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Progress Report

PREDICTION OF RUPTURE STRENGTHS OF GRADE 11, GRADE 22 AND TYPE 304 STEELS BY SIMULATION OF LONG TIME SERVICE

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INTRODUCTION

The long time creep-rupture strengths of alloys, particularly the 100,000-hour rupture strengths, are major factors in the establishment of design stresses for high temperature applications. At the present time, it is virtually impossible to obtain acceptance of 100,000-hour rupture strengths without tests out to longer than 10,000 hours. Even under these circumstances, there is often considerable uncertainty to the strengths at prolonged times. In addition to economic advantages, the following benefits would result from the development of a "practical verification" test (short time) that would define rupture strengths at long times.

(1) Avoidance of steel being placed in service with unexpectedly poor strength.

(2) Development of the controls necessary to produce material with strengths on the high side of the range. Currently, the data cover a wide range of strengths with the code stresses governed by the minimum values. It is contended that the wide range in properties is tolerated only because it is not practical to determine creep-rupture strengths by routine acceptance tests.

(3) Delineation of the effects of manufacturing and fabrication conditions on creep-rupture properties.

An evaluation of possible verification tests has been carried out at The University of Michigan. The research originated from a program sponsored by the Detroit Edison Company. Clarification and extension of the initial results were carried out under the auspices of the Metal Properties Council. Results from the entire investigation are presented in this report.

EXPERIMENTAL BASIS

Preferably, a verification test should indicate the actual creep-rupture strengths for whatever service time period and temperature may be of interest. The two techniques involved in the study, simulated service exposures and parameters, were considered potentially useful as the basis of such a test. The research was focused on the utilization of short time tests to predict strengths at times from 10,000 to 100,000 hours.

Utilization of Simulated Service Exposures

Considerable data has been accumulated at The University of Michigan which indicate that thermally induced structural changes that occur during prolonged service results in the elimination of the instabilities in log stress-log rupture time curves (ref. 1). Thus, the rupture curve for material removed from service can be extrapolated with relative ease and reliability. The available information indicates that the extrapolated strength defines the strength of the unused material.

It was suggested that the long times of service could be simulated by short time exposures at temperatures higher than the service temperature. The result would be a method of determining the long-time strengths of unused material before service with confidence by relatively few tests. The investigation involved the study of specific treatments to simulate long time service and the evaluation of methods of extrapolating short time tests of these heat treated materials.

Extrapolation by Parameter Methods

Parameter techniques are widely used to extrapolate stress-rupture time data (ref. 2). There has been considerable question as to their accuracy.

However, when correctly applied they can lead to reliable extrapolations. Since they are often used for verification testing, some consideration was given to their merits relative to methods based on simulated service exposures.

EXPERIMENTAL MATERIALS

The materials selected for study were Grade 11 (1.25Cr-0.5Mo-0.75Si), Grade 22 (2.25Cr-1Mo) and Type 304 (18Cr-8Ni) steels.

Grade 11 Steel

The material (P11 pipe removed from service) was suited to the investigation because the long time strength at 1000°F had been determined with a great deal of confidence (ref. 1). The pipe had operated for 83,403 hours at 1000°F under 1800 psi stream pressure. It was forged and bored by Midvale-Heppenstall to an O.D. of 12 inches and the I.D. of 9 inches. The heat treatment was a normalize plus temper.* The simulated service exposures were carried out after reheat treatment (renormalized from 1675°F to restore properties typical of unused material) in an attempt to duplicate the rupture properties of the material as removed from service. The specimens, in the longitudinal and transverse directions were 0.350 inch in diameter except for specimens tempered at 1325°F or annealed which were 0.505 inch in diameter.

Grade 22 Steels

The P22 pipe studied had not been in service. The wall thickness was 3-3/4 inches. The heat treatment was established to be either a normalize from 1675° - 1725°F plus tempered at 1225° - 1350°F or an annealing from

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*As near as could be finally determined, the pipe prior to service had been heated at 1750°F for 1 hour, A.C. + tempered at 1225°F for 1.5 hours.

1750°F. The microstructure indicated the normalize plus temper to be the treatment. The specimens, both longitudinal and transverse, were 0.350 inch in diameter except for 0.505-inch diameter specimens used to study simulated service at 1100°F.

In the latter stages, the program was extended to include four unused Grade 22 tubes with O.D., 2-1/4 inches and I.D., 1-1/4 inches. One tube was treated 1 hour at 1400°F and air cooled. A modified isothermal treatment was used for three tubes. Specimens 0.350 inch in diameter were taken in the longitudinal direction.

Type 304 Austentic Steel

The type 304 material was bar stock from the ASTM "Standard Specimen Bank." Very long time creep-rupture tests (ref. 3) had been conducted on the material by the Applied Research Panel of the ASTM-ASME Joint Committee on the Effect of Temperature on Properties of Metals (Project AR-2). Although the stock used was from a different billet than the AR-2 material there was every reason to expect that there would be no significant difference in properties. Using this material reduced any problems associated with uncertainties in long time strengths since tests had been conducted beyond 50,000 hours at 1100° and 1200°F.

The steel was furnished as 5/16-inch round-corner squares water quenched after 1 hour at 1950° - 1975°F. Specimens, 0.250 inch in diameter, were machined from lengthwise quartered stock.

PROCEDURE

There was no established basis for selecting exposure times and temperatures to simulate service. Larson and Miller (ref. 4) proposed the following equation to describe the interrelationship between rupture time and temperature:

$$P = T(C+\text{Log } t)$$

where

T = Temperature, °R

t = Rupture time, hour

P = Parameter

C = Constant

This relationship offered a basis for selecting simulated exposures. Initially the program involved simulation of 83,000 hours of service at 1000°F for P11 and P22 pipes. There was no reason to expect that constants determined to correlate rupture data would also be applicable for selecting the thermal exposures. Arbitrarily, therefore, exposures of 300, 88 and 20 hours at 1200°F were selected. These correspond, respectively, to constants of approximately 15, 20 and 25. For the P22 pipe these exposures had little influence on the rupture properties. Consequently an exposure of 115 hours at 1300°F (C=20) was carried out to simulate 83,000 hours of service at 1100°F.

As there was an uncertainty as to the effect of stress during exposure, samples were exposed with and without stress. The ASME Boiler and Pressure Vessel Committee Code stress of 7800 psi for service at 1000°F (adopted 1951) was used for the stressed exposures. These were carried out in creep-testing units using oversize specimens which were remachined after exposure. Exposures without stress were carried out on machined specimens sealed in evacuated quartz tubes. Rupture tests were conducted at the service temperatures simulated (1000° and 1100°F) on the materials in the heat treated conditions ("original" treatments) and after the simulated exposures. Tests were also carried out at higher temperatures to provide parameter extrapolations to 100,000 hours.

Four Grade 22 steel tubes exhibiting a range of rupture strengths were incorporated into the program. Tests were carried out to 10,000 hours at 1100°F for the as-heat treated materials. The rupture curves at 1100°F were extended to 100,000 hours by "parameter" testing. The tubes were exposed to simulate 10,000 and 100,000 hours at 1100°F (based on C=20 these were, respectively, 100 hours at 1242°F and 100 hours at 1313°F). Specimens were machined from the materials after exposure and rupture tests carried out at 1100°F.

Testing of the Type 304 steel was carried out to determine if the stock supplied had the same properties as the billet used for the AR-2 tests. Rupture tests were conducted at 1200°F and also at higher temperatures at which results of "parameter" tests had been reported (ref. 3). On the basis of the agreement obtained, bar stock was exposed to simulate 100,000 hours of service at 1200°F (C=20). The exposure of 100 hours at 1425°F was carried out prior to the machining specimens for testing. Specimens were also exposed under a stress of 8500 psi (the estimated 100,000-hour strength of the AR-2 material) at 1325°F until the secondary creep stage was attained. (This took about 100 hours and the total creep was about 0.3%.) The exposed materials were rupture tested at temperatures from 1100° to 1425°F.

The simulated service exposures for Type 304 steel did not duplicate the structures evident after long time test exposure. Consequently a number of thermal mechanical treatments were studied which were designed to accelerate the microstructural reactions occurring. The structures obtained were studied using optical and transmission electron microscopy.

RESULTS AND DISCUSSION

The rupture test data are presented in Tables I and II for P11 pipe, Tables IV through VI for P22 pipe, Tables VIII through X for Grade 22 tubes and Table XII for Type 304 stainless steel.

Where longitudinal and transverse specimens were used, the results of the investigation appeared to indicate no marked difference in rupture strength. Accordingly, the results of the tests were combined.

P11 (1.25Cr-0.5Mo-0.75Si) PIPE

AS-REMOVED FROM SERVICE

Consideration of the rupture data (Table 1, Figs. 1,2) for the material from service (ref. 1) led to the following:

(1) The stress-rupture time curves at 1000°F and 1100°F were parallel while the 1200°F curve was slightly steeper (Fig. 1a). The similarity of the slopes of the rupture curves, by the family-of-curves concept, lent confidence in the 83,000-hour strength level at 1000°F of 13,200 psi indicated by straight line extrapolation.

(2) Extrapolation of the rupture data at 1000°F, using the Larson-Miller parameter with a constant C of 20 indicated an 83,000-hour strength of 12,800 psi (Fig. 2). This value is slightly lower than that obtained by straight line extrapolation of the log stress-log rupture time curve.

RENORMALIZED 1675°F + TEMPERED 2 HOURS AT 1200°F

Renormalizing and tempering restored properties characteristic of new pipe. The tests at 1000°F were at much higher stress levels than for the material as-removed from service (Fig. 1b). The data at 1000°F for the reheat treated material could not be extrapolated as a straight line since changes in slope were expected to occur at prolonged times. Consequently higher temperature tests were conducted to permit parameter extrapolation. The Larson-Miller parameter curve (Fig. 2) exhibited "‾‾╲__" type behavior i.e., an increase followed by a decrease in steepness. The stress for rupture in 83,000 hours at 1000°F was indicated to be 13,300 psi essentially the same value as derived by straight line extrapolation of the curve for the material as-removed from service (Table III).

RENORMALIZED 1675°F + EXPOSED TO SIMULATE SERVICE AT 1000°F

Exposure of 20, 88 and 300 hours at 1200°F were used to simulate 83,000 hours of service at 1000°F.

There was evidence that exposure under stress (7800 psi) resulted in slightly lower strengths than for exposure without stress (Fig. 3). This could simply reflect utilization of small amounts of rupture life during the stressed exposures.

In no case was there exact agreement between the stress-rupture time curve for exposed specimens and that established for material removed from service (Fig. 3). Although somewhat steeper, the rupture curves for the materials exposed 88 and 300 hours came quite close over the test stress range (Figs. 3b,c). When extrapolated as straight lines, the rupture curves for the materials exposed 20, 88 and 300 hours indicated 100,000-hour strengths that were respectively, higher, similar and lower than for the material as-removed from service (Table III).

PARAMETER EXTRAPOLATIONS

Parameter testing indicated that the materials as-removed from service and after re-heat treatment had essentially the same 83,000-hour strengths (Fig. 2). These materials had very different short time strengths. To determine the generality of the observation it was decided to check as many treatments as possible using a stress of 12,500 psi and a test time of about 100 hours. The results of the tests run at 1200°F were in close agreement

(Table II). This was true even for reannealed material. Only the material exposed 300 hours at 1200°F resulted in a somewhat lower strength.

MICROSTRUCTURES OF P11 PIPE SAMPLES

The as-removed from service microstructure (Fig. 4a) showed extensive spherioidization of carbides. There was also precipitation within the grains. Simulated service by exposure for 20 hours at 1200°F after normalizing from 1675°F did not appreciably spheroidize the carbides (Fig. 4b). Considerable spheroidization occurred during 88 and 300 hours at 1200°F (Figs. 4c,d), but was not as complete as in the material from service. Also there was less precipitation within the grains. A stress of 7800 psi had no readily apparent effect on the microstructures.

The microstructures of specimens tested for rupture at 1200°F and 12,500 psi were very similar for all heat treated materials. The structures were highly spheroidized with large amounts of intragrannular precipitate. Thus the structures reflected the similarity in rupture strengths observed.

DISCUSSION OF RESULTS FOR P11 STEEL

The material removed from service yielded stress-rupture time curves which did not exhibit the changes in slope so frequently found for new steel (and evident for the reheat treated material). There was no evidence that measurable creep had occurred during service. Calculations, using the actual service temperatures and stresses, indicated that the amount of creep-rupture life used up was negligible. Therefore the difference in results for the unused (reheat treated) material and the steel after service should primarily reflect the result of thermally induced structural changes that occurred during service.

The pipe was thermally weakened by service exposure. Structural changes presumably resulted in the "‾‾__" type rupture curve observed for the reheat treated material. (Microstructural examination indicated that spheroidization of carbides and precipitation of intragrannular carbides occurred during high temperature exposure.) The downward break reflects a weakening reaction while the upward break is due to completion (or a slowing down) of the thermally induced change. Based on this, the structural changes should have been essentially completed during the 83,403-hour service exposure. The linear rupture curve at 1000°F for the material as-removed from service would substantiate this conclusion. As indicated by parameter tests, at very long times the rupture curve must increase in steepness (Fig. 2). This behavior prevents higher strengths occurring for the as-removed from service condition than for the unused steel (as characterized for the reheat treated material). In accordance with the results, at long time periods at 1000°F the rupture curves for these conditions must merge.

None of the simulated service exposures resulted in exact duplication of the microstructure or the stress-rupture characteristics of the material as-removed from service. However, exposure of 88 hours (based on C=20) came extremely close. Straight line extrapolation of the short time data predicted reasonably well the strength at 83,000 hours. This would suggest that for the material studied a constant C of approximately 20 can be used to simulate long times of service. It should also be noted that parameter extrapolation (using Larson-Miller with C=20) for the reheat treated steel gave essentially the same 83,000-hour strength as determined from the as-removed from service material.

Based on a C of 20, the exposures of 20 hours and 300 hours at 1200°F would simulate respectively 16,600 and 360,000 hours at 1000°F. Straight line extrapolation of the data indicated strength levels that were fairly close to those determined by the parameter tests for reheat treated material (Table III).

The steel was thermally weakened and therefore the rupture time for the unused (reheat treated) material must be closely related to (if not controlled by) the final microstructure resulting from the thermally induced structural changes that occur during testing. This results since the life is used up at the greatest rate at the end of the test when the steel is in the weakest structural condition. Assuming no further structural changes, testing of material after simulated service exposure could be expected to yield a linear rupture curve passing through the actual rupture strength at the time simulated. These concepts are consistent with the observed results as follows:

(1) Exposures of 88 and 300 hours at 1200°F (for C=20) simulated times at which thermally induced structural changes were expected to be complete. The rupture curves were essentially linear and extrapolations (to 83,000 and 360,000 hours, respectively) resulted in good strength predictions.

(2) The structurally weakening reactions were not completed by the 20-hour exposure at 1200°F. The rupture curve increased in steepness (due to continued thermal weakening) at long time periods as indicated by the parameter test. However, straight line extrapolation of the shorter time tests did predict reasonably well the prolonged time strength.

A striking feature was the similarity of the rupture strengths at the higher temperatures and times (i.e., high parameter values) for all of the heat treatments evaluated. Correspondingly, the microstructures introduced by heat treatment all tended towards an "equilibrium structure" during the high temperature test exposures. These results would suggest that although it is impossible to heat treat the steel to a range of strengths at low parameter values the influence of heat treatment decreases with increasing time and/or temperature.

Grade 22 (2.25Cr-1Mo) Steels

PIPE MATERIAL

The P22 pipe had not been in service. Consequently, unlike the P11 material, no data were available after prolonged service which would be used as a basis for accurately predicting long time strengths. Therefore, a parameter technique was used to determine the long-time strengths of the original material for comparison with the results of the experiments to simulated service.

Rupture Properties at 1000°F

The original program was designed to use simulation of 83,000 hours of service at 1000°F to check the long-time strength at 1000°F. The exposures were the same as those used for the P11 tests. The test results (Table V, Fig. 5) showed that the exposures of 20, 88 and 300 hours at 1200°F, with or without a stress of 7800 psi had a tendency to reduce the short time strengths. This lowered the steeper portion of the curve evident for the original material at short times. It should be noted that a decrease in steepness is not an uncommon characteristic of stress-rupture time curves (at 1000°F or 1050°F) for 2.25Cr-1Mo steel. Straight line extrapolation of the rupture curves for the exposed materials indicated 83,000-hour strengths similar to that obtained for the unexposed material using the Larson-Miller parameter with C of 20 (Table VII, Figs. 6,7).

The test results and the microstructures (Fig. 8) indicated that the P22 was so stable that the exposures were not significantly affecting the material. This was not unreasonable when checking disclosed that the as-produced pipe had probably been tempered at 1325°F for about 4 hours rather than having been annealed from 1675°F and tempered 2 hours at 1200°F. Tempering at 1325°F was probably so effective in introducing structural changes that the additional heating for short times at 1200°F could not be expected to introduce major modifications in structure. For these reasons exposures were also carried out to simulate service at 1100°F. This temperature was expected to be high enough to induce structural changes during testing that could influence the rupture strengths.

Rupture Strengths Above 1000°F for Original Material

It was apparent from the test data (Table IV, Fig. 6) that the stress rupture curves above 1100°F exhibited drastic increases in slope within the time periods of the tests. This indicated that the rupture curves at lower temperatures particularly at 1100° and 1050°F should not be extrapolated as straight lines. They were therefore extrapolated using the Larson-Miller parameter with a C of 20 (Figs. 6,7).

It should be noted that the difference in strength levels of stress-rupture time curves at 1050°, 1100° and 1150°F was relatively small until the slopes increased. It is not known why this occurred. Published stress-rupture time curves for 2.25Cr-1Mo steel do not normally show such small differences.

Simulation of 83,000 Hours of Service at 1100°F

The simulated service exposure of 115 hours at 1300°F resulted in lower rupture strengths at the shorter time periods than for the unexposed material (Table VI, Figs. 6,7). When extrapolated as a straight line the data at 1100°F indicated the exact same strength at 83,000 hours as determined for the unexposed material using parameter extrapolation.

Based on the Larson-Miller parameter (C=20) an exposure of 115 hours at 1300°F (P=38.9) should also simulate 517,000 hours of service at 1050°F. Straight line extrapolation of the data at 1050°F for the exposed material indicated an 517,000 strength of 7,600 psi. Again, this is the same strength as determined for the unexposed material by parameter extrapolation.

For the exposed material, parameter tests indicated lower long time strengths at 1100°F than determined by straight line extrapolation (Fig. 7, Table VII). At the highest parameter values the strengths were similar to those established for the unexposed material. These characteristics are similar to those previously discussed for P11 pipe.

GRADE 22 TUBES

Four unused tubes with a range of rupture strengths were studied. The objective was to compare strength predictions at 1100°F using exposures to simulate service against the 10,000-hour strengths from actual test data and 100,000-hour strengths determined by parameter extrapolation.

Rupture Strengths for Original Materials

For the as-heat treated materials tests were conducted at 1100°F to times longer than 6000 hours (Table VIII, Fig. 9). This permitted accurate determination of the 10,000-hour strengths (Table XI). The strengths at 100,000 hours were obtained by application of the Larson-Miller parameter (C=20) to 1230° and 1300°F test data.

The materials exhibited a wide range of strengths at short times at 1100°F. The rupture curves for the higher strength materials exhibited marked increases in steepness at about 500 hours. The net result was that the strengths became more similar with time. By 10,000 or 100,000 hours at 1100°F the strengths were almost independent of heat treatment (Table XI).

Simulation of 10,000 Hours at 1100°F

The materials exposed 100 hours at 1242°F to simulate 10,000 hours at 1100°F, had lower short time rupture strengths at 1100°F than the unexposed materials (Table IX, Fig. 9). The decrease in strength due to exposure was greater the higher the short time strength of the original material. When the curves for the exposed materials were extrapolated as straight lines, in all cases the 10,000-hour strengths indicated were essentially the same as determined by actual tests on the unexposed material (Table XI).

Simulation of 100,000 Hours at 1100°F

An exposure of 100 hours at 1313°F was used to simulate 100,000 hours at 1100°F. Straight line extrapolation of the rupture data (Table X) indicated 100,000-hour strengths similar to those determined for the unexposed material by parameter extrapolation (Fig. 9, Table XI).

Microstructures of Grade 22 Tubes

Thermal exposure resulted in carbide spheroidization and the precipitation of intragrannular carbide (Figs. 10 through 13). These reactions were accompanied by a reduction in rupture strength. The results showed the following:

(1) Thermal exposure had the greatest influence on the materials (tubes A and B) which exhibited the highest short time strengths (Figs. 10,11). The marked microstructural changes were accompanied by considerable losses in short time rupture strength (Figs. 9a,b). Also, the rupture curves at 1000°F for these thermally unstable materials exhibited increases in steepness.

(2) For the lower strength materials (tubes C and D) little microstructural change occurred due to the simulated service exposures (Figs. 12,13). Correspondingly the rupture curves did not exhibit marked instabilities and the exposure had little influence on rupture strength (Figs. 9c,d).

(3) With increasing exposure (simulated service or test) the microstructures and rupture strengths became similar (Figs. 10 through 13). As discussed for the P11 material, the results indicate that heat treatment variation can be used to produce widely different strengths at low but not at high parameter values. The extent or generality of this observation requires further checking.

Discussion of Results for P22 Pipe and Grade 22 Tubes

Because of the similarity of the results to those for the P11 material the following comments are considerably abbreviated. Simulated service exposures were used to correctly predict the 10,000-hour strengths of four Grade 22 tubes as determined by actual long time tests. This would tend to suggest that the 100,000-hour strengths determined by simulated service exposures were also close to the actual values. These agreed with those established by parameter tests for the unexposed materials, and therefore, increases confidence in the use of this extrapolation technique.

The tensile strengths after exposures to simulate 10,000 and 100,000 hours were similar (Tables IX, X). This could indicate that although the exposures correctly simulated the factors controlling strength at long times other factors influenced the short time strengths.

The usual extrapolation practice for 2.25Cr-1Mo steel up to 1100°F has been to use straight line log-log curves. Application of the family of curves concept, simulated service exposures and parameter methods, indicate that the rupture curves at 1100°F and probably somewhat lower temperatures can exhibit an increase in steepness. Such a slope change could results in lower 100,000-hour rupture strengths at 1100° and 1050° than determined by straight line extrapolation.

Type 304 (18Cr-8Ni) Stainless Steel

Simulated exposures and parametric characteristics were used to establish long-time strengths which could be compared with those established by actual tests in the AR-2 program. In addition, thermal mechanical treatments were evaluated which were designed to accelerate the microstructural changes occurring during prolonged time test exposures.

COMPARISON OF RUPTURE DATA WITH AR-2 TESTS

Rupture strengths at 1200°F for the stock supplied (Table XII, Fig 14a) were similar to those reported for the AR-2 material (ref. 3). Higher temperature "parameter" tests also demonstrated that the strengths of the two materials were the same.

PARAMETER EXTRAPOLATIONS

The steepness of the rupture curves at 1100° and 1200°F for the AR-2 material increase markedly at about 1000 hours (Fig. 14a). Similar changes in slope are not evident at shorter times at higher temperatures. Thus the data are apparently not consistent with the parameter concept of trade off of time and temperature. This was reflected in the 100,000-hour strengths determined by Larson-Miller extrapolation of the AR-2 "short time parameter tests". Using an optimized constant C of 17.9 or the standard value of 20 considerably higher strengths were obtained than determined by the long time tests (Table XIII). This is clearly evident from Figure 15 where the 1100° and 1200°F test data are presented along with the parameter data.

Extrapolation of the short time data using the Manson-Haferd parameter reportedly resulted in 100,000-hour strengths close to those determined by testing (ref. 3). There is considerable question however, as to whether this is a valid prediction or simply an accident of the downward curvature enforced by the mathematics of the parameter.

SIMULATION OF 100,000 HOURS OF SERVICE AT 1200°F

The simulated service exposure (100 hours at 1425°F) resulted in a slight increase in the short time rupture strength at 1200°F. Extrapolation of the data for the exposed material as a straight line indicated an 100,000-hour strength of 10,200 psi. This strength agrees with that established by Larson-Miller extrapolation for the unexposed material but is higher than indicated by the prolonged time tests (Table XIII).

INFLUENCE OF STRESSED EXPOSURE

Material was exposed under stress in an attempt to introduce a dislocation substructure representative of that which would occur in a test at 1200°F at the approximate 100,000-hour strength. The test exposure conditions (100 hours at 1325°F under 8500 psi) were selected so that second stage creep would be attained and the rupture life utilized would be minimal. The rupture characteristics after stressed exposure were similar to those established for the material exposed without stress for 100 hours at 1425°F (Table XII, Fig. 14b).

The results also showed that the ductility (Table XII) after exposure, with or without stress, is appreciably higher than for the unexposed material. The significance of this is not known.

MICROSTRUCTURAL STUDIES

The results of a study of the microstructures of AR-2 test specimens were reported recently (ref. 5). Sigma and carbide particles were shown to have precipitated during the long time test exposures. It is possible that the increase in steepness of the stress-rupture time curves is associated with the occurrence of one or both of these reactions. Equivalent precipitation did not occur during the parameter tests or simulated service exposures (Fig. 16). Consequently, thermal mechanical treatments were designed to accelerate the precipitation reactions. These could form the basis of a visual test of whether or not a break down in long time rupture strength might be expected. Such a test would not however, provide an estimate of the long time strengths.

The treatments investigated were:

(1) Cold reduction 40% plus 100 hours at 1350°F.

(2) Cold reduction 40% plus 100 hours at 1450°F.

(3) Cold reduction 40% plus 20 minutes at 1625°F plus 100 hours at 1350°F.

(4) Cold reduction 40% plus 20 minutes at 1625°F plus 100 hours at 1450°F.

All of the treatments promoted carbide and sigma precipitation (Fig. 16). The inclusion of the treatment at 1625°F tended to reduce the amount of precipitate formed. A study using transmission electron microscopy showed that the structures (Fig. 17) were very similar to those reported for the long time test specimens. Sigma particles were evident in the grain boundaries while $M_{23}C_6$ carbide was present as a finely dispersed intragranular precipitate.

DISCUSSION OF RESULTS FOR TYPE 304 STEEL

The appearance of sigma phase is almost always accompanied by a loss in creep resistance. There is therefore, a possibility that it was responsible for the increase in steepness of the rupture curves. If so then this would explain why the use of parameters, simulated service exposures or any method that trades an increase in temperature for rupture time can indicate erroneous extrapolated strengths. Sigma phase has a "C" type TTT curve so that it does not form above about 1550°F. Presumably 1100° and 1200°F are near the temperature of maximum sigma. Therefore, precipitation at these temperatures cannot be simulated by shorter time higher temperature exposures.

If carbide formation was the controlling factor, then the response was different to that for the CrMo steels. For the latter materials, there was a parameter relation. The yield strengths at 1100°F and 1200°F do not appear to have been determined. It is, however, entirely possible that the increase in slope of the stress-rupture time curves is related to decreasing amounts of yielding when the stress was applied.

Further research is necessary to clarify the above questions. It is considered important to develop the capability of correctly predicting the long time rupture characteristics of Type 304 steels. This could lead to the development of a practical short time test that reliably predicts 100,000-hour strengths of materials for which "C" type reactions influence the properties. At the present time no such method is available.

General Discussion

For all of the steels studied there was close agreement between the strengths determined by parameter testing of unexposed materials with those established by the simulated service technique. This was not entirely unexpected. Both methods are highly dependent on the acceleration of thermally induced metallurgical processes by trading time for temperature. The basic relationship used in both cases was the Larson-Miller parameter.

The oxidation effects differed. Extrapolations of rupture data for Grade 11 and Grade 22 steels using parameter methods have been questioned due to the extensive surface oxidation that occurs during the high temperature exposures. On the other hand, predictions based on simulated service exposures are not suspect on this basis. Specimens were machined after high temperature exposure and tested at the relatively low service temperature. The similarity of the strengths determined by the two techniques is therefore evidence that parameter methods can correctly predict long time strengths even under circumstances where extensive oxidation occurs.

It is probable that the accuracy of the strength predictions for the unexposed materials could have been improved by utilization of methods other than the Larson-Miller parameter with C of 20. This, however, was beyond the scope of the investigation.

A verification test should be as simple as possible. For parameter extrapolation the number of tests required can be limited by using fixed constants. Hence methods such as the Larson-Miller parameter with C of 20 or the Manson Compromise method are most attractive. It is of interest to compare the minimum test points required for these methods and simulated service exposures to determine any long time strength.

(1) The material could be exposed to simulate 100,000 hours of service, and subsequently rupture tested. A minimum of two short time rupture tests would be required to permit straight line extrapolation to the 100,000-hour strength. The testing could be reduced if it were possible by a single test to characterize the rupture behavior of the exposed material (i.e., the structure developed). Such a test was not defined by the present study.

(2) Parameter testing to determine an 100,000 hour strength requires at least two "high temperature" tests.

Thus the results do not show that the use of simulated service exposures at the present stage of development have an advantage over parameters as the basis of a verification test.

SUMMARY AND CONCLUSIONS

A study was made of the use of simulated service exposures as the basis of a verification test. The technique was utilized to predict the long time strengths for Grade 11, Grade 22 and Type 304 steels. The strengths were also determined by parameter extrapolation. Consideration of the results led to the following:

(1) Simulated service exposures reduced the uncertainties in the extrapolation of log stress-log rupture time curves for Grade 11 and Grade 22 steels. The rupture curves for the exposed materials did not exhibit the instabilities evident for unused steel. The evidence indicated that straight line extrapolation of short time rupture data for exposed materials gave good predictions of the long time strengths.

The strengths determined by simulated service exposures were similar to those established by parameter testing of unexposed material. Assuming these were reasonably accurate determinations of the 100,000-hour strengths then values obtained by straight line extrapolation were in many cases in error by significant amounts.

For both steels the results indicated that heat treatment variations resulted in a wide range of rupture strengths at low parameter values. At longer times and/or higher temperatures (high parameter values) differences in heat treatment had little influence on strength.

(2) Accurate strength predictions at 1200°F were not obtained for the Type 304 (AR-2) steel by use of the simulated service technique (or parameter testing). This was probably due to the occurrence of a "C" type metallurgical reaction. It is recommended that additional research be conducted, directed at the development of methods for predicting long time strengths under these circumstances.

(3) Simulated service exposures were not shown to offer a better basis for a verification test than parameter methods.

ACKNOWLEDGMENTS

Acknowledgment is expressed to The Detroit Edison Company and The Metal Properties Council for sponsoring the research. Special thanks and appreciation are expressed to the late Professor James W. Freeman under whose guidance the research was conducted. The encouragement of I. M. Rohrig and J. J. Bodzin of The Detroit Edison Company, the M. P. C. Subcommittee I—Task Force on Acceptance Testing, C. E. Spaeder Chairman, has been greatly appreciated.

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1. Cullen, T. M., Rohrig, I. A., and Freeman, J. W., "Creep-Rupture Properties of 1.25Cr-0.5Mo Steel After Service at 1000°F," Journal of Basic Engineering, 88, 669 (1966).

2. "Time-Temperature Parameters for Creep-Rupture Analysis," ASM Publication No. D8-100 (1968).

3. Williams, W. Lee, "Parameter and Long Life Creep-Rupture Tests of Type 304 Steel," Time-Temperature Parameters for Creep-Rupture Analysis, ASM Publication No. D8-100, (1968).

4. Larson, F. R. and Miller, J., "A Time Temperature Relationship for Rupture and Creep Stress," Transactions of The American Society of Mechanical Engineers, 74, 765 (1952).

5. Biss, V., "Metallographic Examination of Type 304 Stainless Steel Creep-Rupture Specimens," RP-32-1969-7, Climax Molybdenum Company of Michigan, March 27, 1970 (unpublished).

TABLE I

Rupture Test Data for P11 (1.25Cr-0.5Mo-0.75Si) Material As Removed from Service after 83,000 Hours at 1000°F

Specimen Code	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
Longitudinal Orientation					
A - 1	1000	38,300	STTT	41	77
A - 4	1000	24,000	72	51	68
A - 2	1000	22,000	183	44	78
A - 13	1000	22,000	106	37	76
A - 6	1000	18,000	1566	27	59
A - 5	1100	18,000	44	53	74
A - 3	1100	16,000	194	48	76
A - 7	1100	15,000	425	44	67
A - 10	1100	14,000	1019	31	48
A - 11	1200	12,500	63	37	71
A - 12	1200	11,000	184	39	63
A - 16	1200	8,000	1505	14	36
Transverse Orientation					
B - 2	1000	24,000	39	51	73
B - 1	1000	22,000	179	43	67
B - 3	1000	20,000	434	46	56

STTT - Short Time Tensile Test

TABLE II

Rupture Test Data for Simulated 83,000 Hours of Service at 1000°F on P11 (1.25Cr-0.5Mo-0.75Si) Steel Pipe

Specimen Code*	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
Base Material - Re-Normalized 1675°F + 2 Hours at 1200°F					
1L13	1000	54,300	STTT	32	77
1L14	1000	40,000	174	35	74
1L16	1000	39,000	313	25	71
1L15	1000	34,000	900	37	75
1T7	1000	37,000	833	20	60
1T8	1000	31,000	1057	25	61
1L34	1050	25,000	252	23	72
1L29	1100	25,000	41	44	81
1L	1100	16,000	658	45	61
1L30	1150	20,000	24	61	58
1T16	1150	17,500	33	40	79
1L33	1200	13,000	72	34	74
1L31	1200	11,000	269	32	53
1T15	1200	15,800	21	21	66
1L	1200	8,000	1056	20	38
Re - Normalized 1675°F + 20 Hours at 1200°F (C=25)					
1L1	1000	49,200	STTT	36	81
1L2	1000	40,000	8.5	46	77
1L	1000	35,000	30	47	80
1L3	1000	28,000	438	33	81
1L4	1000	26,500	567	49	80
1T1	1000	34,000	27	37	74
1T2	1000	24,000	694	51	75

* Code L - Longitudinal Specimen
T - Transverse Specimen
STTT - Short Time Tensil Test

TABLE II (Cont.)

Specimen Code	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
1L35	1200	12,500	109	50	72
Re-Normalized 1675°F + 88 Hours at 1200°F (C=20)					
1L5	1000	46,750	STTT	39	81
1L6	1000	35,000	12	45	79
1L	1000	30,000	33	52	84
1L8	1000	25,000	116	23	79
1L7	1000	22,000	382	39	84
1L	1000	20,000	826	51	82
1T3	1000	30,000	50	49	74
1T4	1000	20,000	1003	45	78
1L35	1200	12,500	75	60	79
Re-Normalized 1675°F + 300 Hours at 1200°F (C=15)					
1L9	1000	45,000	STTT	39	81
1L10	1000	35,000	12	37	80
1L11	1000	24,000	160	49	83
1L12	1000	18,000	1224	62	67
1T5	1000	30,000	24	47	73
1T6	1000	20,000	677	61	79
1L32	1200	12,500	35	67	84
Re-Normalized 1675°F + Tempered at 1325°F for 1 Hour + 88 Hours at 1200°F					
1L40	1000	25,000	153	61	83
1L47	1000	21,000	761	47	85
1L48	1200	12,500	102	50	80
Annealed 1675°F, 1 Hour, F.C. at 125°F per Hour to 1300°F and F.C. to Room Temperature in 16 Hours					
D-11	1200	12,500	91	53	78

TABLE II (Cont.)

Specimen Code	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
Re-Normalized 1675°F + 20 Hours at 1200°F, under 7,800 psi					
1L17	1000	52,250	STTT	37	82
1L19	1000	40,000	5.9	36	76
1L20	1000	30,000	131	44	65
1T9	1000	35,000	15	41	72
1T10	1000	25,000	507	51	77
Re-Normalized 1625°F + 88 Hours at 1200°F, under 7,800 psi					
1L21	1000	45,000	STTT	39	82
1L22	1000	32,000	10	45	81
1L23	1000	23,000	378	62	82
1L24	1000	20,000	980	48	79
1T11	1000	26,000	99.6	54	78
1T12	1000	21,000	565	61	80
Re-Normalized 1675°F + 300 Hours at 1200°F, under 7,800 psi					
1L25	1000	39,125	STTT	39	82
1L	1000	30,000	13	36	79
1L26	1000	24,000	110	36	79
1L27	1000	20,000	455	39	78
1L28	1000	17,500	1288	52	72
1T13	1000	22,000	289	57	77
1T14	1000	19,000	630	64	77

TABLE III

Long-Time Strengths at 1000°F for P11 Pipe

Condition	Extrapolation* Method	Rupture Strength (psi)
83,000-Hour Strengths		
As Removed from Service	SL	13,200
	LM-20	12,800
"Original"—Re-normalized + 2 hrs at 1200°F	SL	—
	LM-20	13,300
Simulated Service Exposures		
Re-normalized + 20 hrs at 1200°F	SL	15,300
	LM-20	13,000
Re-normalized + 80 hrs at 1200°F	SL	11,900
	LM-20	12,200
Re-normalized + 300 hrs at 1200°F	SL	10,900
	LM-20	10,900
16,600-Hour Strengths		
"Original"—Re-normalized + 2 hrs at 1200°F	LM-20	17,000
Simulated Service Exposure		
Re-normalized + 20 hrs at 1200°F	SL	19,200
360,000-Hour Strength		
"Original"—Re-normalized + 2 hrs at 1200°F	LM-20	10,600
Simulated Service Exposure		
Re-normalized + 300 hrs at 1200°F	SL	9,600

*SL—Straight line rupture curve.
LM-20 Larson-Miller parameter with C of 20.

TABLE IV

Rupture Test Data for the Original P22 (2.25Cr-1Mo) Steel Pipe (As Produced + 2 Hours at 1200°F)

Specimen Code	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
2L16	1000	50,000	STTT	28	79
2T1	1000	35,000	31	42	80
2L17	1000	31,000	72	69	85
2L18	1000	27,000	239	50	86
2L21	1050	25,000	49	40	87
2L19	1050	19,000	1210	41	86
2L46	1050	18,500	2190	51	86
2L47	1100	19,000	233	47	88
2L29	1100	18,000	360	42	85
2T23	1100	17,000	1752	25	81
2T3	1100	15,000	3465	27	77
2T4	1150	19,000	53	40	88
2T24	1150	17,000	308	41	87
2L25**	1150	13,000	1035	43	86
2T2	1200	13,000	225	43	87
2L26**	1200	10,000	754	34	88
2L27**	1250	10,000	141	43	74
2L28**	1300	10,000	55	58	94
2T8 **	1300	8,000	119	77	95
2L20	1300	7,000	168	33	93
2L33	1300	4,000	1096	35	91

Code L - Longitudinal Specimen
T - Transverse Specimen

STTT - Short Time Tensile Test
** - Exposed for 20 hours at 1200°F - used on the basis that this would not influence the properties

TABLE V

Simulated 83,000 Hours of Service at 1000°F on P22 (2.25Cr-1Mo) Steel Pipe

Specimen Code*	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
			Exposed 20 Hours at 1200°F (C = 25)		
2L22	1000	50,500	STTT	29	79
2T5	1000	35,000	26	48	81
2L23	1000	31,000	66	46	83
2L24	1000	25,000	520	43	85
2T6	1000	23,000	1801	44	86
2T7	1000	22,000			
			Exposed 88 Hours at 1200°F (C = 20)		
2L30	1000	50,500	STTT	32	79
2T11	1000	49,600	STTT	27	68
2L31	1000	31,000	34	50	83
2L32	1000	27,000	166	77	84
2T12	1000	22,000	1767	30	81
			Exposed 300 Hours at 1200°F (C = 15)		
2L38	1000	47,000	STTT	37	82
2T17	1000	31,000	109	38	82
2L39	1000	28,000	105	46	84
			Exposed 300 Hours at 1200°F, under 7,800 psi		
2L42	1000	44,700	STTT	27	78
2T20	1000	35,000	7.4	22	75
2T22	1000	27,000	124	29	82

*Code L - Longitudinal Specimen
T - Transverse Specimen
STTT - Short Time Tensile Test

TABLE VI

Simulated 83,000 Hours of Service at 1100°F on P22 (2.25Cr-1Mo) Steel Pipe

Specimen Code*	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
		Exposed 115 Hours at 1300°F (C=20)			
2L13	1050	20,000	182	63	87
2L14	1050	17,500	597	62	85
2L10	1100	16,000	155	64	89
2L9	1100	14,000	451	44	89
2L11	1100	12,500	1297	53	90
2L15	1250	9,000	108	100	91
2L12	1300	8,000	38	86	95
2T19	1300	7,000	140	47	96
2L40	1300	4,000	1272	31	93

*Code L - Longitudinal Specimen
T - Transverse Specimen

TABLE VII

Long-Time Strengths for Grade 22 Pipe

Condition	Extrapolation* Method	Rupture Strength (psi)
83,000-Hour Strength at 1000°F		
"Original"—As Produced + 2 hours at 1200°F	SL	13,000
	LM-20	16,000
Simulated Service Exposures		
As Produced + 20 hrs at 1200°F	SL	15,800
As Produced + 88 hrs at 1200°F	SL	15,900
As Produced + 300 hrs at 1200°F	SL	15,000
83,000-Hour Strength at 1100°F		
"Original"—As Produced + 2 hrs at 1200°F	SL	14,200
	LM-20	7,600
Simulated Service Exposure		
As Produced + 115 hrs at 1300°F	SL	7,600
	LM-20	6,700

*SL—Straight line rupture curve
LM-20 Larson-Miller parameter with C of 20

TABLE VIII

Rupture Test Data for the Original Grade 22 Steel Tubes

Tube	Temp.	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
Heat Treated 1 hour at 1450°F, Air Cooled					
A	1100	16,500	864	43	63
		14,500	1575	43	67
		13,500	3225	36	56
		12,000	7014	28	51
	1230	10,181	155		85
		10,000	174	32	88
		6,000	1672	23	79
	1300	6,000	216	28	90
Modified Iso-Thermal Treatment					
B	1100	21,000	150	50	75
		19,000	613	38	54
		19,000	464	31	56
		16,000	1279	30	36
		12,500	2382		
		10,000	8475	12	52
B	1230	12,500	43		86
		9,000	291	54	87
		5,000	2335	20	57
	1300	9,000	16		89
		6,000	210		72
		4,000	651	25	69
C	1100	20,000	55	45	75
		17,500	139	43	69
		15,000	496	37	57
		12,500	1942		42
		10,000	10,327		36
	1230	10,000	141	53	72
		8,000	500	33	60
		5,000	3788	14	52

TABLE VIII (Concluded)

Rupture Test Data for the Original Grade 22 Steel Tubes

Tube	Temp.	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
Modified Iso-Thermal Treatment					
C	1300	8,000	19		73
		6,000	334	35	67
		6,000	256	66	81
		4,000	777		51
D	1100	20,000	12	47	70
		15,000	106	34	51
		12,500	466	47	48
		12,000	861	34	42
		10,500	1578	22	43
		9,000	5871	20	36
	1230	8,500	145	32	61
		6,000	1551		34
	1300	7,000	93	52	78
		4,475	837		49

TABLE IX

Tensile and Rupture Data at 1100°F for Grade 22 Steel Tubes
Exposed to Simulate 10,000 Hours at 1100°F

Tube	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
Heat Treated 1 hour at 1450°F, Air Cooled				
A	29,500	STTT	53	86
	17,500	40	51	86
	15,000	189	61	86
	12,000	1572	39	83
Modified Iso-Thermal Treatment				
B	30,600	STTT	56	91
	17,500	20	59	87
	17,500	68	47	89
	15,000	247	37	89
	12,000	1915	43	76
C	29,700	STTT	56	89
	17,500	51	35	76
	15,000	246	55	65
	12,000	1910	36	54
D	28,000	STTT	54	83
	15,000	29	50	70
	13,500	209	51	66
	13,500	274	38	59
	12,000	450	53	67
	10,000	1927	30	49

STTT—Short Time Tensile Test

TABLE X

Tensile and Rupture Data at 1100°F for Grade 22 Steel Tubes Exposed to Simulate 100,000 Hours at 1100°F

Tube	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
Heat Treated 1 hour at 1450°F, Air Cooled				
A	30,100	STTT	53	88
	17,500	53	60	87
	15,000	156	51	87
	12,000	741	41	87
Modified Iso-Thermal Treatment				
B	32,400	STTT	52	90
	17,500	41	54	89
	15,000	156	65	88
	12,000	574	74	92
	10,000	2165	48	86
C	31,300	STTT	52	87
	17,500	32	57	81
	15,000	163	62	79
	12,000	568	33	74
	10,000	3184		
D	28,900	STTT	57	86
	15,000	9	65	64
	13,500	189	59	65
	12,000	512	52	63
	10,000	1450	35	53

STTT—Short Time Tensile Test

TABLE XI

Long-Time Strengths at 1100°F for Grade 22 Tubes

Tube	Condition	Extrapolation* Method	Rupture Strength (psi) 10,000 Hour	Rupture Strength (psi) 100,000 Hour
A	Original	SL	11,100	7,800
		LM-20	10,900	6,500
	Simulated Exposures	SL	10,100	6,100
B	Original	SL	9,700	5,900
		LM-20	9,700	5,900
	Simulated Exposures	SL	9,800	5,800
C	Original	SL	10,000	7,500
		LM-20	10,000	7,000
	Simulated Exposures	SL	10,000	6,700
D	Original	SL	8,400	6,300
		LM-20	8,400	6,300
	Simulated Exposures	SL	8,200	6,200

*SL Straight line rupture curve
LM-20 Larson-Miller parameters with C of 20

TABLE XII

Rupture Test Data for Type 304 Stainless Steel in the Original Condition and After Simulated Service Exposure

Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	R.A. (%)
Annealed 1950 - 1975°F, 1 hour W.Q.				
1200	24,000	92	29	29
1200	18,500	790	25	22
1300	16,500	98	37	35
1300	13,500	516	33	27
1335	13,500	160	39	31
1350	28,225	0.2	55	47
1425	7,500	1173	21	24
1450	8,000	311	-	30
1500	7,500	141	43	40
Annealed + 100 hours at 1425°F				
1200	30,000	15	-	39
1200	24,000	149	49	48
1200	21,000	415	57	55
1200	18,500	1295	75	56
1200	18,000	1030	64	63
1300	16,500	115	92	57
1300	13,500	421	79	61
1350	13,500	117	-	-
1350	13,500	123	76	62
1425	7,500	838	44	36
Annealed + 100 hours at 1325°F, under 8500 psi				
1100	40,000	20	-	48
1200	30,000	14	-	55
1200	24,000	155	59	47
1200	21,000	374	57	52
1200	18,000	1033	56	49
1350	13,500	148	53	41

TABLE XIII

Long-Time Strengths for Type 304 Austentic Steel

Temperature (°F)	Extrapolation Method	100,000 Hour Strength (psi)
	As Produced Material	
1100	Straight Line - Tests to 1,000 hrs.	19,000
1100	Straight Line - Tests to 50,000 hrs.	13,500
1100	Larson-Miller Parameter (C=20)	16,200
1100	Larson-Miller Optimized Parameter (C=17.95)	14,900
1200	Straight Line - Tests to 1,000 hrs.	10,200
1200	Straight Line - Tests to 50,000 hrs.	8,000
1200	Larson-Miller Parameter (C=20)	11,000
1200	Larson-Miller Optimized Parameter (C=17.95)	9,800
	Simulated Service at 1200°F by Heating 100 hours at 1425°F	
1200	Straight Line Log - Log	10,200
1200	Parameter	10,200

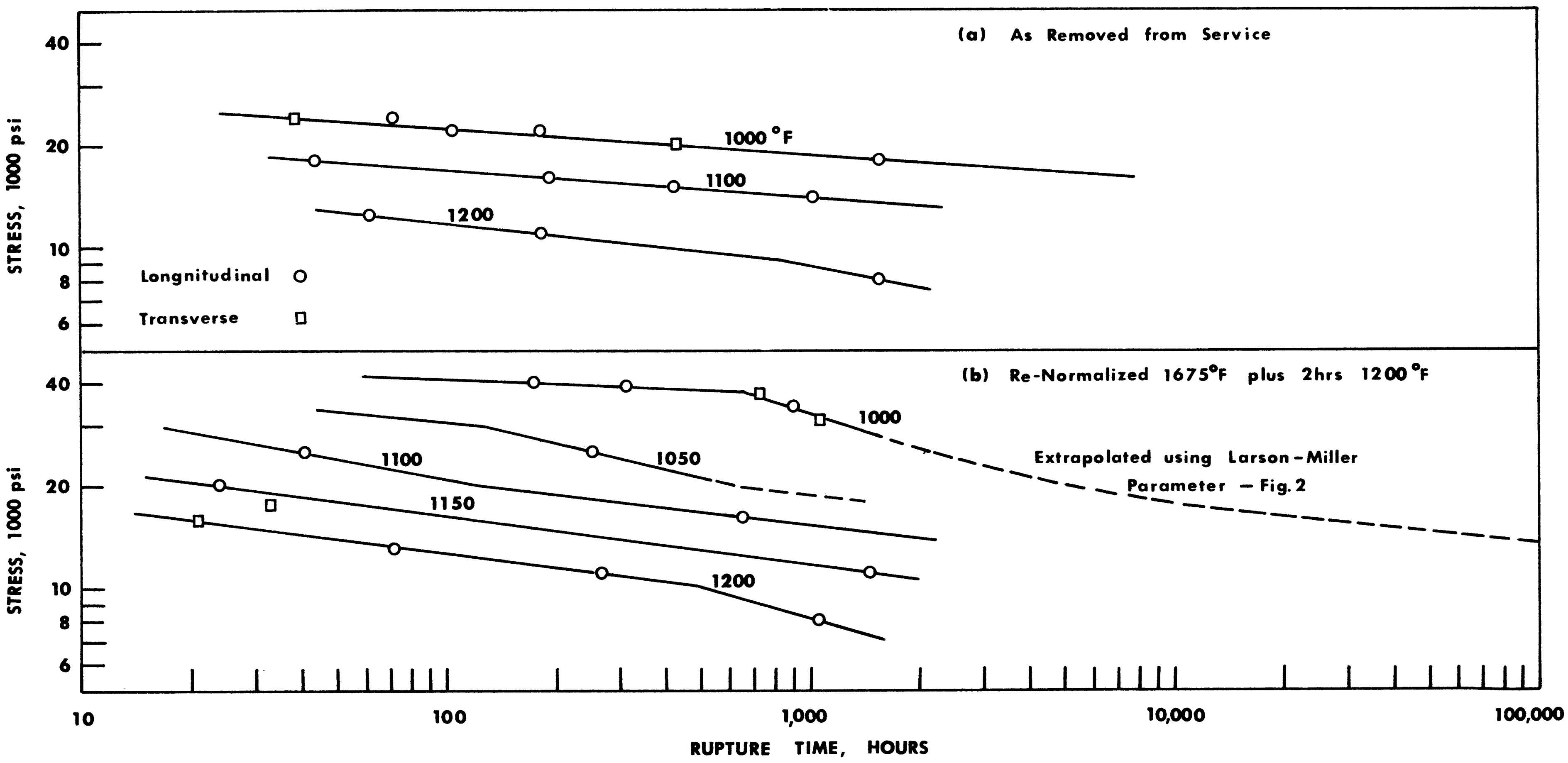


Figure 1. Stress versus Rupture Time Data for P11 Pipe As-Removed from Service and after Reheat Treatment.

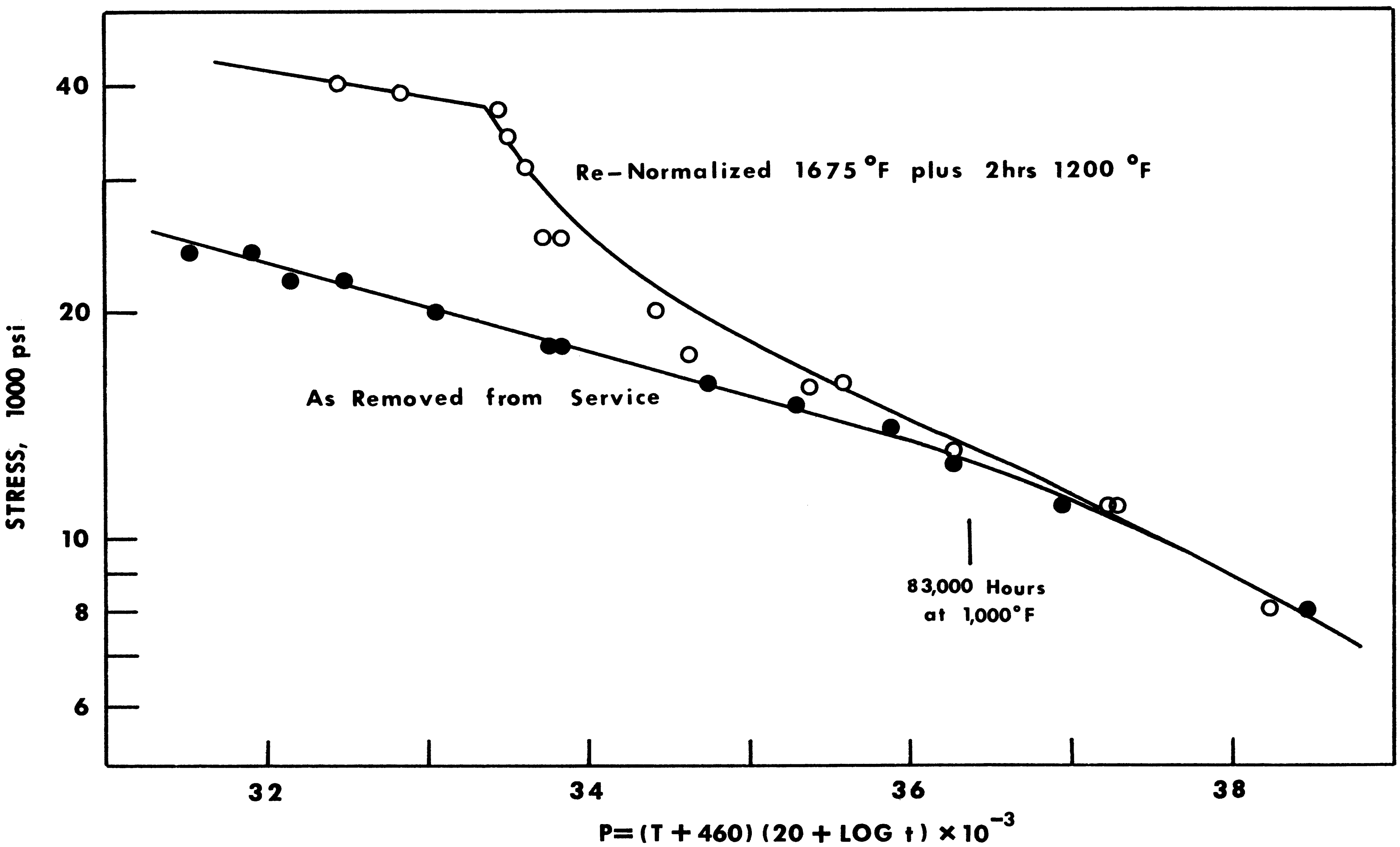


Figure 2. Stress versus Larson-Miller Parameter Curves for P11 Pipe As Removed from Service and after Reheat Treatment.

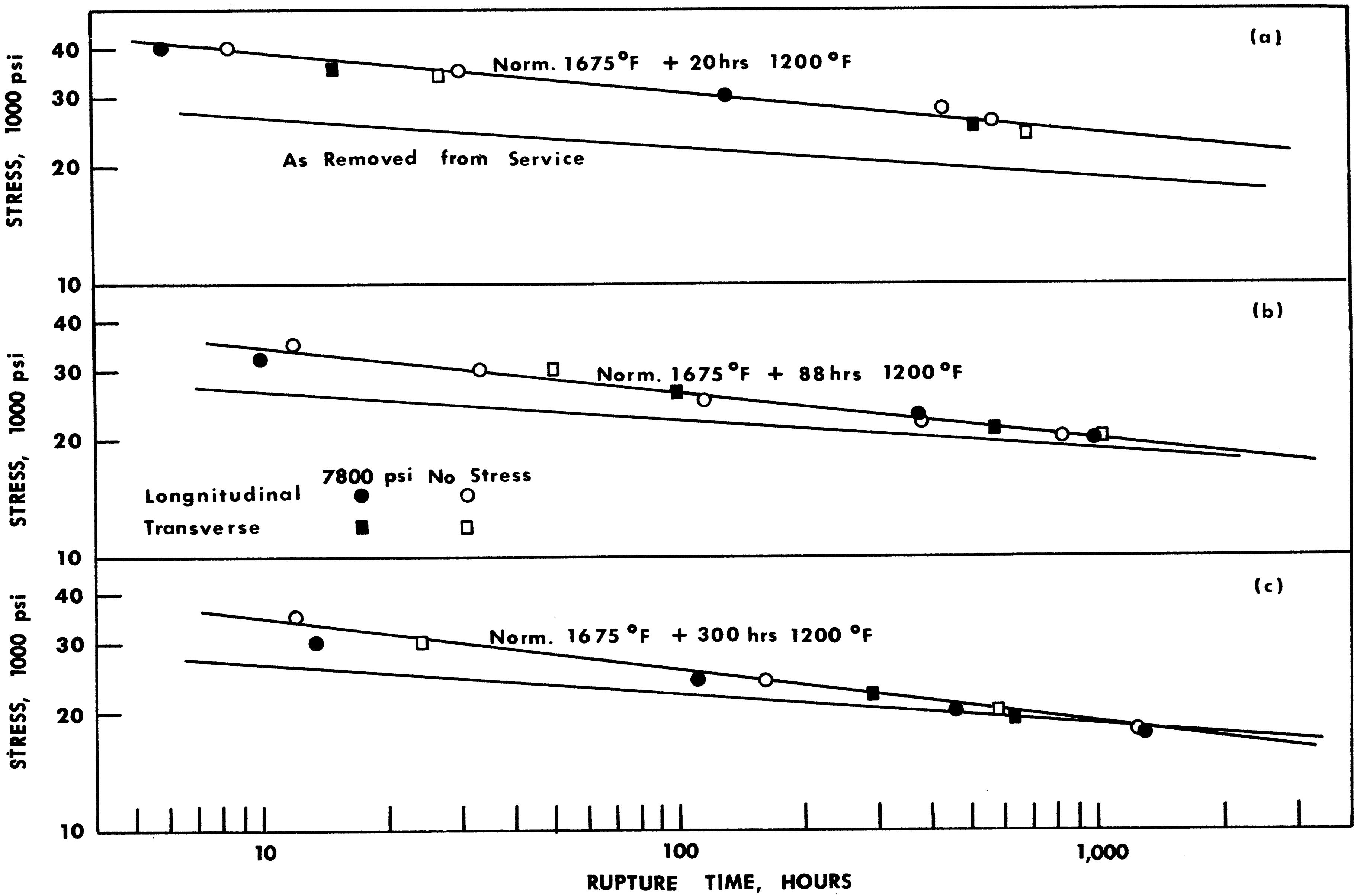
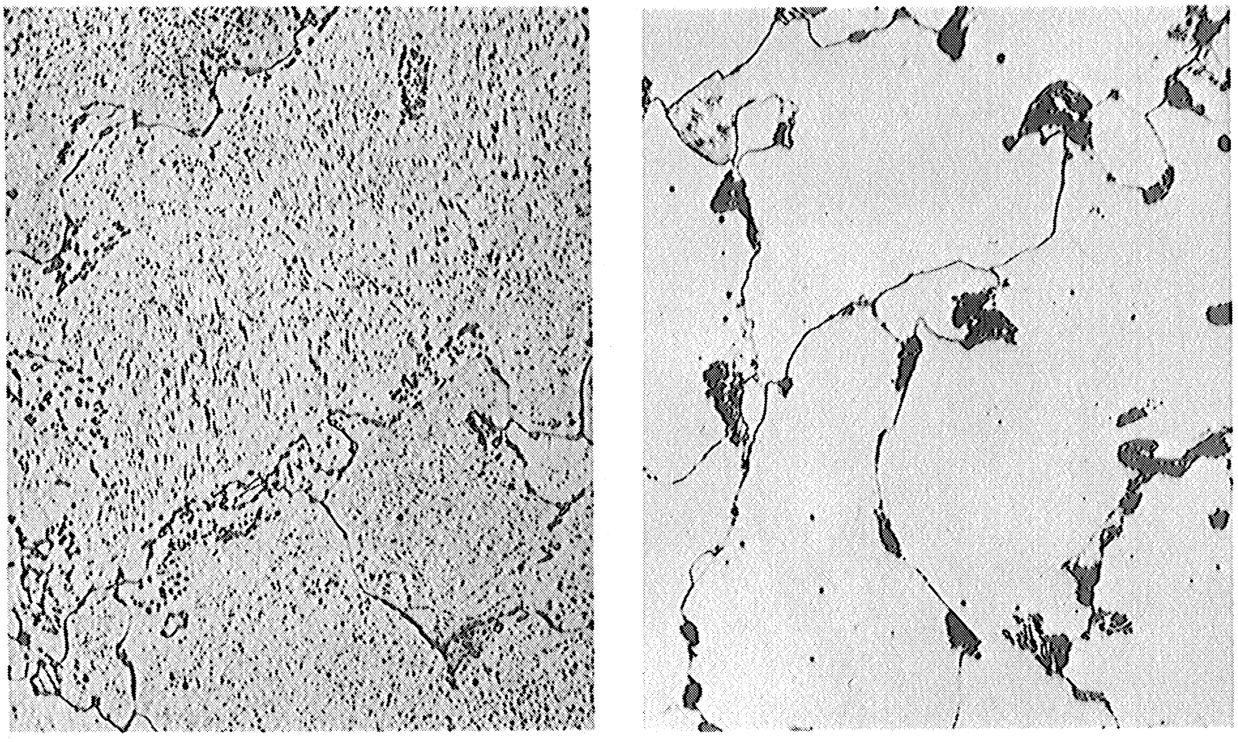
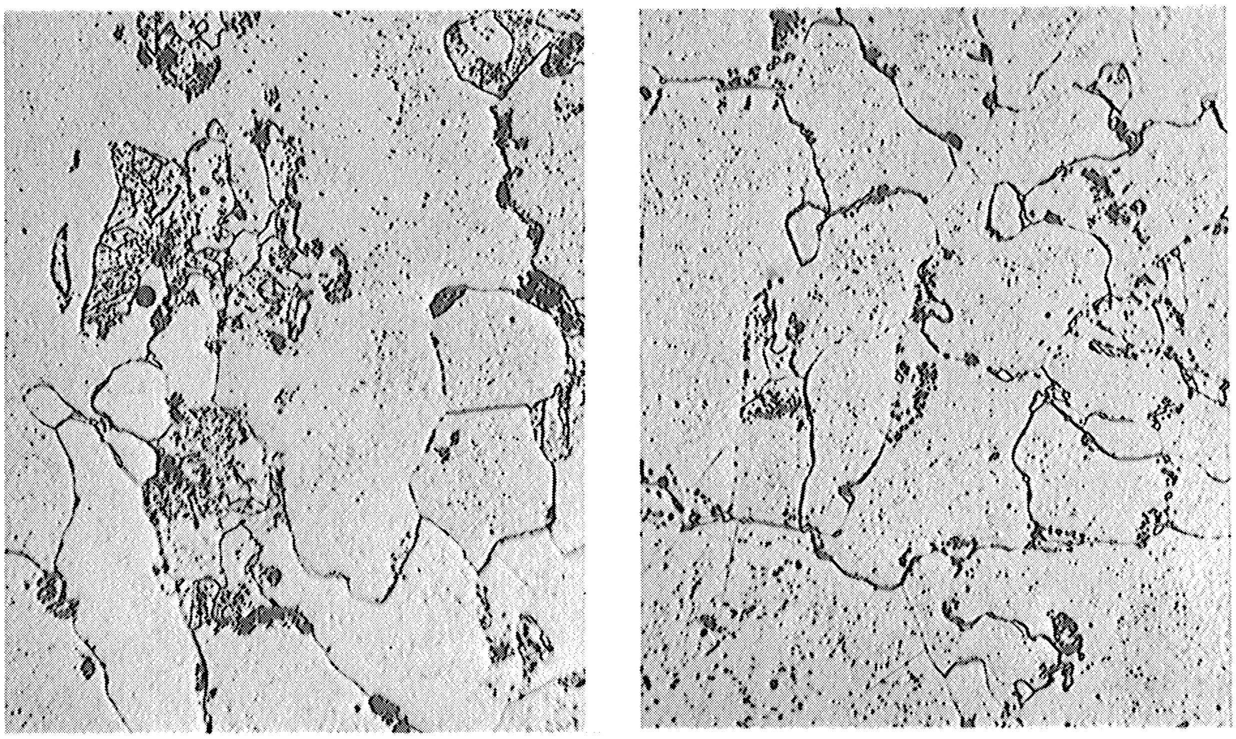


Figure 3. Stress-Rupture Time Curves at 1000°F for P11 Pipe As-Removed from Service and after Reheat Treatment and Exposure to Simulate Service at 1000°F.



(a) As-Removed from Service (b) Re-Norm. 1675°F + 20 Hrs. 1200°F



(c) Re-Norm. 1675°F + 88 Hrs. 1200°F (d) Re-Norm. 1675°F + 300 Hrs. 1200°F

Figure 4: Microstructures of P11 Pipe X1,000.

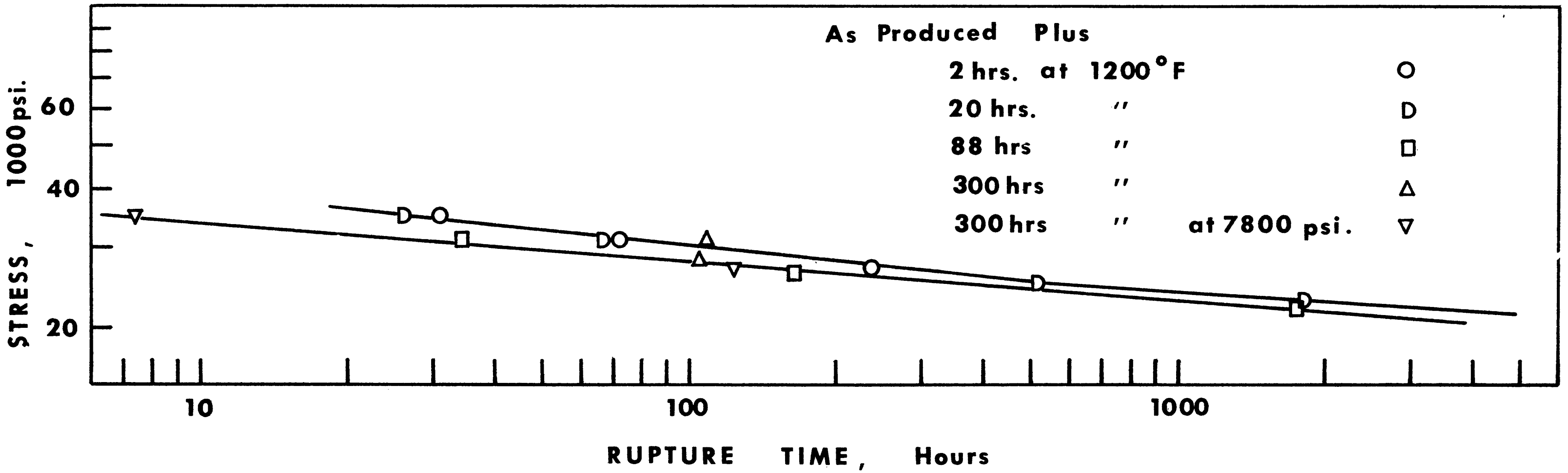


Figure 5: Stress-Rupture Time Curves at 1000°F for P22 Pipe in the Original Heat Treated Condition and after Exposure to Simulate Service at 1000°F.

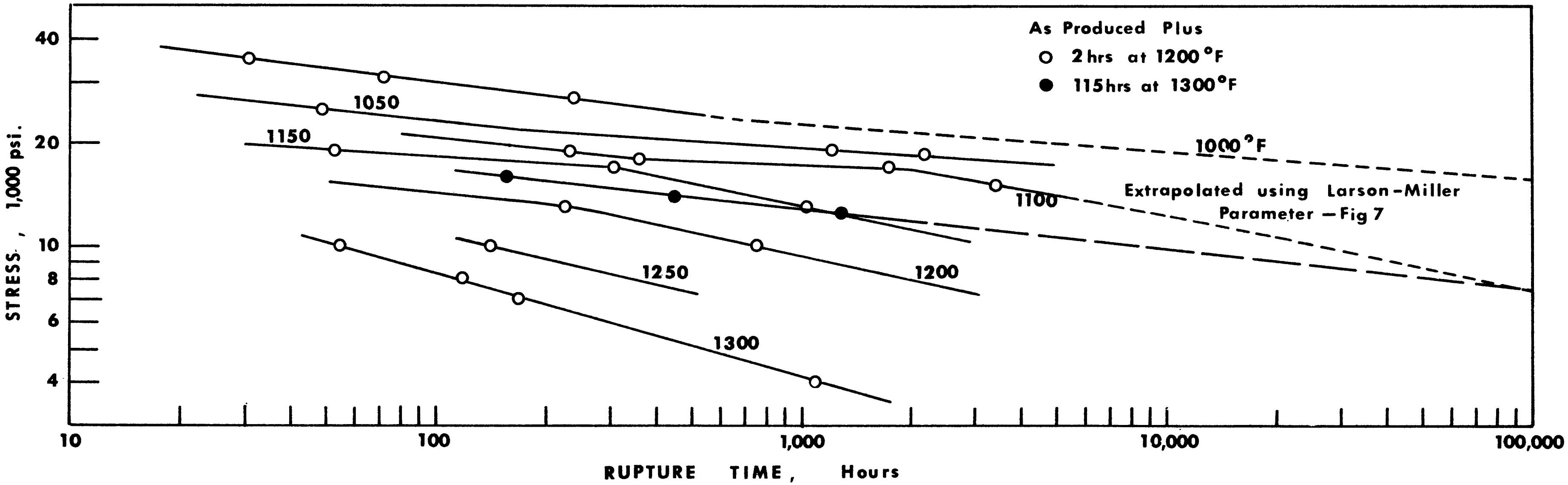


Figure 6: Stress-Rupture Time Curves for P22 Pipe in the Original Heat Treated Condition and after Exposure to Simulate Service at 1100°F.

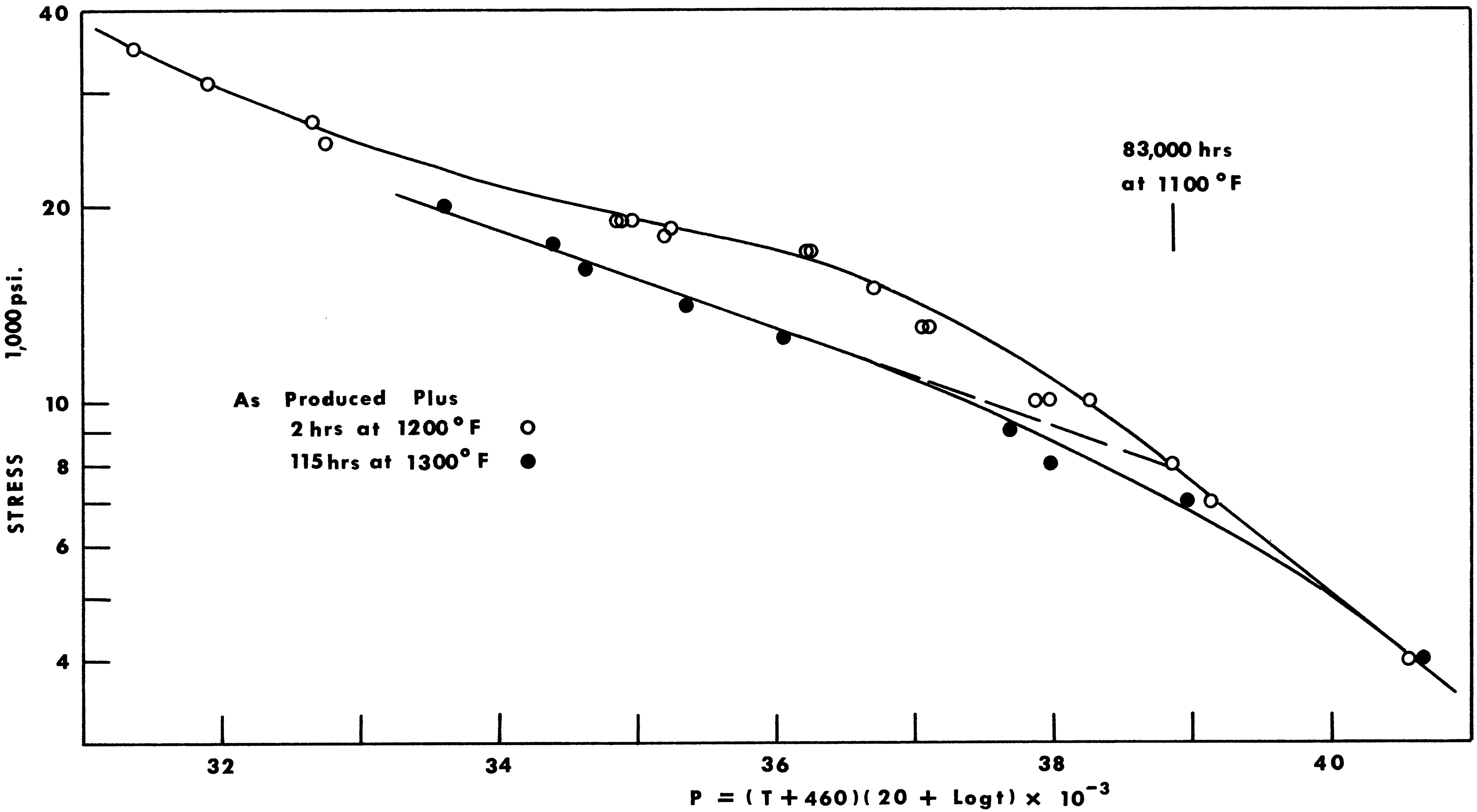
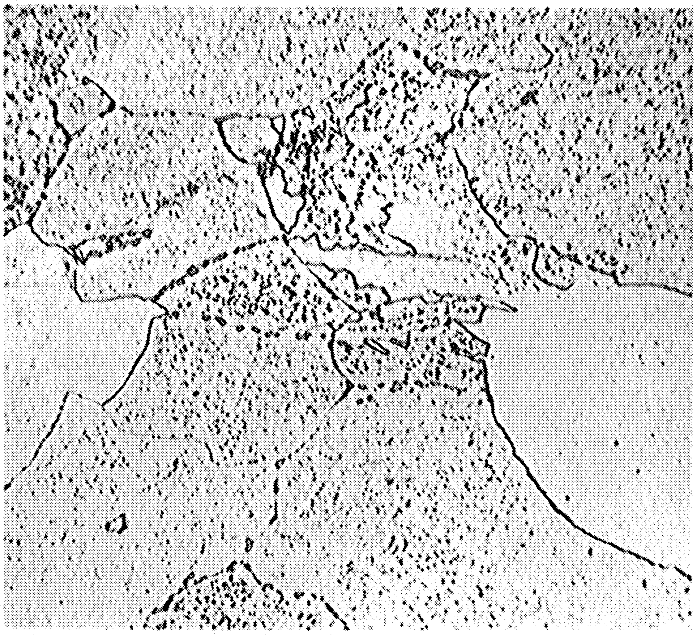
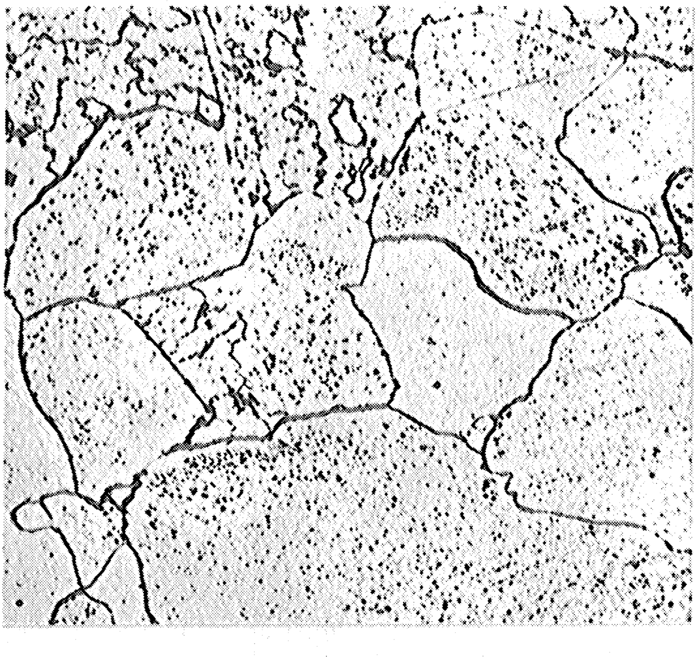


Figure 7: Stress versus Larson-Miller Parameter Curves for P22 Pipe in the Original Heat Treated Condition and after Exposure to Simulate Service at 1100°F.



(a) As Produced + 2 Hrs. at 1200°F



(b) As Produced + 88 Hrs. at 1200°F

Figure 8: Microstructures of P22 Pipe. X 1,000

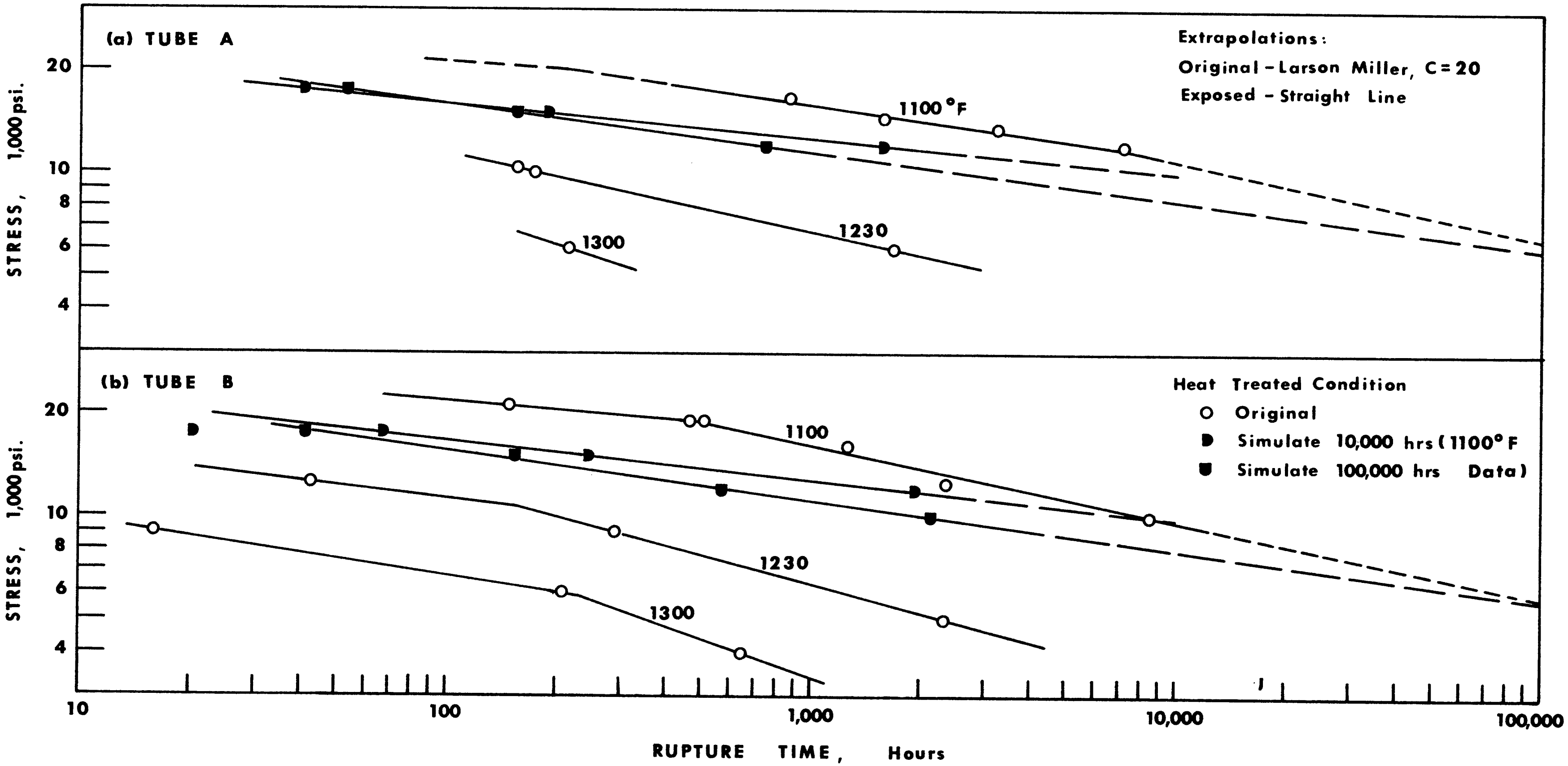


Figure 9: Stress-Rupture Time Curves for Grade 22 Tubes in the Original Heat Treated Conditions and after Exposure to Simulate 10,000 and 100,000 Hours at 1100°F.

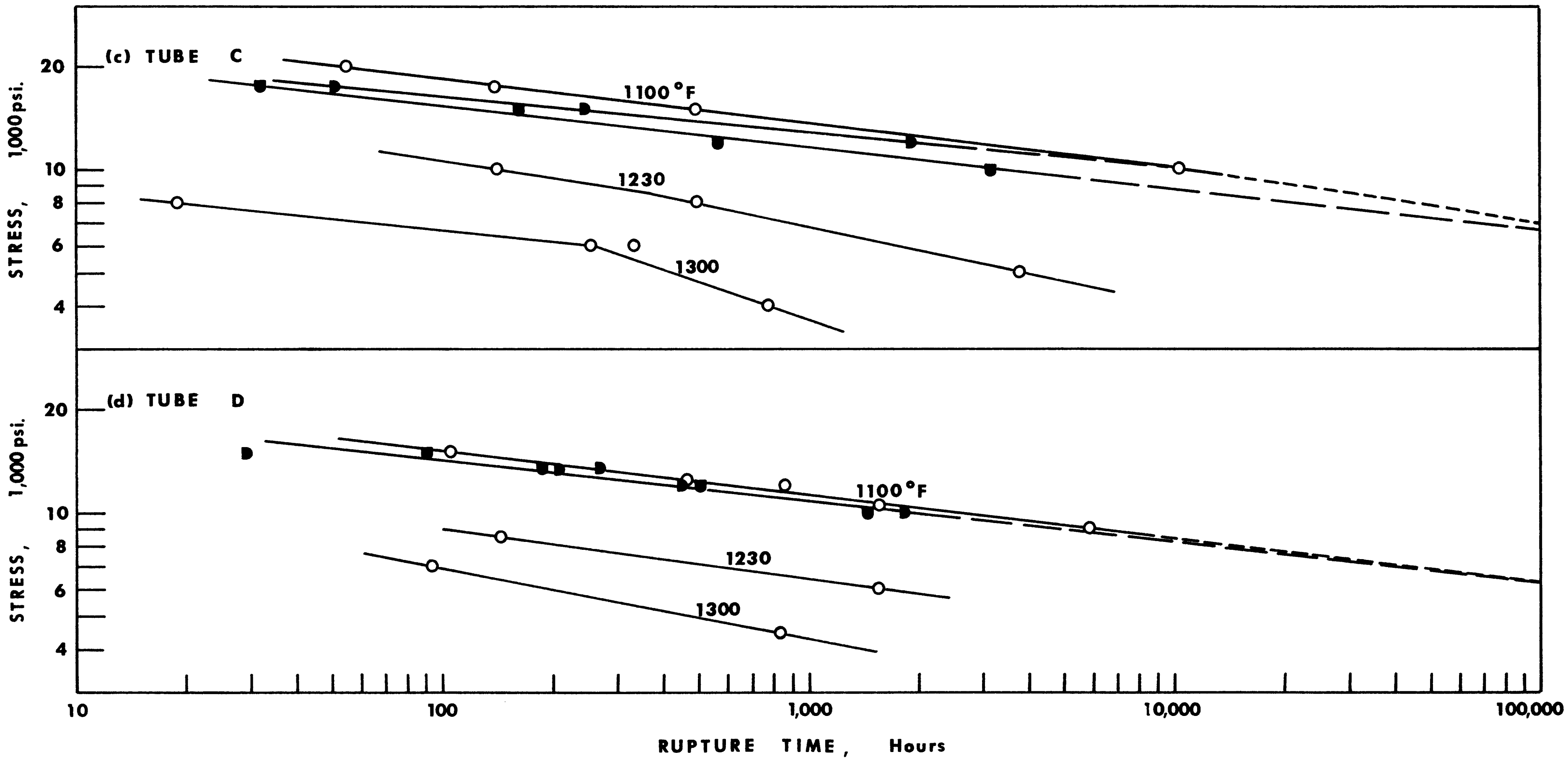
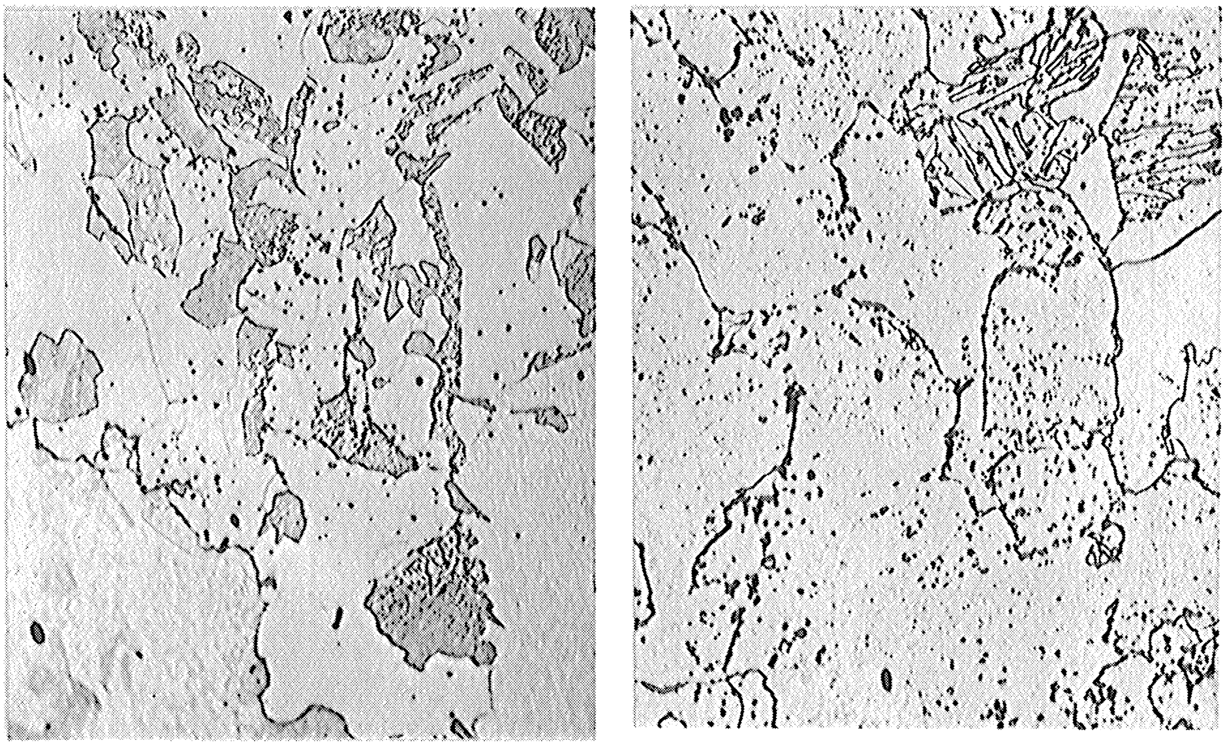
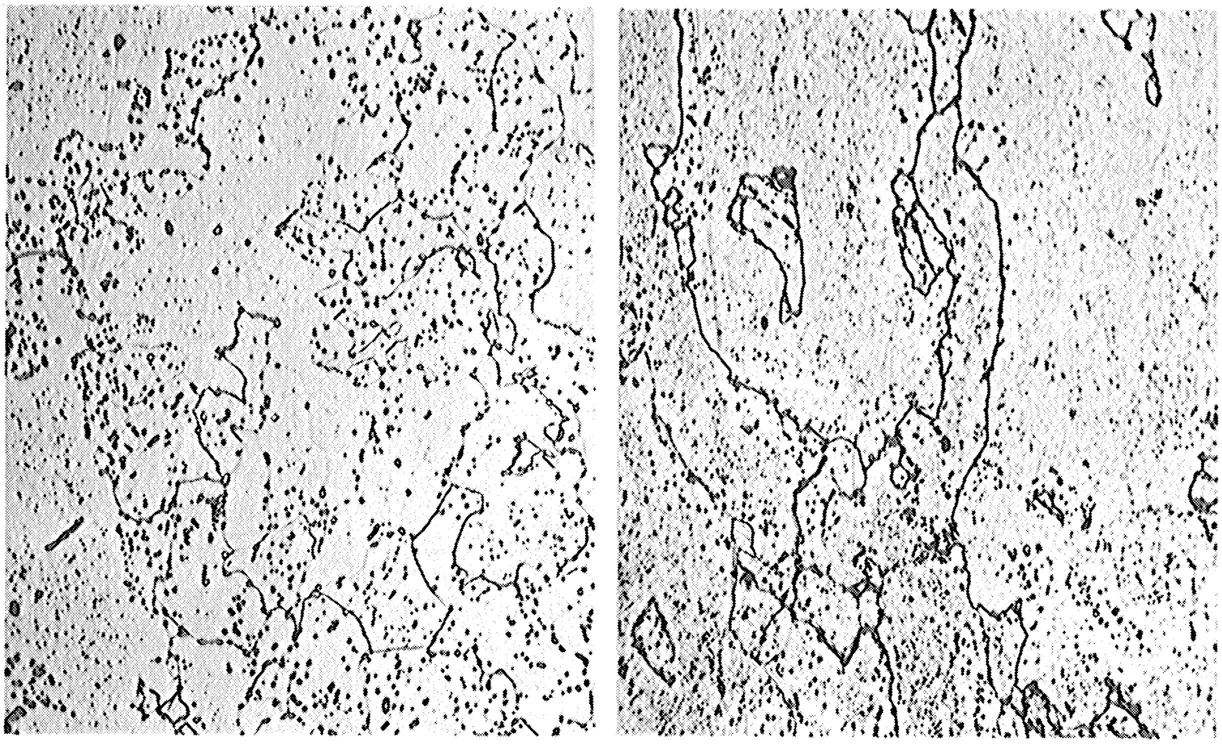


Figure 9: (Continued)



(a) As Produced

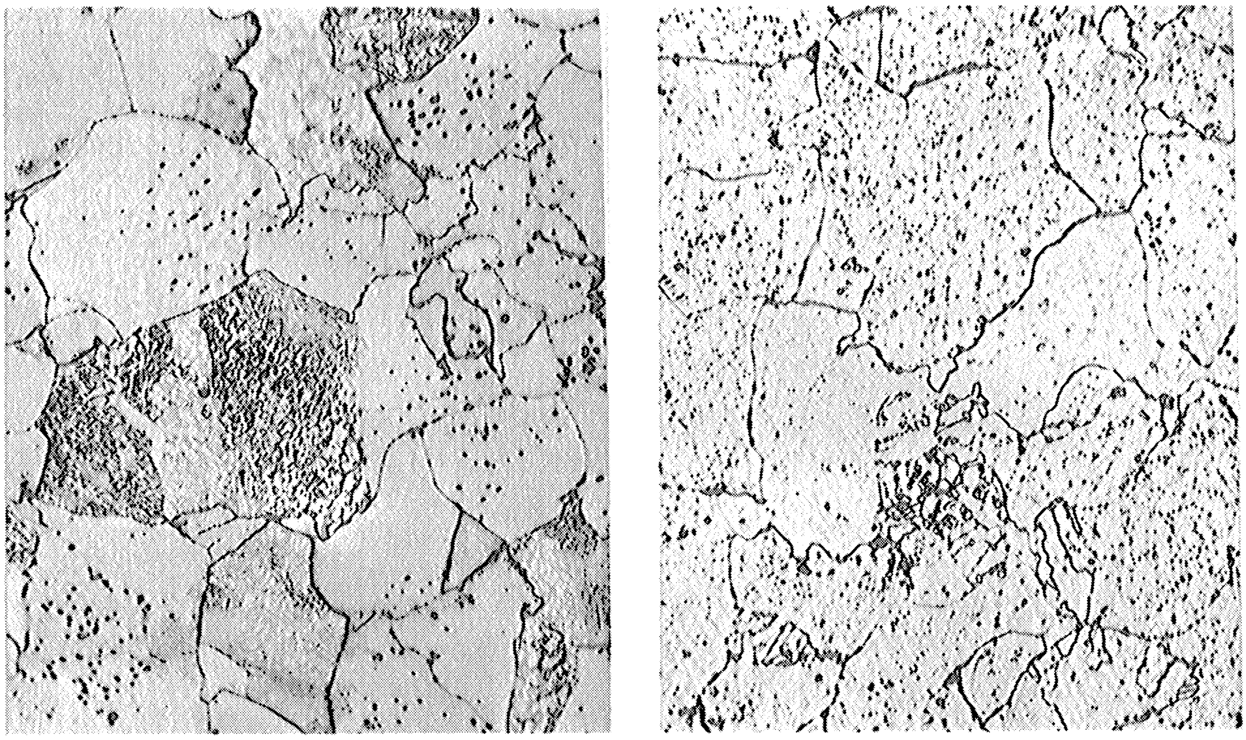
(b) Simulated 10,000 Hrs. at 1100°F



(c) Simulated 100,000 Hrs. at 1100°F

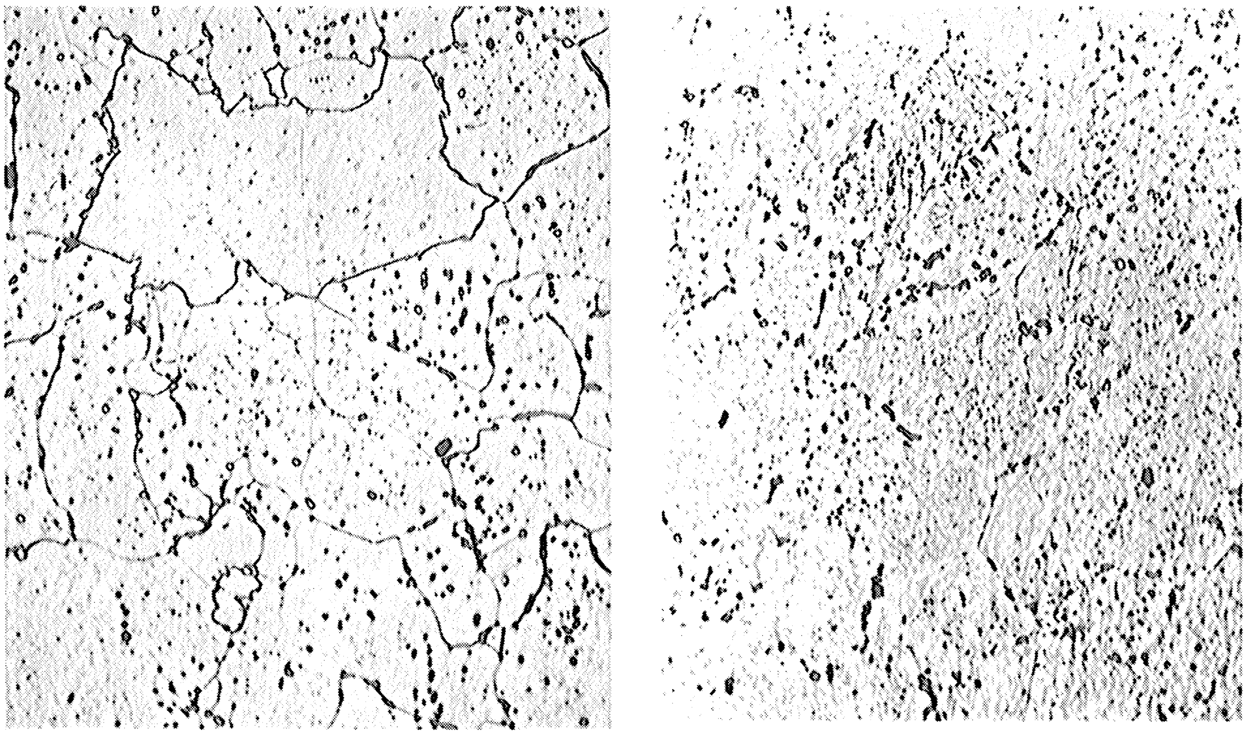
(d) 7014 Hour Test at 1100°F

Figure 10: Microstructures of Grade 22, Tube A. X1,000



(a) As Produced

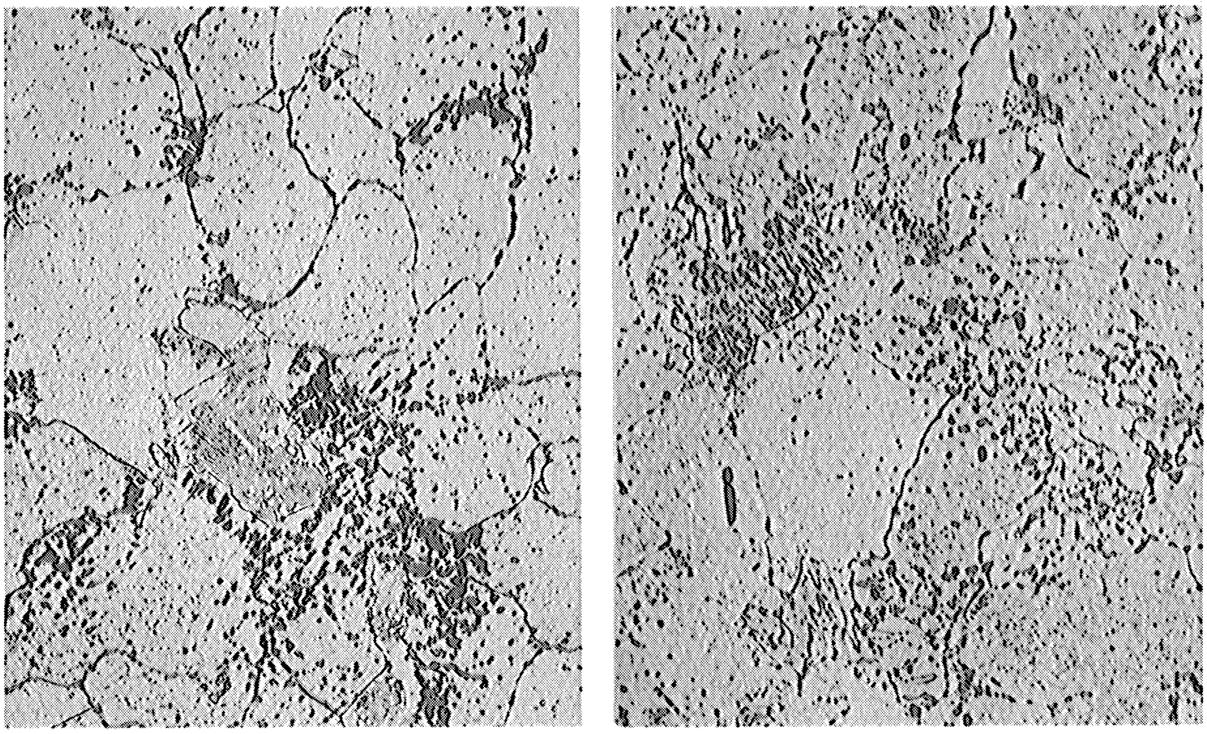
(b) Simulated 10,000 Hrs. at 1100°F



(c) Simulated 100,000 Hrs. at 1100°F

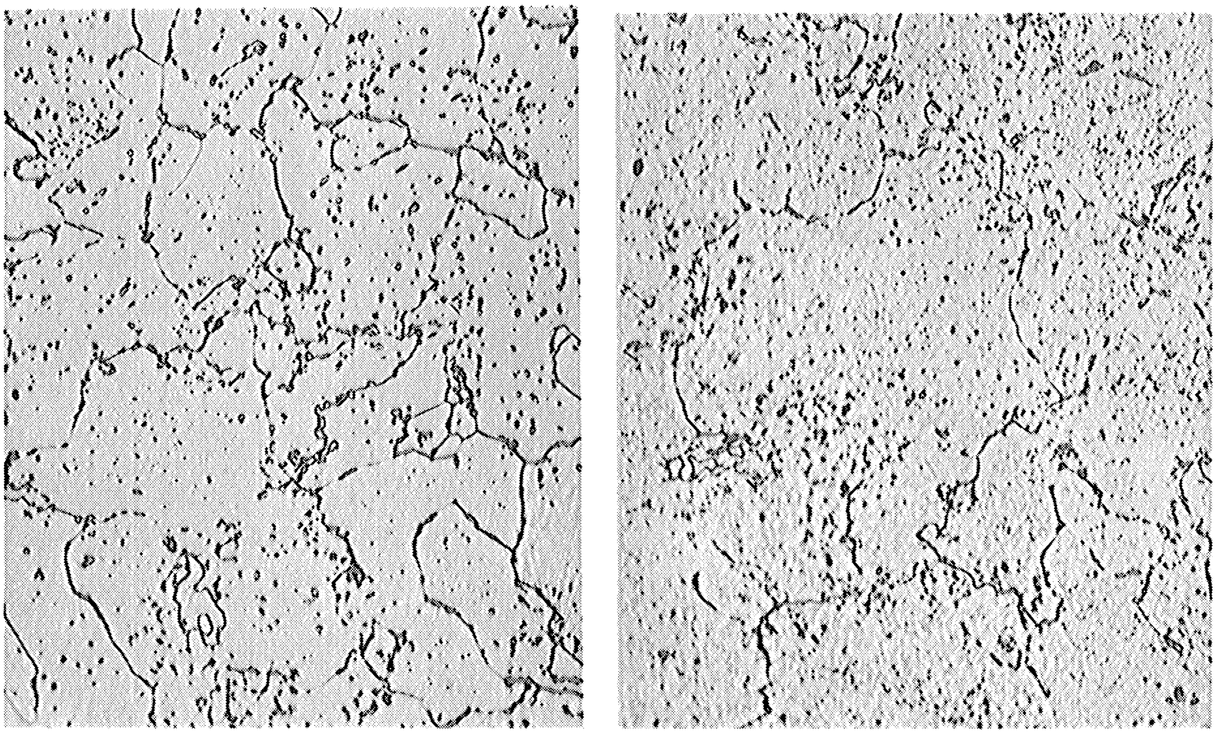
(d) 8475 Hour Test at 1100°F

Figure 11: Microstructures of Grade 22, Tube B. X 1,000



(a) As Produced

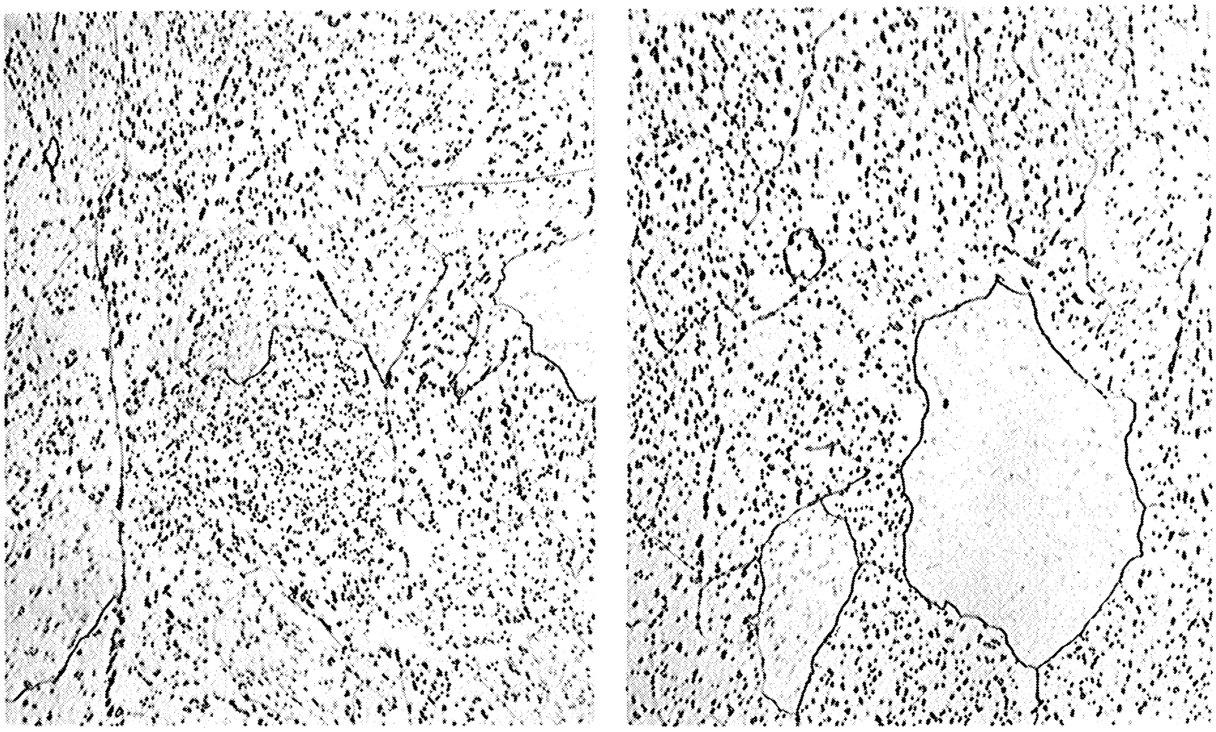
(b) Simulated 10,000 Hrs. at 1100°F



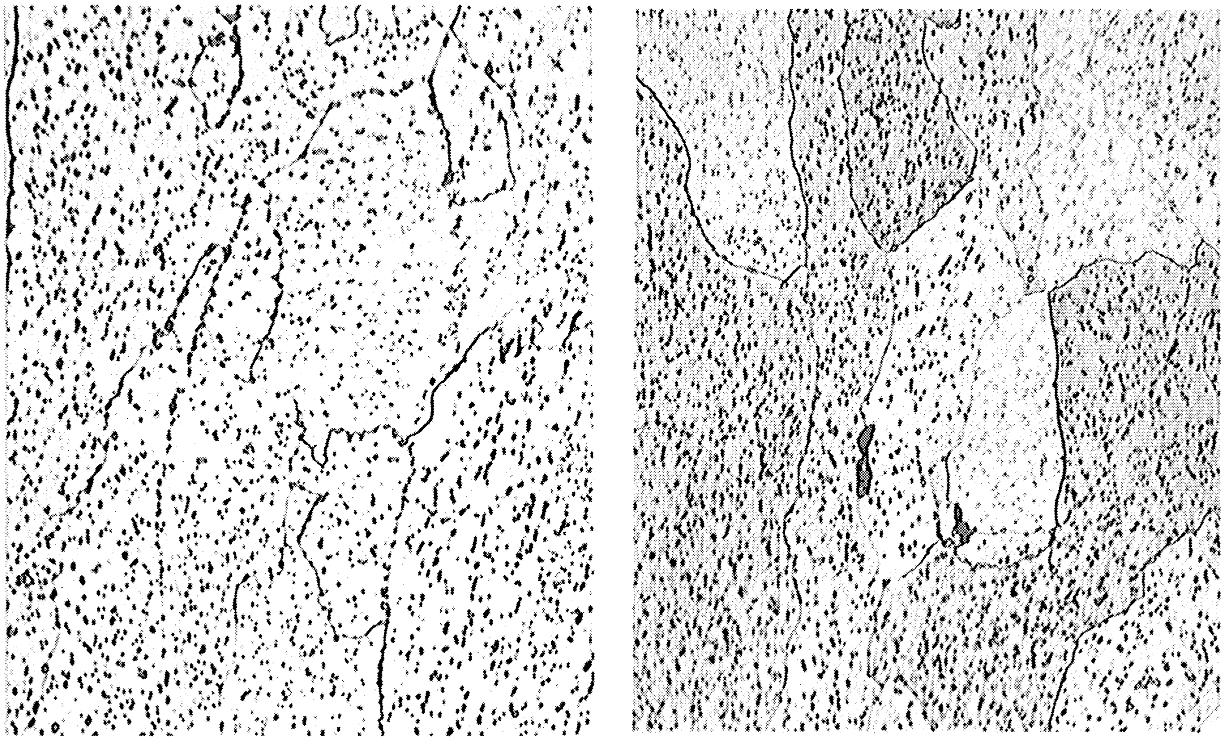
(c) Simulated 100,000 Hrs. at 1100°F

(d) 10,327 Hour Test at 1100°F

Figure 12: Microstructures of Grade 22, Tube C. X 1,000



(a) As Produced (b) Simulated 10,000 Hrs. at 1100°F



(c) Simulated 100,000 Hrs. at 1100°F (d) 5871 Hour Test at 1100°F

Figure 13: Microstructures of Grade 22, Tube D. X 1,000

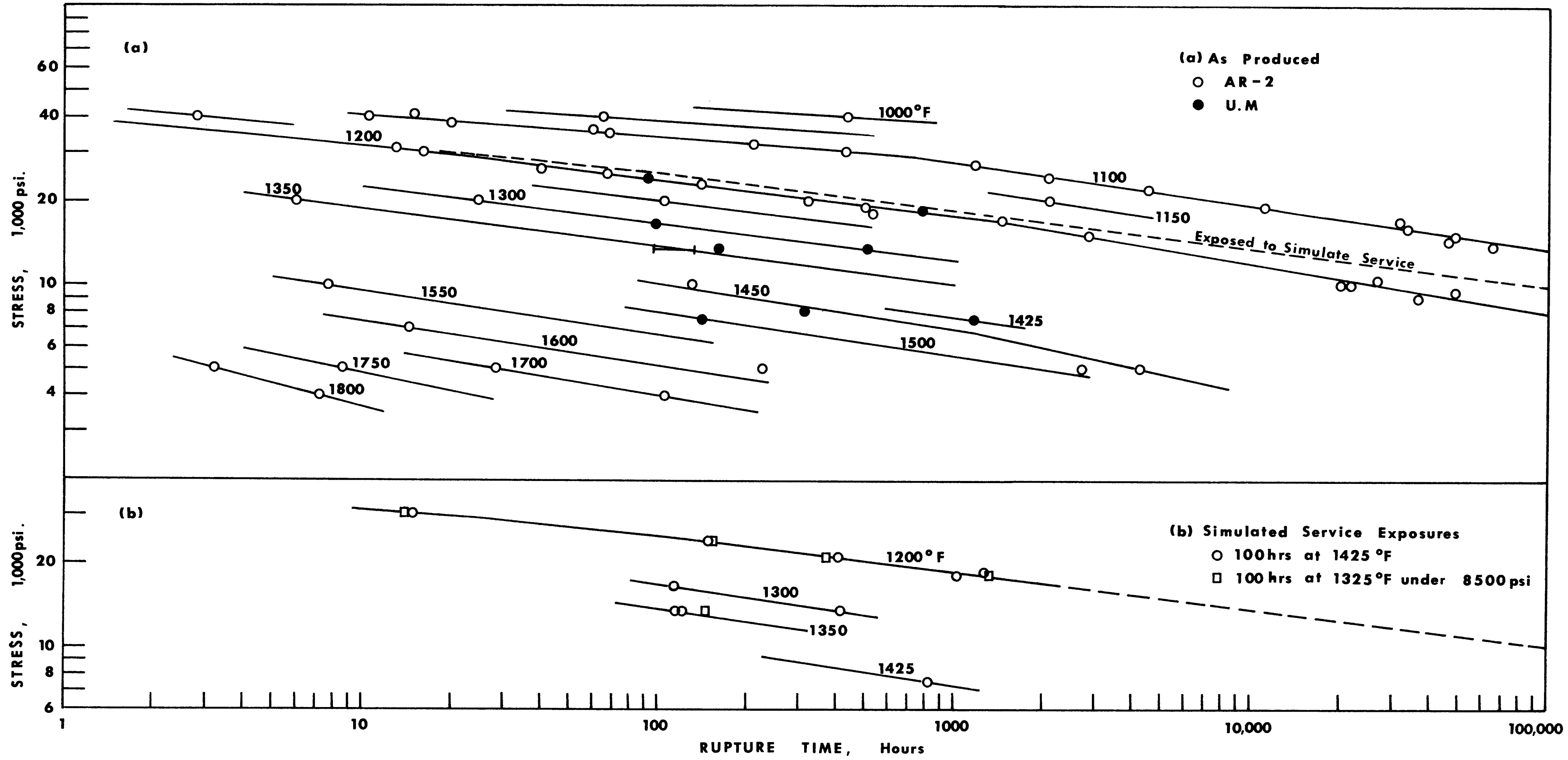


Figure 14: Stress-Rupture Time Curves for Type 304 Austenitic Stainless Steel in the Original Heat Treated Condition and after Exposure to Simulate Service at 1200°F.

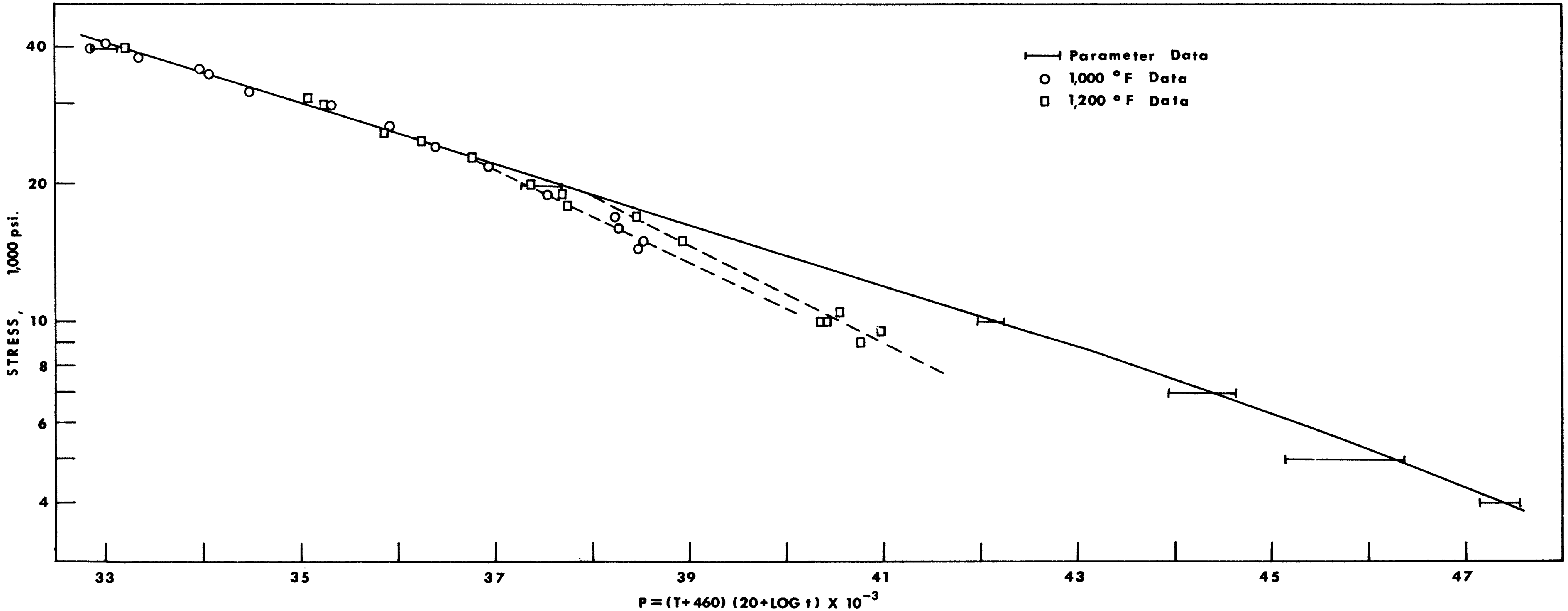
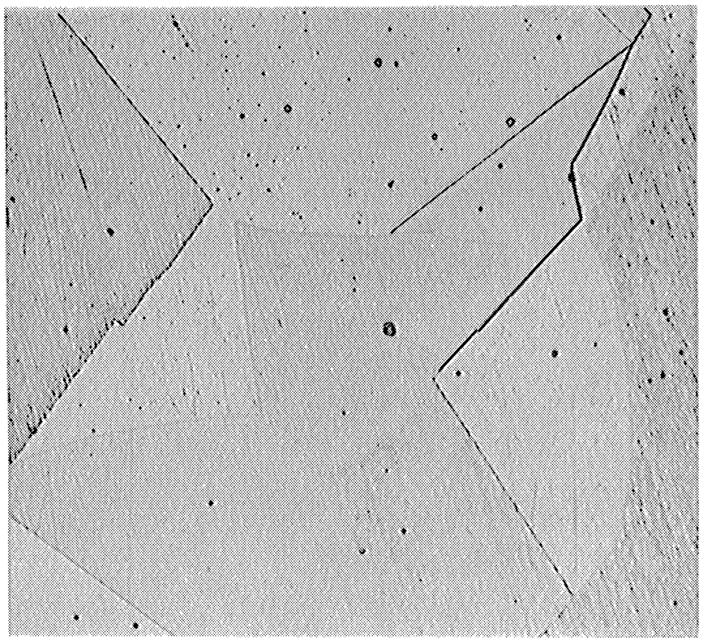
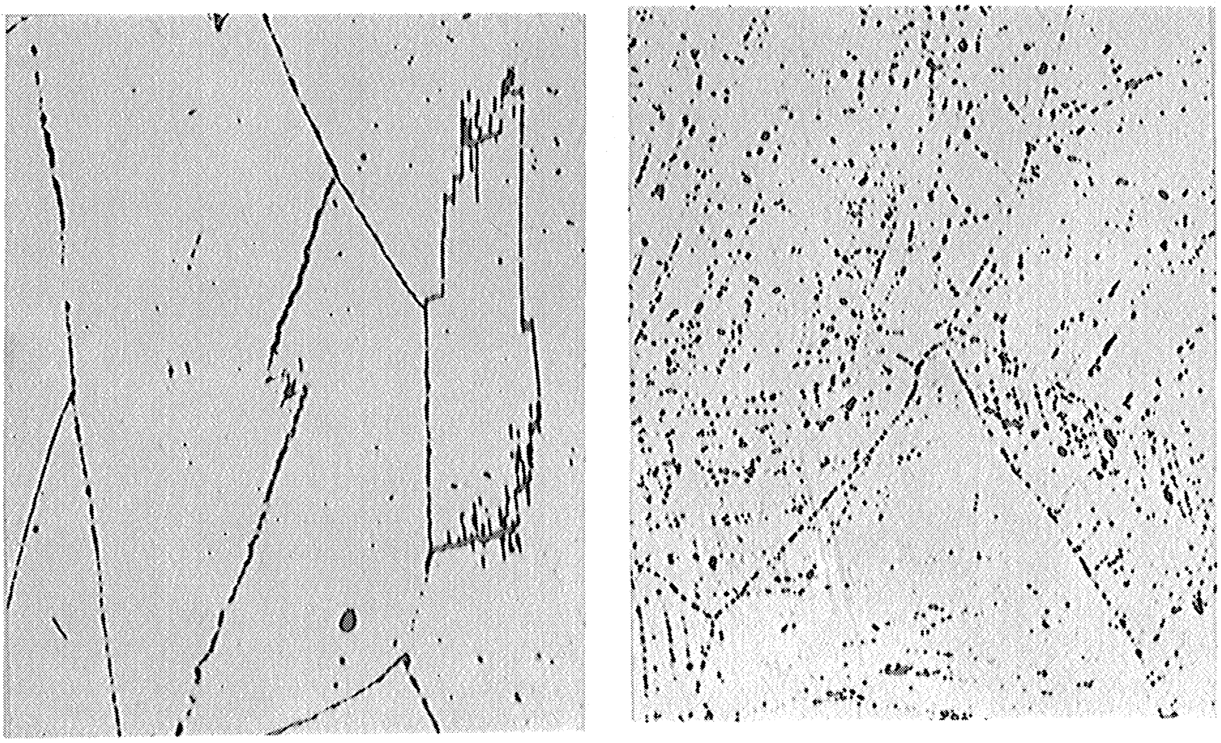


Figure15: Stress versus Larson-Miller Parameter Curves (C = 20) for Type 304 (AR-2) Material in the Original Heat Treated Condition (ref.3)



(a) As Produced



(b) Exposed 100 Hours at 1425°F

(c) Cold Reduced 40 Percent plus 20 Min. at 1625°F plus 100 Hours at 1425°F

Figure 16: Microstructures of Type 304 Austenitic Stainless Steel. X 1,000

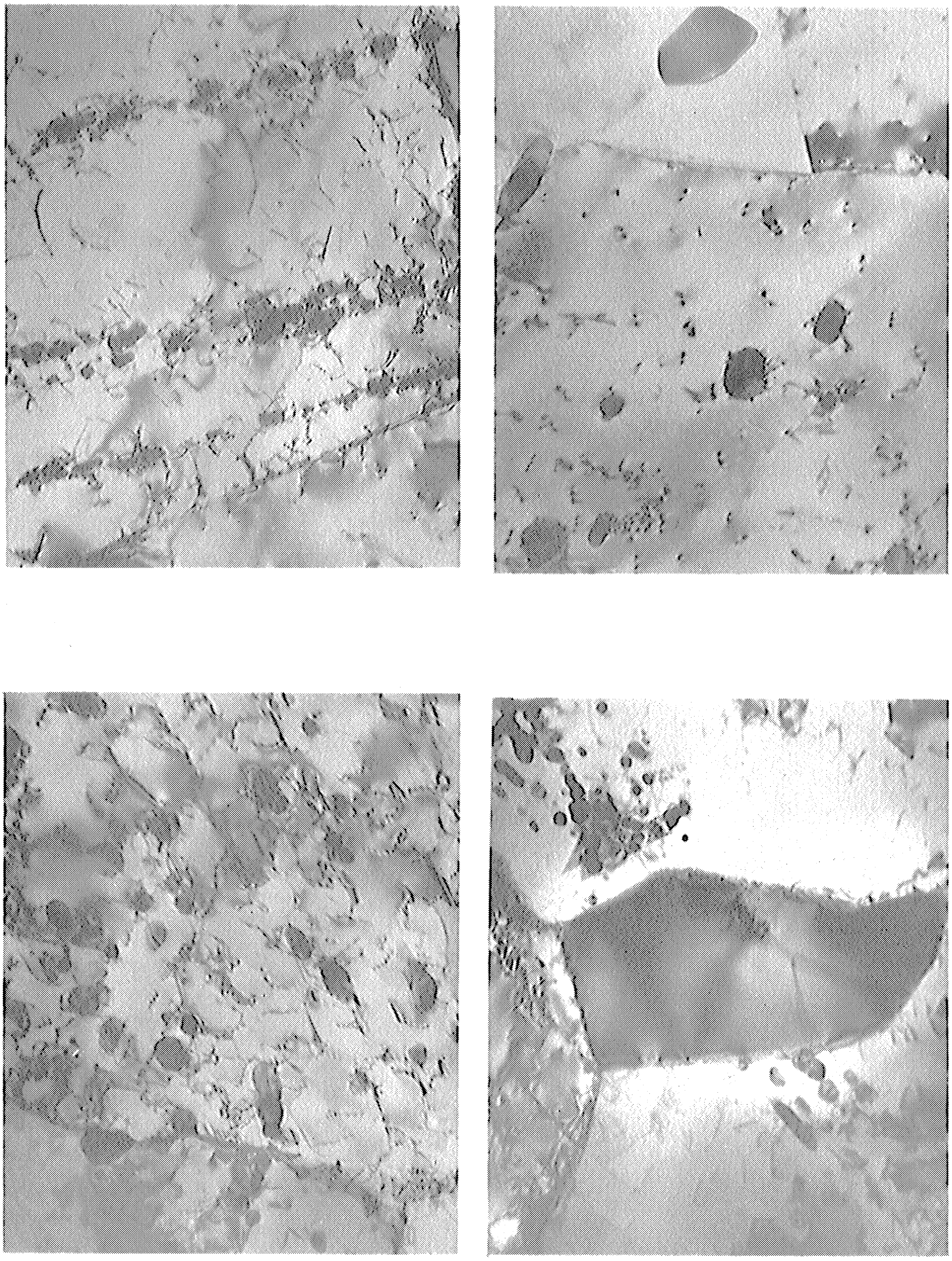


Figure 17: Transmission Electron Micrographs of Type 304 Steel, Cold Reduced 40 Percent and Exposed 100 Hours at 1350°F. X 20,000