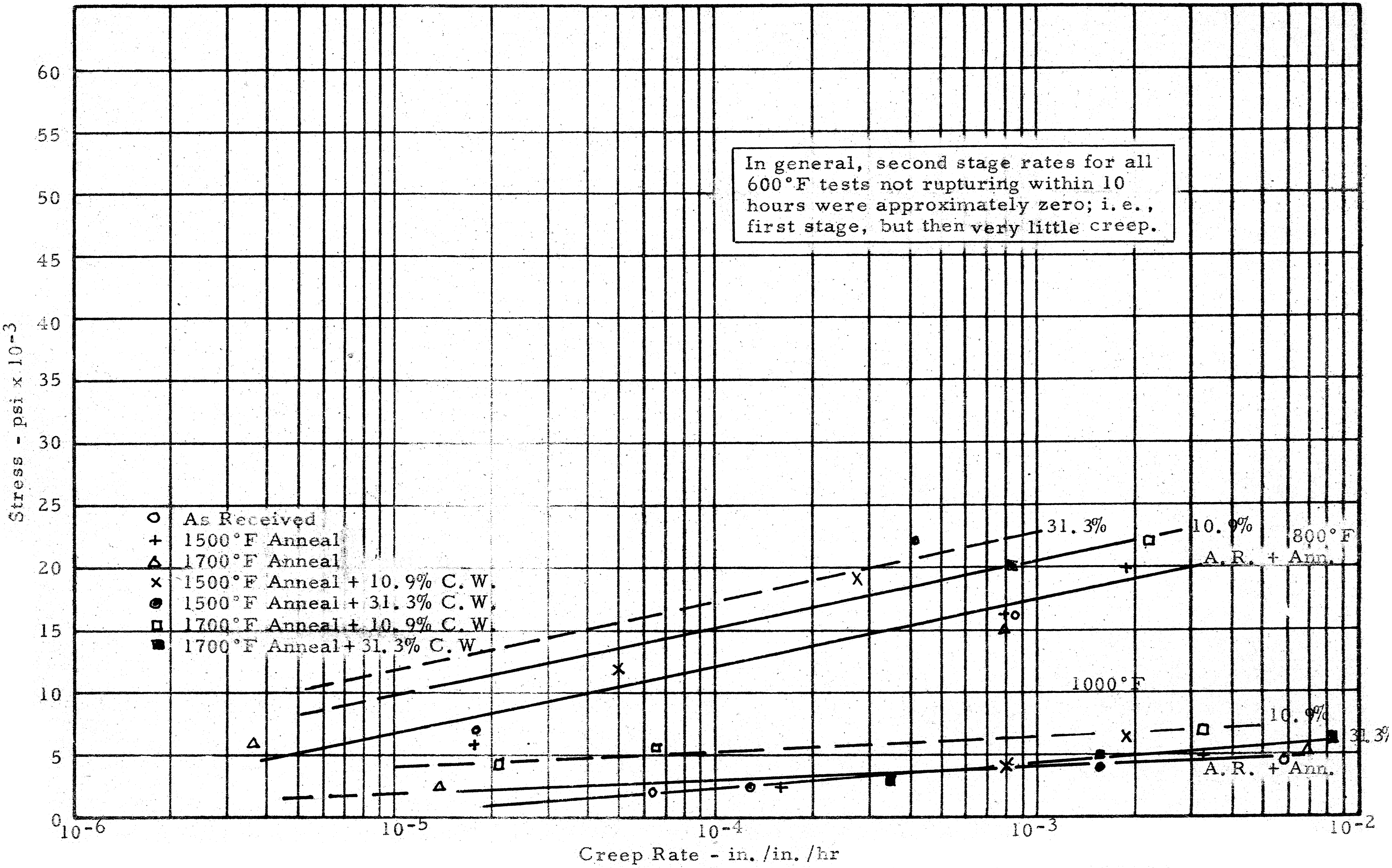


Figure 7. - Stress Versus Minimum Creep Rate at 800° and 1000°F for Ti 75A Treated as Indicated.

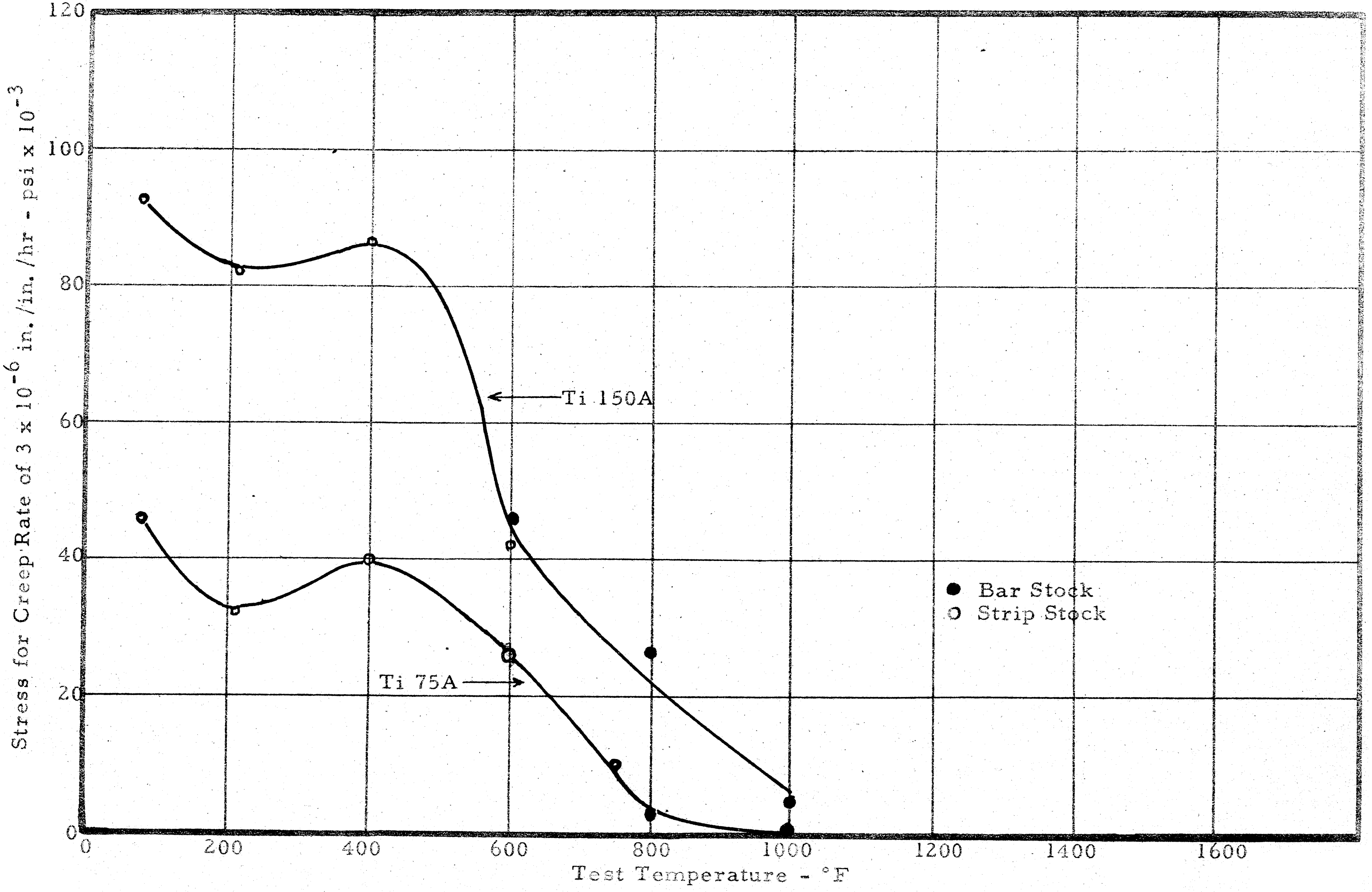


Figure 8. - Test Temperature Versus Stress for Minimum Creep Rate of 3 x 10^{-6} in./in./hr for Ti 75A and Ti 150A. (Points for Strip Stock obtained under Contract AF 33(038)-14111)

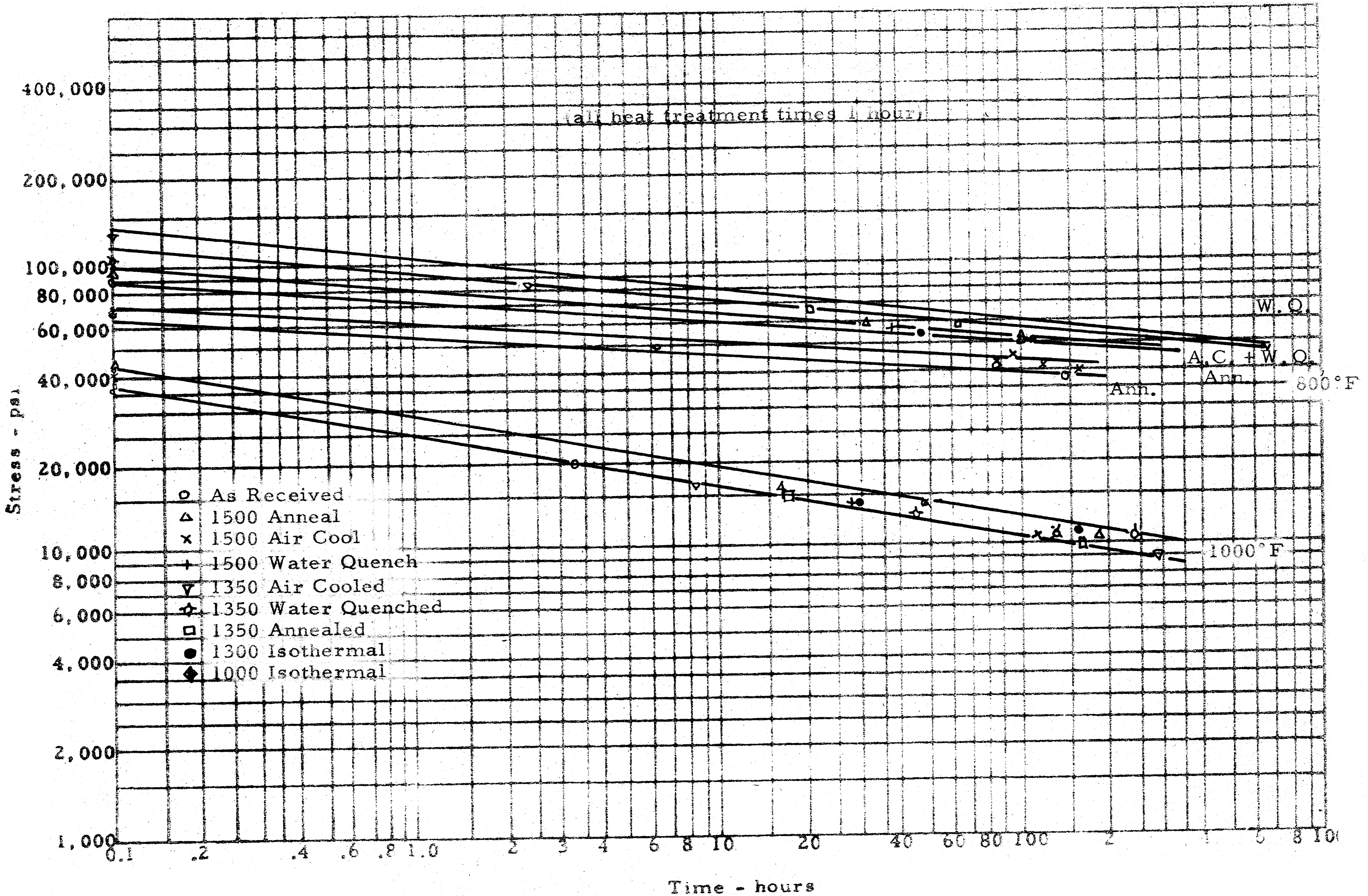


Figure 9. - Stress Versus Time to Rupture at 800° and 1000°F for Ti 150A Heat Treated as Indicated.

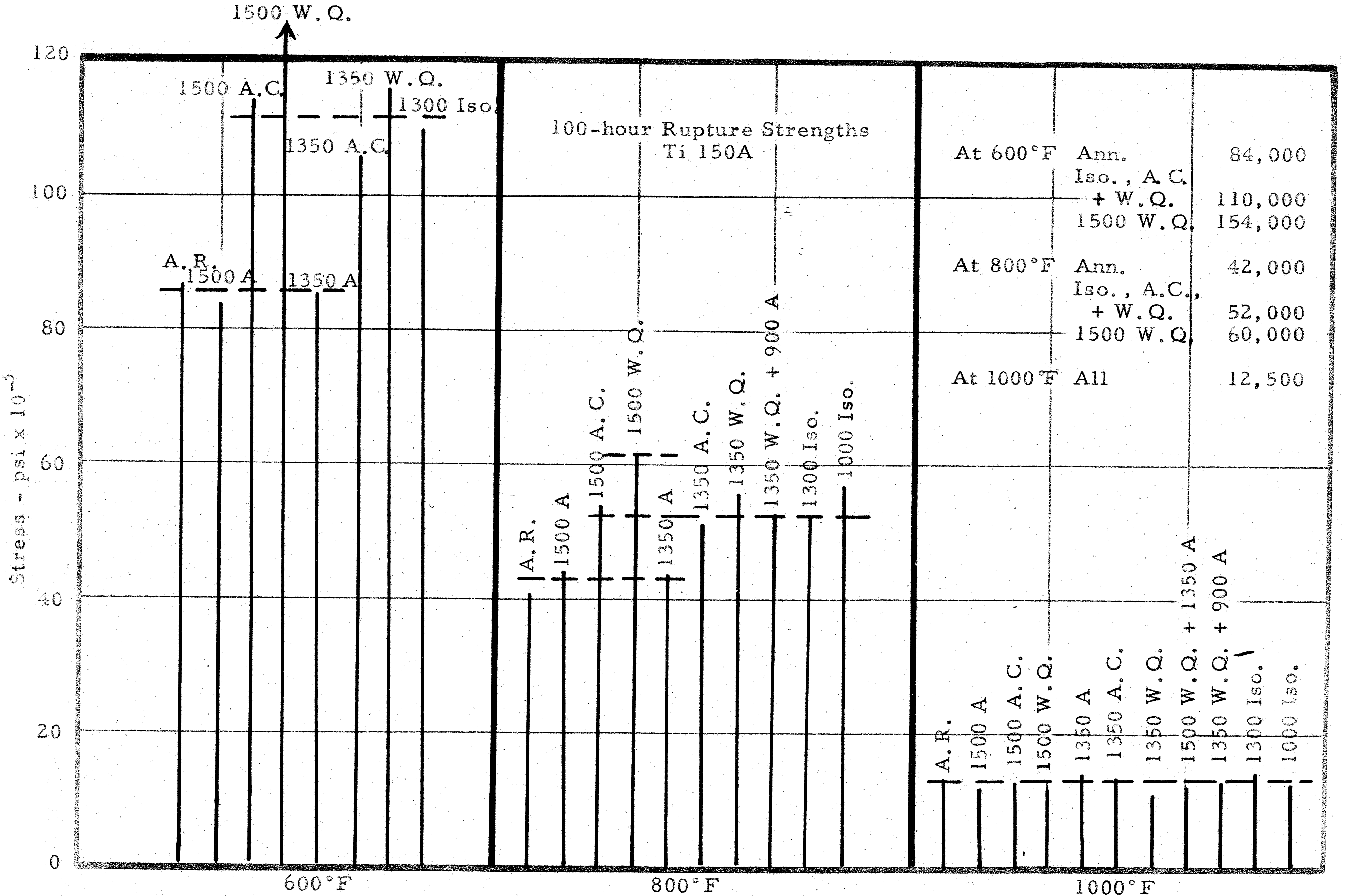


Figure 10. - One Hundred-Hour Rupture Strength at 600°, 800° and 1000°F for Ti 150A Heat Treated One Hour as Indicated.

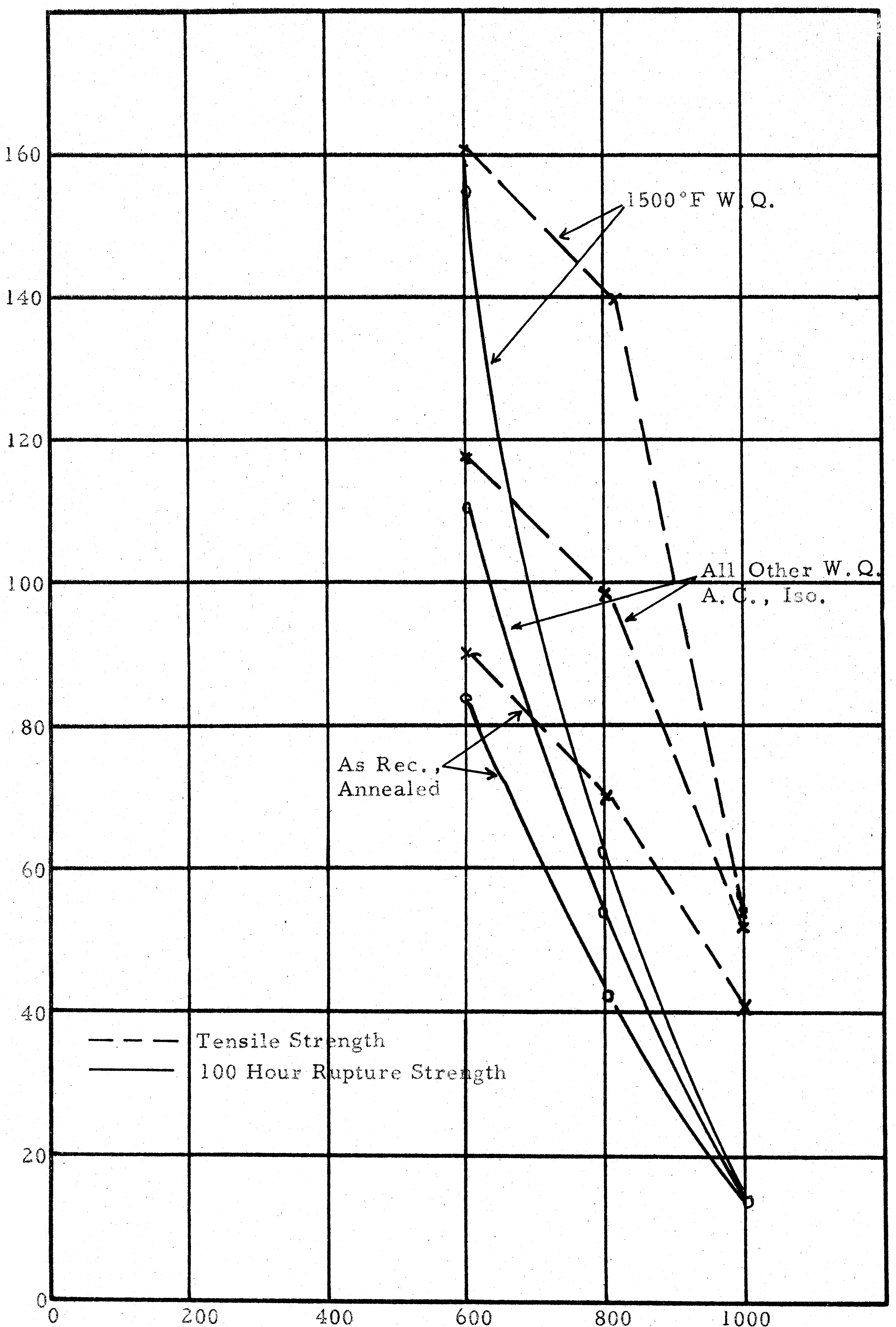


Figure 11. - Test Temperature Versus Tensile Strength and 100-hour Rupture Strength of Ti 150A Heat Treatment as Indicated.

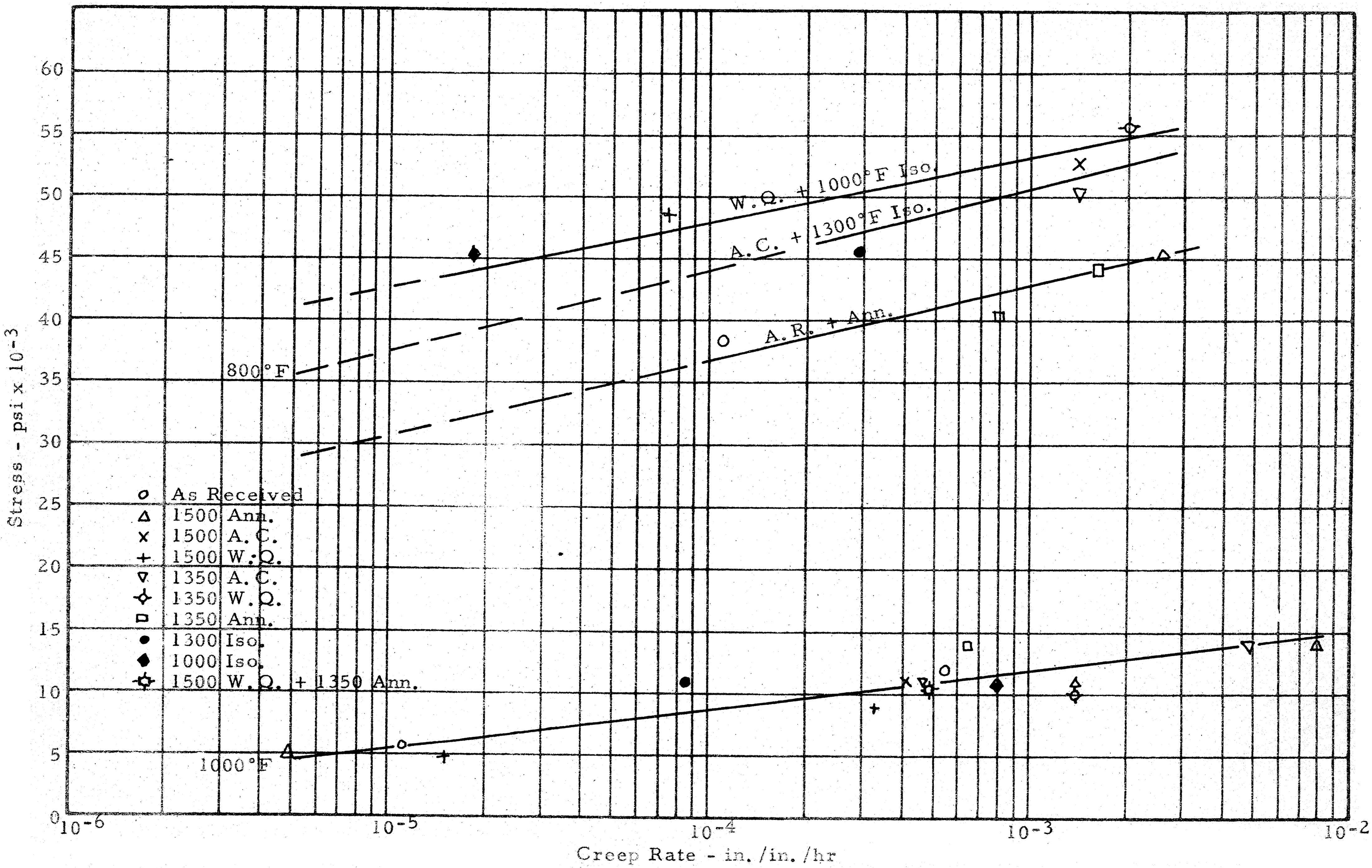


Figure 12. - Stress Versus Minimum Creep Rate at 800° and 1000°F for Ti 150A Heat Treated as Indicated.

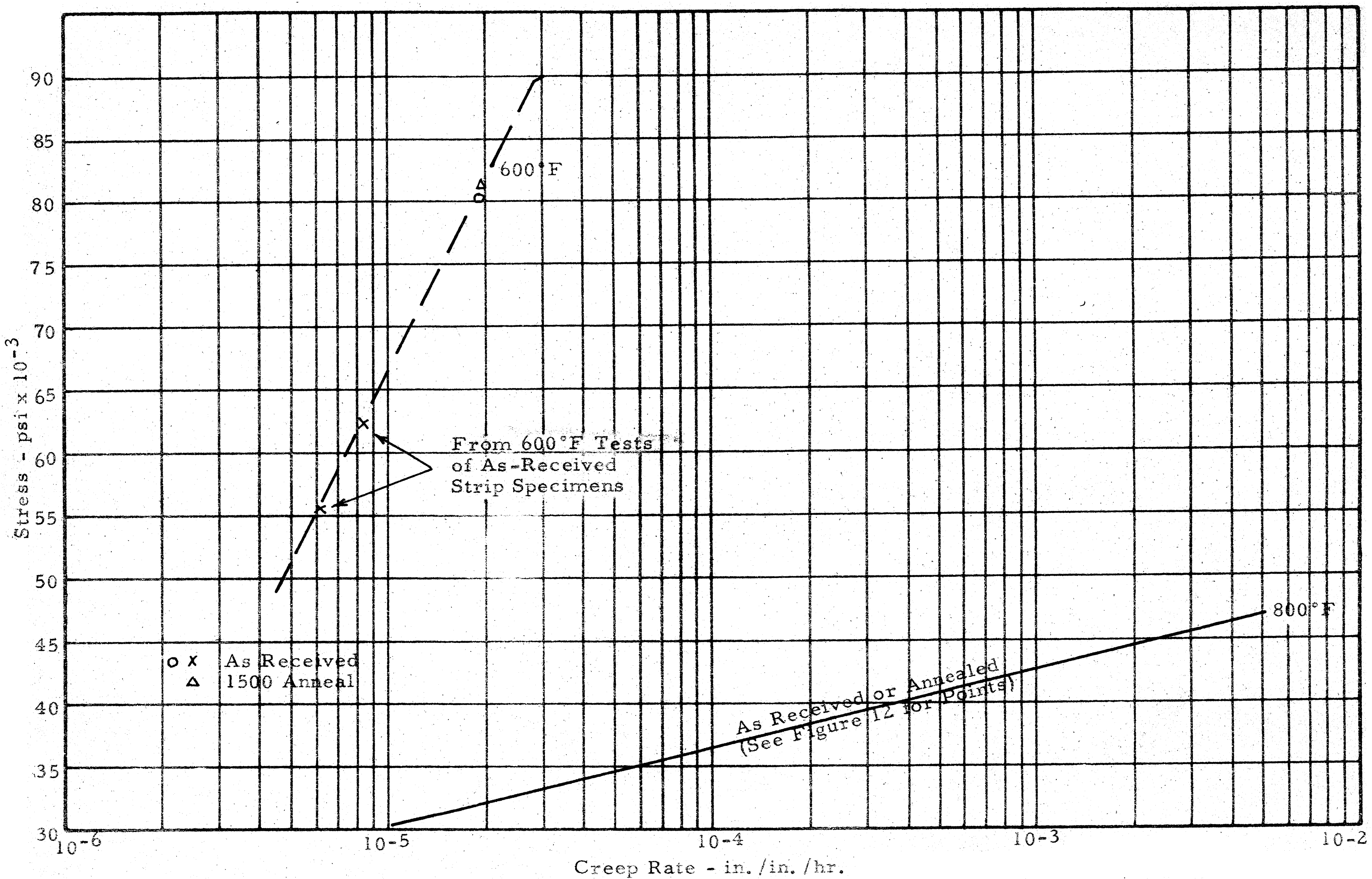


Figure 13. - Stress Versus Minimum Creep Rate at 600° and 800°F for Ti 150A Heat Treated as Indicated.

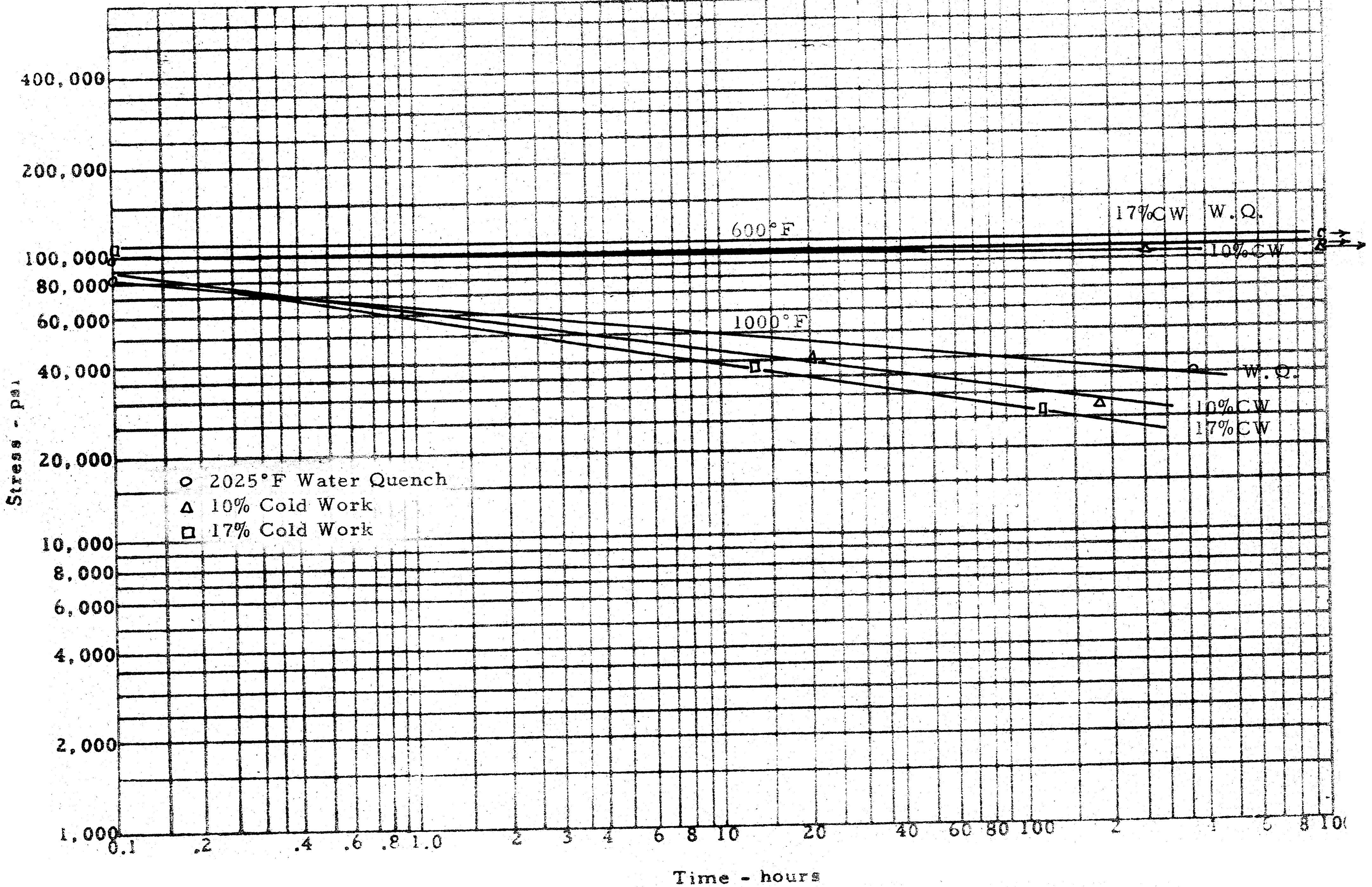


Figure 14. - Stress Versus Time for Rupture at 600° and 1000°F for 6% Al-Ti Treated as Indicated.

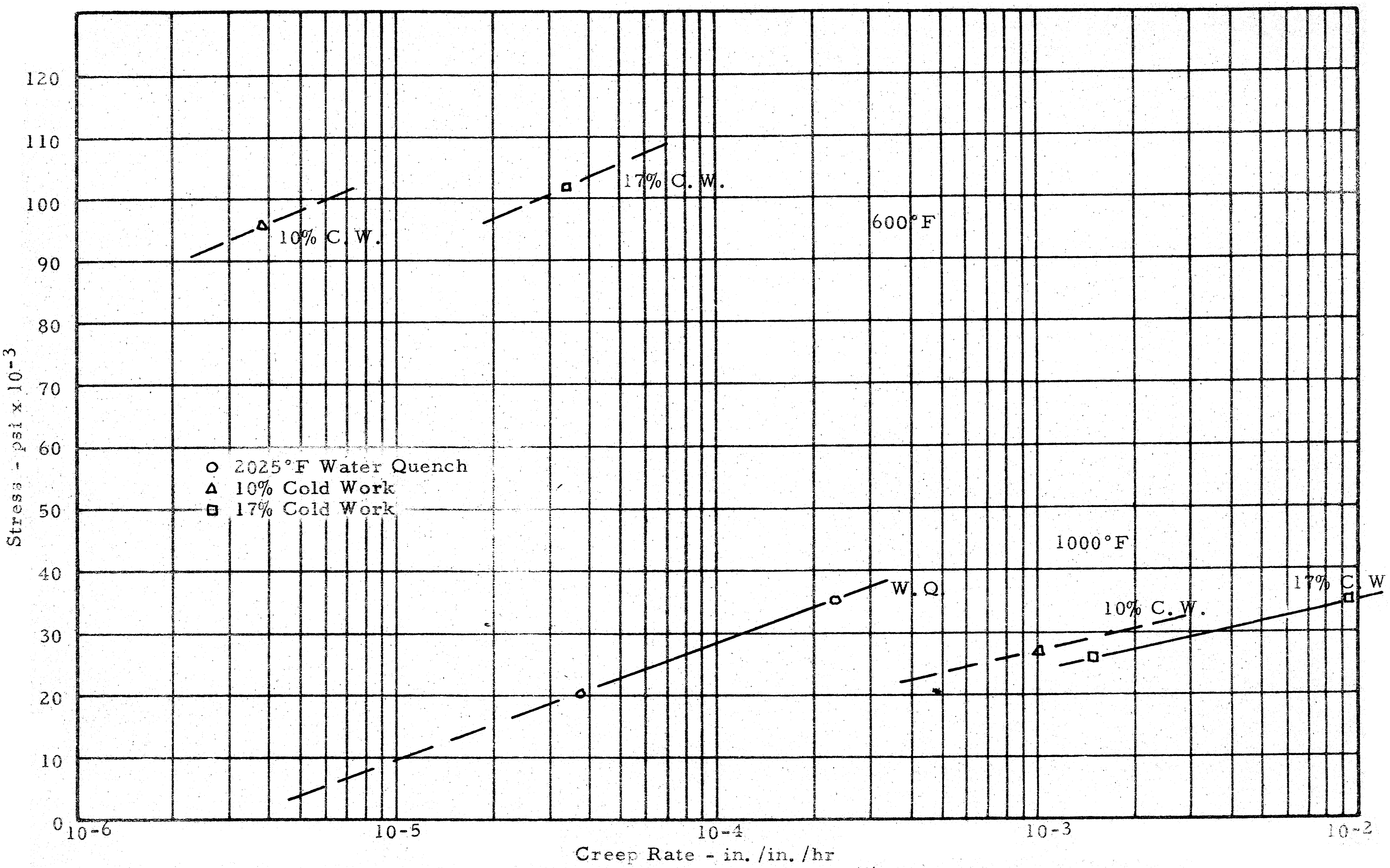


Figure 15. - Stress Versus Minimum Creep Rate at 600° and 1000°F for 6% Al-Ti Treated as Indicated.

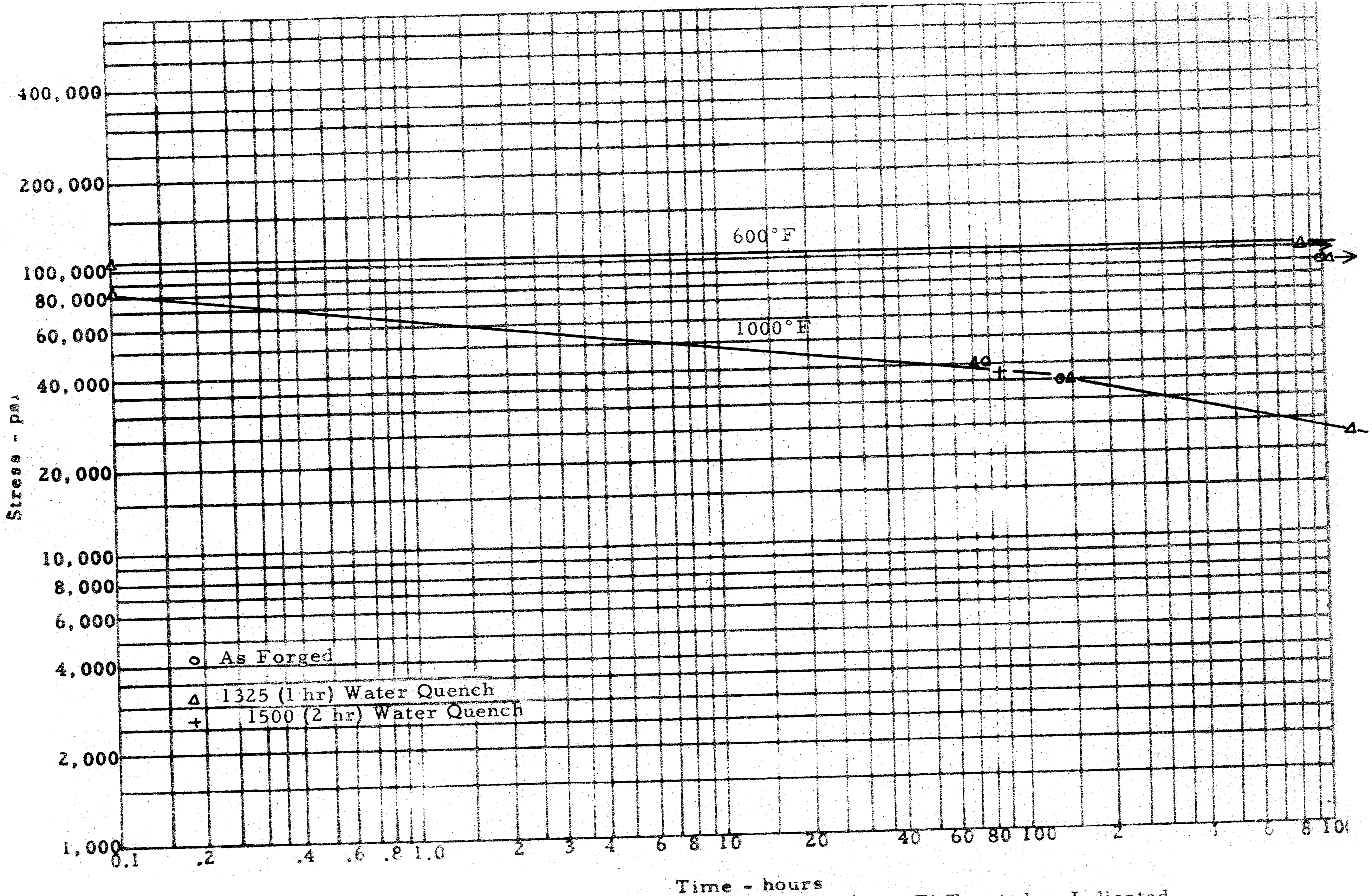


Figure 16. - Stress Versus Time to Rupture at 600° and 1000°F for 30% Mo-Ti Treated as Indicated.

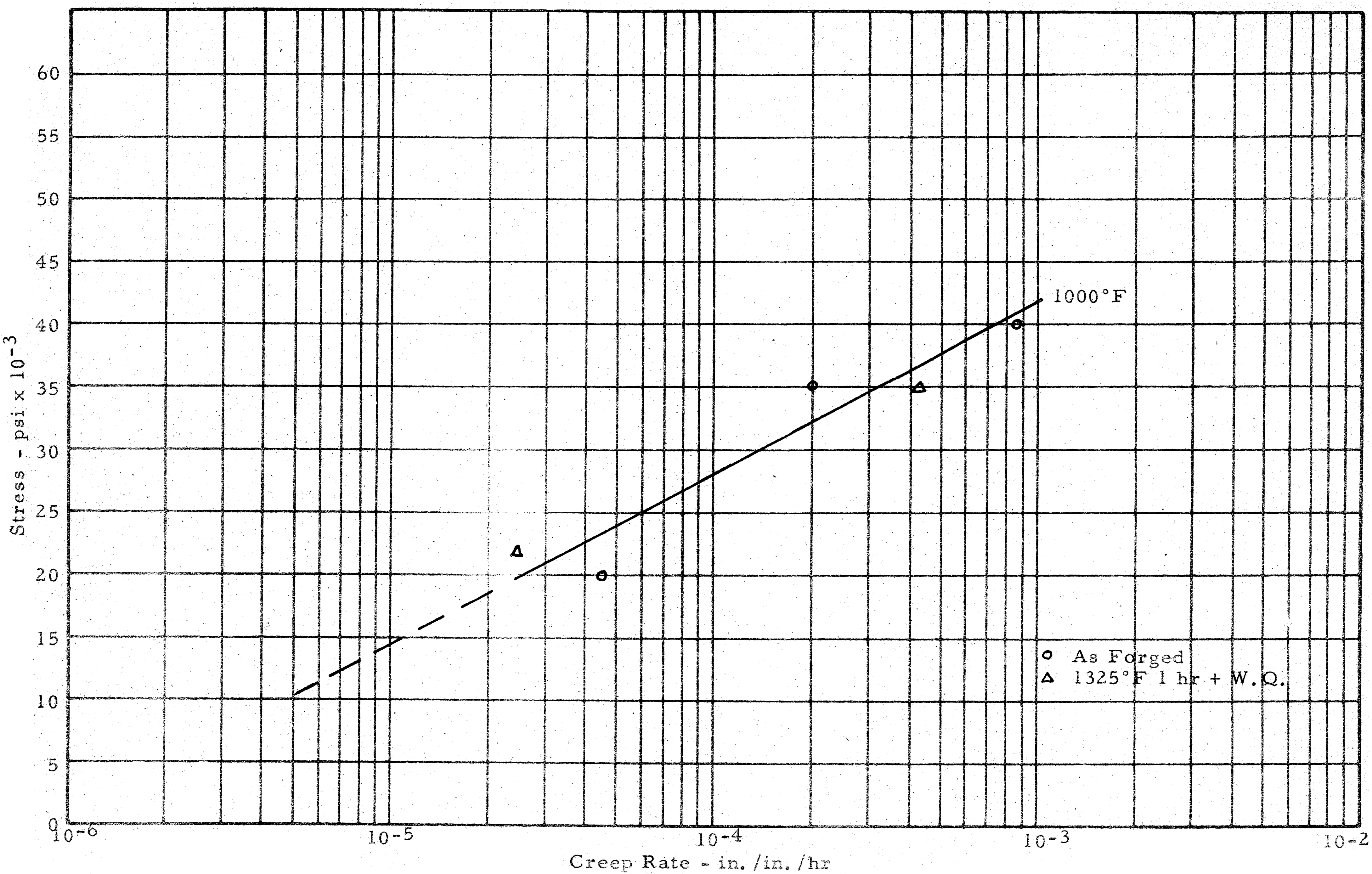


Figure 17. - Stress Versus Minimum Creep Rate at 1000°F for 30% Mo-Ti Treated as Indicated.

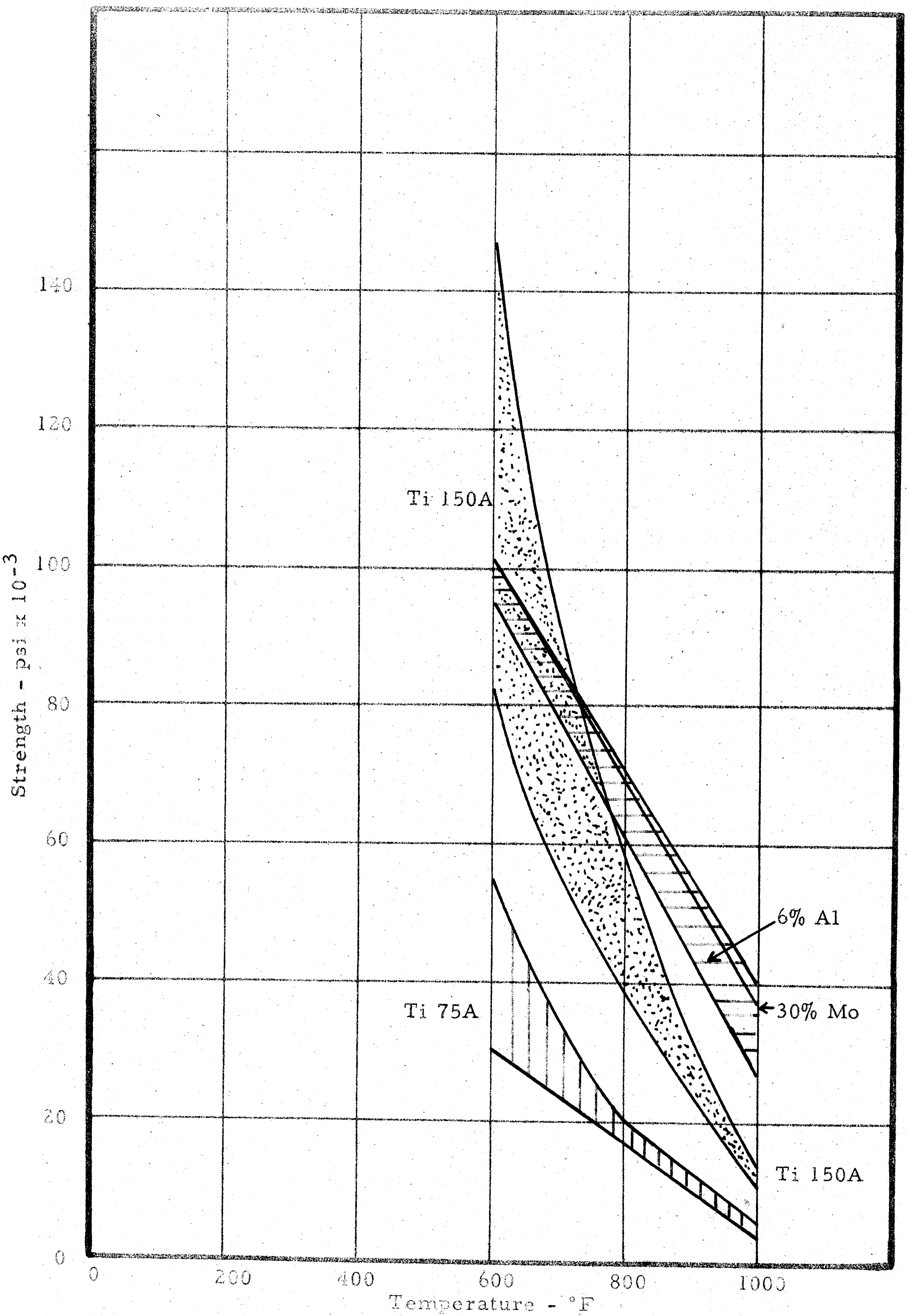


Figure 18. - Test Temperature Versus 100-hour Rupture Strength for Titanium Alloys as Indicated.

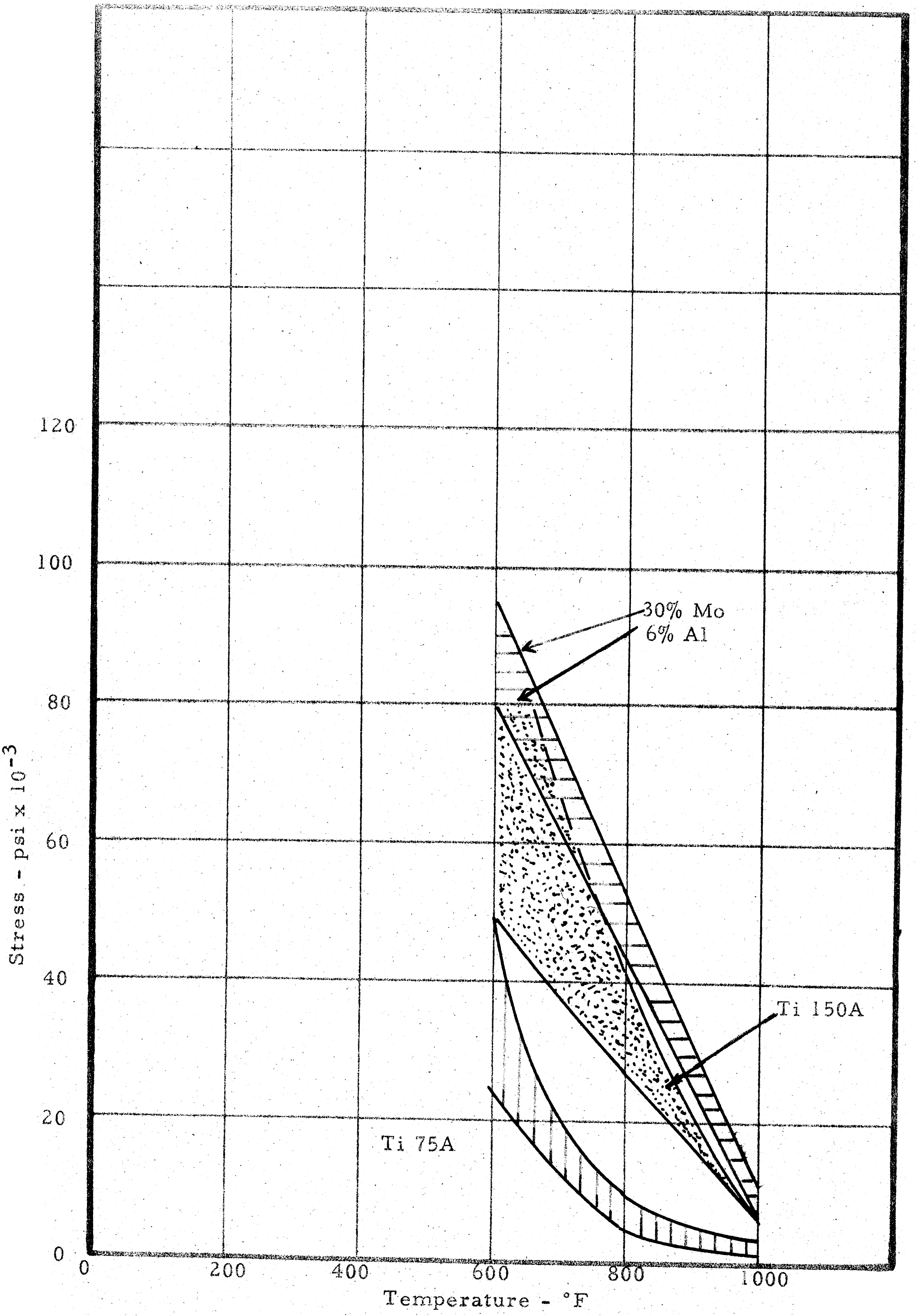


Figure 19. - Test Temperature Versus Stress for Minimum Creep Rate of 5×10^{-6} in. /in. /hr for Titanium Alloys as Indicated.

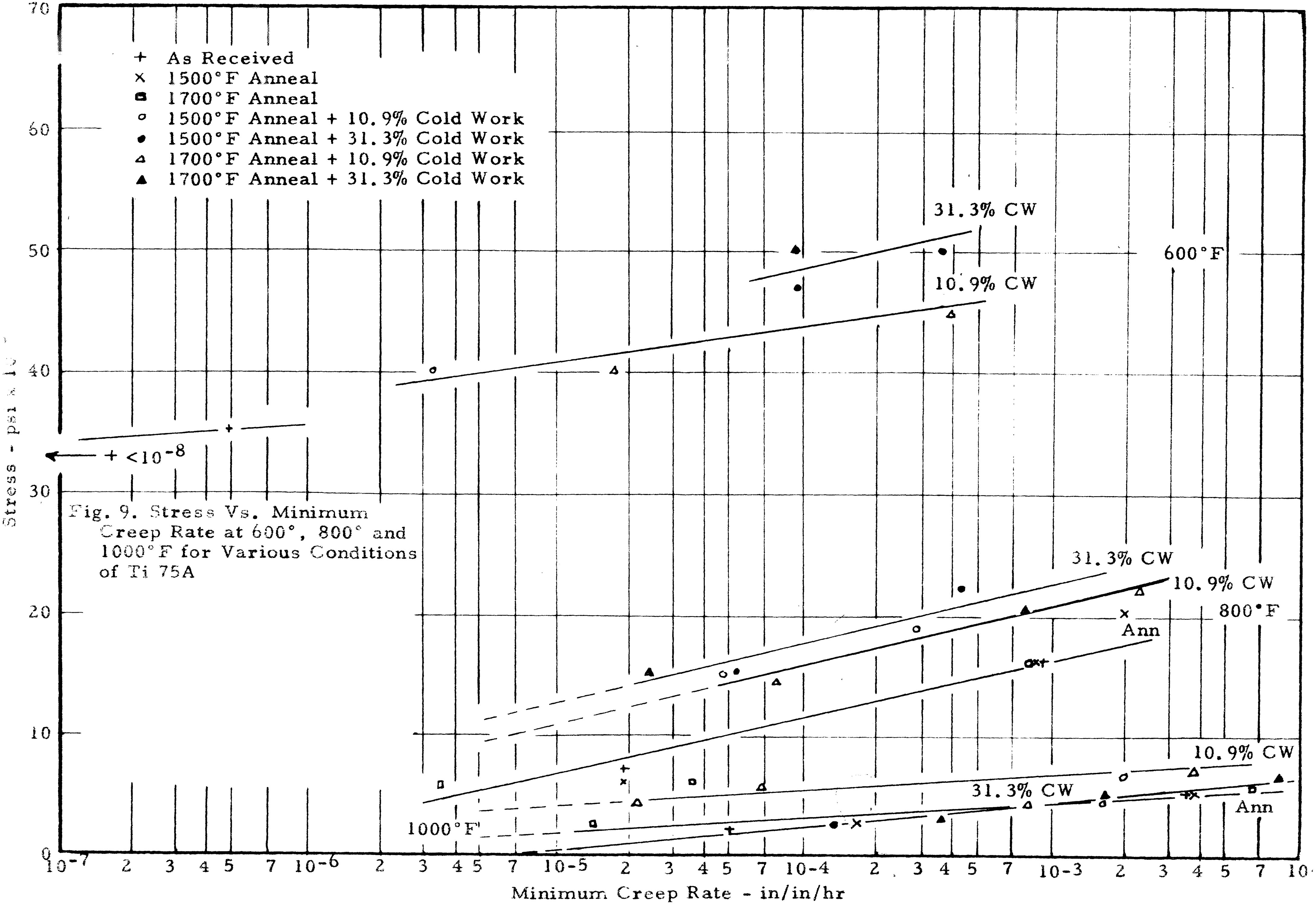


Fig. 9. Stress Vs. Minimum Creep Rate at 600°, 800° and 1000°F for Various Conditions of Ti 75A

53-183

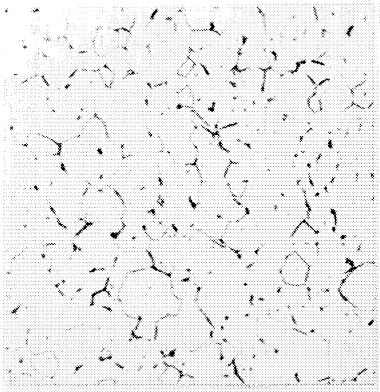


Figure 20 X250

Ti 75A - 1700°F Annealed

53-492

Figure 21 X250

Ti 75A - 1700°F Annealed + 27.8 hr. 1000°F and 6,500 psi

53-493

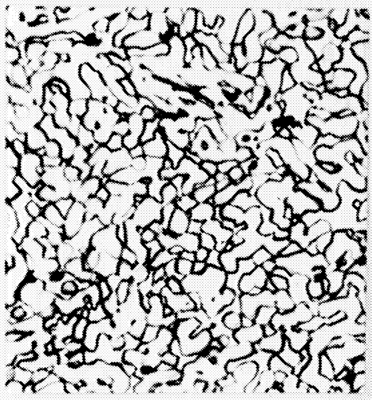


Figure 22 X1000

Ti 150A - As Received + 979.3 hr. 600°F and 80,000 psi

53-494

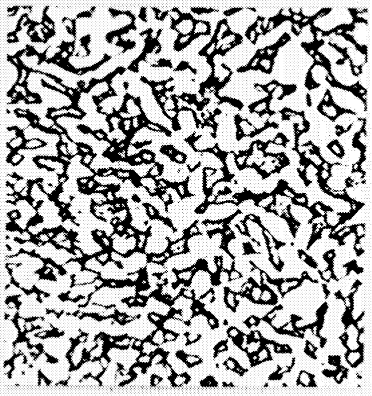


Figure 23 X1000

Ti 150A - As Received + 150.2 hr. 1000°F and 12,000 psi

53-495

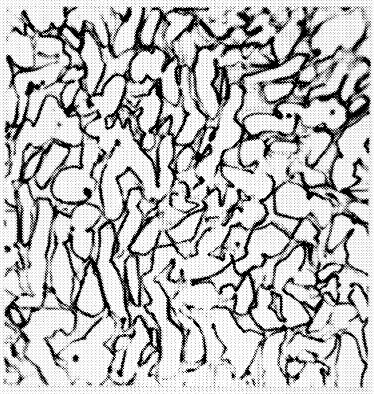


Figure 24 X1000

Ti 150A -1500°F Annealed. Tensile Tested at 800°F

53-496

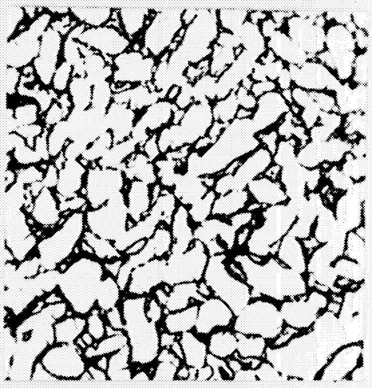


Figure 25 X1000

Ti 150A - 1500°F Annealed + 116 hr. 1000°F and 11,000 psi

All Heat Treatment Times 1 Hour
Electropolished
Etchant: Ti 75A - 2 HF, 2 HNO_3, 100 H_2O
Ti 150A - 1 HF, 1 Glycerine

53-497

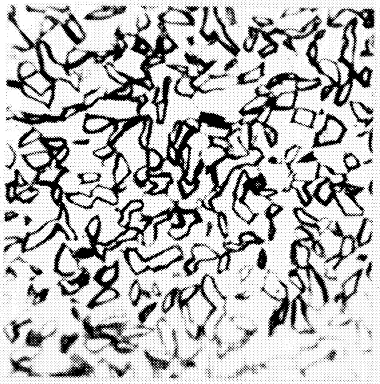
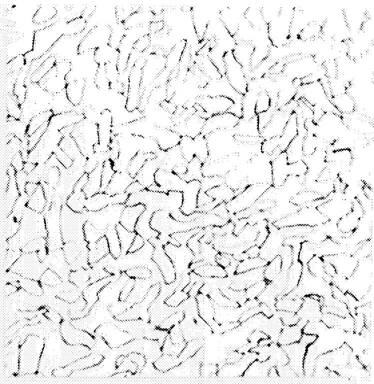


Figure 26 X1000

Ti 150A - 1500°F Air Cooled. Tensile Tested at 800°F



53-498

Figure 27 X1000

Ti 150A - 1500°F Air Cooled + 100.5 hr. 800°F and 52,000 psi

53-499

Figure 28 X1000

Ti 150A - 1500°F Air Cooled. Tensile Tested at 1000°F

53-500

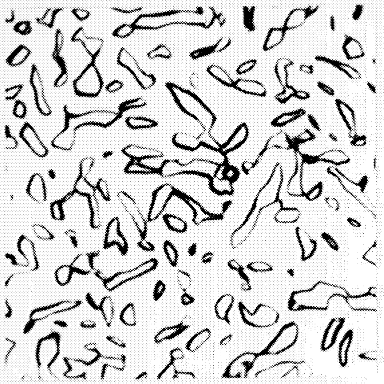
Figure 29 X1000

Ti 150A - 1500°F Air Cooled + 16.1 hr. 1000°F and 16,000 psi

53-501

Figure 30 X1000

Ti 150A - 1500°F Air Cooled + 188.8 hr. 1000°F and 11,000 psi



53-502

Figure 31 X1000

Ti 150A - 1500°F Water Quench + 2.3 hr. 800°F and 85,000 psi

All Heat Treatment Time 1 Hour
Electropolished
Etchant: 1 HF, 1 Glycerine

53-503

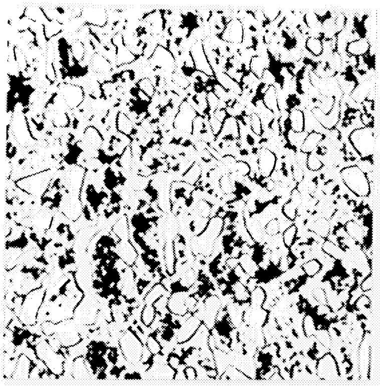
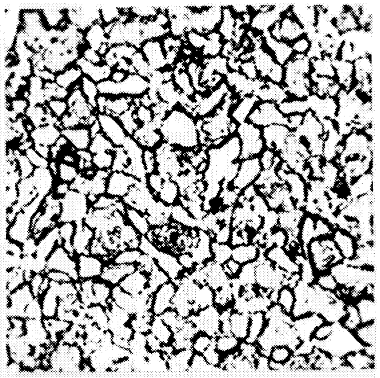


Figure 32 X1000

Ti 150A - 1500°F Water Quench. Tensile Tested at 1000°F



53-504

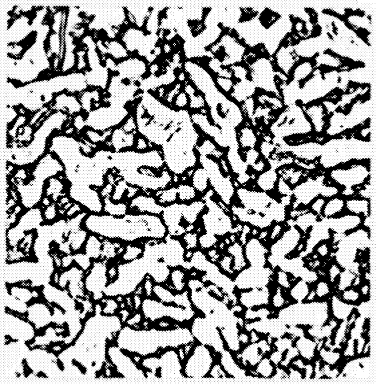
Figure 33 X1000

Ti 150A - 1500°F Water Quenched + 348.8 hr. 1000°F and 9,000 psi

53-505

Figure 34 X1000

Ti 150A - 1350°F Annealed. Tensile Tested at 800°F



53-506

Figure 35 X1000

Ti 150A - 1350°F Annealed 34 hr. 1000°F and 14,000 psi

53-507

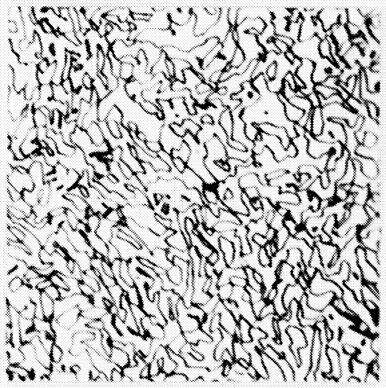
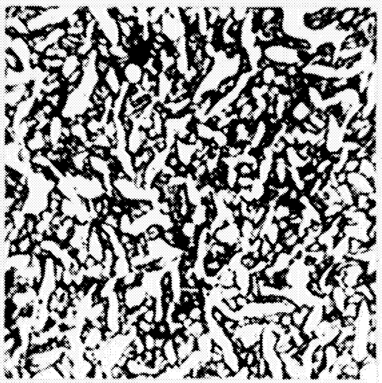


Figure 36 X1000

Ti 150A - 1350°F Air Cooled 43.5 hr. 800°F and 55,000 psi



53-508

Figure 37 X1000

Ti 150A - 1350°F Air Cooled + 194.3 hr. 1000°F and 11,000 psi

All Heat Treatment Times 1 Hour
Electropolished
Etchant: 1 HF, 1 Glycerine

53-509

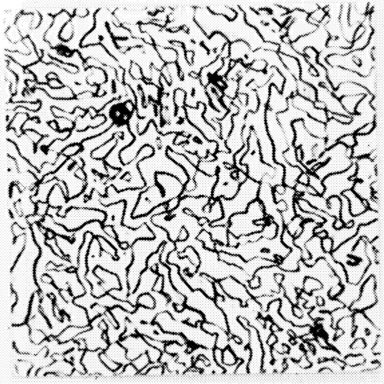


Figure 38 X1000

Ti 150A - 1350°F Water Quench. Tensile Tested at 600°F

53-510

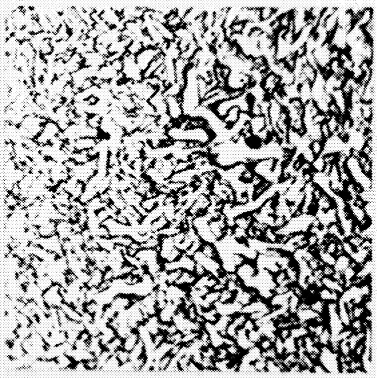


Figure 39 X1000

Ti 150A - 1350°F Water Quench + 16.7 hr. 1000°F and 15,000 psi

53-511

Figure 40 X1000

Ti 150A - 1500°F Water Quench + 1350°F Annealed Tensile Tested at 1000°F

53-512

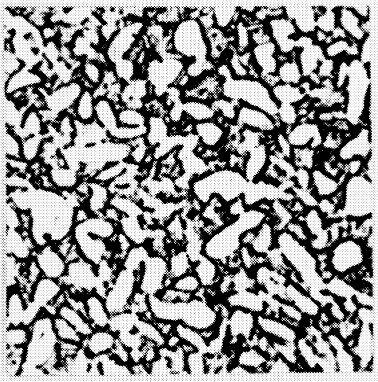


Figure 41 X1000

Ti 150A - 1500°F W.Q. + 1350°F Annealed + 43 hr. 1000°F and 13,000 psi

53-513

Figure 42 X1000

Ti 150A - 1350°F Water Quench + 900°F Anneal. Tensile Tested at 75°F

53-514

Figure 43 X1000

Ti 150A - 1350°F Water Quench + 900°F Anneal. Tensile Tested at 800°F

All Heat Treatment Times 1 Hour
Electropolished
Etchant: 1 HF, 1 Glycerine

53 - 515

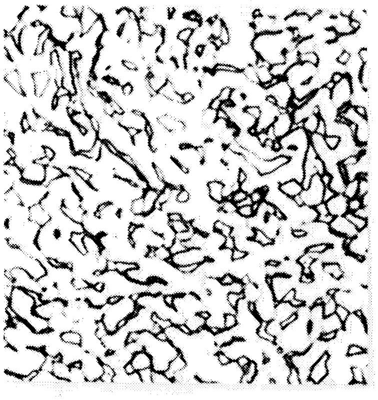


Figure 44 X1000

Ti 150A - 1350°F W.Q. + 900°F Anneal + 37 hr. 800°F and 58,000 psi

53 - 516

Figure 45 X100

6% Al-Ti - 2025°F Water Quench. Tensile Tested at 1000°F

53 - 517

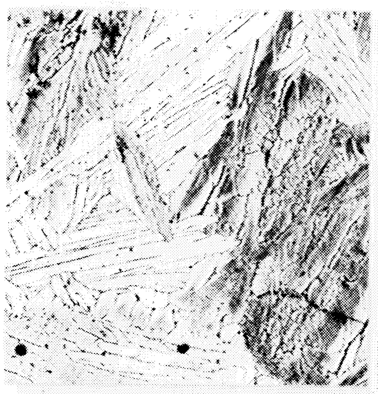


Figure 46 X50

6% Al-Ti - 2025°F W.Q. 1443.9 hr. 600°F, 96,000 psi + accidental overheat to at least 1600°F

53 - 518

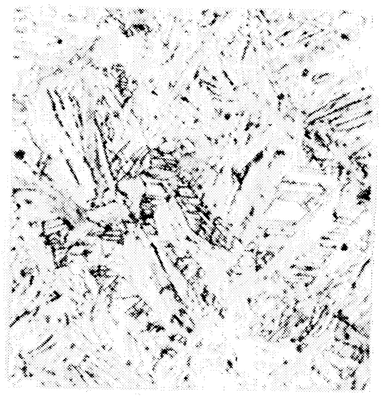


Figure 47 X250

6% Al-Ti - Cold Worked 17% + 1172.2 hr. 600°F and 101,000 psi

53 - 519

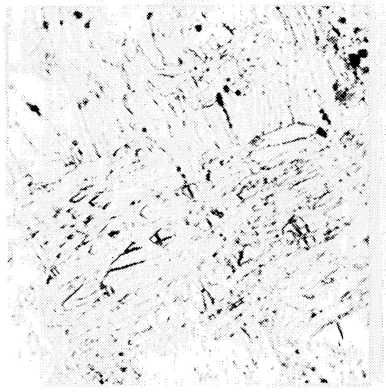


Figure 48 X250

6% Al-Ti - Cold Worked 17%. Tensile Tested at 1000°F

53 - 520

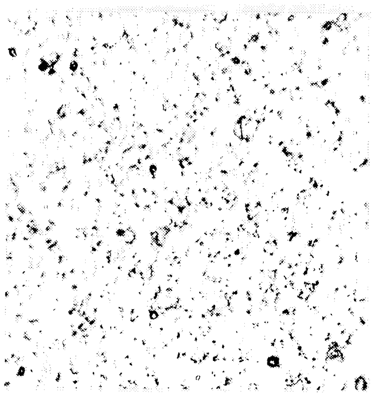


Figure 49 X250

6% Al-Ti - Cold Worked 17% + 13.4 hr. 1000°F and 37,000 psi

All Heat Treatment Times 1 Hour
Electropolished
Etchant: Ti 150A - 1 HF, 1 Glycerine
6% Al-Ti - 2 HF, 2 HNO_3, 100 H_2O

53-521

Figure 50 X250

6% Al-Ti - Cold Worked 10%. Tensile Tested at 600°F

53-522

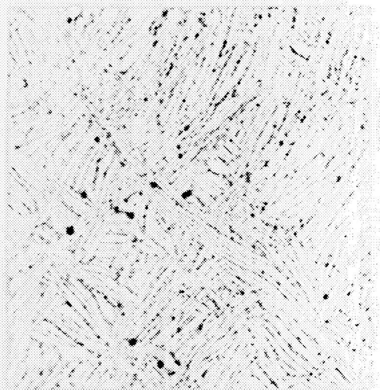
Figure 51 X250

6% Al-Ti - Cold Worked 10% + 1216 hr. 600°F and 96,500 psi

53-523

Figure 52 X250

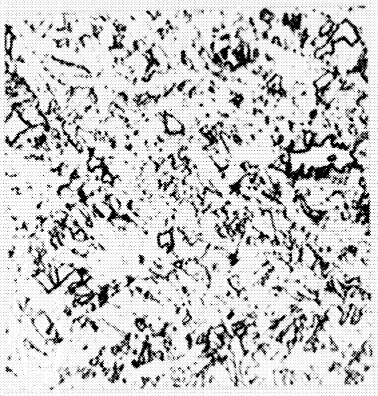
6% Al-Ti - Cold Worked 10%. Tensile Tested at 1000°F



53-524

Figure 53 X250

6% Al-Ti - Cold Worked 10% + 20.5 hr. 1000°F and 40,000 psi



53-525

Figure 54 X250

6% Al-Ti - Cold Worked 10% + 176.4 hr. 1000°F and 26,800 psi

All Heat Treatment Times 1 Hour
Electropolished
Etchant: 6% Al-Ti - 2 HF, 2 HNO_3, 98 H_2O

53-526

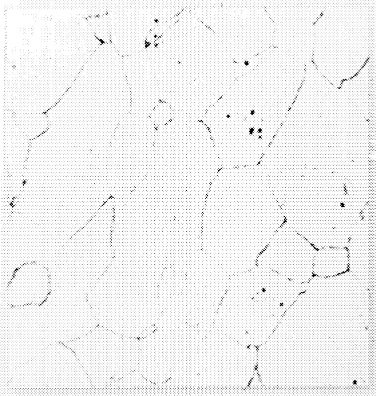
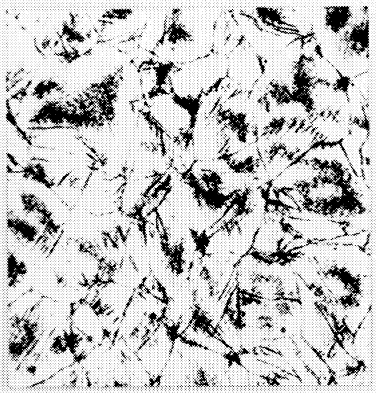


Figure 55 X250

30% Mo-Ti As Forged + 77 hr. 1000°F and 40,000 psi



53-527

Figure 56 X250

30% Mo-Ti As Forged + 133 hr. 1000°F and 35,000 psi

53-528

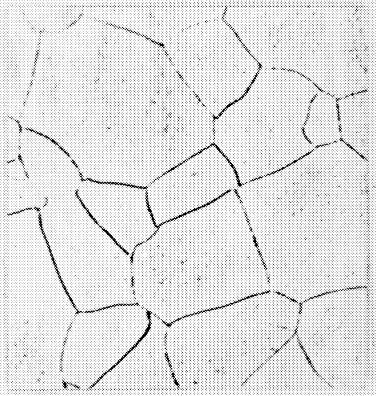
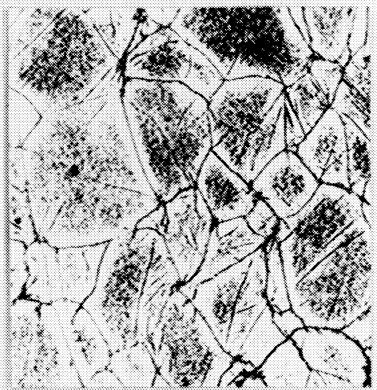


Figure 57 X250

30% Mo-Ti - 1325°F Water Quenched + 836 hr. 600°F and 100,000 psi



53-529

Figure 58 X250

30% Mo-Ti - 1325°F Water Quenched + 141.2 hr. 1000°F and 35,000 psi

53-530

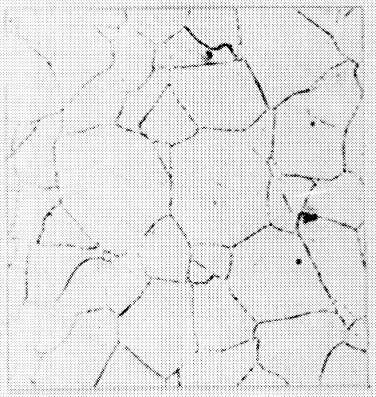
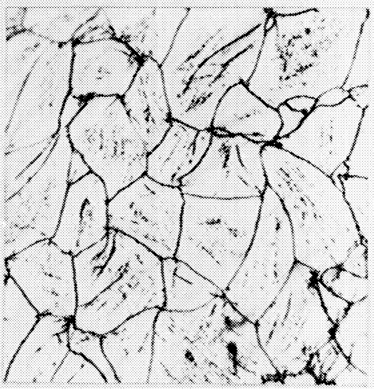


Figure 59 X250

30% Mo-Ti - 1500°F (2hr.) Water Quenched. Tensile Tested at 1000°F



53-531

Figure 60 X250

30% Mo-Ti - 1500°F (2hr.) Water Quenched + 83.4 hr. 1000°F and 37,500 psi

All Heat Treatment Times 1 Hour Unless Specified
Electropolished
Etchant: 30% Mo-Ti - 1 HF, 1 Glycerine