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PART 2

HIGH-TEMPERATURE PROPERTIES OF FOUR LOW-ALLOY STEELS FOR JET-ENGINE TURBINE WHEELS

Part 2. A Survey of the Relations Between Microstructure and Elevated-Temperature Properties of Four Low-Alloyed Steels at 700° to 1200°F

ADRON I. RUSH
JAMES W. FREEMAN

UNIVERSITY OF MICHIGAN

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FOREWORD

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ABSTRACT

The relationships between type of microstructure and properties at 700° to 1200°F were surveyed for four low alloyed steels. The steels were SAE 4340, 1.25 Cr - Mo - Si - V ("17-22A"S), 3 Cr - Mo - W - V (H-40), and 13 Cr - Mo - W - V (C-422). Near pure structures were produced by isothermal transformation at a series of temperatures. Martensitic structures were produced by oil quenching. Normalized specimens were also included. Maximum Brinell hardness was kept at 280-320 by tempering the structures which had higher hardness as transformed.

The results indicated that bainitic structures had maximum strength over the temperature range. Tempered martensite in general had intermediate to low strengths. Pearlites were relatively weak at low temperatures, but became similar to the bainites at the higher temperatures. There was considerable variation between high and low temperature bainite and between fine and coarse pearlite. Normalized materials apparently have generally high levels of strength because the usual structures developed are predominantly bainite.

In most cases, rather wide variations in structure were possible with rather uniform properties. There were, however, usually a predominantly strong and an abnormally weak structure within the generalizations. Alloy content controlled the level of strength for a given structure. Thus, while martensitic structures compared unfavorably to the bainites for SAE 4340 and "17-22A"S, the martensitic structure of the C-422 alloy was superior to the lower alloyed steels at the higher temperature and longer time periods. Reasonably good correlations were developed between the structures and properties of turbine wheels of the four alloys on the basis of the results of the survey. The general results from the survey appear to be useful for general guidance in heat treating alloys for high temperature service. However, the survey is very limited and care should be used in extending the data until all the factors have been investigated.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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INTRODUCTION

Normal heat-treatment of medium carbon low alloyed steels can result in microstructures ranging from martensite through the bainites and pearlites, depending upon the section sizes and cooling conditions. A survey has been carried out to relate the possible structures to rupture and creep properties at temperatures from 700° to 1200°F. Four steels were used: 4340, 1.25 Cr - 0.5 Mo - 0.75 Si - 0.25 V ("17-22A"S), 3 Cr - 0.5 Mo - 0.5 W - 0.8 V (H-40), and 13 Cr - 1 Mo - 0.8 W - 0.25 V (C-422). The relationships obtained were extended to correlate the structures and properties of normalized bar stock and turbine wheel forgings of the same alloys.

The structures developed in such steels depend on their transformation characteristics and cooling rates during heat-treatment. It has been known that the properties at elevated temperatures vary with the structures, but the relationships have not been defined. For this reason, an investigation was undertaken to survey the relative creep and rupture strengths of microstructures ranging from martensite through the bainites and pearlites. Nearly "pure structures", produced by isothermal transformation at a number of temperatures, were evaluated by a limited number of creep and rupture tests. The information obtained was checked by correlating the structures and properties with those of normalized (air quenched) bar stock. The structure of turbine wheel forgings of the same alloys were determined and correlated with previously reported properties (Ref. 1).

Very little information is available relating microstructures of such steels to properties at high temperatures. The usual superior creep strength of the normalized structure in comparison to martensite produced by liquid quenching when both were tempered to the same hardness has been long recognized. It has been noted that the normalized structure with high strength usually had a predominantly bainitic structure. Other studies had shown that above some limiting temperature pearlitic structures became superior. These generalities were very difficult to use in practice. A rather wide range in structures is possible within the general classifications of pearlite and bainite. Secondly, the more common commercial heat-treatments involve continuous cooling transformation which may produce mixed structures.

One of the major objectives of the investigation was to obtain information that might lead to the increased use of low-alloy steels for applications heretofore requiring high-alloy strategic materials. Creep and rupture properties can be the controlling factors in the use of low-alloyed hardenable steels over the temperature range of 700° to 1200°F. There are a number of applications or possible applications for such materials in jet engines for aircraft within this temperature range. Increasing air temperatures in compressors are leading to consideration of more use of such materials. At least one jet engine uses alloys of the type studied for turbine wheels. Such alloys require only small amounts of such scarce elements as nickel, chromium, and molybdenum, and no columbium or cobalt. Their fabrication characteristics are far superior to high alloyed austenitic steels and super alloys. Both of these characteristics are of considerable strategic importance.

Information relating microstructure to properties at elevated temperatures has a number of applications. The metallurgist can use such information to select the best conditions and equipment for heat-treatment of a specific section size. Secondly, it would enable proper decisions regarding the usual variations in structure to be expected in practice. It is often difficult to obtain equipment for heat-treatment which will produce ideal structures. Variation in section size in any specific part requires compromises in heat-treatment for best overall properties. Furthermore, the variation in response to heat-treatment normally encountered in practice, and to be expected from the usual heat-to-heat transformation characteristics, as well as plant procedure, requires that good basic information be available for the establishment of sound inspection control.

TEST MATERIALS

The chemical compositions of the bar stock material used for the study of the properties of isothermally transformed structures and structures obtained by conventional normalizing and quenching treatments were as follows:

Steel	Heat	C	Mn	Si	Cr	Ni	Mo	V	W	Cu
4340	19053	0.40	0.70	0.30	0.78	1.75	0.26	--	--	0.12
"17-22A"S	24797	0.30	0.63	0.60	1.25	0.25	0.52	0.25	--	0.10
"17-22A"S	10420	0.29	0.61	0.67	1.30	0.18	0.47	0.26	--	--
H-40	K-2509	0.29	0.48	0.26	3.05	0.49	0.49	0.85	0.55	0.15
C-422	W-3561	0.23	0.81	0.16	13.19	0.65	1.03	0.25	0.84	--

Since the amount of work originally contemplated was enlarged during the course of the investigation, it was necessary to obtain additional bar stock. Additional stock of the 4340 steel was obtained from the same heat as originally used, but it was necessary, however, to accept additional stock from another heat of "17-22A"S. The original supply of H-40 and C-422 bar stock was sufficient for the investigation.

The chemical composition and heat treatments of the turbine wheels whose microstructures and properties were correlated as part of this investigation have been outlined previously in Reference 1. It was possible to obtain bar stock from the same heats as the turbine wheels for the H-40 and C-422 steels, but it was necessary to accept different heats for the SAE 4340 and "17-22A"S bar stock.

SELECTION OF MICROSTRUCTURES AND TESTING CONDITIONS

The initial step was to establish transformation conditions for the possible structures in the four steels, prepare specimens with structures to survey the range in structures, and to select suitable survey test conditions.

Transformation Conditions

The initial step in the study was to obtain isothermal transformation diagrams for the four steels. Inasmuch as several diagrams have been published for SAE 4340 steel, it was not believed necessary to establish one for this material. The diagram published by the United States Steel Company (Ref. 2) was used for this study and is reproduced in Figure 1. Similar diagrams were determined for the "17-22A"S, H-40, and C-422 steels, as shown in Figures 2, 3, and 4.

Following the determination of the isothermal transformation diagrams, time and temperatures of transformation were selected to obtain certain idealized microstructures which would cover the range of structures possible. The treatments and resulting structures are outlined in Tables I through III. The names of the idealized structures are a convenient way of identifying for discussion purposes the treatments and structures used. It is important to recognize, however, as shown in the tables, that in some cases the actual structures deviated from the idealized structure. Photomicrographs illustrating typical microstructures are shown in Figures 5 through 26 for the four steels.

The major reason for the variations between idealized aim structures and the actual structures was the time for complete transformation. Partial transformation to the desired structure could be obtained, but the time to complete the transformation would have been excessive. For example, "upper bainite" in the 4340 steel was only 70 percent bainite with 30 percent martensite after transforming 28 hours at 850°F. The transformation diagram, however, indicates that times in excess of a week would be required to obtain complete transformation. When considerably longer times than those used would not have resulted in appreciably greater transformation, it was deemed advisable to accept the structures most closely resembling those which might be obtained in practice. Furthermore, prolonged transformation times might have resulted in tempering of the first formed transformation products.

Both standard 0.505- and 0.250-inch test bars were used. The 0.505-inch specimens were employed for the normalized and oil-quenched bars and for transformations in the pearlitic range. For transformation in the bainitic range, the 0.250-inch specimens were used to assure rapid cooling to the isotherm so that transformation could not occur at higher temperatures. It was necessary also to use 0.250-inch specimens for all structures when the high stresses involved at the 700° and 900°F testing temperatures exceeded the capacity of the testing units for the larger diameter specimens. Prior to heat treating, the bar stock was rough machined to cylindrical bars 0.8 and 0.4 inches in diameter and final machining was performed after all heat treating operations had been completed.

Austenitizing of the bars was performed in electrical resistance furnaces for the lower temperatures and in a gas fired muffle furnace for temperatures above 1800°F. To assure uniform temperatures in the salt baths used for isothermal transformations, agitation was accomplished by means of a stirrer driven by an air motor.

An austenitizing temperature of 1750°F was used for the 4340 and "17-22A"S materials, whereas 1950° and 1900°F were employed for the H-40 and C-422 steels, respectively. The selection of these temperatures was based on their use for the heat treatment of the turbine wheels, and, with the exception of the 1750°F temperature for the 4340 material, were those most commonly used for the subject materials. The 1750°F austenitizing temperature for the 4340 was somewhat higher than normally used, but can be justified on the basis of the large section sizes involved in the turbine wheels.

The aim hardness was 300 Brinell with the range of 280 to 320 being considered acceptable. When the as-transformed or heat-treated hardnesses exceeded 320 BHN, tempering was used to reduce the hardness to about 300 Brinell. The microstructures after tempering and after prolonged testing at 1000°F for 4340 and 1100°F for the other alloys are also illustrated in the same figures as the as-transformed structures.

The transformation temperatures were chosen in the following manner.

SAE 4340 and "17-22A"S Steels

The highest temperature was chosen in the upper limit of the pearlitic nose of the curve such that transformation would occur in a reasonable time, and the resulting structure was designated "upper pearlite." The lower temperature limit below the pearlite nose of the curve where only pearlite would form was chosen for the "lower pearlite" structure. The "middle pearlite" structure was obtained by transformation at an intermediate temperature.

The same procedure was used for choosing transformation temperatures in the bainitic region. Additional microstructures were obtained by normalizing and tempering and oil quenching and tempering according to the schedule shown in Tables I and II. These treatments resulted in a mixed martensitic-bainitic and a completely martensitic microstructure, respectively.

Photomicrographs of the resulting microstructures are shown in Figures 5 through 12 for the SAE 4340 material and in Figures 13 through 20 for "17-22A"S.

Complete transformation to the desired structures was obtained except for the "upper bainitic" and "middle bainitic" structures. For 4340 only 70 percent completion was secured for the upper bainitic structure and for "17-22A"S, 60 and 97 percent completion were obtained for the upper and middle bainites respectively.

H-40 Steel

All transformations in the upper nose of the H-40 diagram resulted in a fine carbide precipitate. Therefore, only one transformation temperature was chosen and the resulting structure referred to as "pearlite."

Only one transformation product in the bainitic region was studied since the temperature range in which the bainitic structures could be obtained within reasonable times was quite narrow.

In addition, as for 4340 and "17-22A"S, the elevated temperature properties were obtained for normalized and tempered and oil-quenched and tempered bar stock.

Photomicrographs of the resulting structures are shown in Figures 21 through 24, and Table III presents the pertinent data regarding these structures.

C-422 Steel

As shown in Figure 4, the only transformation which began in a reasonable time period for the C-422 material was a grain boundary carbide precipitate, and this transformation apparently was not complete in a very long time. Consequently, the C-422 bar stock was investigated in the normalized and tempered and quenched and tempered conditions only.

Both of these treatments produced complete martensitic structures, as shown in Figures 25 and 26.

Evaluation of the High-Temperature Properties of the Various Structures

The general objective of the tests was to determine the relative strengths of the various structures by survey tests in the temperature range of 700° to 1200°F. At 700° and 900°F, the evaluation was mainly on the basis of creep and total deformation characteristics, the controlling factors at those temperatures. Stress-rupture and total deformation in 1000 hours were the more useful criteria at 1000° and 1100°F, and short-time rupture data were the basis of comparison at the higher temperatures, 1100° and 1200°F, depending upon the material. In each case, as few tests as possible to obtain an indication of strength were used. This alone led to a rather extensive testing program. Furthermore, it was considered advisable to survey the magnitude of the effects before undertaking extensive testing of individual structures.

The survey tests employed for the different materials are outlined below.

SAE 4340 Steel

At 700°F, comparisons were based on a single stress of 90,000 psi. It resulted in total deformations in 1000 hours of about 1.0 percent for the stronger structures. No attempts were made to obtain stress-rupture data since at this temperature the stresses would have to be well above the yield strengths.

At 900°F, comparisons were based on two stresses, 55,000 psi and 40,000 psi. The former was selected to yield for the stronger structures approximately 1000-hour stress-rupture tests, whereas the latter was expected to give total deformation values in the order of 1.0 percent in 1000 hours. Although, in general, creep and total deformation values are of more interest at this temperature, it was believed that the low strength of the 4340 material at high temperatures made a knowledge of its rupture properties at 900°F useful.

The most extensive data were obtained for 4340 at 1000°F since this is about the upper limit of useful application of this steel for relatively long periods, and because the most extensive data on the turbine wheels were obtained at this temperature. In general, two to four tests were run on each microstructure to obtain creep and total deformation data, as well as to establish the stress-rupture curves for the stronger microstructures.

At 1100°F, two stresses were employed -- 18,000 psi to establish the short-time rupture strengths and 4,500 psi to obtain creep and total deformation data.

"17-22A"S Steel

In general, the testing procedures for "17-22A"S were similar to those outlined above for 4340 steel. However, the wide spread in strengths of the different microstructures at 700°F required the use of two stresses to obtain a better evaluation of the strengths. The initial stress of 115,000 psi did not prove to be very useful in evaluating the structures at 700°F. In most cases, this stress was too high, as evidenced by the rupture of most of the specimens in rather short-time periods. Since at 700°F, yield strengths govern the maximum stress which can be used, additional tests were conducted using a stress between the proportional limit and 0.2-percent offset yield strength (approximately the 0.05-percent offset yield strength) as the sorting stress. Because of the flat slope of the stress - creep rate curve at 700°F, this method of selecting stresses did not result in exactly comparable total deformation and creep data, but it was believed that a better evaluation would be obtained on the basis of behavior at the various yield stresses than at a fixed stress which would have been both above and below the yield strength of the various structures.

At 900°F, one stress, 70,000 psi, gave either rather long time rupture data or satisfactory total deformation data.

For this steel, the most extensive data were obtained at 1100°F, the temperature for which the most data were available for the turbine wheels. Several tests were run on each material to obtain stress-rupture, total deformation, and creep data.

At 1200°F, two stress levels, 14,000 and 7,500 psi, were employed to obtain short-time stress-rupture data, as well as a limited amount of longer time rupture and total deformation data.

H-40 Steel

A single stress was employed at both 700° and 900°F, 90,000 and 65,000 psi, respectively. These stresses produced creep and total deformation data for the stronger structures and rupture data for the weaker structures. As for the "17-22A"S material, rather extensive data were obtained at 1100°F. At 1200°F, the testing was limited to short-time stress-rupture data at a single stress, 25,000 psi.

C-422 Steel

As noted previously, isothermally transformed structures were not obtained for the C-422 material. Because of its higher alloy content and less probable use at lower temperatures, testing of the normalized and oil-quenched bar stock was limited to 1100°F. The stress-rupture curve was established by three tests on the normalized material, and a single stress test estimated to give 1.0 percent total deformation in 1000 hours was run for the oil-quenched bar stock.

RESULTS

As indicated in the previous section describing the procedures employed, creep rate and total deformation data were obtained at the lower temperatures, 700° and 900°F; stress-rupture, creep rate, and total deformation at the intermediate temperatures, 1000° and 1100°F; and at the higher temperatures, 1100° and 1200°F, depending upon the material, emphasis was placed on the short-time rupture data.

The complete test data are presented for all four steels in Tables IV through VII. Because of the survey nature of the data, the conventional stress-creep rate, stress-rupture time, and stress-total deformation time curves could not be prepared. However, as will be discussed later, the test data are presented in graphical form, along with the turbine wheel data for those temperatures where complete curves were available for the wheels.

SAE 4340 Steel

The test data from the survey of the relative strengths of the structures are given in Table IV. Table VIII and Figures 27 through 30 summarize the strength values obtained from these data. In order to show the relative strengths more clearly, Table IX and Figure 31 have been prepared. The important trends from these data were:

1. The bainites had the highest strength over the entire temperature range for the criteria of Table IX.

2. Maximum strength shifted from lower to middle to upper bainite with increasing temperature.

3. The mixed bainitic and martensitic structure resulting from normalizing the bar stock had strengths approximately the same as the strongest bainite. From a structural analysis viewpoint, the normalized structure most closely approached upper bainite. At the lower temperatures it tended to be stronger and at the higher temperatures somewhat weaker than upper bainite.

4. At 700° and 900°F, the indications are that substantially increased strength can be obtained by heat treating to fine or medium bainites. The difference between structures tends to become less with increasing temperature, however, so that the penalty for structural variation is not so great.

5. Tempered martensite appeared to retain about the same relative strength to the bainites at all temperatures, being somewhat weaker. At 1000° and 1100°F, however, the pearlites tended to compare more favorably with the bainites and actually be stronger than the martensite. Careful inspection of the data shows that at 1000° and 1100°F, the martensite tended to become the weakest of all structures for limited deformation and prolonged time periods.

6. As would be expected, there were shifts in relative positions between the structures with both test temperature and criterion of strength. The pearlites tended to compare more favorably the higher the temperature, the longer the time period, and the smaller the total deformation. This was particularly true for upper pearlite, which tended to have high strength at limited deformations at 1000° and 1100°F, but did not compare as well on the basis of rupture strength. The test stresses being above the yield strength of the pearlites at 700° and 900°F certainly contributed to their poor showing.

7. It is perhaps significant that there was a tendency for a shift in relative strengths of pearlites with increasing test temperature from lower to upper pearlite, as was the case for the bainites.

8. The significance of the indicated relative strengths of the structures at 700° and 900°F is somewhat difficult to estimate. The limited number of tests did not permit establishment of stresses for rupture or total deformation in a given time period. Comparisons based on time for fracture or to reach a given deformation, or the creep rate, at a fixed stress often exaggerate differences which might be rather small insofar as the influence on the stress for a given strength is concerned.

9. The ductility data from the rupture tests are rather meager for drawing definite conclusions. Review of the data in Table IV indicates the following:

(a) At 900°F, elongations decrease very rapidly with time for fracture. When this influence of fracture time is taken into consideration, the pearlites gave at least as low, if not lower, ductility than the bainites. There is a suggestion that lower bainite and the normalized structure retained the best ductility.

(b) At 1000°F, the pearlitic and oil-quenched samples tended to have slightly better ductility than the bainitic and normalized samples.

(c) At 1100°F, the meager data show no outstanding difference beyond the suggestion that upper pearlite and the oil-quenched material had slightly better ductility.

The individual test data for the survey of "17-22A"S at 700°, 900°, 1100°, and 1200°F are given in Table V, and the strength values obtained from these data are summarized in Table X and Figures 32 through 35. Table XI and Figure 36 have been prepared to show the relative strengths of the structures more clearly.

The shift in structures for optimum strength was not as consistent as for 4340 steel. There appear to be at least three factors influencing the relations between structures and properties which complicate definite conclusions as to optimum structures. The margin between a number of structures was rather small and experimental variations could therefore affect the precise order of strengths. Two heats of steel were used for test specimens. Both heats had essentially the same time-temperature-transformation curves. However, Heat 24797 tended to give higher hardness, particularly in the pearlitic region, than Heat 10420. The latter heat had noticeably more ferrite than the former. This, however, did not seem to account for all the difference in hardness and considerable experience with the alloy suggests that there were in addition secondary hardening differences between the heats not reflected in the microstructures. Because creep resistance appears to be closely related to secondary hardening, this may have been a factor not readily apparent in test performance.

With these restrictions in mind, the data appear to indicate the following trends:

1. The bainites showed the highest strengths for all criteria of Table XI for the temperature range of 700° to 1100°F. The maximum strength shifted from middle bainite at 700° and 900°F to lower bainite at 1100°F, as indicated in Figure 36.

2. The maximum strength at 1200°F was shown by the upper pearlitic structure.

3. The mixed bainitic and martensitic structure obtained by normalizing bar stock had strengths approximately equal to the best bainite at 1100°F and best pearlite at 1200°F. At 700° and 900°F, the mixed structure was slightly weaker than the middle bainitic structures. From a microstructural viewpoint, the normalized structure most closely resembled the middle bainitic structure, except that the former contained somewhat more martensite.

4. The pearlitic structures were surprisingly strong over the entire range of temperature. Although the upper pearlitic structure was the weakest at 700° and 900°F, it showed considerable improvement at 1100°F, and was the strongest at 1200°F. The middle pearlitic structure was only slightly lower than the bainitic and martensitic structures at 700°F and gave good rupture strength at 900°F. At 1100° and 1200°F, where the range in strengths was quite narrow, the middle pearlite was only slightly inferior to the best structures. The lower pearlite tended to show intermediate to low strengths over the entire temperature range.

5. The relative strength of the martensitic structure tended to decrease with increasing testing temperature. At 900°F, the martensitic structure gave creep rates similar to the best bainitic structure, but at 1200°F it revealed the lowest 100-hour rupture strength.

6. Comparison of the elongation values at fracture, shown in Table V, indicates the following:

(a) Good ductility was obtained at 700° and 900°F, and what data are available at longer time periods at 900°F show little decrease in elongation.

(b) The elongation at 1100°F tends to be low and decreases with increasing time. The rather sparse data indicate best ductility for fracture in short time periods for the upper pearlite and martensitic structures, whereas the lower pearlite gave the best long time elongations.

(c) Relatively low elongations are shown for short time periods at 1200°F, but the deformation increases with increasing time.

(d) The magnitude of the ductility seems to be independent of the structure.

H-40 Steel

Table VI presents the individual test data for the survey of relative strengths and Table XII and Figures 37 through 40 summarize the strength values obtained from these data.

The trends indicated by these data were as follows:

1. The bainitic structure exhibited properties nearly equal or superior to the other structures over the temperature range of 700° to 1100°F. At 700° and 900°F, the bainitic structure gave the best properties on the basis of creep and total deformation data. At 1100°F, the bainitic structure was somewhat weaker than the normalized structure on the basis of creep and total deformation strengths, even though it exhibited slightly better rupture strengths.

2. The pearlitic structure had properties slightly better than those for the other treatments at 1200°F, as indicated by short-time rupture and total deformation data.

3. The martensitic structure gave properties very similar to the mixed structure obtained by normalizing over the entire temperature range with the following exceptions:

(a) The martensitic structure was slightly weaker at 1100°F on the basis of creep and total deformation data.

(b) At 1200°F, the martensitic structure was the weakest of all treatments, although the difference was relatively small.

4. Good elongation to fracture was obtained for all conditions with the exception of the normalized structure which was quite brittle at 1100°F. At 1100°F, only one specimen fractured in the reduced section and three test bars failed either at the shoulder radius or in the threaded end with brittle type fractures. The martensitic structure tended to show the greatest ductility at all temperatures of testing.

C-422 Steel

The individual test data are presented in Table VII and the relative strengths are summarized in Table XIII and the graphs of Figures 41 through 43. The limited data obtained for this steel indicate that the properties of the oil quenched and normalized bar stock appeared to be nearly identical, as might have been expected from the similar microstructures.

Microstructural Changes during Testing

The microstructural changes occurring during testing and illustrated in Figures 5 through 26 were of the order to be expected. Little or no change in structure or hardness was observed for the upper and middle pearlitic bar stock. However, the lower pearlitic structure of both the 4340 and "17-22A"S revealed considerable spheroidization during testing at 1000° and 1100°F, respectively. These changes were reflected in both the considerable decrease in hardness during testing, Figures 5 and 15, and in the low high-temperature properties observed for this structure. In general, the bainitic and martensitic structures showed the normal amount of tempering to be expected from testing at 1000° to 1100°F. The higher alloyed steels indicated less tempering of the microstructure and a greater retention of hardness during testing than the lower alloy steels.

CORRELATION OF STRUCTURES AND PROPERTIES OF TURBINE WHEELS

A previous report (Ref. 1) presented the results of a survey of the rupture, total deformation, and creep properties of forged turbine wheels of the same steels used for the previously discussed survey of the high-temperature properties of microstructures. The chemical composition and heat treatments of these wheels are reproduced in Tables XIV and XV. The properties obtained from the wheels are summarized in Tables XVI through XIX and Figures 44 through 60.

Three heat treatments were used in the wheel testing program. Separate wheels of each alloy were normalized, oil quenched, and "isothermally transformed" from the same austenitizing temperature used in the bar stock studies. The isothermal treatment consisted of quenching in water until the wheel became black, removing from the water until the glow returned from interior heat, and repeating the cycle until the glow did not return. The wheels were then placed in a furnace at 700°F for 8 hours. This was omitted for C-422 alloy due to lack of transformation at intermediate temperatures. The properties obtained are representative of those resulting from the structures established by these treatments of a contour forging 19-1/2 inches in diameter by approximately 3-3/8 inches thick at the rim and 4-5/8 inches thick at the center with an integral stub shaft and boss at the center.

As part of the present investigation, the microstructures of the wheels were carefully established. Photomicrographs were taken to show representative structures near the rim, at the center, and midway between the two. These structures are shown by the following figures:

1. SAE 4340 steel - Figures 44, 45, 46, and 47.

2. "17-22A"S steel - Figures 48, 49, 50, and 51.

3. H-40 Steel - Figures 52 through 57. As originally received, the H-40 wheels were found to be too hard and were subsequently retempered. The microstructural analysis was carried out on the as-received material. Figure 55 shows that the retempering did not noticeably change the microstructure.

4. C-422 Steel - Figures 58, 59, and 60.

In each case, photomicrographs were included to show typical structures after prolonged testing at the temperatures where the most extensive testing was carried out on the wheels, 1000°F for SAE 4340 and 1100°F for the other three steels.

Samples were examined at each location to determine structural variation through the thickness of the disks. Actually, there was very little variation between the surface and center at the three locations, although considerable variation was observed between rim and hub areas in some instances. The photographs were actually taken at a location midway between the surface and central plane of the wheel and are considered to be representative of those existing at the locations of the various test specimens. The photographs of the structure at the position midway between the rim and hub are most representative of the radial specimens used to establish the stress-rupture, total deformation, and creep curves for the wheels. The rim structures are representative of those existing at the location of the tangential check tests taken at the rim. The structure at the central hub area is representative of that of some of the room temperature tensile tests and of check tests run to determine the stress-rupture properties of that area.

In general, the correlation between the properties of the turbine wheels and their microstructures appears to be rather good. In some instances, the degree of correlation may be obscured by misinterpretation as to the microstructure of the turbine wheels. All turbine wheels, except the normalized 4340 wheel, were tempered prior to examination. Tempering tended to obscure the basic microstructure and therefore uncertainty existed in some cases as to the true structure. For example, it is rather difficult to distinguish between the various bainites in the tempered condition, as well as between tempered lower bainite and tempered martensite. Furthermore, the structures of the turbine wheels were formed upon continuous cooling transformation and thus the microstructures might be expected to consist of several components.

SAE 4340 Steel

The microstructure of the normalized wheel, Figure 44, consisted principally of bainite with moderate amounts of untempered martensite. Greater amounts of martensite were present in the center sections of the wheel, but this apparent anomaly may be attributed to the greater retention of the cast structure and accompanying segregation in the center portions of the wheels. Both the microscopic and macroscopic examination of the wheels indicated less hot working in the center sections.

The predominant bainitic structure away from the center appeared to be quite similar to that obtained for the upper bainitic and normalized bar stock. The upper bainitic bar stock had an untempered-bainitic martensitic structure similar to the normalized wheel. The normalized bar stock also was similar, except that it had been tempered. Table XVI and Figures 27 through 30 show that these observations of comparative microstructure appear to agree with the observed high temperature properties. The major difference in properties between the wheel and bar stock structures was the high strength at short time periods for limited deformations shown by the wheel and not indicated by the bar stock structures. In this respect, the normalized bar stock appeared to agree with the turbine wheel data slightly better than did the upper bainitic structure. At about 1000 hours, the bar stock structures gave about the same strength for limited deformations. For some reason, the stress-time curves had much less slope for the bar stock than for the wheels as a result of less creep resistance at high stresses.

The relationships existing between the properties of the interrupted-quenched wheel and the bar stock materials were similar to those observed for the normalized wheel. This agreement in properties appears to be in accordance with the similarity of structures between the interrupted-quenched and normalized wheels. The photomicrographs of Figures 44 and 46 indicate that the structures of the two wheels were probably similar except for tempering. It was believed that any differences were quickly eliminated during heating for testing.

The structure of the oil-quenched wheel appeared to be a uniformly tempered martensite similar to that of the oil-quenched bar stock, Figures 11 and 45. The properties of the oil-quenched wheel and bar stock appeared to be of the same order, but some differences were noted. The short-time rupture strength of the bar stock was slightly lower and the 1000-hour strength slightly higher than for the wheel. Also, the bar stock showed better strength for limited deformation at 1000 hours. Thus, the bar stock material did not exhibit the break in the stress-time curves shown by the wheel material. Perhaps these differences were the result of the different heat treating conditions. The oil-quenched wheel was quenched from 1550°F and tempered an unknown time at 1050°F as compared to 1750°F for the bar stock, followed by a temper of 10 hours at 1100°F. The higher tempering temperature for the bar stock may have resulted in a more stable structure that gave higher properties at long time periods.

"17-22A"S Steel

Examination of the microstructure of the normalized wheel revealed a tempered bainitic-ferritic structure near the rim and a tempered pearlitic-ferritic structure containing patches of bainite in the hub area as shown in Figure 48. The bainite in the center areas appeared to be the result of local inhomogeneity resulting in alteration of local transformation characteristics. Because of the mixed nature of the structure, it was not strictly comparable to any of the isothermally transformed structures of the bar stock, but with the exception of the bainitic areas it most closely resembled the middle and lower pearlitic structures. Although extensive data were not obtained for this wheel because of its inferior properties, the available data shown in Table XVII and Figures 32 through 35 indicate that the properties of the pearlitic bar stock materials were generally quite similar to the wheel.

The original microstructure of the oil-quenched wheel was difficult to ascertain in the tempered condition. The structure shown in Figure 49 appeared to be a mixture of tempered bainite and martensite, but this conclusion is uncertain because of the similarity in appearance of martensite and lower bainite when both have been tempered. Actually, the structure of the wheel seemed to be more nearly like that of the middle bainitic bar stock structure, Figure 17, except that the wheel structure appeared to be more highly tempered. However, as shown in Table XVII and Figures 32 through 35, the properties of the wheel did not agree quite as well with the middle bainitic structure as with the lower bainite and tempered bainitic-martensitic structure of the normalized bar. The middle bainitic structure had slightly lower properties than the wheel, particularly for limited deformation in 100 hours and for creep, whereas the lower bainitic and normalized structures had properties of the same order for all criteria. This correlation appears to corroborate the initial statement that the structure was probably tempered bainite and martensite, but that considerable lower bainite might have been present.

The interrupted-quenched wheel appeared to be tempered martensite or low temperature bainite at the rim and tempered upper or middle bainite, with possible patches of martensite, in the hub areas, Figure 50. As previously mentioned, however, the initial structure is difficult to determine accurately in the tempered condition. Although little data were available for the interrupted-quenched wheel, Table XVII and Figures 32 through 35 indicate that its properties were quite similar to the oil-quenched wheel and to the lower bainitic and normalized bars.

H-40 Steel

As mentioned previously, little difference in properties was observed for the three H-40 steel wheels. Examination of Figures 52, 53, and 54 reveals that there was also little or no difference in microstructure. All three wheels appeared to have tempered bainitic-martensitic structures. In the as-received condition, all three wheels exhibited hardness values above the range of 280 to 320 Brinell desired and therefore coupons cut from the wheels were retempered to obtain the desired hardness. The microstructures of Figure 55 indicate that retempering caused little or no change in structure, although the hardness was reduced considerably. Comparison of the wheel structures with those of the bar stock indicate that the bainitic structure most closely resembled those of the wheels, except for grain size. In all cases, the grain size of the wheels was considerably coarser than that of the bar stock. Comparison of properties, Table XVIII and Figures 37 through 40, indicated rather good agreement between the wheels and the bainitic bar stock, insofar as rupture strength was concerned, but the bar stock gave total deformation and creep strengths considerably lower than the oil-quenched wheel, total deformation and creep data not being obtained for the other wheels. However, although the structure of the normalized bar stock did not agree with the wheel structures as well as the bainitic material, its properties gave better agreement insofar as total deformation and creep data were concerned. It would appear that the higher total deformation and creep strengths and better short-time rupture strength of the wheels could be attributed to their coarser structure, although such a conclusion would have to be corroborated by tests.

C-422 Steel

The microstructures of both C-422 wheels were tempered martensite and appeared to differ mainly in that the oil-quenched wheel appeared to be more highly tempered. However, the structures seem to be somewhat anomalous in that the rim structure of the oil-quenched wheel appears to be more nearly like the normalized wheel than does the center portion, Figures 58 and 59. It might be expected that the slower cooling rate at the center of the oil-quenched wheel would result in a structure similar to the normalized wheel. On the other hand, the oil-quenched wheel showed greater amounts of delta ferrite in the center sections than was observed for the normalized wheel. Apparently, the delta ferrite was associated with the retained dendritic structure of the ingot and the accompanying segregation of alloying elements. The conclusion that the structures differed mainly in the degree of tempering seems to be substantiated by the fact that the structures were quite similar after prolonged testing as shown in Figure 60.

The microstructures of the oil-quenched and normalized bar stock were nearly identical and quite similar to the wheel structures, except that they appeared to be more highly tempered and did not show any delta ferrite.

As shown in Table XIX and Figures 41 through 43, the normalized bar stock properties were almost identical with those of the oil-quenched wheel, and the limited data for the oil-quenched bar indicated similar agreement. However, for some reason not explained by the data, the normalized wheel gave properties somewhat lower than the oil-quenched wheel and both bar stock treatments.

DISCUSSION

The principal purpose of the work reported herein was to survey the relationships between high-temperature properties and microstructures of low alloy steels. In particular, it was desired to determine the relationships between temperature of transformation and elevated temperature properties over a range of testing temperatures, and whether a particular structure exhibited superior properties at one or all temperatures. A secondary purpose was to apply the results by explaining high-temperature properties of turbine wheels heat treated by normalizing and tempering, oil quenching and tempering, and an interrupted quench and temper.

Data are presented in this report for a limited number of tests to survey the stress-rupture, total deformation, and creep rate properties of six isothermally transformed structures, as well as normalized and tempered and oil quenched and tempered structures of bar stock material in the temperature range of 700° to 1200°F. Whenever transformation characteristics permitted, three structures transformed in the pearlitic transformation range and three in the bainitic range have been studied. Four steels were used with varying degrees of transformation characteristics.

Principles of Heat Treatment

When the hardness level is restricted to approximately 300 BHN, transformation conditions must be controlled to produce either bainite or martensite. Vanadium bearing steels apparently are not quite so restricted in that transformation in the lower part of the pearlitic region also will meet this requirement. Within these restrictions, the principles of heat treatment for service at high temperatures may be summarized as follows:

1. Conditions of heat treatment producing bainite will give, on an average, maximum or near maximum strengths over the temperature range of 700° to 1200°F for criteria of strength based on times between 100 and 1000 hours.

2. Within the generalization that bainite is the preferred structure for strength there is considerable variation.

For 4340 steel, maximum strength progresses from lower to middle to upper bainite with increasing temperature. In each case there is generally a substantial margin in favor of one of the bainites and a considerable penalty for one of the others. Thus, there is an incentive for precise control of structure versus service temperature.

For "17-22A"S steel, the bainitic structure having the maximum strength varied less regularly with test temperature and criterion of strength. What is perhaps more important is that one of the bainites, at almost all temperatures, tended to be well on the low side of the strength range. Again, there is considerable value in precise structure control, at least to avoid the low strength bainitic structures, and at 700° to 900°F to obtain the maximum strength.

3. Normalizing of the bar stock generally produced near maximum strengths for both steels. Apparently a range in bainitic structures, together with some martensite produces a good average structure. In those cases where the normalized structure compared unfavorably with one or more of the "pure" structures, it will be noted that it had strengths near to those of the pure structures it most closely resembled.

For normalizing to produce a high level of properties, the cooling rate should be such as to allow the major part of the transformation to occur in the bainitic region. A predominance of martensite or pearlite due to section size and transformation characteristics could have inferior properties.

4. The survey creep, total deformation, and rupture data show that martensitic structures tend to fall off in comparative strength to the other structures with increasing temperatures and time for a given criterion of strength. The differences are quite substantial in comparison to the strongest bainitic structure, with the possible exception of "17-22A"S steel at 1100°F. It should also be noted that at most of the temperatures the martensite outranks at least one of the bainitic structures. Only in the case of "17-22A"S at 700°F did the martensitic structure give better properties than the normalized bar stock. There is some indication that martensitic structures tend to undergo less deformation during first-stage creep, but have higher secondary creep rates so that they can compare more favorably on the basis of limited deformations at short-time periods.

5. The limited rupture data did not show a predominant variation in elongation and reduction of area in rupture tests for the bainitic structures, martensite or normalized stock for 4340 steel. The same is largely true for "17-22A"S steel except that slightly lower values seem characteristic of lower bainitic and the normalized structures at 1100°F and for middle bainite and the normalized structures at 1200°F. The data for H-40 show that although all

structures gave exceptionally good elongation and reduction of area values at 700°, 900°, and 1200°F, the normalized structure exhibited extremely low ductility at 1100°F. The other structures gave good ductility at 1100°F, although the bainitic material tended to show slightly lower values than the pearlitic and martensitic bar stock.

Where lower hardness values than 300 BHN are permissible, consideration can be given to pearlitic structures. The following principles appear to govern the use of pearlitic structures:

1. Pearlitic structures have low comparative strengths at low temperatures due to low tensile and yield strengths. In the case of "17-22A"S steel, where lower and middle pearlite may have relatively high hardness, their strengths were only slightly below the bainitic structures. Thus, pearlitic structures would not ordinarily be suitable for use at 700° and 900°F except for relatively low stress applications. Fine to medium pearlite in "17-22A"S steel would not, however, be particularly harmful provided secondary hardening kept the hardness up.

2. Because pearlites compare far more favorably at the higher temperatures, little or no sacrifice in strength may be involved by using pearlitic structures. It should be noted, however, that lower (fine) pearlite appeared to be unduly weak in both 4340 and "17-22A"S steels at the higher temperature. If pearlitic structures are to be used at the higher temperatures, relatively coarse pearlite from transformation in the upper part of the pearlite range should be obtained.

3. The presence of some pearlite in a steel of the type of "17-22A"S apparently would not be particularly detrimental at any temperature provided the hardness was sufficiently high.

4. Although data are sparse, there was no indication that pearlitic structures had any significantly better elongation and reduction of area in rupture tests at any temperature. In fact, the upper pearlite with high strength at the higher temperatures tended to have the lowest values.

Relationship between Type of Structure and Chemical Composition

The data are reported and discussed in terms of the types of microstructure without regard to alloy content. It should be recognized, however, that the alloy content influences the level of strength for the various structures. This was true even at 700°F where the 4340 had lower strength than the "17-22A"S even at the same initial hardness. Apparently "17-22A"S also was superior to H-40 for similar structures at 700°F. The "17-22A"S structures maintained strength better with increasing temperature than the 4340 steel. It was necessary to go to higher temperatures and longer time periods before the influence of increased alloy content became more apparent. Thus, at 1000 hours at 1100°F, the H-40 material was stronger than "17-22A"S and the C-422 was stronger than the H-40 for similar bainitic and martensitic structures. Since the H-40 and C-422 steels could not be transformed to a true pearlitic structure, comparisons of this type of structure are difficult to make. However, the "pearlitic" H-40 structure, which was actually more nearly a spheroidized structure, was considerably stronger at 1200°F than the "17-22A"S pearlitic structures for 100-hour rupture times.

Estimation of Strengths from Microstructures

The correlation of microstructures for continuously cooled normalized bar stock and for the turbine wheels indicates that reasonably good estimates of probable strength can be made from microstructure. In the case of the wheels, this was aided by not too much variation in strength between the structures involved. It is doubtful that microexamination alone would be good enough to determine whether the structure with the very highest strength had been obtained or not.

The wheels had generally higher short time strengths than the isothermally transformed structures. There was also a slight tendency for the normalized bar stock to do likewise. It is uncertain whether or not this was due to continuous cooling transformation or to other factors not yet established. Certainly this could not have been predicted from present knowledge of microstructures.

The variation between heats of "17-22A"S steel with similar microstructure in the pearlitic range was not evident from the microstructure. If the variation was due to secondary hardening or to minor differences in transformation characteristics, it is doubtful if microstructures would ever be useful for establishing such variations.

At present, microstructure examinations showing predominantly bainitic structures indicate a relatively high level of strength. It is possible that some estimate could be made of the relative level within the range for bainites, although this is difficult for steels of the "17-22A"S type. The relative strengths from martensitic or pearlitic structures could also be estimated. The variation within the types of pearlite probably could also be estimated.

Limitations of Results

Experience indicates that the relations developed between structure and properties are quite reliable for the steels when heat treated at the usual temperatures. In using the results of this investigation, however, due consideration should be given to a number of factors:

1. The survey of properties was very limited. Careful analysis of the data suggests that a few of the values ought to be checked before too much reliance on detail of results is accepted.

2. The relative strengths for various time-temperature-total deformation-creep conditions could be fairly complex for the structures. This has not been well covered by the survey tests. Thus, more complete testing of structures might well show the relationships for varying service requirements better than the data reported. In particular, caution should be used where comparisons were based on time for fracture, time for a limited total deformation, or on creep rates at single stresses. Such comparisons often suggest much wider differences than the more practical evaluation of the variation in stress for fracture or total deformation in a given time period or the stress for a given creep rate.

3. One of the most severe limitations is the omission of checks between heats or determination of the effect of varying prior history. The two heats of "17-22A"S bar stock suggest that at least in the pearlite region substantial variations can be present even when the transformation diagrams indicate no great difference.

4. Only one temperature of heat treatment was involved for each steel. The influence of varying this factor on relative strengths of the structures was not checked. Likewise, any effects of tempering conditions have not been studied or the effects of tempering to varying hardness levels.

5. The evaluation of relative strengths for continuously cooled structures has not been well checked. The evaluation seems quite good on a qualitative basis for normalized bar stock and for forged wheels. However, the

higher strengths at short time periods suggest that estimations of strength of continuously cooled structures, other than martensite, should be checked further.

CONCLUSIONS

A survey of the variations in properties at 700° to 1200°F of four low alloyed hardenable steels with possible variations in microstructure has been carried out. The survey covered martensitic, bainitic, and pearlitic structures obtained by isothermal transformation. Tempering was used to reduce hardness to 300 Brinell when the structure was initially harder. Principles developed were checked against the properties of normalized bar stock and heat-treated turbine wheels. The results indicate the following conclusions:

1. Wide ranges in structure were easily obtainable in SAE 4340 and a 1.25 Cr - 0.75 Si - 0.5 Mo - 0.25 V steel. Increased sluggishness of transformation limits the range of structures possible in reasonable time periods for the 3 Cr - 0.5 Mo - 0.5 W - 0.8 V steel, while the structure of a 13 Cr - 1 Mo - 0.8 W - 0.25 V steel was limited to tempered martensite at 300 Brinell hardness.

2. In those steels subject to transformation within the pearlitic and bainitic regions in reasonable time periods, a substantial range in properties is possible. In general, bainitic structures had the maximum strength over the entire temperature range. Martensite ranged from medium to low strength with increasing temperature. Pearlites increased in relative strength with increasing temperature to approximately the same level as the bainites at the highest temperatures.

3. Within each type of structure, considerable variation in strength can exist. In general, the maximum strength shifted from structures produced by transformation in the lower part of the bainite or pearlite regions of the transformation diagram to the upper temperature regions as the test temperature increased. There were variations in this, particularly for vanadium-bearing steel where secondary hardening characteristics probably influence the strength of the individual structures. In addition, there were shifts in relative strength, depending on the criterion of strength used at individual temperatures.

4. In most cases, surprisingly wide ranges in structure had similar strengths at elevated temperatures. In almost every case, there were, however, outstandingly strong or weak structures.

5. Normalizing generally results in a high level of strength because it tends to produce predominantly bainitic structures. It should be recognized, however, that in normalizing the section size and transformation characteristics of the steel must be such as to cause bainites to form for this generalization to hold.

6. Reasonably good correlation between structures and properties of turbine wheels was obtained by applying the results of this investigation. Some discrepancy was observed in that the wheels had higher strengths at short time periods than were observed for the isothermal structures.

7. The generalities stated for the relations between structure and properties apparently hold quite well for the steels investigated. The structures, however, do not indicate level of properties for different steels. Alloy content influences the actual strengths. The low Cr - Mo - V steel was superior to 4340 at all temperatures. The higher alloyed steels only became superior to the low Cr - Mo - V steel at the higher temperatures and longer time periods.

8. The trends shown by the data appear to be quite reliable. However, the test data were limited in many respects and due consideration should be given to the limitations.

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TABLE I

TYPE STRUCTURES, HEAT TREATMENTS AND ACTUAL STRUCTURES FOR 4340 STEEL

(All 4340 bar stock austenitized at 1750°F for 1 hour.)

Aim Structure	Transformation Conditions		Approximate Structure Obtained	B H N	Tempering		B H N
	Temp (°F)	Time (hrs)			Temp (°F)	Time (hrs)	
Upper Pearlite	1240	10	80% medium pearlite + 20% ferrite	212/221	None	--	212/221
Middle Pearlite	1150	14	95% fine pearlite and fine carbide-ferrite aggregate + 5% ferrite	197/233	None	--	197/233
Lower Pearlite	1050	111	99% very fine carbide-ferrite aggregate + 1% ferrite	255/275	None	--	255/275
Upper Bainite	850	28	70% coarse bainite + 30% martensite	319/327	None	--	319/327
Middle Bainite	750	24	100% medium acicular bainite	293/313	None	--	293/313
Lower Bainite	650	1-1/2	100% fine acicular bainite	430	1100	1-1/4	277/301
Normalized	Air Cooled from 1750		35% martensite + 65% bainites	385	1100	1	300/311
Oil Quenched	Oil Quenched from 1750		100% martensite	585	1100	10	304/309

TABLE II

TYPE STRUCTURES, HEAT TREATMENTS AND ACTUAL STRUCTURES OF 1.25 Cr-Mo-Si-V ("17-22A"S) STEEL

(All "17-22A"S bar stock austenitized at 1750°F for 1 hour.)

Aim Structure	Transformation Conditions		Approximate Structure Obtained	B H N	Tempering		B H N
	Temp (°F)	Time (hrs)			Temp (°F)	Time (hrs)	
Upper Pearlite	1300	1-1/2	45% medium pearlite + 55% ferrite	196/237(a)	None	--	196/237
Middle Pearlite	1225	1-1/2	40% medium fine pearlite + 60% ferrite	266/285	None	--	266/285
Lower Pearlite	1150	10	40% fine pearlite + 60% ferrite	375	1200	12	263/313
Upper Bainite	900	2	60% medium bainite + 40% martensite	465	1200	16	284/327
Middle Bainite	800	1/2	97% fine acicular bainite + 3% martensite	360	1200	4	307/310
Lower Bainite	700	1/12	100% fine acicular bainite	365	1200	12	273/302
Normalized	Air Cooled from 1750		15% martensite + 85% coarse bainites	355	1200	10	302/313
Oil Quenched	Oil Quenched from 1750		100% martensite	525	1300	1	272/310

(a) Hardness values of approximately 310 were obtained for this transformation temperature for Heat No. 24797. Hardnesses reported are for Heat 10420.

TABLE III

TYPE STRUCTURES, HEAT TREATMENTS AND ACTUAL STRUCTURES FOR 3 Cr-Mo-W-V (H-40) STEEL

(All H-40 bar stock austenitized at 1950°F for 1 hour.)

Aim Structure	Transformation Conditions		Approximate Structure Obtained	B H N	Tempering		B H N
	Temp (°F)	Time (hrs)			Temp (°F)	Time (hrs)	
Pearlite	1300	24	fine carbide precipitate	190/200	None	--	190/200
Bainite	750	10	100% bainite	480	1300	1	293/313
Normalized	Air Cooled from 1950		20% martensite + 80% bainites	435	1200	18	310/321
Oil Quenched	Oil Quenched from 1950		100% martensite	523	1200	12	290/323

TABLE IV

RUPTURE, TOTAL DEFORMATION, AND CREEP DATA AT 700°, 900°, 1000°, AND 1100°F FOR ISOTHERMALLY TRANSFORMED 4340 STEEL

Structure	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 1 in.)	Reduction of Area (%)	Deformation on Loading (in./in.)	Time to Reach Specified Total Deformation (hours) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hour)
700°F											
Middle Pearlite	199	90,000	10.7	23.0	57.0	0.03274	a	a	a	a	--
Lower Pearlite	221	90,000	98.8	21.8	56.5	0.01650	a	a	a	a	0.0432
Upper Bainite	324	90,000	1316 (d)	--	--	0.00465	a	a	1	198	0.00032
Middle Bainite	309	90,000	1315 (d)	--	--	0.00472	a	a	~1	1291	0.00019
Lower Bainite	277	90,000	1485 (d)	--	--	0.00440	a	a	~1	2000(b)	0.00016
Oil Quenched	304	90,000	1350 (d)	--	--	0.00430	a	a	2	675	0.00027
Normalized	300	90,000	1294 (d)	--	--	0.00467	a	a	1	1000	0.00016
900°F											
Upper Pearlite	217	55,000	4.5	51.0	68.8	0.01502	a	a	a	a	--
	219	40,000	108.6	23.0	35.0	0.00475	a	a	--	--	--
Middle Pearlite	231	55,000	9.7	28.0	56.0	0.00701	a	a	a	<1	--
	295	40,000	326.2	10.0	11.0	0.00225	a	a	4	35	0.0125
Lower Pearlite	260	55,000	20	34.5	37.9	0.00313	a	a	<1	~1	0.55
	255	40,000	402.3	5.0	5.0	0.00177	a	<1	19	125	0.00387
Upper Bainite	325	55,000	1215	6.0	6.4	0.00265	a	a	6	48	0.00163
	320	40,000	1105 (d)	--	--	0.00268	a	a	8	125	0.00019
Middle Bainite	313	55,000	1417	4.1 (c)	4.7	0.00380	a	a	1	51	0.00064
	302	40,000	1009 (d)	--	--	0.00260	a	a	60	2200(b)	0.00021
Lower Bainite	277	55,000	897	18.5 (c)	15.4	0.00250	a	a	8	51	0.0053
	290	40,000	1985(d)	--	--	0.00243	a	a	38	225	0.00107
Oil Quenched	306	55,000	381	19.5	39.5	0.00269	a	a	2	13	0.0148
	302	40,000	2338	4.0	5.5	0.00175	a	<1	50	355	0.00111
Normalized	300	55,000	842	12.0	22.4	0.00260	a	a	8	64	0.00414
	300	40,000	1919 (d)	--	--	0.00164	a	5	1160	>3000(b)	0.00015

TABLE IV, Continued

Structure	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in.)	Reduction of Area (%)	Deformation on Loading (in./in.)	Time to Reach Specified Total Deformation (hours) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hour)
					1000°F						
Upper Pearlite	219	13,000	1103 (d)	--	--	0.00044	6	63	528	1400(b)	0.00057
Middle Pearlite	225	31,000	52.2	10.0	9.5	0.00169	a	--	--	--	--
	197	15,000	989 (d)	--	--	0.00116	a	10	135	570	0.00113
	229	13,000	1539 (d)	--	--	0.00053	10	52	515	1175	0.00060
Lower Pearlite	270	13,000	848	21.4	24.8	0.00068	~2	6	46	141	0.00537
Upper Bainite	327	31,000	389	10.0	10.1	0.00185	a	<1	10	75	0.0072
	325	20,000	1736	5.2	5.6	0.00118	a	10	130	475	0.00124
	325	15,500	1005 (d)	--	--	0.00096	<1	25	470	1500(b)	0.00042
	322	13,000	1075 (d)	--	--	0.00057	5	91	1130(b)	--	0.00023
Middle Bainite	295	31,000	261	5.9	5.6	0.00190	a	<1	18	85	0.0070
	291	20,000	1518	3.0	4.1	0.00119	a	4	85	450	0.00145
	307	13,000	1706 (d)	--	--	0.00068	4	42	472	1920(b)	0.00030
Lower Bainite	291	31,000	210	9.4	17.0	0.00161	a	<1	6	26	0.0179
	294	13,000	1035 (d)	--	--	0.00055	2	32	300	1104(b)	0.00053
Oil Quenched	310	30,000	182	10.9	14.1	0.00144	a	1	4	20	0.022
	309	19,000	918	12.6	15.0	0.00094	<1	8	70	245	0.00295
	306	13,000	1025 (d)	--	--	0.00060	3	27	248	628	0.00115
Normalized	290	31,000	371	5.5	7.4	0.00126	a	5	50	145	0.00505
	300	20,000	1392	5.0	4.0	0.0009	~1	20	228	650	0.00116
	301	12,000	1000 (d)	--	--	0.00050	12	114	802	2150(b)	0.00037
					1100°F						
Upper Pearlite	218	18,000	21.7	28.0	27.0	0.00152	a	--	--	--	--
	212	4,500	1146 (d)	--	--	0.00053	52	235	893	1900(b)	0.00046
Middle Pearlite	217	18,000	43.5	7.5	8.6	0.00097	--	--	--	--	--
	233	4,500	1148 (d)	--	--	0.00024	25	93	315	643	0.00139
Lower Pearlite	255	18,000	27.2	7.0	11.4	0.00108	a	--	--	~4.5	--
	275	4,250	1007 (d)	--	--	0.00032	9	21	90	217	0.00390
Upper Bainite	323	18,000	106	12.2	11.6	0.00130	--	--	--	--	--
	319	4,500	990 (d)	--	--	0.00026	17	78	552	1600 (b)	0.00048
Middle Bainite	293	18,000	80	8.2	10.2	0.00080	--	--	--	~18	--
	302	4,500	1343 (d)	--	--	0.00025	13	55	432	1550(b)	0.00044
Lower Bainite	293	18,000	54.2	12.6	16.8	0.00139	a	--	--	~7	--
	301	4,500	1008 (d)	--	--	0.00042	3	19	156	436	0.00172
Oil Quenched	290	18,000	43.5	20.0	25.2	0.00148	a	--	--	~2	--
	309	4,500	1080 (d)	--	--	0.00027	5	22	104	258	0.0024
Normalized	293	18,000	69.6	7.0	11.7	0.00116	a	--	--	--	--
	299	6,000	1150 (d)	--	--	0.00035	8	26	100	286	0.0026
	311	4,000	1056 (d)	--	--	0.00017	18	96	484	1400(b)	0.00052
	292	2,000	1060 (d)	--	--	0.0001	86	302	1550(b)	--	0.00022

(a) Specimen reached this deformation in loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen, elongation percent in one inch.
(d) Test discontinued at this time.

TABLE V

RUPTURE, TOTAL DEFORMATION, AND CREEP DATA AT 700°, 900°, 1100°, AND 1200°F FOR ISOTHERMALLY TRANSFORMED STRUCTURES OF A 1.25 CR-MO-SI-V ("17-22A"S) STEEL

Structure	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in.)	Reduction of Area (%)	Deformation on Loading (in./in.)	Time to Reach Specified Total Deformation (hours) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hour)
					700°F						
Upper Pearlite	233(g)	69,000	1080 (d)	--	--	0.0024	a	a	(h)	(h)	0.00003
Middle Pearlite	267	115,000	265.2	20.0 (c)	59.2	0.0095	a	a	a	<1	0.0095
	295	95,000	1105 (d)	--	--	0.00495	a	a	--	>2000(b)	0.00008
Lower Pearlite	263	115,000	(f)	19.0 (c)	61.0	--	--	--	--	--	--
	290(g)	93,000	1080 (d)	--	--	0.0176	a	a	a	a	0.00019
Upper Bainite	284	115,000	147	20.2 (c)	62.0	0.0071	a	a	a	<1	0.0180
	(g)	108,000	1105 (d)	--	--	0.0056	a	a	a	1000	0.0001
Middle Bainite	309	115,000	1827 (d)	--	--	0.0061	a	a	a	45	0.00029
	309	104,000	1105 (d)	--	--	0.0051	a	a	a	>2000(b)	0.00005
Lower Bainite	275	115,000	59.4	18.8 (c)	66.7	0.00815	a	a	a	<1	0.0452
Oil Quenched	278	115,000	289	19.8 (c)	63.3	0.0067	a	a	a	1	0.0095
	298(g)	107,000	1145 (d)	--	--	0.0055	a	a	a	1000	0.0001
Normalized	302	115,000	132	21.0 (c)	61.9	0.0066	a	a	a	1	0.0220
	307	102,000	1145 (d)	--	--	0.00465	a	a	∼1	>2000(b)	0.00007
					900°F						
Upper Pearlite	196(g)	70,000	112	29.0 (c)	60.0	0.01479	a	a	a	a	0.0576
Middle Pearlite	266	70,000	1484	13.0 (c)	25.0	0.00570	a	a	a	24	0.0023
Lower Pearlite	266	70,000	1205 (d)	--	--	0.00406	a	a	2	53	0.00223
Upper Bainite	289	70,000	686	30.0 (c)	59.5	0.00355	a	a	1	50	0.00504
Middle Bainite	307	70,000	1648 (d)	--	--	0.00323	a	a	65	2500(b)	0.00014
Lower Bainite	283	70,000	1456	24.0 (c)	56.2	0.00350	a	a	12	362	0.00115
Oil Quenched	272	70,000	756	30.3 (c)	64.0	0.00378	a	a	3	50	0.00384
Normalized	303	70,000	1482 (d)	--	--	0.00335	a	a	24	1400	0.00030

TABLE V, Continued

Structure	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in.)	Reduction of Area (%)	Deformation on Loading (in. /in.)	Time to Reach Specified Total Deformation (hours) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hour)
					1100°F						
Upper Pearlite	196(g)	41,000	4.4	22.2	27.0	0.00510	a	a	a	--	--
	238(g)	19,000	1298 (d)	--	--	0.0009	3	75	475	958	0.00072
	309	19,000	565	4.4	5.1	0.00082	1	17	159	336	0.00204
	313	15,000	1095 (d)	--	--	0.0006	14	108	622	1460(b)	0.00059
Middle Pearlite	285	19,000	669 (e)	3.0	2.8	0.00110	a	10	185	430	0.00145
Lower Pearlite	290(g)	41,000	42.0	8.5	8.7	0.00226	a	a	4	12	--
	291	15,000	652	15.5	17.1	0.00065	24	54	107	218	0.00340
Upper Bainite	310(g)	41,000	51.5	7.2	8.6	0.00269	a	a	4	13	--
	327	19,000	796	5.8	6.6	0.00110	a	8	177	447	0.00140
	317	15,500	1007(d)	--	--	0.00073	5	65	388	798	0.00094
Middle Bainite	309	41,000	88.2	5.1	4.9	0.00217	a	a	6	19	--
	310	19,000	815	4.0 (c)	3.0	0.00096	a	30	222	575	0.0015
Lower Bainite	290 (g)	41,000	92.8	5.0	4.0	0.00252	a	a	9	32	0.0165
	--	21,000	889	2.0	5.6	0.00174	a	6	198	604	0.00113
	303	14,000	1033 (d)	--	--	0.00078	2	67	621	1700(b)	0.00043
Oil Quenched	293	41,000	23.4	28.0	27.5	0.00173	a	a	a	a	0.0065
	306	20,000	666	4.5	--	0.0011	1	13	139	345	0.00186
	302	15,000	1061 (d)	--	--	0.00079	<1	50	470	1006	0.00085
Normalized	309	41,000	111.5	2.5	3.1	0.00212	a	a	26	--	0.00614
	311	20,000	773	2.0	--	0.00090	1	46	375	656	0.00086
	317	17,000	1035(d)	--	--	0.00079	14	177	875	1200(b)	0.00045
	291	14,000	1150 (d)	--	--	0.00065	50	230	1200	--	0.0003
	302	10,000	1060(d)	--	--	0.0004	32	140	1700(b)	--	0.00016
					1200°F						
Upper Pearlite	219(g)	14,000	215.1	6.5	8.8	0.00056	3	12	47	103	0.0072
	237(g)	7,500	1892	2.0	(e)	0.00030	40	182	590	1050	0.00066
Middle Pearlite	302	14,000	132.4	6.0	7.1	0.00056	2	7	23	51	0.0162
	276	7,500	1033	10.0	(e)	0.00034	10	46	196	370	0.00198
Lower Pearlite	293(g)	14,000	100.2	10.2	10.4	0.00093	<1	4	15	31	0.028
	293	7,500	349	17.0	(e)	0.00040	8	20	67	120	0.00656
Upper Bainite	310(g)	14,000	84.7	7.4	9.4	0.00086	<1	5	17	--	--
	320	7,500	456	22.5 (c)	35.8	0.00054	1	8	45	104	0.00810
Middle Bainite	309	14,000	151.6	6.2	7.9	0.00098	a	9	41	87	0.00845
	310	7,500	812	19.1 (c)	(e)	0.00050	10	26	115	228	0.00316
Lower Bainite	299(g)	14,000	104.4	7.0	13.2	0.00112	a	5	20	45	0.019
	273	7,500	709	22.9(c)	34.6	0.00048	6	30	112	229	0.00360
Oil Quenched	298	14,000	73.1	8.0	14.9	0.00096	a	4	14	--	--
	310	7,500	575	30.0	39.8	0.00058	6	17	69	144	0.00660
Normalized	304	14,000	167.1	4.0	5.0	0.00066	5	20	65	~140	0.00640
	313	7,500	918	10.0	14.9	0.00046	6	46	176	333	0.00230

(a) Specimen reach this deformation on loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen, elongation percent in one inch.
(d) Test discontinued at this time.
(e) Broke in shoulder radius.
(f) Broke on loading.
(g) Heat No. 10420; all other tests Heat No. 24797.
(h) Deformation not obtained during testing period and would have required excessive extrapolation.

TABLE VI

RUPTURE, TOTAL DEFORMATION, AND CREEP DATA AT 700°, 900°, 1100°, AND 1200°F FOR ISOTHERMALLY TRANSFORMED H-40 STEEL

Structure	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in.)	Reduction of Area (%)	Deformation on Loading (in. /in.)	Time to Reach Specified Total Deformation (hours) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hour)
					700°F						
Pearlite	193	90,000	24	22.0 (c)	61.0	0.03306	a	a	a	a	--
Bainite	293	90,000	1170 (d)	--	--	0.00324	a	a	1040	(g)	0.00010
Oil Quenched	290	90,000	1514 (d)	--	--	0.00410	a	a	15	2000(b)	0.00019
Normalized	310	90,000	1292 (d)	--	--	0.00416	a	a	13	1700(b)	0.00017
					900°F						
Pearlite	198	65,000	3.3	22.0 (c)	68.0	0.01080	a	a	a	a	--
Bainite	309	65,000	1193 (d)	--	--	0.00332	a	a	21	297	0.00027
Oil Quenched	290	65,000	917	31.0 (c)	68.0	0.00359	a	a	1	50	0.00463
Normalized	320	65,000	1052	18.0 (c)	36.0	0.00301	a	a	10	85	0.00328
					1100°F						
Pearlite	190	30,000	23	49.0	82.0	--	--	--	--	--	--
Bainite	313	35,000	405	12.0 (c)	33.0	0.00140	a	<1	13	110	0.00585
	295	31,000	930	10.3	20.0	0.00021	a	a	52	232	0.00239
	308	28,000	1005(d)	--	--	0.00168	a	a	132	470	0.00144
	312	23,000	1095(d)	--	--	0.00101	a	36	396	843	0.00073
Oil Quenched	320	40,000	136	12.5	46	0.00232	a	a	10	39	0.016
	321	30,000	865	20.0	26.0	0.00150	a	2	94	279	0.00237
	323	24,000	1032(d)	--	--	0.00120	a	24	300	862	0.00083
Normalized	315	43,000	48.4	(f)	--	0.00226	a	a	27	--	0.0058
	310	40,000	193	5.0	13.6	0.00231	a	a	20	89	0.0074
	312	34,000	272	(e)	--	0.00165	a	6	162	--	0.00148
	320	31,000	720	(e)	--	0.00152	a	7	274	677	0.00105
	316	27,500	1130 (d)	--	--	0.00135	a	36	430	1054	0.00064
					1200°F						
Pearlite	200	25,000	142	23.0	58.0	0.00198	a	a	13	47	--
Bainite	293	25,000	86	27 (c)	52	0.00177	a	--	4	18	--
Oil Quenched	300	25,000	62	45	74	0.00185	a	<1	4	14	--
Normalized	315	25,000	100	17	45	0.00142	a	1	9	38	--

(a) Specimen reached this deformation on loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen, elongation given as percent in one inch.
(d) Test discontinued at this time.
(e) Specimen fractured in shoulder radius.
(f) Specimen fractured in threaded end.
(g) Would have required excessive extrapolation for duration of test.

TABLE VII

RUPTURE, TOTAL DEFORMATION, AND CREEP DATA AT 1100°F FOR HEAT TREATED BAR STOCK OF C-422 STEEL

Treatment	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in.)	Reduction of Area (%)	Deformation on Loading (in./in.)	Time to Reach Specified Total Deformation (hours)				Minimum Creep Rate (%/hour)
							0.1%	0.2%	0.5%	1.0%	
1100°F											
Oil Quenched	307	30,000	1003 (d)	--	--	0.00159	a	~1	133	951	0.00049
Normalized	306	39,000	366	20.9	69.1	0.00214	a	a	9	46	0.00628
Normalized	299	35,000	816	19.6	46.5	0.00204	a	a	16	157	0.00224
Normalized	303	30,000	1120 (d)	--	--	0.00153	a	~3	112	690	0.00088

TABLE VIII

RUPTURE, TOTAL DEFORMATION, AND CREEP STRENGTHS

AT 1000° AND 1100°F FOR TURBINE WHEELS

AND ISOTHERMALLY TRANSFORMED BAR STOCK OF SAE 4340 STEEL

Structure	Rupture Strength (psi)		One-Percent Total Deformation Strength (psi)		0.001%/Hour Creep Strength
	100-hr	1000-hr	100-hr	1000-hr	(psi)
			1000°F		
Upper Pearlite	--	--	--	14,000	(15,000)
Middle Pearlite	26,000	(16,000)	--	13,000	14,500
Lower Pearlite	--	12,000	14,000	--	--
Upper Bainite	46,000	23,000	29,000	17,000	19,000
Middle Bainite	39,000	22,000	29,000	16,000	18,000
Lower Bainite	38,000	(20,000)	24,000	13,000	15,000
Oil Quench. Barstock	35,000	18,500	23,000	11,000	12,000
Norm. Barstock	46,000	22,000	33,000	17,000	19,000
Norm. Disk	48,000	24,000	43,000	17,000	25,000
Oil Quench. Disk	38,000	15,000	23,000	--	--
Int. Quench Disk	48,000	22,000	46,000	17,000	--
			1100°F		
Upper Pearlite	(12,000)	--	--	6,000	--
Middle Pearlite	(15,000)	--	--	3,000	--
Lower Pearlite	(13,000)	--	7,000	--	--
Upper Bainite	18,000	--	--	6,000	--
Middle Bainite	17,000	--	13,000	6,000	--
Lower Bainite	15,000	--	11,000	2,000	--
Norm. Barstock	16,500	--	8,000	4,500	--
Oil Quench. Barstock	(14,000)	--	9,000	--	--
Norm. Disk	18,000	--	11,000	--	--
Oil Quench. Disk	16,000	--	(6,000)	--	--
Int. Quench Disk	19,000	--	15,000	--	--

( ) Indicate approximate values.

TABLE IX

RELATIVE STRENGTHS OF STRUCTURES FOR 4340 STEEL

Temp (°F)	Criterion of Strength	Order of Strength of Microstructures: First	Second	Third	Fourth	Fifth	Sixth	Seventh	Normalized Bar Stock
700	Hours for 1.0% total deformation at 90,000 psi	lower bainite 2020 (a)	middle bainite 1291	martensite 675	upper bainite 198	lower pearlite (b)	middle pearlite (b)	--	1000
	Minimum creep rate at 90,000 psi (%/hr)	lower bainite 0.00016	middle bainite 0.00019	martensite 0.00027	upper bainite 0.00032	lower pearlite 0.0432	middle pearlite (c)	--	0.00016
900	Hours for 1.0% total deformation at 40,000 psi	middle bainite 2200 (a)	martensite 355	lower bainite 225	upper bainite 125	lower pearlite 125	middle pearlite 35	upper pearlite (c)	>3000(a)
	Minimum creep rate at 40,000 psi (%/hr)	upper bainite 0.00019	middle bainite 0.00021	lower bainite 0.00107	martensite 0.00111	lower pearlite 0.00387	middle pearlite 0.0125	upper pearlite (c)	0.00015
	Hours for rupture at 55,000 psi	middle bainite 1417	upper bainite 1215	lower bainite 897	martensite 381	lower pearlite 20	middle pearlite 9.7	upper pearlite 4.5	842
1000	Stress for 1.0% total deformation in 1000 hours (psi)	upper bainite 17,000	middle bainite 16,000	upper pearlite 14,000	lower bainite 13,000	middle pearlite 13,000	martensite 11,000	lower pearlite (c)	17,000
	Stress for rupture in 1000 hours (psi)	upper bainite 23,000	middle bainite 22,000	upper pearlite (a)	lower bainite 20,000(a)	martensite 18,500	middle pearlite 16,000(a)	lower pearlite 12,000	22,000
1100	Stress for rupture in 100 hours (psi)	upper bainite 18,000	middle bainite 17,000	lower bainite 15,000	middle pearlite 15,000(a)	martensite 14,000(a)	lower pearlite 13,000(a)	upper pearlite 12,000(a)	16,500

(a) Estimated values.
(b) Exceeded value on loading.
(c) Not determined due to low strength.

Note: 100% indicated structures except for upper bainite which contained 30% martensite.
Normalized structure - 65% bainites + 35% martensite.

TABLE X

RUPTURE, TOTAL DEFORMATION, AND CREEP STRENGTHS

AT 1100° AND 1200°F FOR TURBINE WHEELS

AND ISOTHERMALLY TRANSFORMED BAR STOCK OF "17-22A"S STEEL

Structure	Rupture Strength (psi)		One-Percent Total Deformation Strength (psi)		0.001%/Hour Creep Strength (psi)
	100-hr	1000-hr	100-hr	1000-hr	
			1100°F		
Upper Pearlite	(25,000)	(17,500)[a]	(22,000)	16,000	16,500
Middle Pearlite	--	17,500	--	--	17,000
Lower Pearlite	30,000	13,000	22,000	--	(10,000)
Upper Bainite	34,000	18,000	28,000	14,000	16,000
Middle Bainite	39,000	18,000	30,000	15,000	15,000
Lower Bainite	40,000	20,000	33,000	17,000	20,000
Oil Quench. Barstock	30,000	18,000	26,000	15,000	15,000
Norm. Barstock	44,000	18,000	(34,000)	18,000	22,000
Oil Quench. Disk	41,000	19,000	36,000	17,000	21,500
Int. Quench Disk	42,000	22,000	--	--	--
Norm. Disk	35,000	15,500	--	--	--
			1200°F		
Upper Pearlite	17,000	9,000	14,000	7,500	--
Middle Pearlite	15,000	7,600	12,000	4,000	--
Lower Pearlite	14,000	(4,400)	8,000	--	--
Upper Bainite	13,000	5,600	7,500	--	--
Middle Bainite	16,500	7,000	13,000	--	--
Lower Bainite	14,500	6,700	11,000	(2,000)	--
Oil Quench. Barstock	12,500	6,400	9,000	--	--
Norm. Barstock	17,000	7,200	16,000	(3,000)	--
Oil Quench. Disk	14,000	--	11,000	--	--
Int. Quench Disk	--	--	--	--	--
Norm. Disk	--	--	--	--	--

(a) Based on Heat 10420 which gave low hardness.

( ) Indicate approximate values.

TABLE XI

RELATIVE STRENGTHS OF STRUCTURES FOR "17-22A"S STEEL

Temp (°F)	Criterion of Strength	Order of Strength of Microstructures: First	Second	Third	Fourth	Fifth	Sixth	Seventh	Normalized Bar Stock
700	Stress for creep rate of 0.0001%/hr (psi)	middle bainite 108,000	upper bainite 108,000	martensite 107,000	middle pearlite 96,000	lower pearlite 93,000	lower bainite ~91,000	upper pearlite 72,000	103,000
	Hours for rupture at 115,000 psi	middle bainite >1827	martensite 289	middle pearlite 265.2	upper bainite 147	lower bainite 59.4	lower pearlite broke on loading	upper pearlite (a)	132
900	Hours for 1.0% total deformation at 70,000 psi	middle bainite 2500(b)	lower bainite 362	lower pearlite 53	martensite 50	upper bainite 50	middle pearlite 24	upper pearlite (c)	1400
	Hours for rupture at 70,000 psi	middle bainite >1648	middle pearlite 1484	lower bainite 1456	lower pearlite >1205	martensite 756	upper bainite 686	upper pearlite 112	>1482
1100	Stress for 1.0% total deformation in 1000 hours (psi)	lower bainite 17,000	upper pearlite 16,000	middle pearlite 16,000(d)	middle bainite 15,000	martensite 15,000	upper bainite 14,000	lower pearlite (a)	18,000
	Stress for creep rate of 0.001%/hr (psi)	lower bainite 20,000	middle pearlite 17,000	upper pearlite 16,500	upper bainite 16,000	middle bainite 15,000	martensite 15,000	lower pearlite 10,000(d)	22,000
	Stress for rupture in 1000 hours (psi)	lower bainite 20,000	upper bainite 18,000	middle bainite 18,000	martensite 18,000	middle pearlite 17,500	upper pearlite 17,500	lower pearlite 13,000	18,000
1200	Stress for 1.0% total deformation in 100 hours (psi)	upper pearlite 14,000	middle bainite 13,000	middle pearlite 12,000	lower bainite 11,000	martensite 9,000	lower pearlite 8,000	upper bainite 7,500	16,000
	Stress for rupture in 100 hours (psi)	upper pearlite 17,000	middle bainite 16,500	middle pearlite 15,000	lower bainite 14,500	lower pearlite 14,000	upper bainite 13,000	martensite 12,500	17,000

(a) Not determined because of low strength.
(b) Extrapolated from time-elongation curve.
(c) Exceeded one-percent deformation on loading.
(d) Estimated from insufficient data.

TABLE XII

RUPTURE, TOTAL DEFORMATION, AND CREEP STRENGTHS
AT 1100° AND 1200°F FOR TURBINE WHEELS
AND ISOTHERMALLY TRANSFORMED BAR STOCK OF H-40 STEEL

Structure	Rupture Strength (psi)		One-Percent Total Deformation Strength (psi)		0.001%/Hour Creep Strength (psi)
	100-hr	1000-hr	100-hr	1000-hr	
			1100°F		
Pearlite	--	--	--	--	--
Bainite	(43,000)	30,500	35,000	22,000	25,000
Oil Quench. Barstock	42,000	29,000	35,000	23,000	25,000
Norm. Barstock	41,000	29,000	39,000	28,000	31,000
Oil Quench. Disk	48,000	32,000	42,000	31,000	34,500
Norm. Disk	45,000	32,500	--	--	--
Int. Quench Disk	47,000	30,500	--	--	--
			1200°F		
Pearlite	26,000	--	--	--	--
Bainite	24,000	--	--	--	--
Oil Quench. Barstock	23,000	--	--	--	--
Norm. Barstock	25,000	--	--	--	--
Oil Quench. Disk	30,000	--	--	--	--

( ) Indicate approximate values.

TABLE XIII

RUPTURE, TOTAL DEFORMATION, AND CREEP STRENGTHS
AT 1100°F FOR TURBINE WHEELS
AND HEAT TREATED BAR STOCK OF C-422 STEEL

Structure	Rupture Strength (psi)		1.0% Total Deformation Strength (psi)		0.001%/hr Creep Strength (psi)
	100-hr	1000-hr	100-hr	1000-hr	
			1100°F		
Oil-Quenched Bar Stock	--	--	--	30,000	--
Normalized Bar Stock	(44,000)	34,000	36,000	29,000	31,000
Oil-Quenched Wheel	43,000	36,000	36,000	30,000	32,000
Normalized Wheel	39,000	32,000	32,500	(28,000)	30,000

( ) Indicate approximate values.

TABLE XIV

CHEMICAL COMPOSITION OF FORGED TURBINE WHEELS

Type Steel	C (%)	Mn (%)	Si (%)	P (%)	S (%)	Cr (%)	Ni (%)	Mo (%)	V (%)	W (%)	Cu (%)	Manufacturer's Heat Number
4340	0.40	0.76	0.29	0.010	0.015	0.74	1.91	0.50	--	--	--	656601
"17-22A"S	0.30	0.57	0.60	0.018	0.019	1.22	0.23	0.49	0.24	--	0.13	38516
H-40	0.29	0.48	0.26	0.012	0.018	3.05	0.49	0.49	0.85	0.55	0.15	K-2509
C-422	0.23	0.81	0.16	0.011	0.012	13.19	0.65	1.03	0.25	0.84	--	W-3561

TABLE XV

HEAT TREATMENTS OF FORGED TURBINE WHEELS

<u>4340 Steel</u>

All forgings were isothermally annealed for 15 hours at 1200°F directly from the forging operation.

	Surface Brinell Hardness	
	Rim	Hub
Disk No. 1 - Normalized Forging		
1st Treatment: Air Cooled from 1750°F and tempered 2 hours at 1200°F	217	229
2nd Treatment: Renormalized from 1750°F (no tempering)	285	285
Disk No. 3 - Oil Quenched Forging		
1st Treatment: Oil Quenched from 1750°F and tempered 8 hours at 1200°F	269	255
2nd Treatment: Oil Quenched from 1550°F and tempered at 1050°F	302	285
Disk No. 4 - Interrupted Quench Forging		
Water Quenched from 1750°F until black, then withdrawn until glow returned. This was repeated until glow did not return upon withdrawal from water. It was then transferred to a furnace at 700°F and held for 8 hours. It was then tempered for 2 hours at 1200°F	302	293

<u>"17-22A"S Steel</u>

All forgings were isothermally annealed for 8 hours at 1200°F directly from the forging operation.

	Surface Brinell Hardness	
	Rim	Hub
Disk No. 1 - Normalized Forging		
(a) Air Cooled from 1750°F and tempered 2 hours at 1200°F	302	285
Disk No. 3 - Oil Quenched Forging		
(a) Oil Quenched from 1750°F and tempered 8 hours at 1200°F	302	302
Disk No. 4 - Interrupted Quench Forging		
(a) Quenched in water until black, withdrawn until glow returned, requenched until black and process repeated until glow did not return. The forging was then placed directly in a furnace at 700°F for 8 hours, then tempered at 1200°F for 2 hours	399	399
(b) Retempered for 2 more hours at 1200°F	341	331

H-40 Steel

All forgings were isothermally annealed for 8 hours at 1200°F directly from forging.

	Surface Brinell Hardness Rim	Hub
Disk No. 1 - Normalized Forging		
(a) Air Cooled from 1950°F and tempered 2 hours at 1200°F	429	444
(b) Retempered 3 more hours at 1200°F	341	341
Disk No. 3 - Oil Quenched Forging		
(a) Oil Quenched from 1950°F and tempered 8 hours at 1200°F	415	415
(b) Tempered 3 more hours at 1200°F	341	352
Disk No. 4 - Interrupted Quench Forging		
(a) Interrupted Quench from 1950°F in water as previously described for other steels; then tempered at 1200°F for 2 hours	389	363
(b) Retempered for 3 more hours at 1200°F	341	331
Final Treatments for All Forgings		
Subsequently, bars cut from all three forgings were retempered for 4 more hours at 1250°F	287 to 322	

C-422 Steel

All forgings were isothermally annealed for 8 hours at 1200°F directly from forging.

	Surface Brinell Hardness Rim	Hub
Disk No. 1 - Normalized Forging		
1st Treatment: Air Cooled from 1900°F and tempered for 2 hours at 1200°F	321	331
2nd Treatment: Full Annealed for 6 hours at 1600°F and furnace cooled; then air cooled from 1900°F and double tempered 2 + 2 hours at 1200°F	285	293
Disk No. 4 - Oil Quenched Forging		
1st Treatment: Oil Quenched from 1900°F and tempered 8 hours at 1200°F	285	285
2nd Treatment: Full Annealed at 1600°F for 6 hours and furnace cooled; then oil quenched from 1900°F and double tempered 2 + 2 hours at 1200°F	302	311

NOTE: Second treatments required due to hard spots after first treatment.

TABLE XVI

COMPARISON OF MICROSTRUCTURES AND PROPERTIES OF TURBINE WHEELS WITH COMPARABLE STRUCTURES FOR BAR STOCK OF SAE 4340 STEEL AT 1000° AND 1100°F

Treatment	Microstructure	Figure No.	Temp (°F)	Rupture Strength (psi)		One-Percent Total Deformation Strength (psi)		0.001%/hr Creep Strength (psi)
				100-hr	1000-hr	100-hr	1000-hr	
Normalized Wheel	Bainite + Martensite	44	1000	48,000	24,000	43,000	17,000	25,000
Interrupted Quench Wheel	Tempered Bainite + Martensite	46	1000	48,000	22,000	46,000	17,000	--
Upper Bainite Bar Stock	70% Bainite + 30% Martensite	8	1000	46,000	23,000	29,000	17,000	19,000
Normalized Bar Stock	65% Bainite + 35% Martensite	11	1000	46,000	22,000	33,000	17,000	19,000
Oil Quenched Wheel	Tempered Martensite	45	1000	38,000	15,000	23,000	--	--
Oil Quenched Bar Stock	Tempered Martensite	12	1000	35,000	18,500	23,000	11,000	12,000
Normalized Wheel	Bainite + Martensite	44	1100	18,000	--	11,000	--	--
Interrupted Quench Wheel	Tempered Bainite + Martensite	46	1100	19,000	--	15,000	--	--
Upper Bainite Bar Stock	70% Bainite + 30% Martensite	8	1100	18,000	--	--	--	--
Oil Quenched Wheel	Tempered Martensite	45	1100	16,000	--	(6,000)	--	--
Oil Quenched Bar Stock	Tempered Martensite	12	1100	(14,000)	--	9,000	--	--

TABLE XVII

COMPARISON OF MICROSTRUCTURES AND PROPERTIES OF TURBINE WHEELS

WITH COMPARABLE STRUCTURES FOR BAR STOCK OF "17-22A"S STEEL AT 1100° AND 1200°F

Treatment	Microstructure	Figure No.	Temp (°F)	Rupture Strength (psi)		One-Percent Total Deformation Strength (psi)		0.001%/hr Creep Strength (psi)
				100-hr	1000-hr	100-hr	1000-hr	
Normalized Wheel	Pearlite + Ferrite + Bainite	48	1100	35,000	15,500	--	--	--
Lower Pearlite Bar Stock	40% Pearlite + 60% Ferrite	15	1100	30,000	13,000	22,000	--	--
Oil Quenched Wheel	Tempered Bainite + Martensite	49	1100	41,000	19,000	36,000	17,000	21,500
Interrupted Quench Wheel	Tempered Bainite + Martensite	50	1100	42,000	22,000	--	--	--
Lower Bainite	100% Fine Acicular Bainite	18	1100	40,000	20,000	33,000	17,000	20,000
Middle Bainite	97% Fine Acicular Bainite + 3% Martensite	17	1100	39,000	18,000	30,000	15,000	15,000
Normalized Bar Stock	85% Coarse Bainite + 15% Martensite	20	1100	44,000	18,000	(34,000)	18,000	22,000
Oil Quenched Wheel	Tempered Bainite + Martensite	49	1200	14,000	--	11,000	--	--
Lower Bainite	100% Fine Acicular Bainite	18	1200	14,500	6,700	11,000	--	--
Middle Bainite	95% Fine Acicular Bainite + 3% Martensite	17	1200	16,500	7,000	13,000	--	--
Normalized Bar Stock	85% Coarse Bainite + 15% Martensite	20	1200	17,000	7,200	16,000	--	--

TABLE XVIII

COMPARISON OF MICROSTRUCTURES AND PROPERTIES OF TURBINE WHEELS WITH COMPARABLE STRUCTURES FOR BAR STOCK OF H-40 STEEL AT 1100°F

Treatment	Microstructure	Figure No.	Temp (°F)	Rupture Strength (psi)		One-Percent Total Deformation Strength (psi)		0.001%/hr Creep Strength (psi)
				100-hr	1000-hr	100-hr	1000-hr	
Oil Quenched Wheel	Tempered Bainite + Martensite	53	1100	48,000	32,000	42,000	31,000	34,500
Interrupted Quench Wheel	Tempered Bainite + Martensite	54	1100	47,000	30,500	--	--	--
Normalized Wheel	Tempered Bainite + Martensite	52	1100	45,000	32,500	--	--	--
Bainitic Bar Stock	100% Bainite	22	1100	(43,000)	30,500	35,000	22,000	25,000
Normalized Bar Stock	80% Bainite + 20% Martensite	24	1100	41,000	29,000	39,000	28,000	31,000

TABLE XIX

COMPARISON OF MICROSTRUCTURES AND PROPERTIES OF TURBINE WHEELS

WITH COMPARABLE STRUCTURES FOR BAR STOCK OF C-422 STEEL AT 1100°F

Treatment	Microstructure	Figure No.	Temp (°F)	Rupture Strength (psi)		One-Percent Total Deformation Strength (psi)		0.001%/hr Creep Strength (psi)
				100-hr	1000-hr	100-hr	1000-hr	
Oil Quenched Wheel	Tempered Martensite	59	1100	43,000	36,000	36,000	30,000	32,000
Normalized Wheel	Tempered Martensite	58	1100	39,000	32,000	32,500	(28,000)	30,000
Normalized Bar Stock	Tempered Martensite	26	1100	(44,000)	34,000	36,000	29,000	31,000
Oil Quenched Bar Stock	Tempered Martensite	25	1100	--	--	--	30,000	--

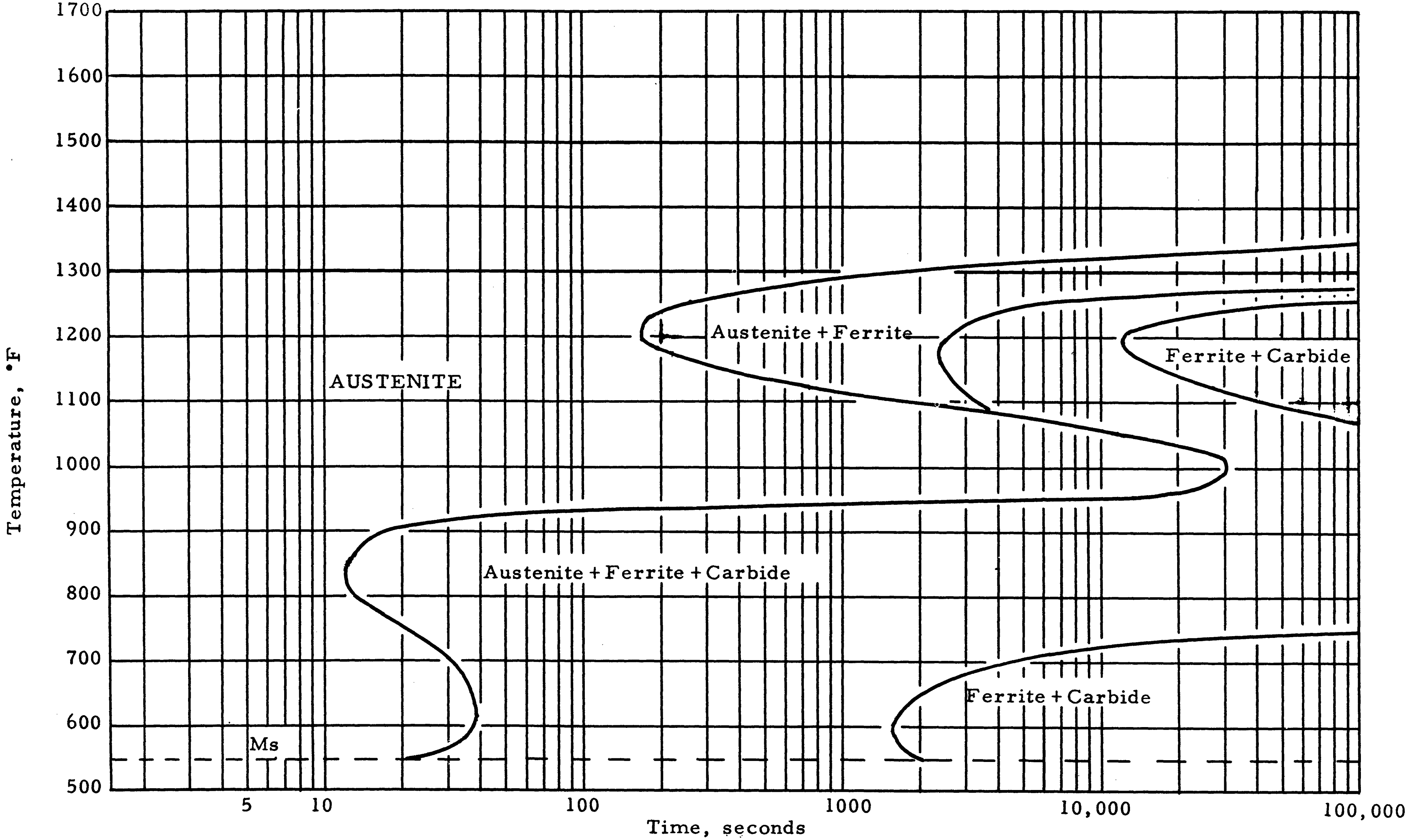


Figure 1. Time-Temperature Transformation Curves for 4340, Austenitized 1550°F, Grain Size 7/8. (Atlas of Isothermal Diagrams, United States Steel, 1951.)

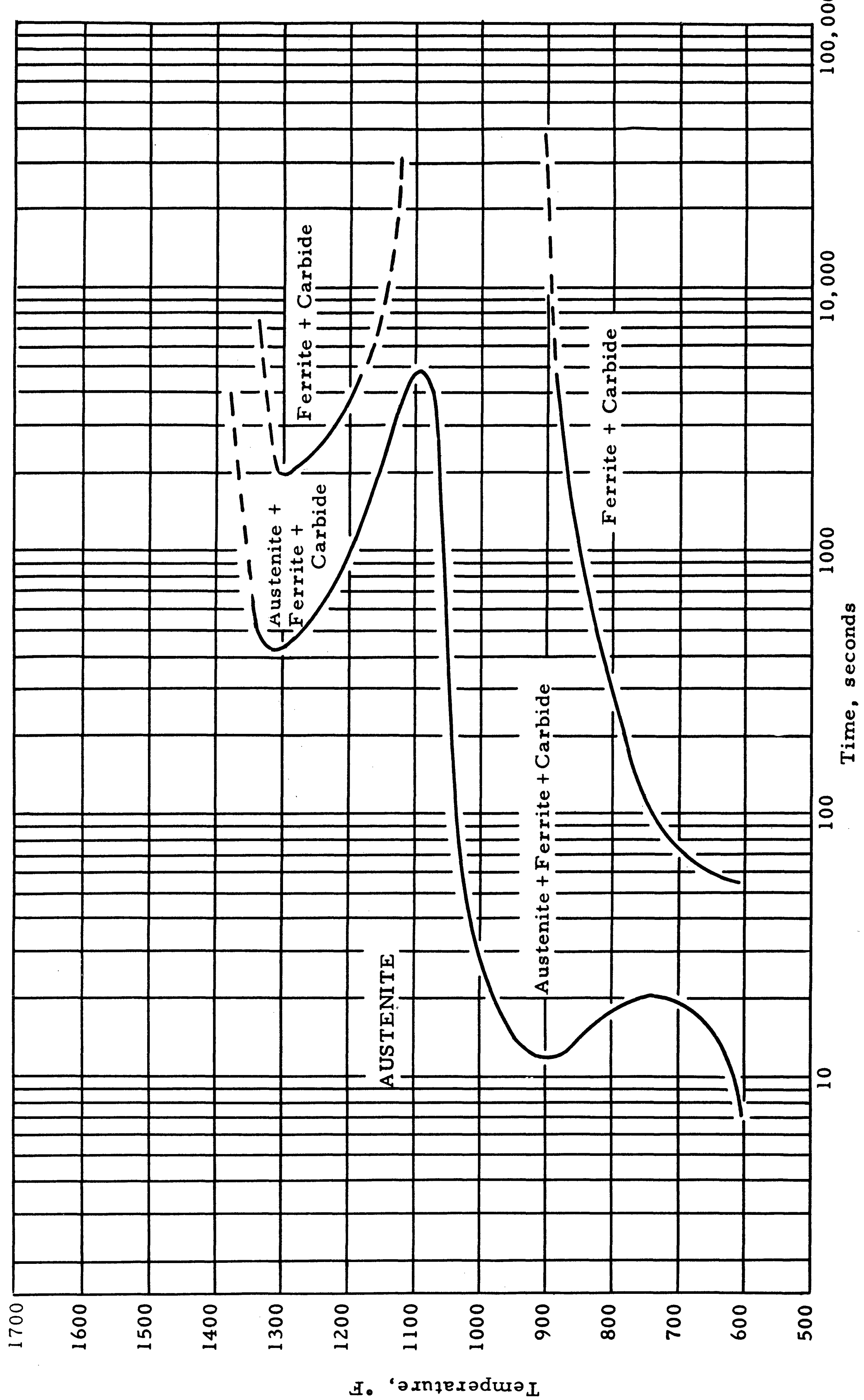


Figure 2. Time-Temperature Transformation Curves for Timken "17-22A"S, Austenitized at 1750°F.

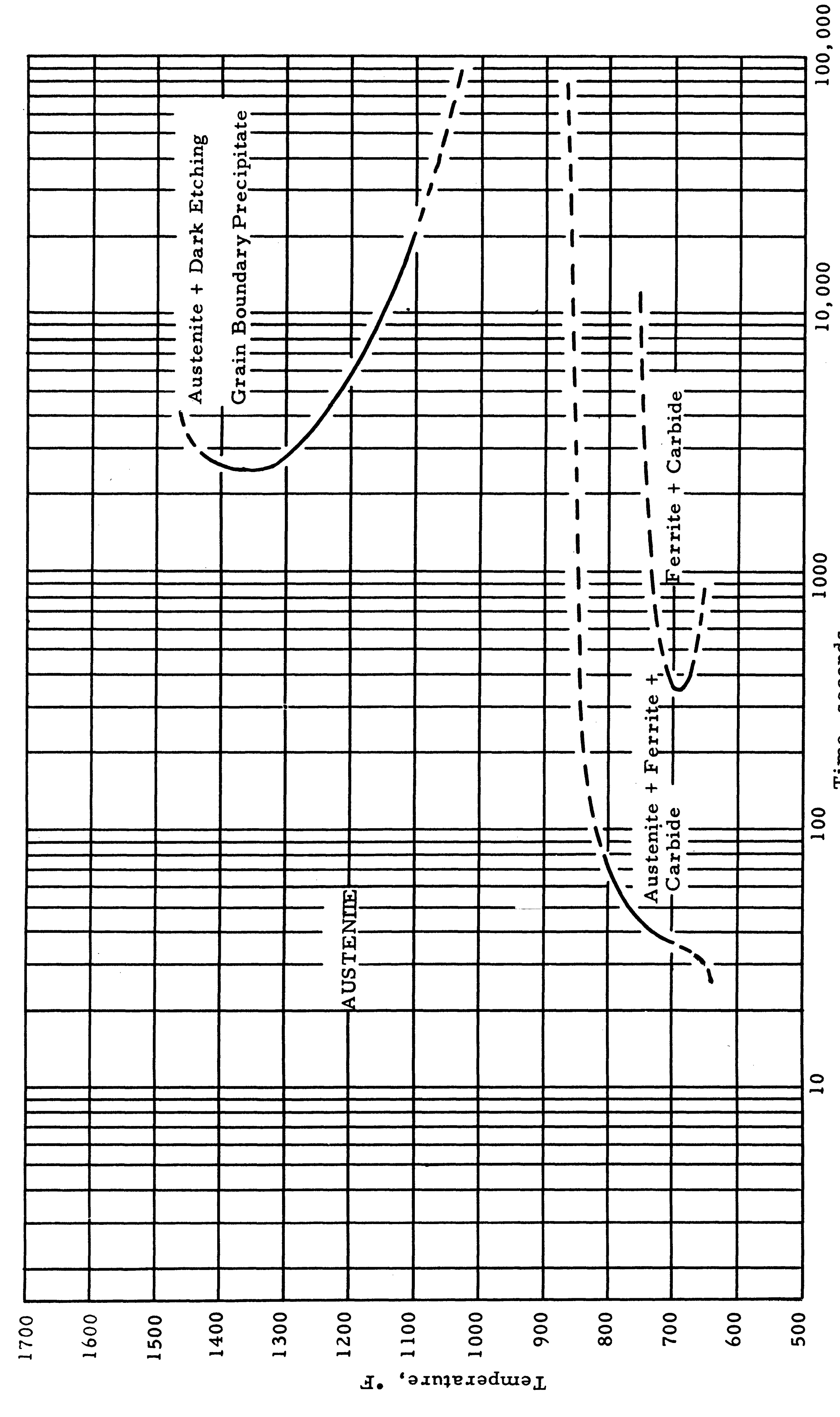


Figure 3. Time-Temperature Transformation Curve for H-40, Austenitized at 1950°F.

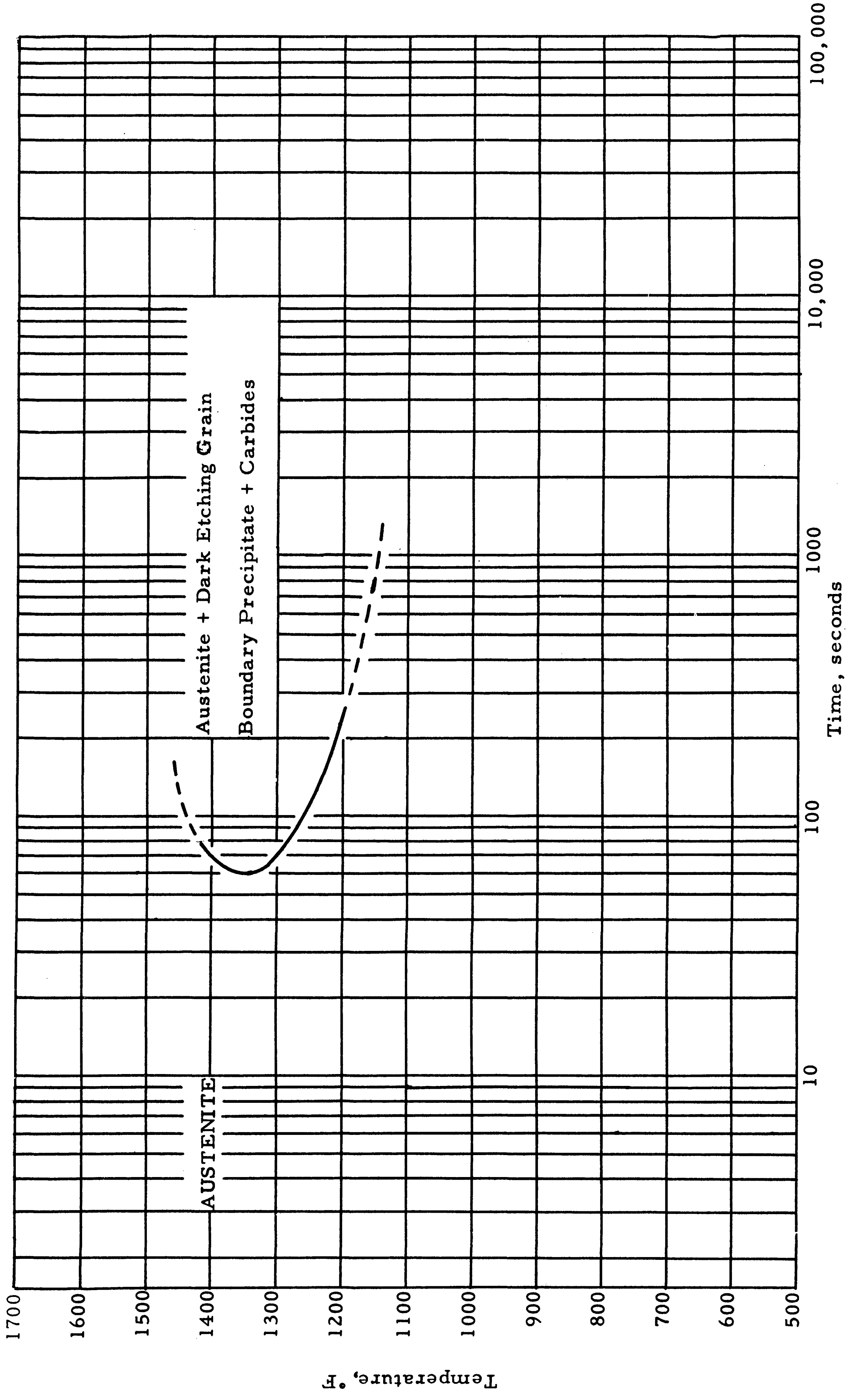
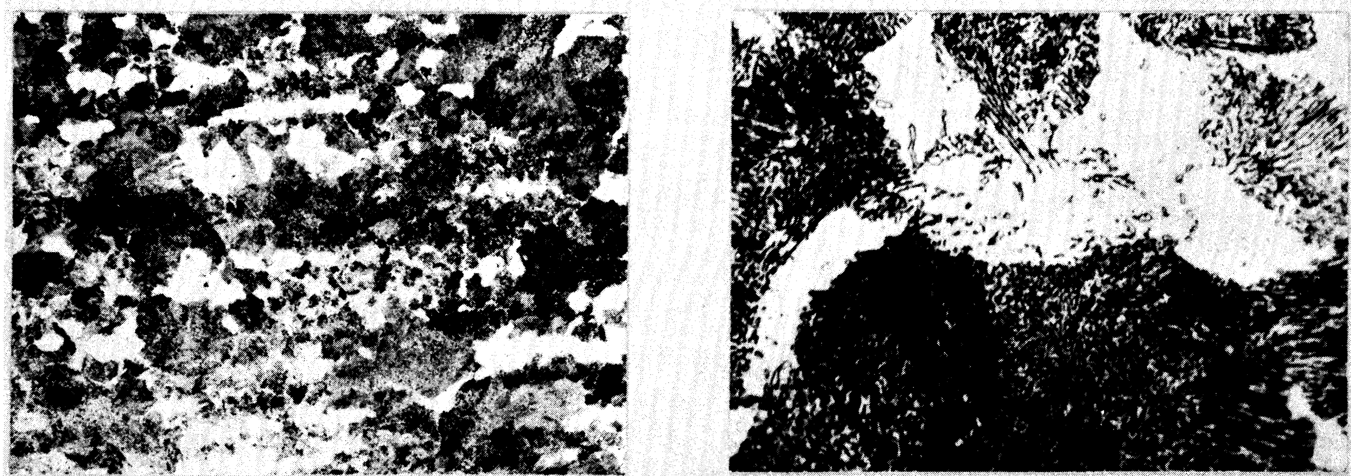


Figure 4. Time-Temperature Transformation Curve for C-422, Austenitized at 1900°F.

X100D X1000D

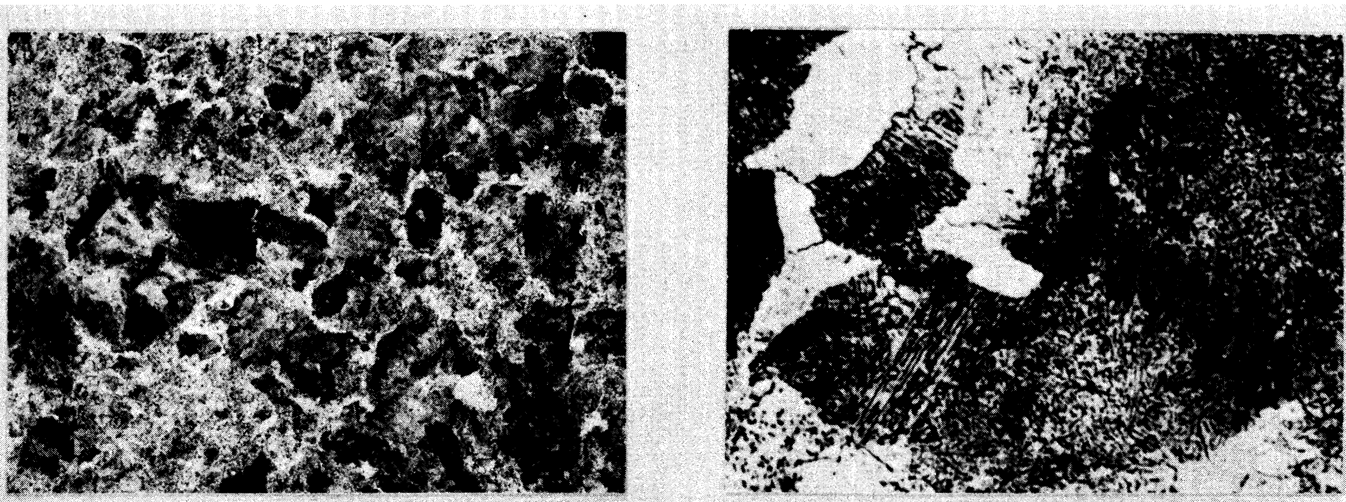
(a) Austenitized 1750°F + 10 hrs at 1240°F - 219 BHN.



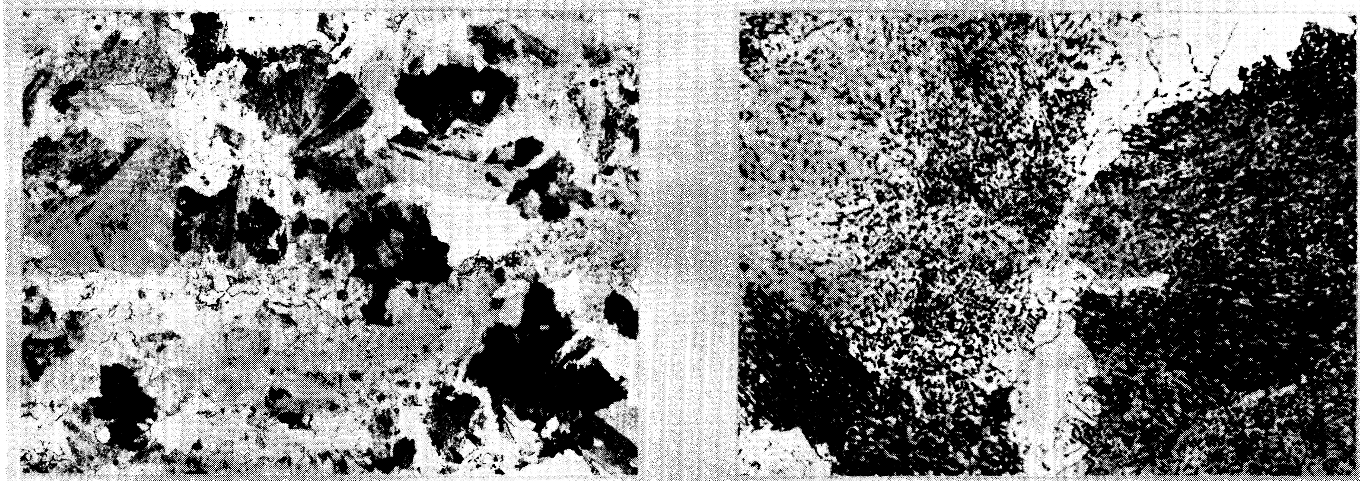
(b) Austenitized 1750°F + 10 hrs at 1240°F + creep tested 1100 hrs at 1000°F and 13,000 psi - 199 BHN.

Figure 5. 4340 Bar Stock (a) As Transformed to Upper Pearlite and (b) after Creep Testing at 1000°F.

X100D X1000D



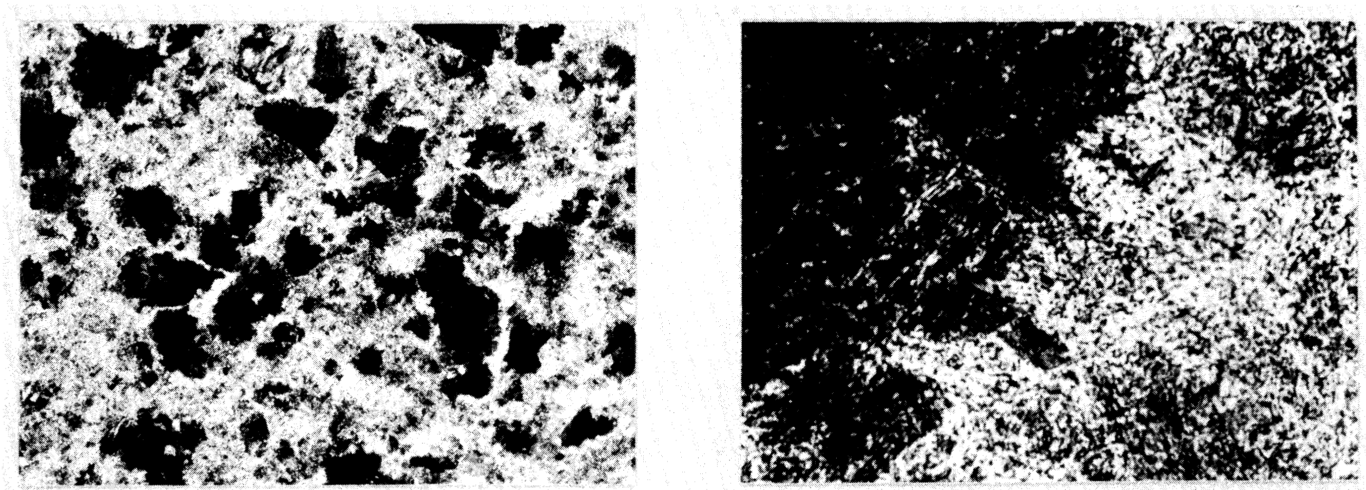
(a) Austenitized 1750°F + 14 hrs at 1150°F - 229 BHN.



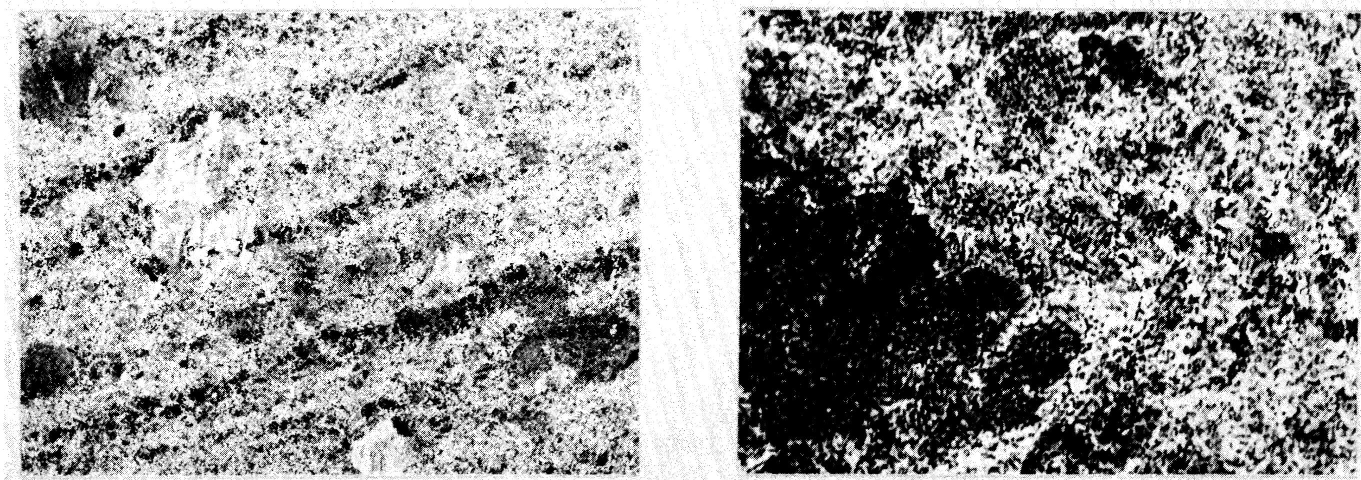
(b) Austenitized 1750°F + 14 hrs at 1150°F + creep tested 1539 hrs at 1000°F and 13,000 psi - 233 BHN.

Figure 6. 4340 Bar Stock (a) as Transformed to Middle Pearlite and (b) after Creep Testing at 1000°F

X100D X1000D



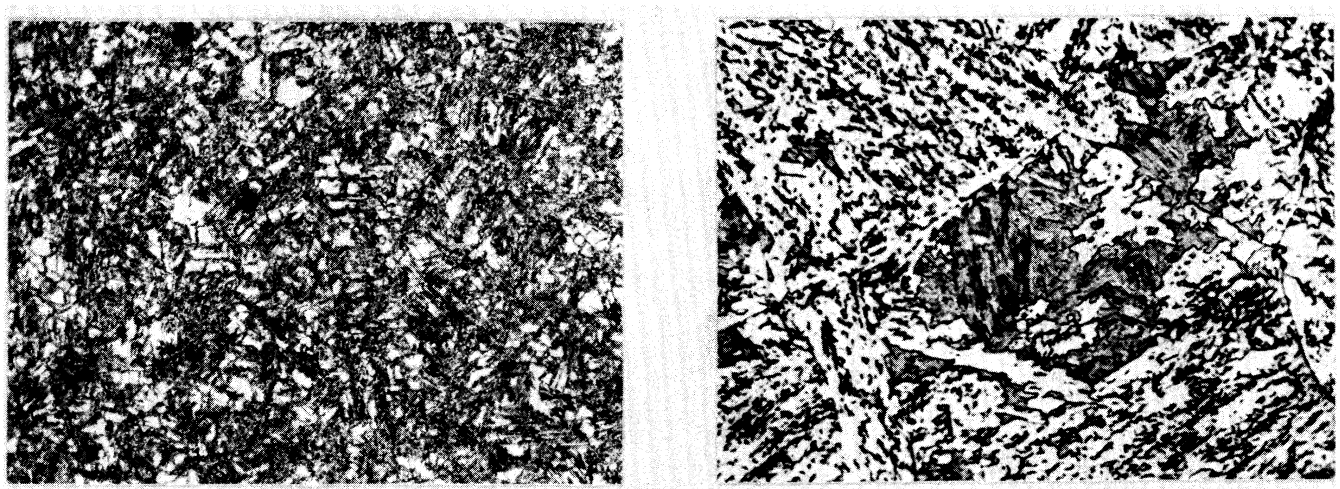
(a) Austenitized 1750°F + 111 hrs at 1050°F - 270 BHN.



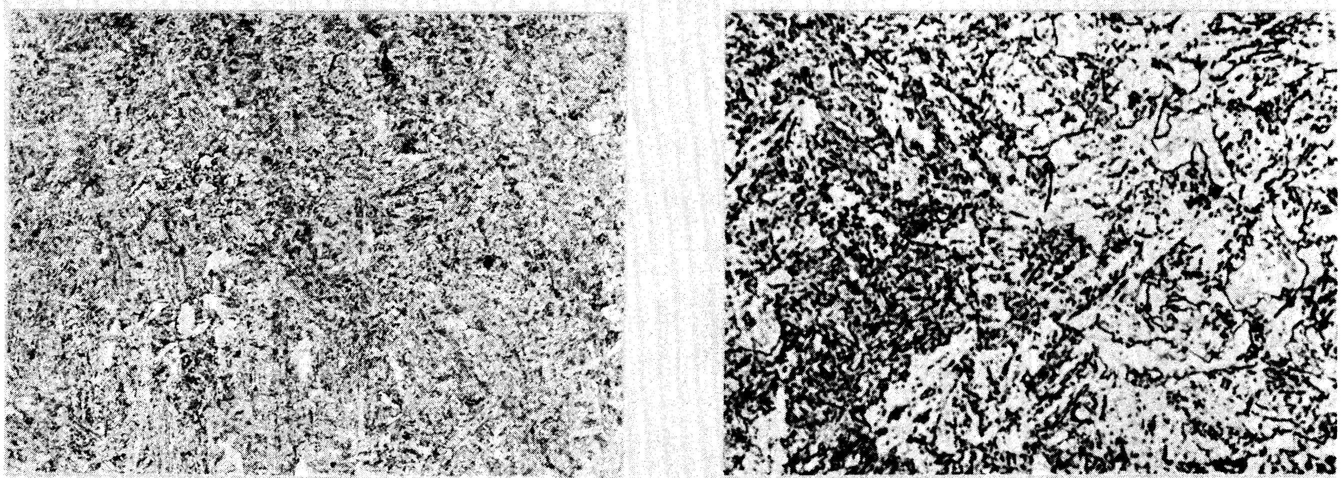
(b) Austenitized 1750°F + 111 hrs at 1050°F + creep-rupture tested 850 hrs at 1000°F and 13,000 psi - 210 BHN.

Figure 7. 4340 Bar Stock (a) As Transformed to Lower Pearlite and (b) after Creep-Rupture Testing at 1000°F.

X100D X1000D



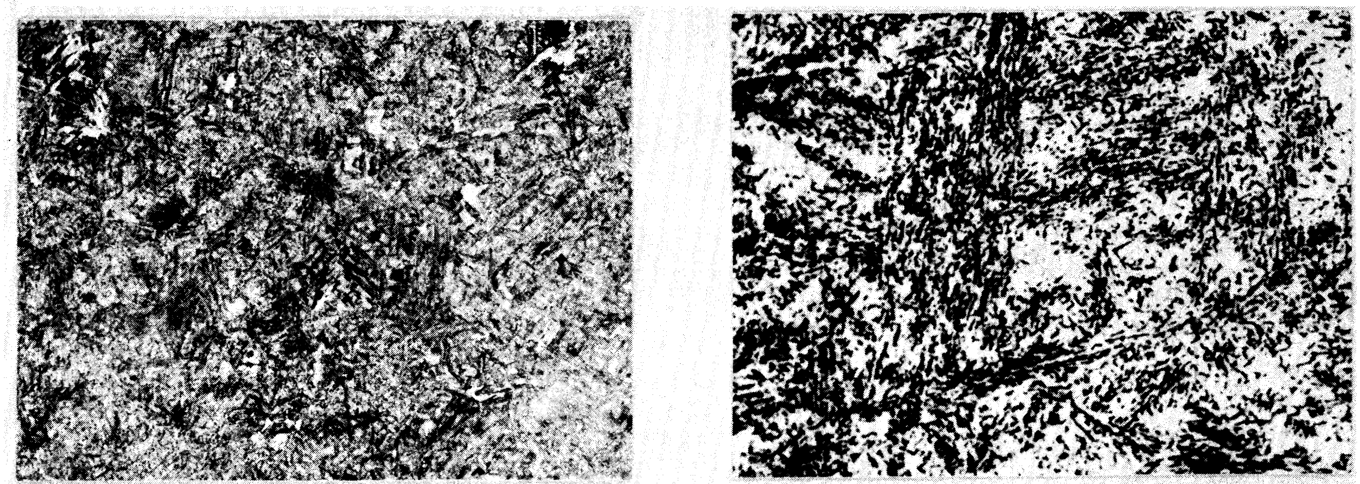
(a) Austenitized 1750°F + 28 hrs at 850°F - 320 BHN.



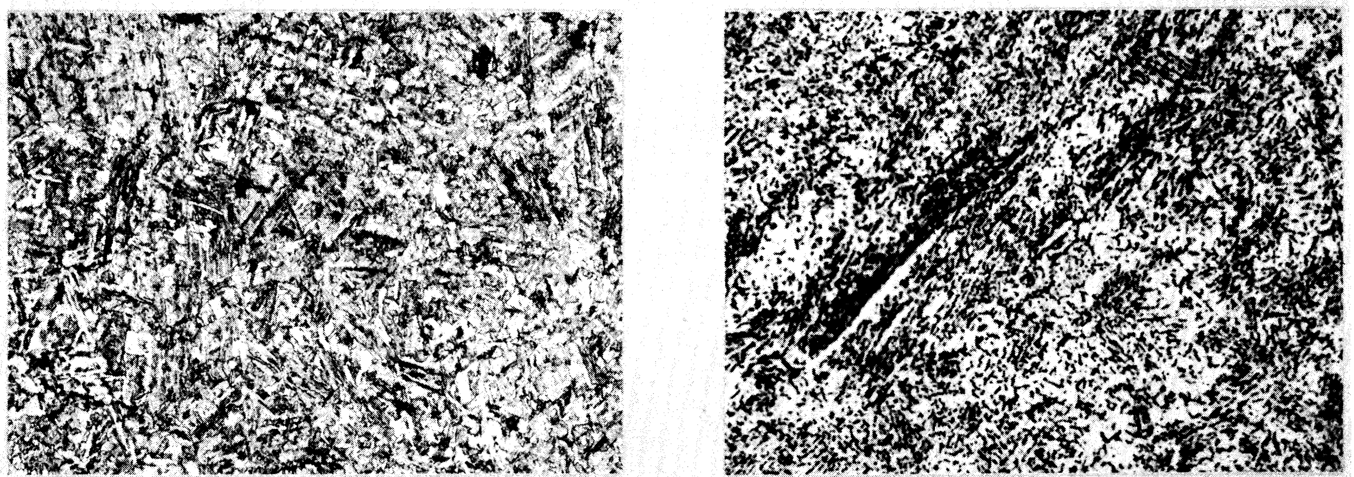
(b) Austenitized 1750°F + 28 hrs at 850°F + creep tested 1005 hrs at 1000°F and 15,500 psi - 255 BHN.

Figure 8. 4340 Bar Stock (a) As Transformed to Upper Bainite and (b) after Creep Testing at 1000°F

X100D X1000D



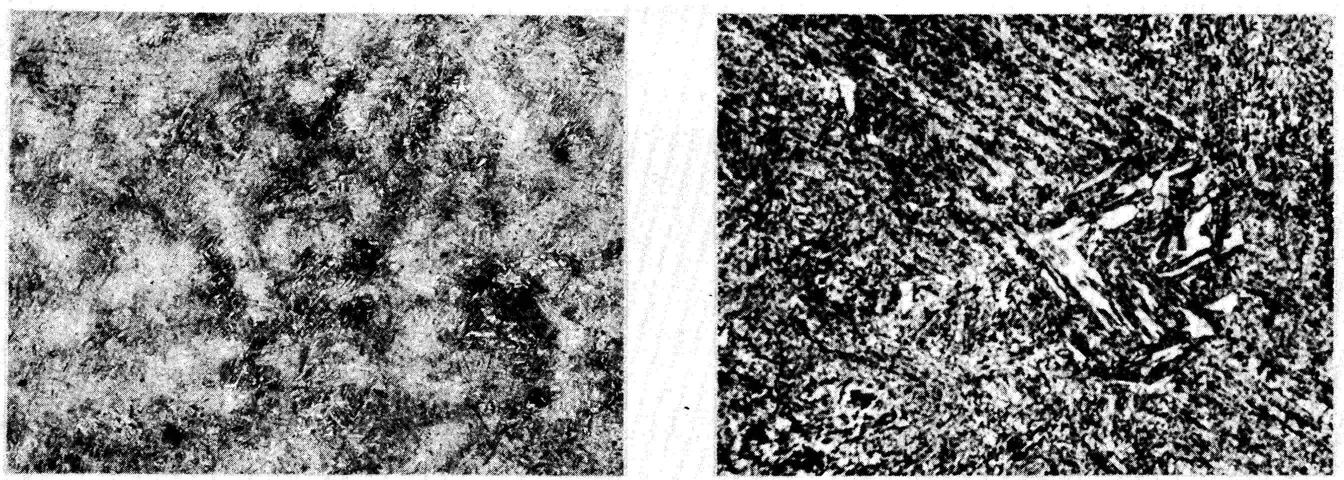
(a) Austenitized 1750°F + 24 hrs at 750°F - 291 BHN.



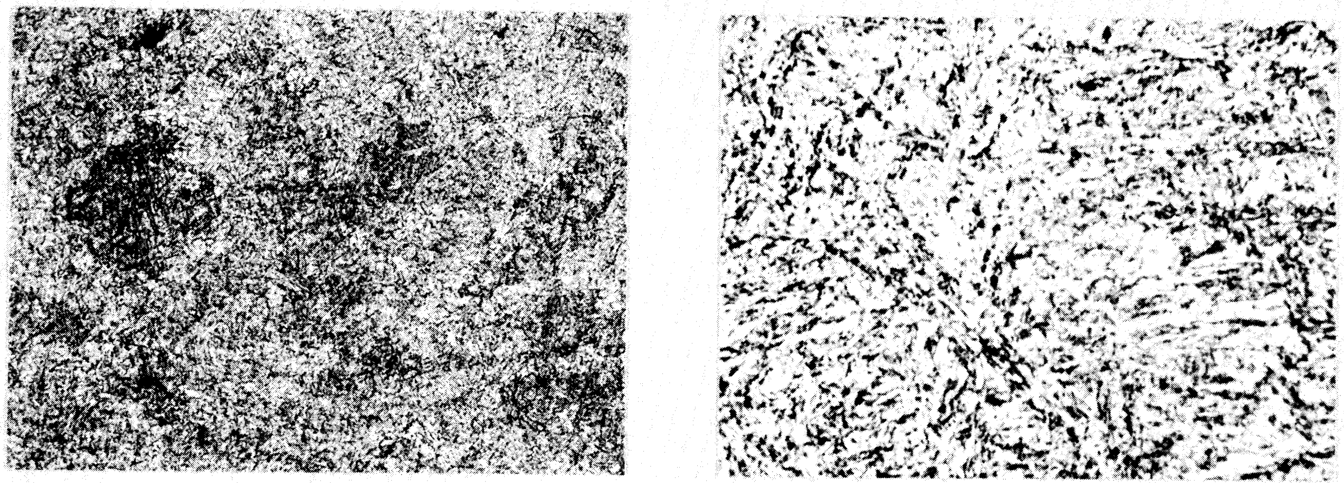
(b) Austenitized 1750°F + 24 hrs at 750°F + creep-rupture tested 1518 hrs at 1000°F and 20,000 psi - 240 BHN.

Figure 9. 4340 Bar Stock (a) As Transformed to Middle Bainite and (b) after Creep Testing at 1000°F.

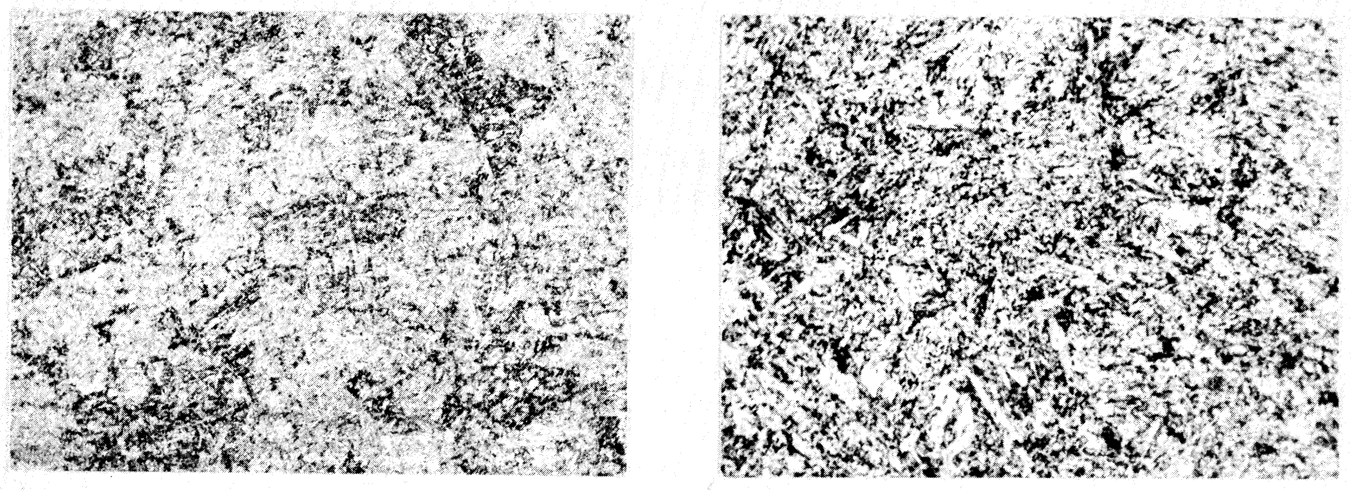
X100D X1000D



(a) Austenitized 1750°F + 1-1/2 hrs at 650°F - 431 BHN



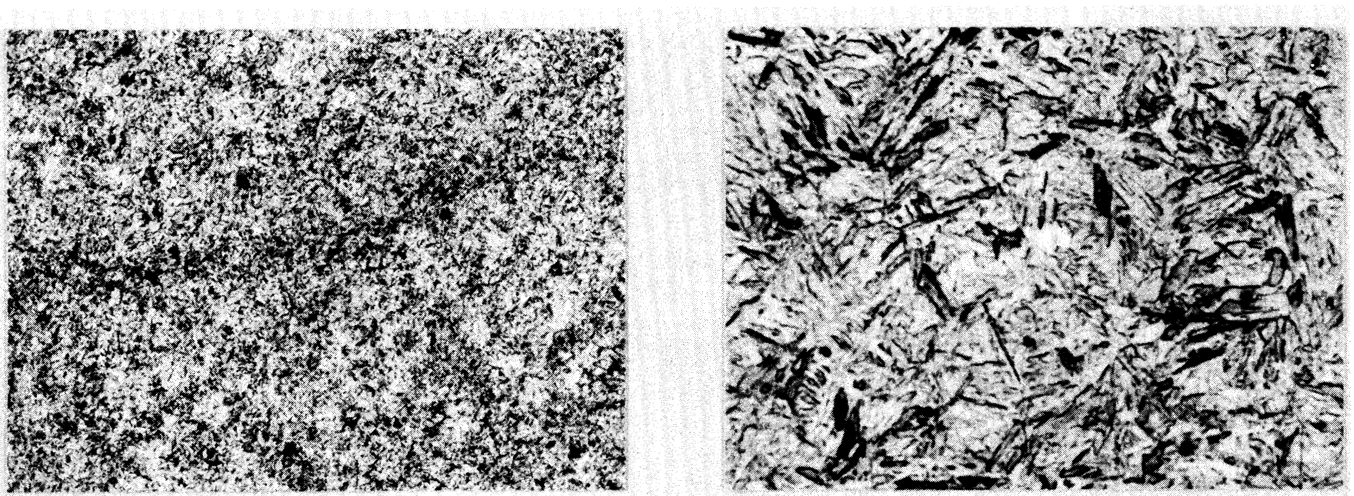
(b) Austenitized 1750°F + 1-1/2 hrs at 650°F + tempered 1-1/4 hrs at 1100°F - 300 BHN.



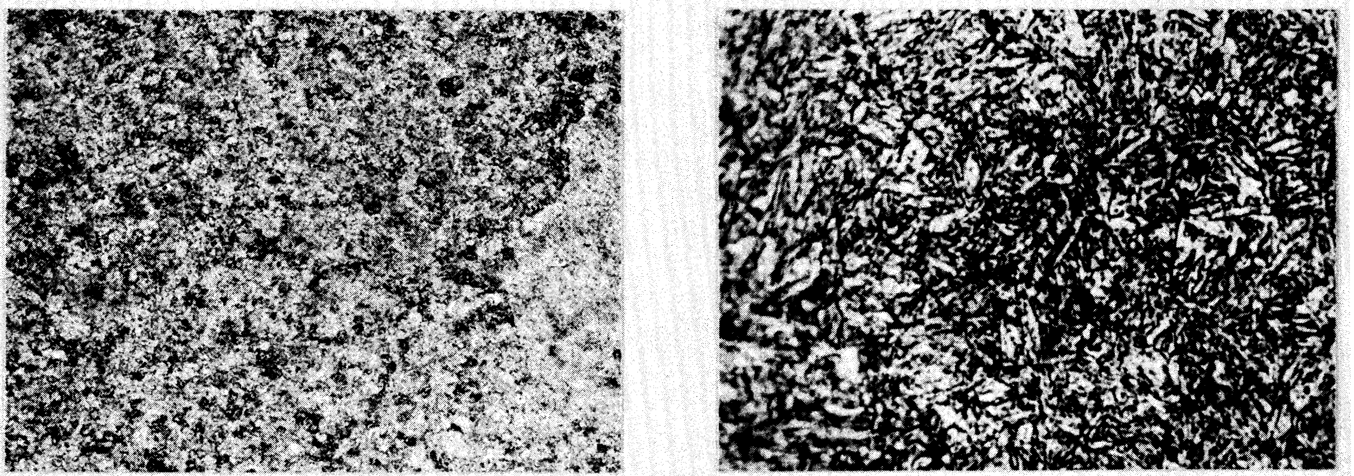
(c) Austenitized 1750°F + 1-1/2 hrs at 650°F + tempered 1-1/4 hrs at 1100°F + creep tested 1035 hrs at 1000°F and 13,000 psi - 270 BHN.

Figure 10. 4340 Bar Stock (a) As Transformed to Lower Bainite, (b) As Tempered to 300 BHN, and (c) after Creep Testing at 1000°F.

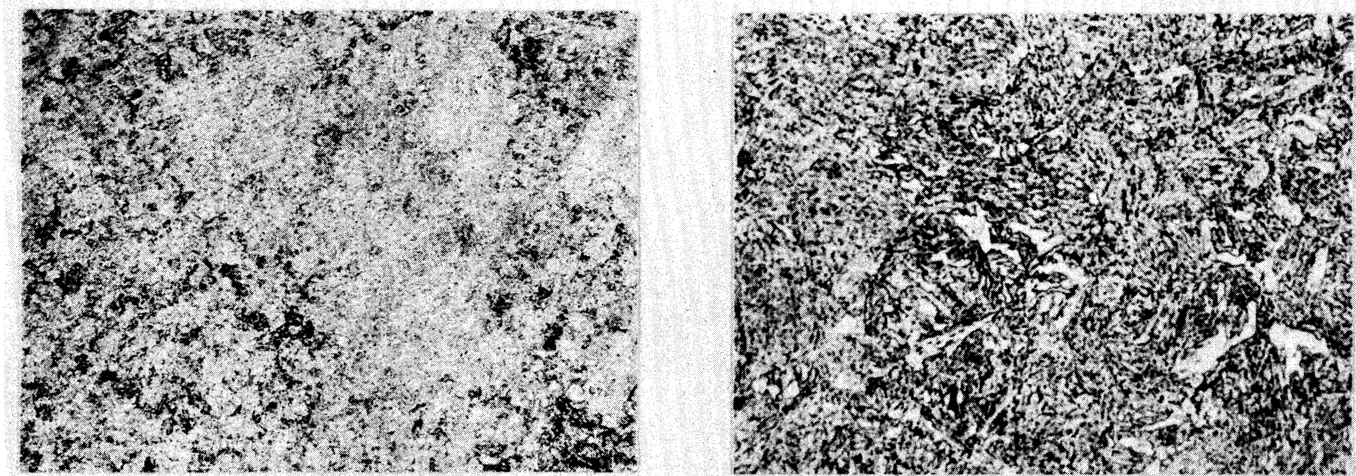
X100D X1000D



(a) Oil quenched 1750°F - 585 BHN.



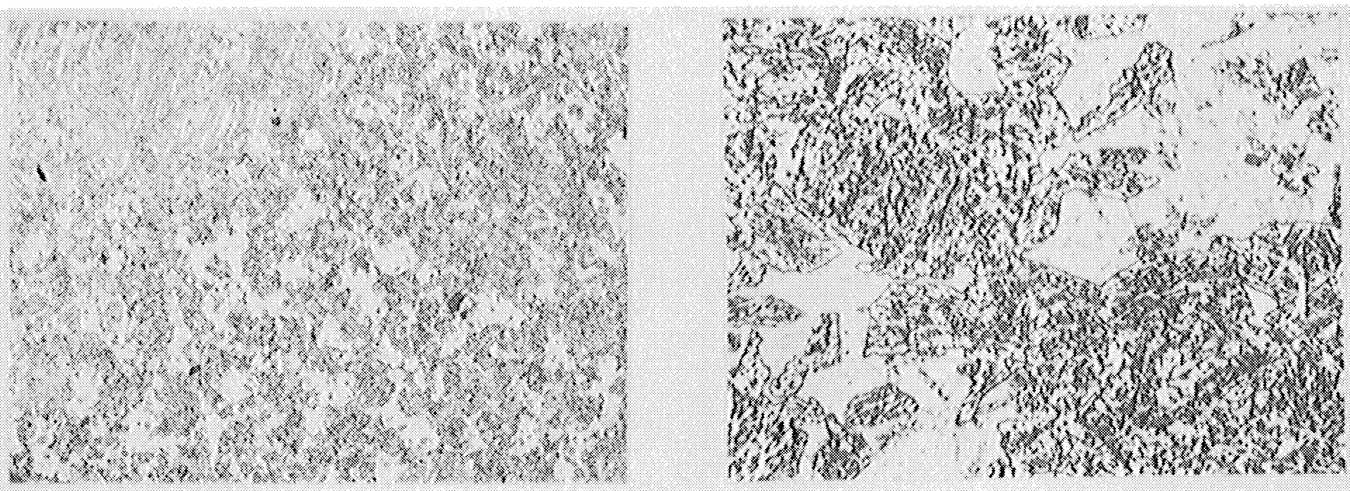
(b) Oil quenched 1750°F + tempered 10 hrs at 1100°F - 310 BHN.



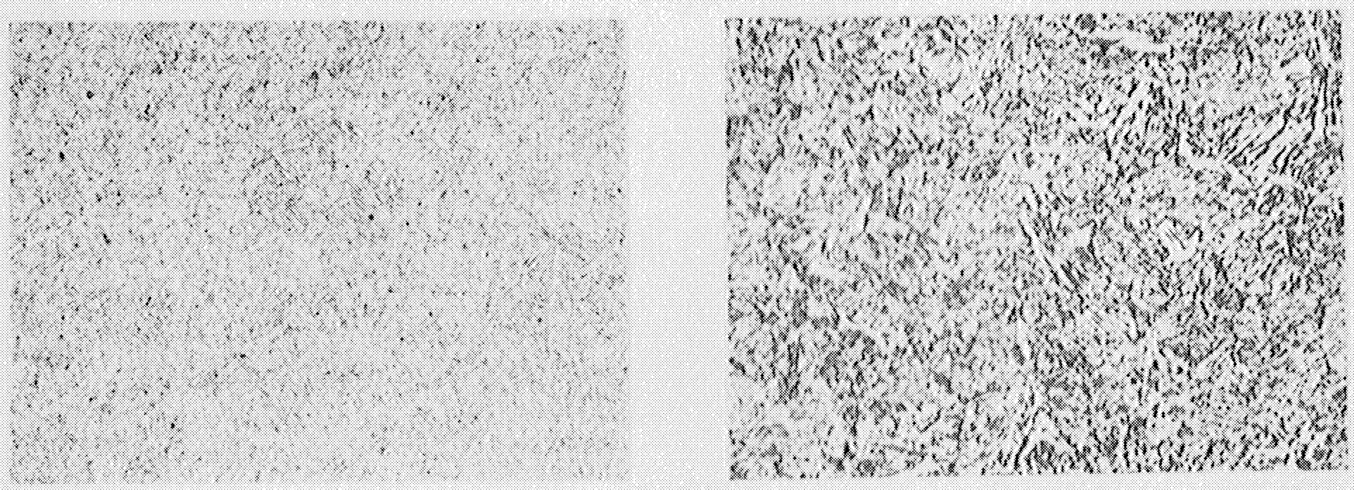
(c) Oil quenched 1750°F + tempered 10 hrs at 1100°F + creep tested 1025 hrs at 1000°F and 13,000 psi - 270 BHN.

Figure 11. 4340 Bar Stock (a) As Oil Quenched, (b) As Tempered to 300 BHN, and (c) after Creep Testing at 1000°F.

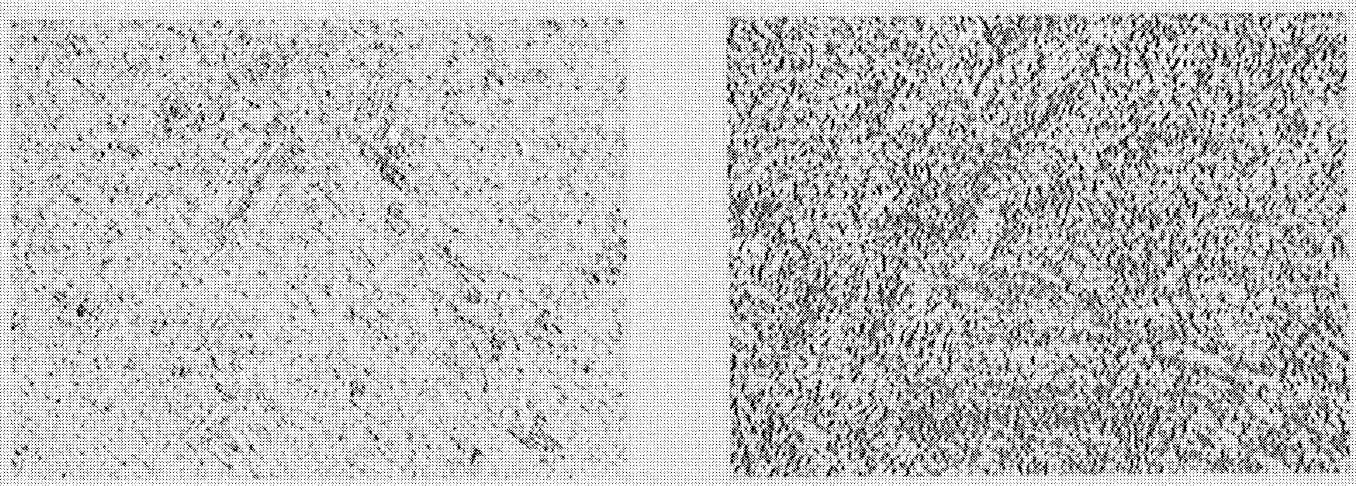
X100D X1000D



(a) Normalized 1750°F - 390 BHN.



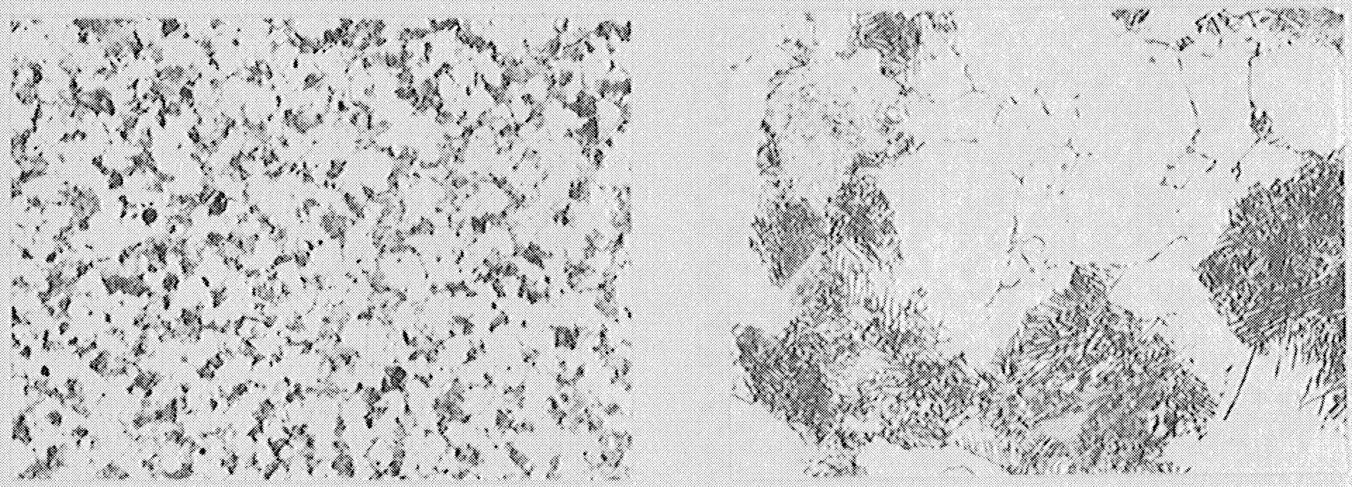
(b) Normalized 1750°F + tempered 1 hr at 1100°F - 300 BHN.



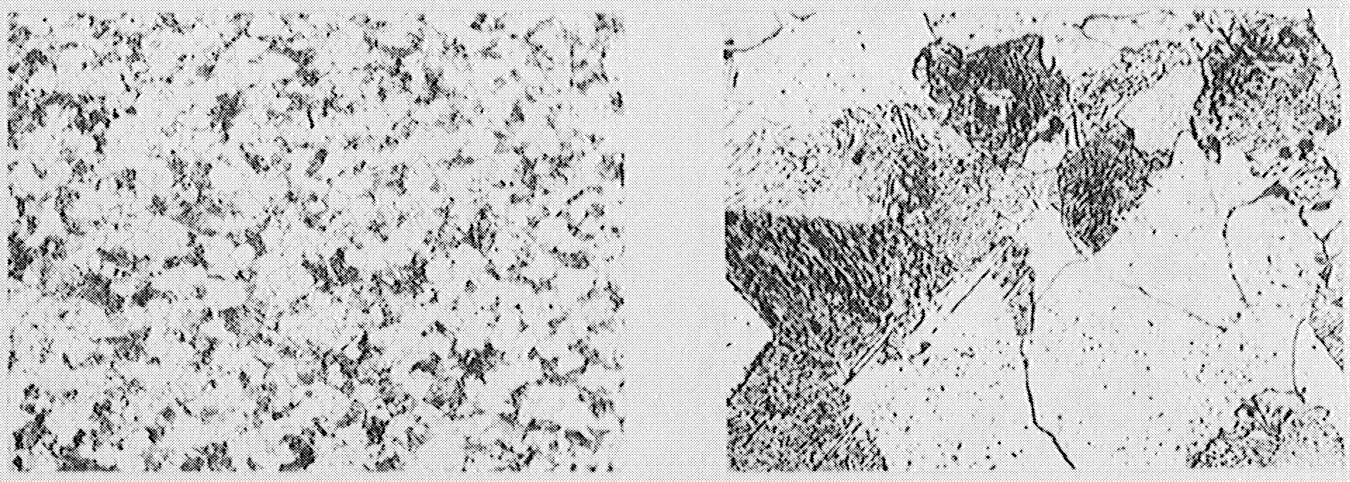
(c) Normalized 1750°F + tempered 1 hr at 1100°F + creep tested 1392 hrs at 1000°F and 20,000 psi - 260 BHN.

Figure 12. 4340 Bar Stock (a) As Normalized, (b) As Tempered to 300 BHN, and (c) after Creep Testing at 1000°F.

X100D X1000D



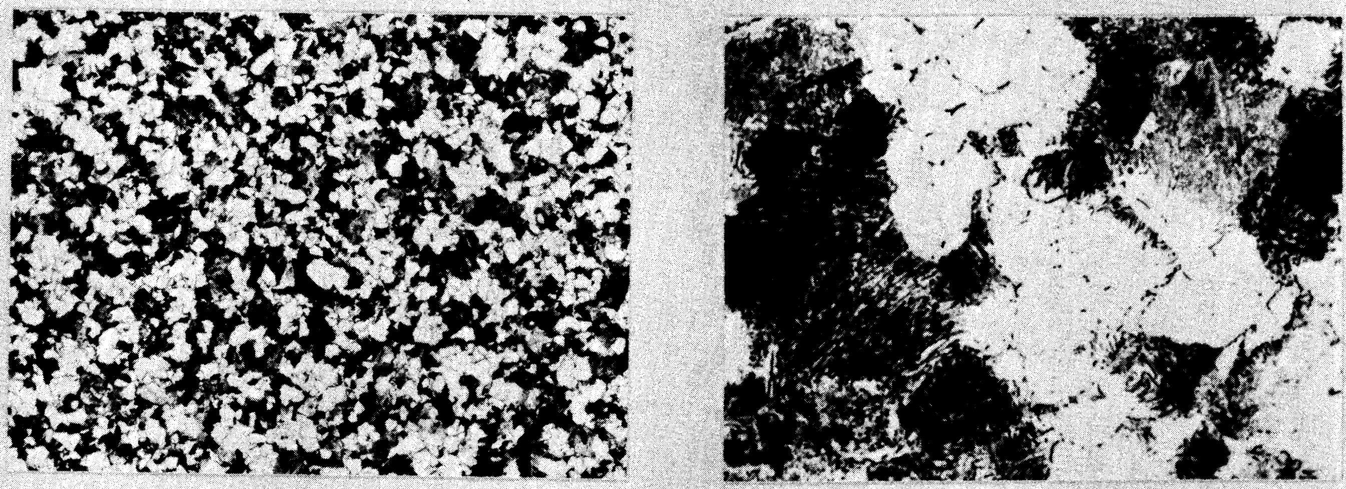
(a) Austenitized 1750°F + 1-1/2 hrs at 1300°F - 196/237 BHN.



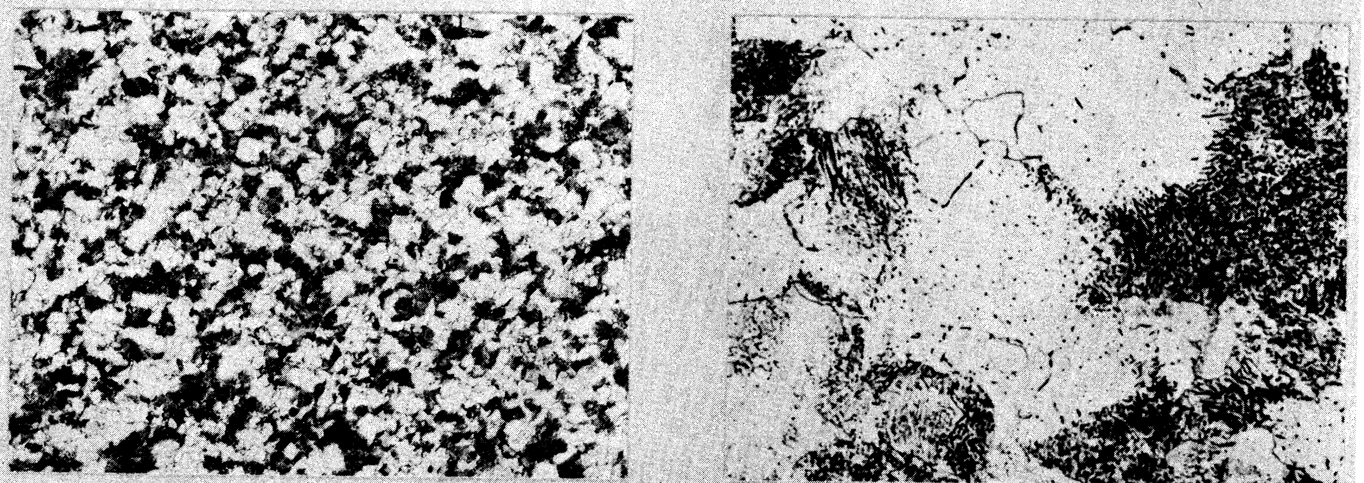
(b) Austenitized 1750°F + 1-1/2 hrs at 1300°F + creep-rupture tested 1298 hrs at 1100°F and 19,000 psi - 210 BHN.

Figure 13. "17-22A"S Bar Stock (a) As Transformed to Upper Pearlite, and (b) after Creep-Rupture Testing at 1100°F.

X100D X1000D



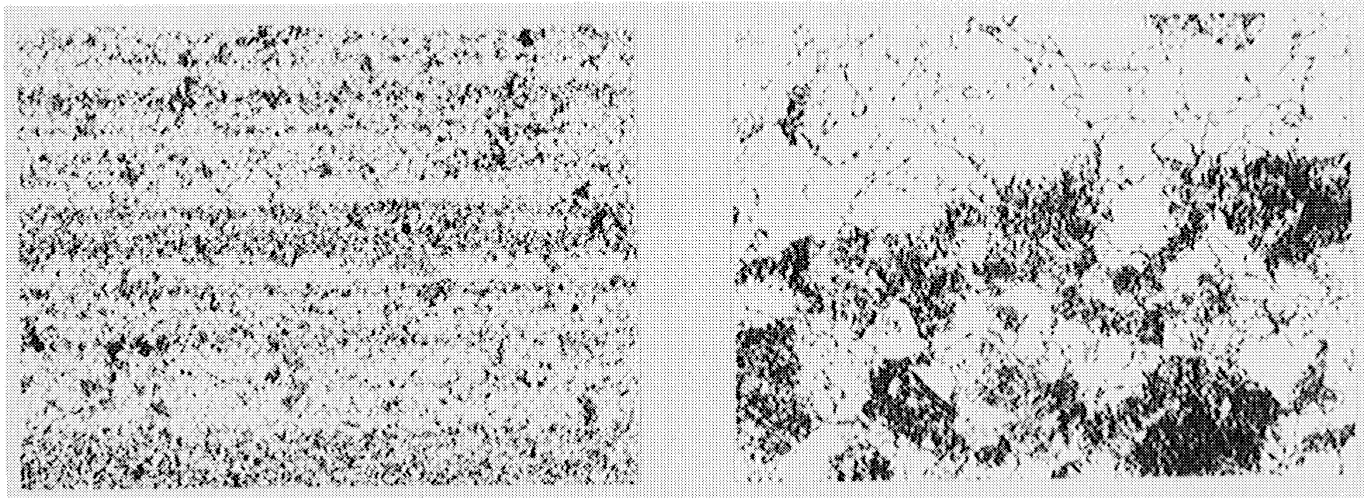
(a) Austenitized 1750°F + 1-1/2 hrs at 1225°F - 285 BHN.



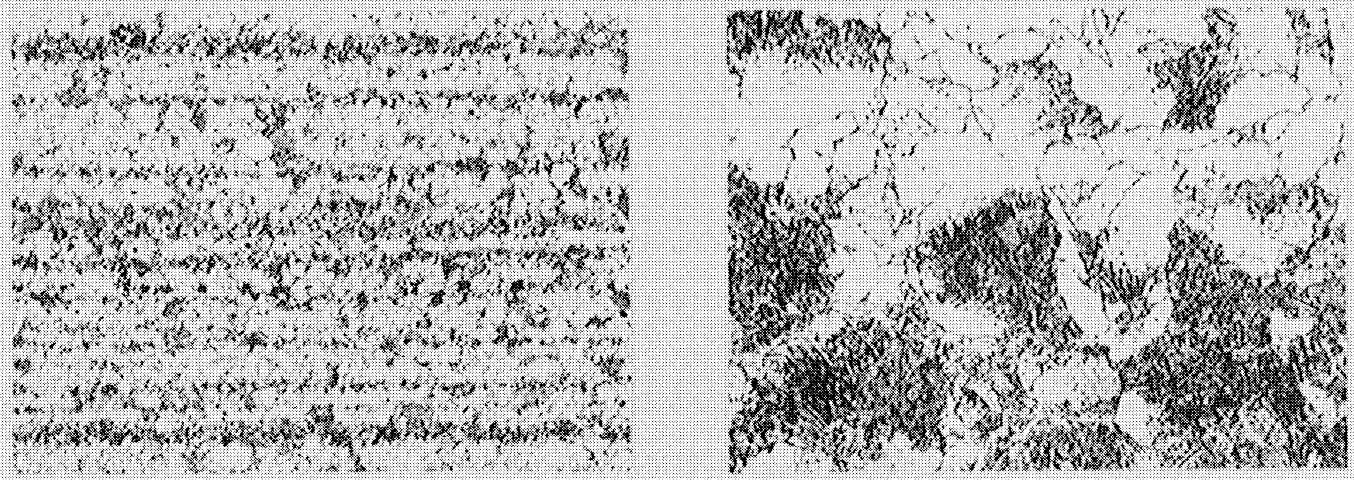
(b) Austenitized 1750°F + 1-1/2 hrs at 1225°F + creep tested 669 hrs at 1100°F and 19,000 psi - 259 BHN.

Figure 14. "17-22A"S Bar Stock (a) As Transformed to Middle Pearlite and (b) after Creep-Rupture Testing at 1100°F.

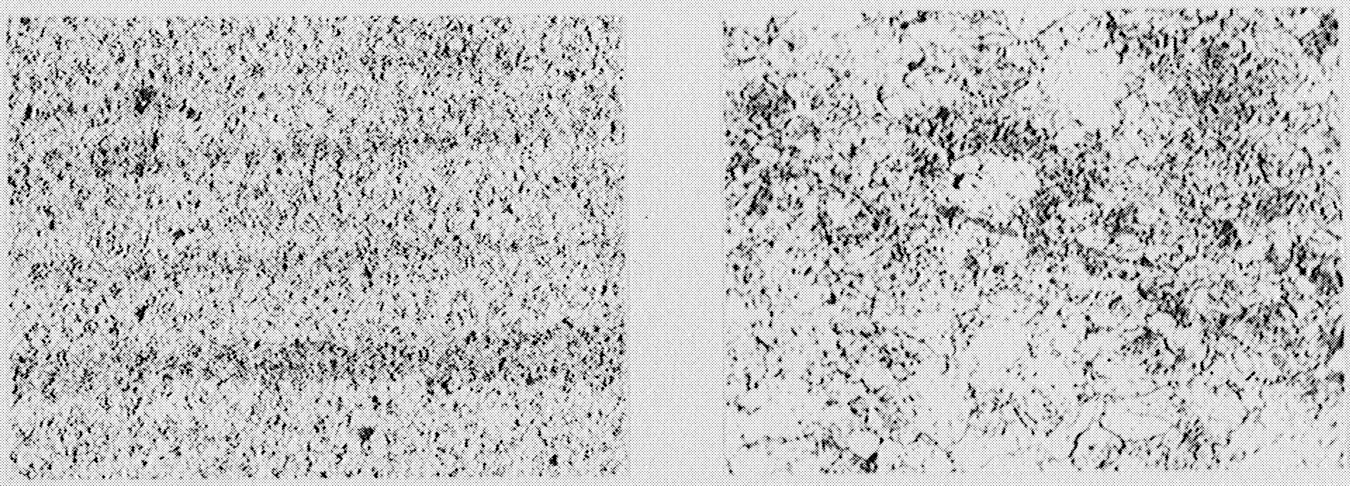
X100D X1000D



(a) Austenitized 1750°F + 10 hrs at 1100°F - 375 BHN.



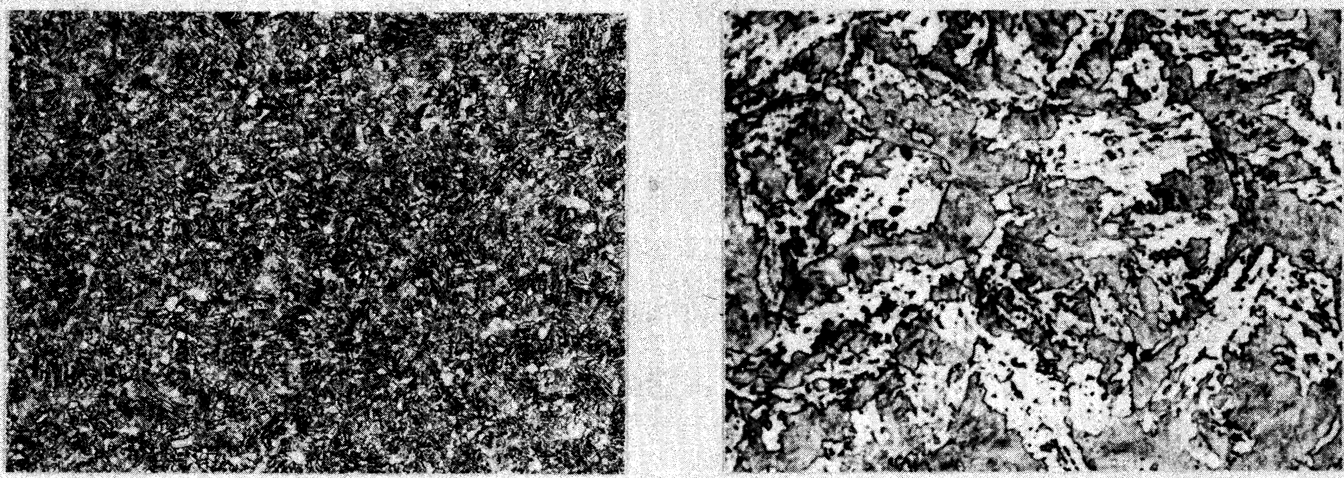
(b) Austenitized 1750°F + 10 hrs at 1150°F + tempered 12 hrs at 1200°F - 291 BHN.



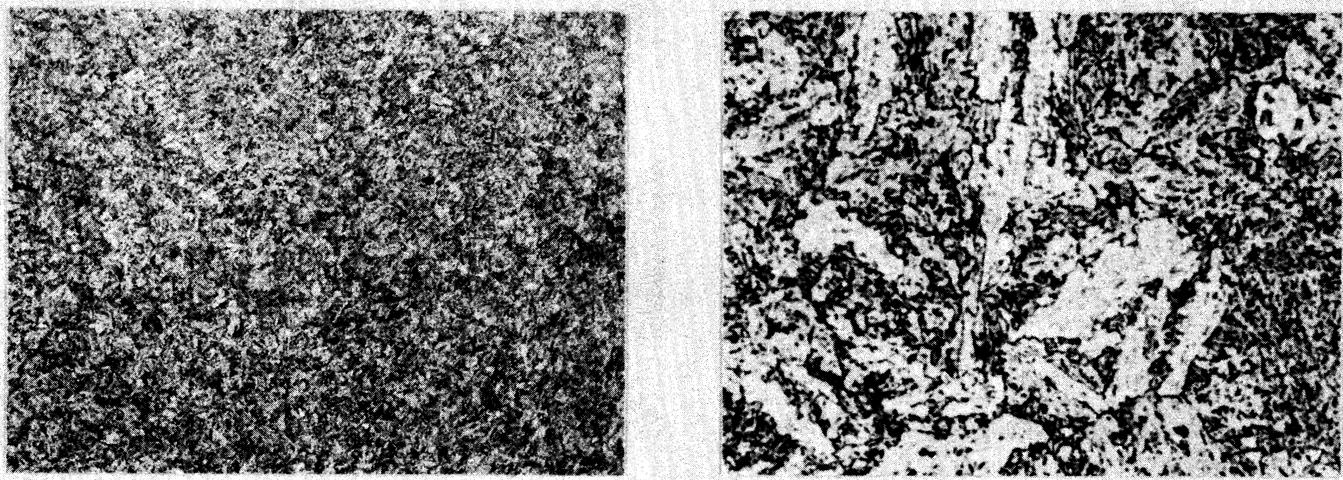
(c) Austenitized 1750°F + 10 hrs at 1150°F + Tempered 12 hrs at 1200°F + creep-rupture tested 652 hrs at 1100°F and 15,000 psi - 220 BHN.

Figure 15. "17-22A"S Bar Stock (a) As Transformed to Lower Pearlite, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

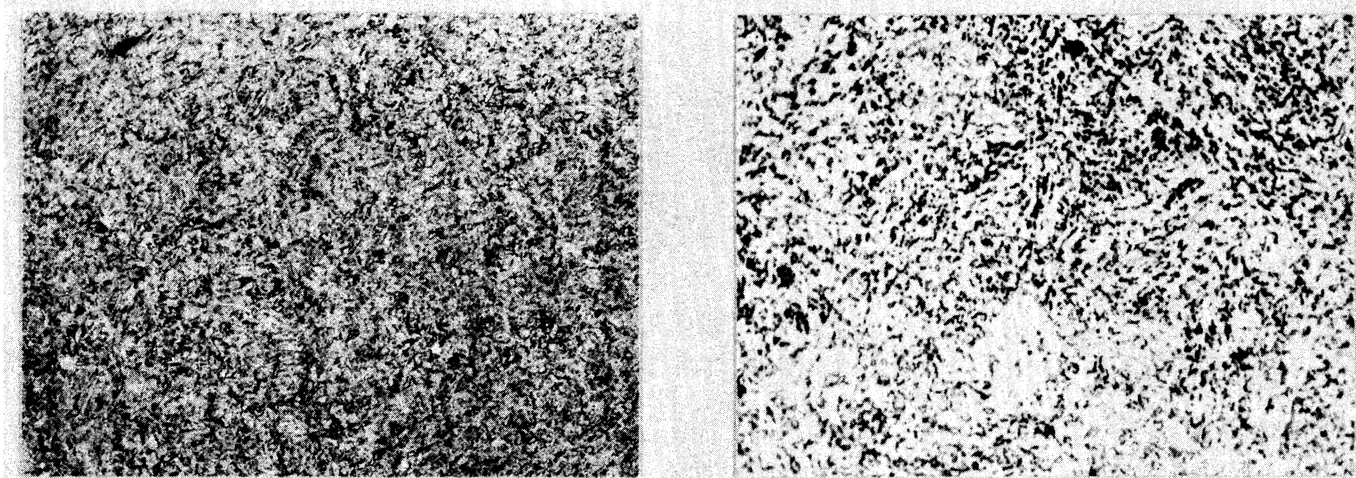
X100D X1000D



(a) Austenitized 1750°F + 2 hrs at 900°F - 466 BHN.



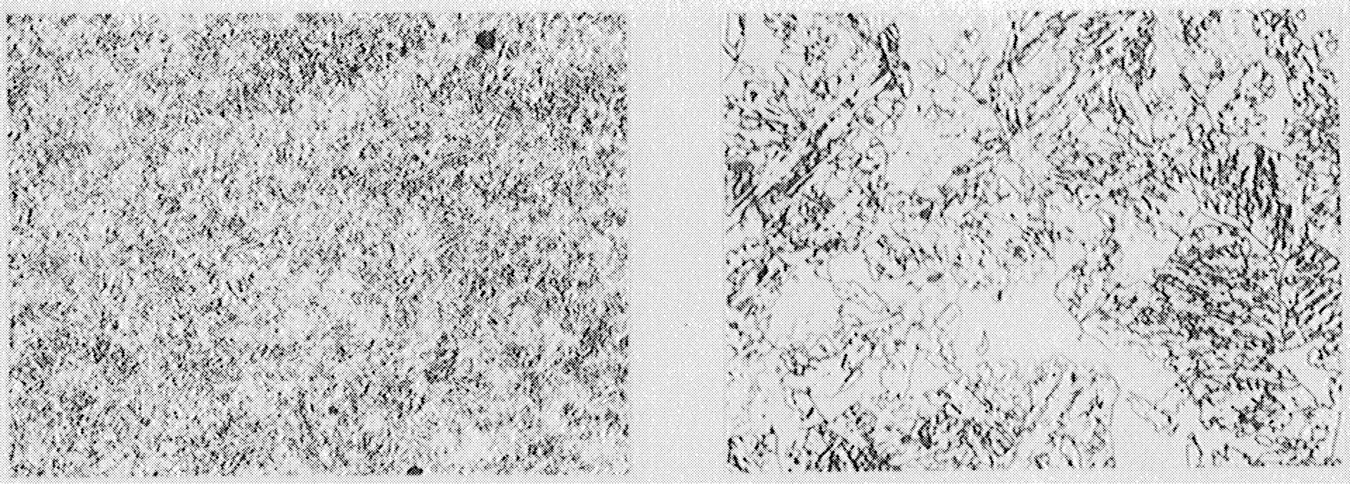
(b) Austenitized 1750°F + 2 hrs at 900°F + tempered 16 hrs at 1200°F - 320 BHN.



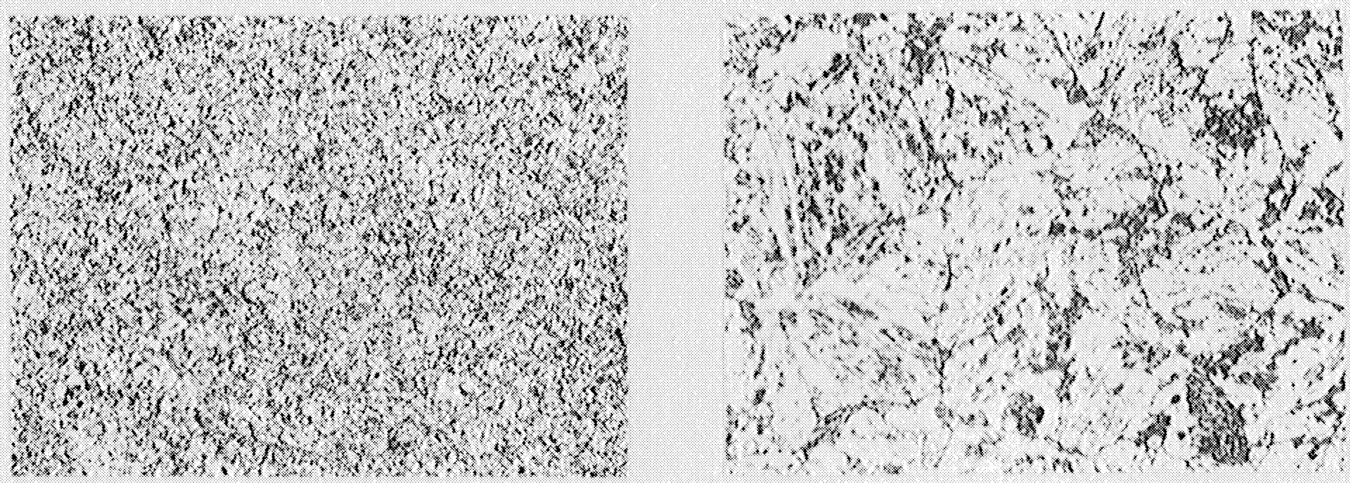
(c) Austenitized 1750°F + 2 hrs at 900°F + tempered 16 hrs at 1200°F + creep-rupture tested 796 hrs at 1100°F and 19,000 psi - 242 BHN.

Figure 16. "17-22A"S Bar Stock (a) As Transformed to Upper Bainite, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

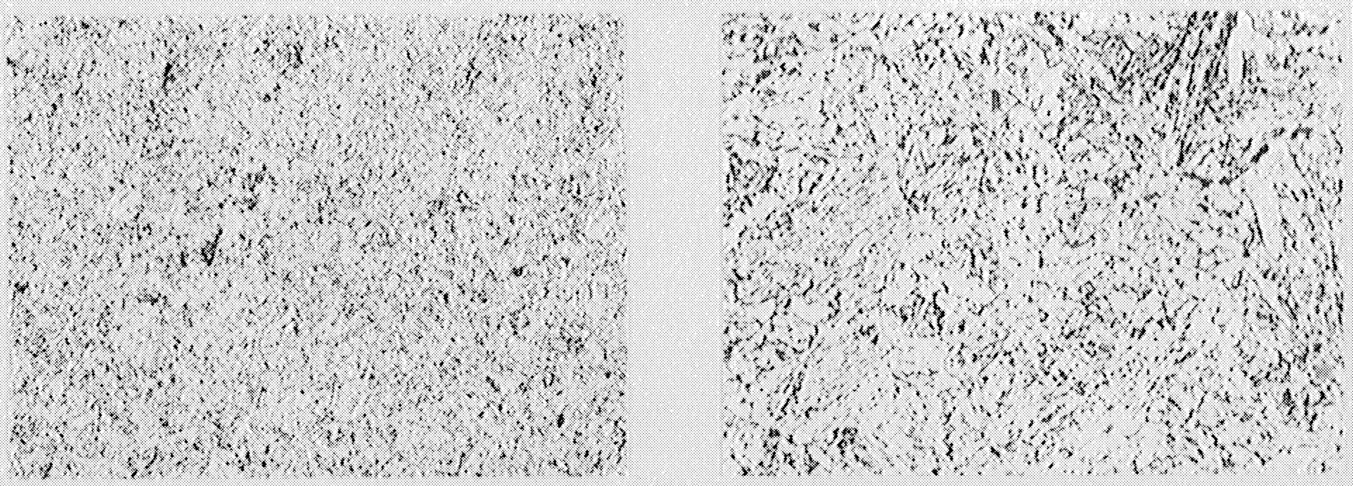
X100D X1000D



(a) Austenitized 1750°F + 1/2 hr at 800°F - 360 BHN.



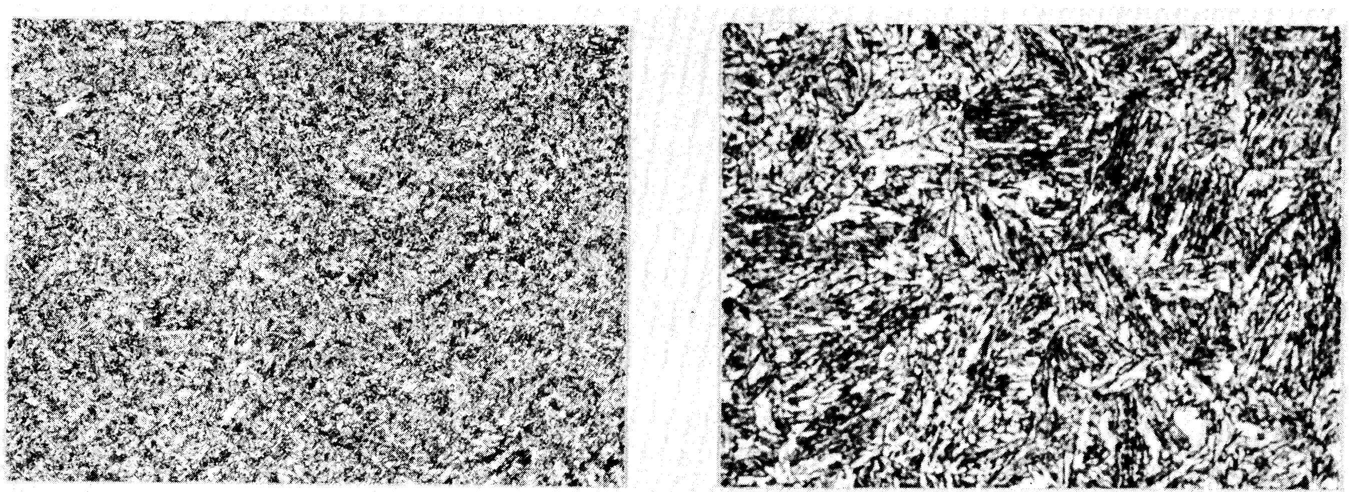
(b) Austenitized 1750°F + 1/2 hr at 800°F + 4 hrs at 1200°F - 310 BHN.



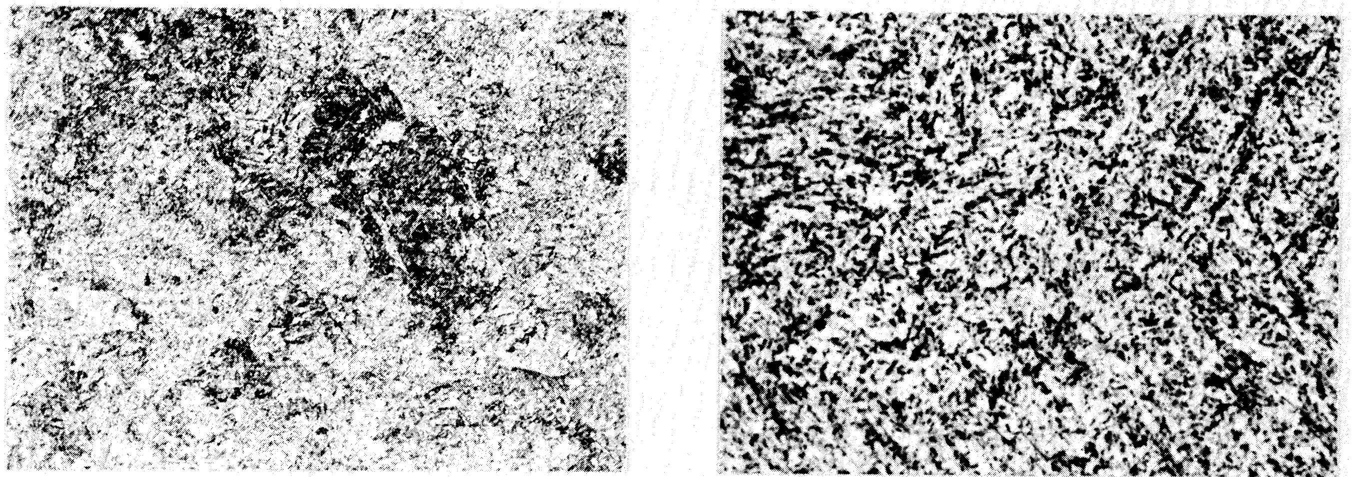
(c) Austenitized 1750°F + 1/2 hr at 800°F + 4 hrs at 1200°F + creep-rupture tested 815 hrs at 1100°F and 19,000 psi - 256 BHN.

Figure 17. "17-22A"S Bar Stock (a) As Transformed to Middle Bainite, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

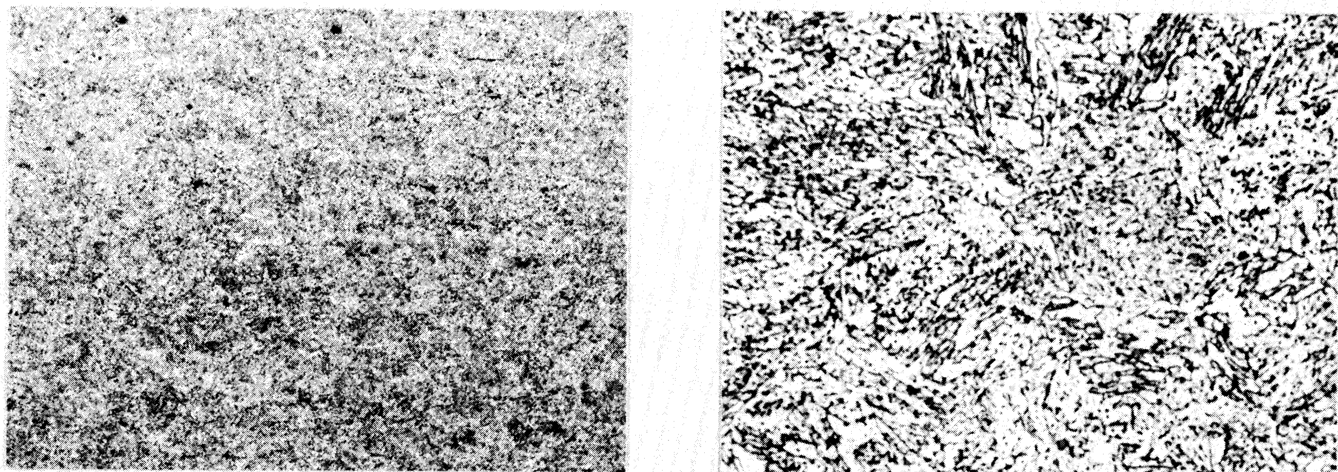
X100D X1000D



(a) Austenitized 1750°F + 5 minutes at 700°F - 365 BHN.



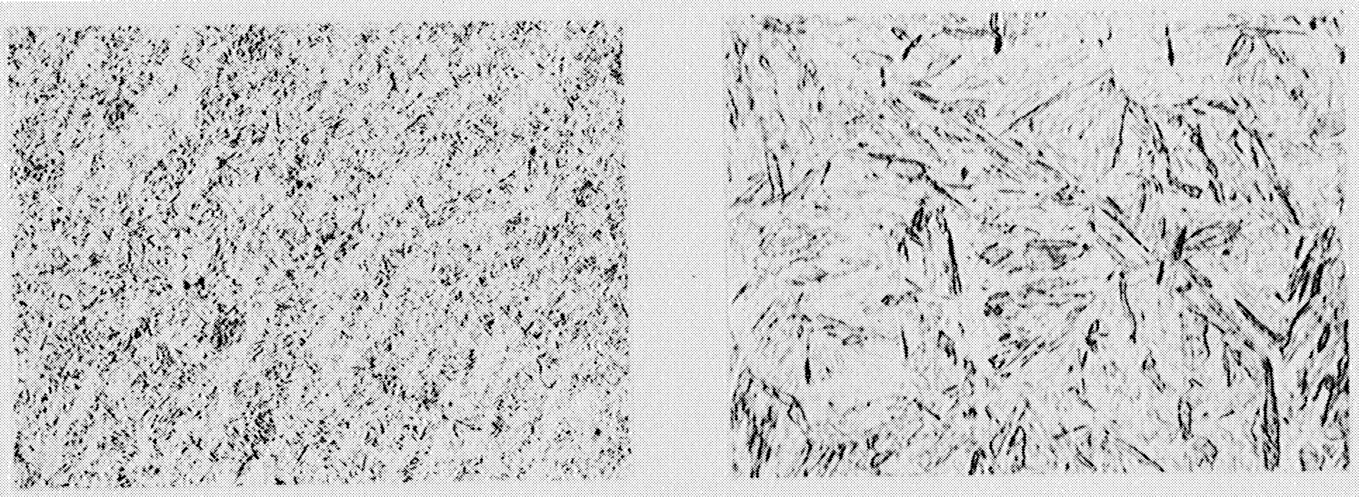
(b) Austenitized 1750°F + 5 minutes at 700°F + tempered 12 hrs at 1200°F - 302 BHN.



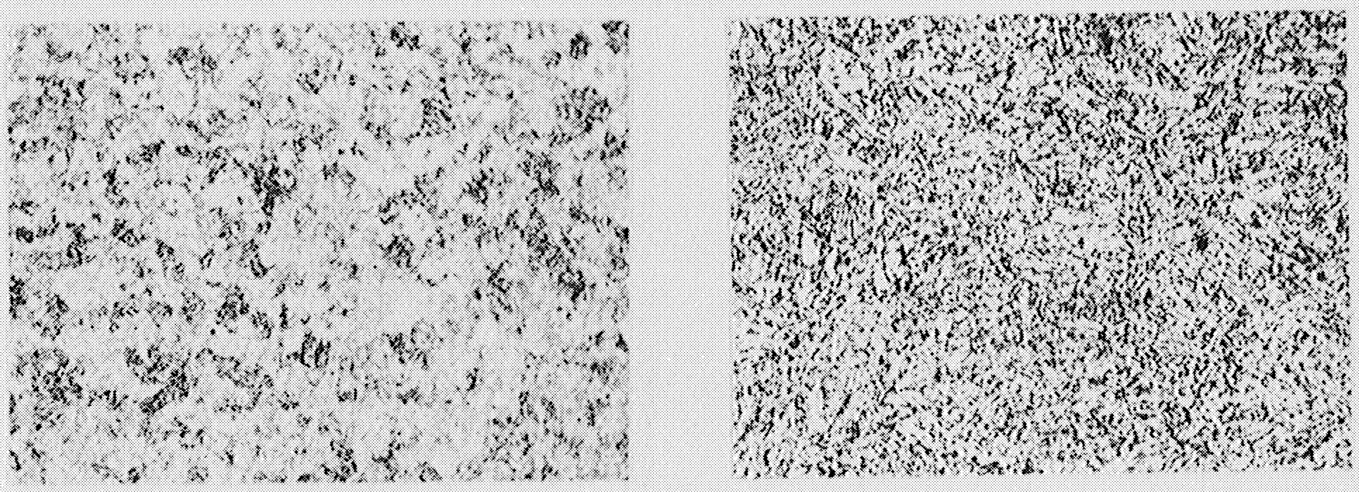
(c) Austenitized 1750°F + 5 minutes at 700°F + tempered 12 hrs at 1200°F + creep tested 1033 hrs at 1100°F and 19,000 psi - 260 BHN.

Figure 18. "17-22A"S Bar Stock (a) As Transformed to Lower Bainite, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F

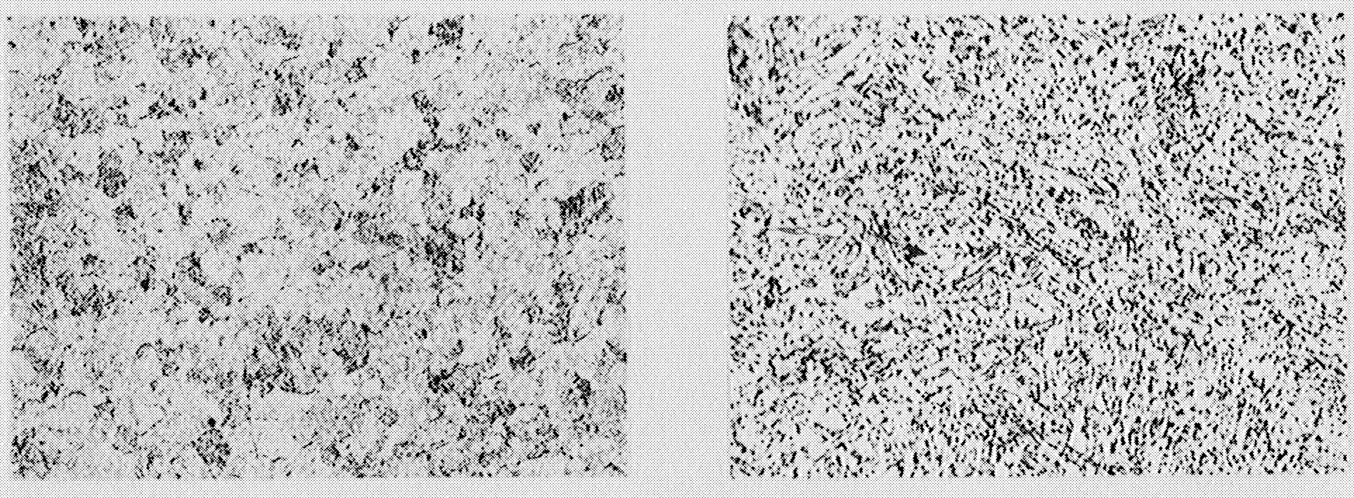
X100D X1000D



(a) Oil quenched 1750°F - 524 BHN.



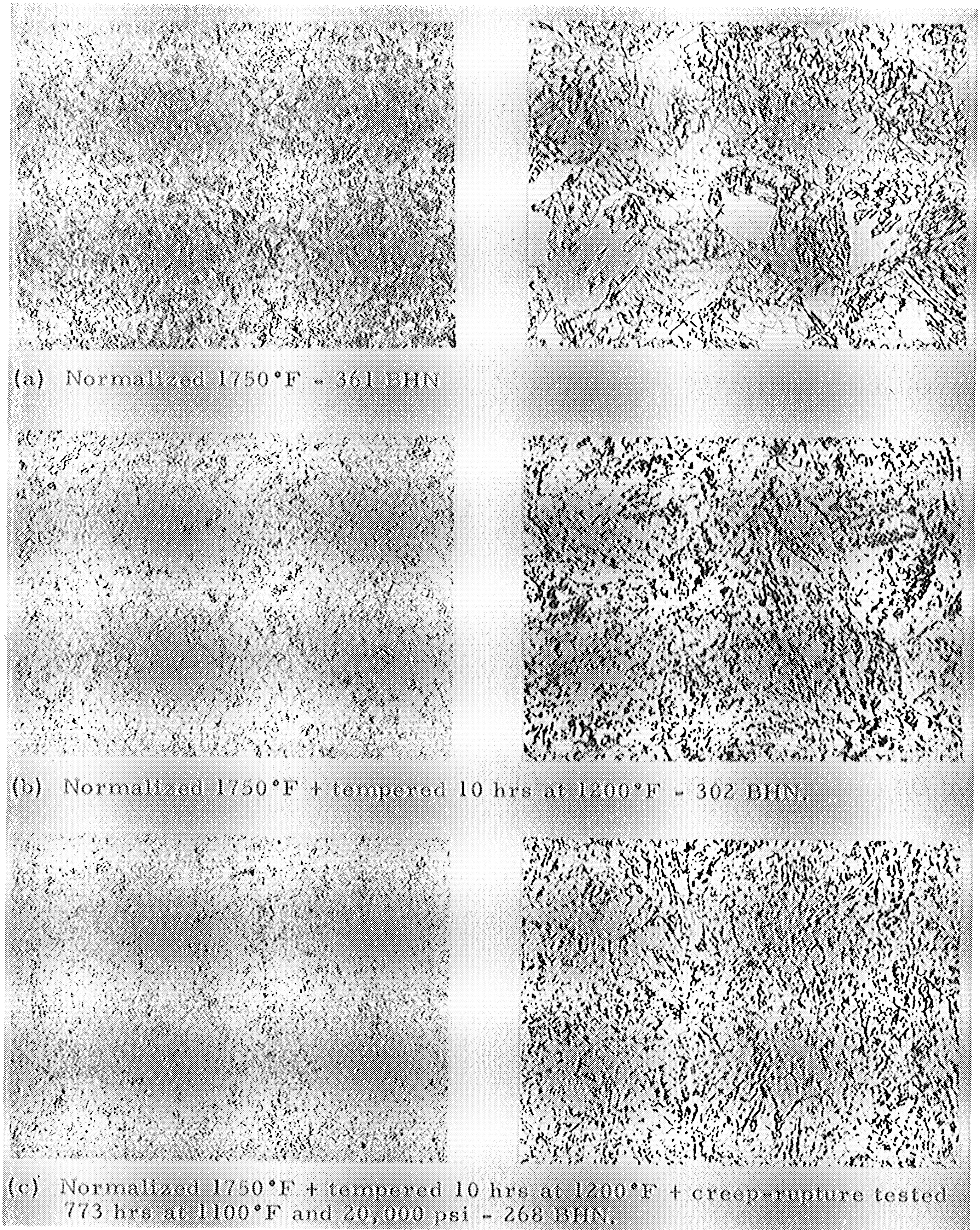
(b) Oil quenched 1750°F + tempered 1 hr at 1300°F - 305 BHN.



(c) Oil quenched 1750°F + tempered 1 hr at 1300°F + creep-rupture tested 666 hrs at 1100°F and 20,000 psi - 265 BHN.

Figure 19. "17-22A"S Bar Stock (a) As Oil Quenched, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

X100D X1000D



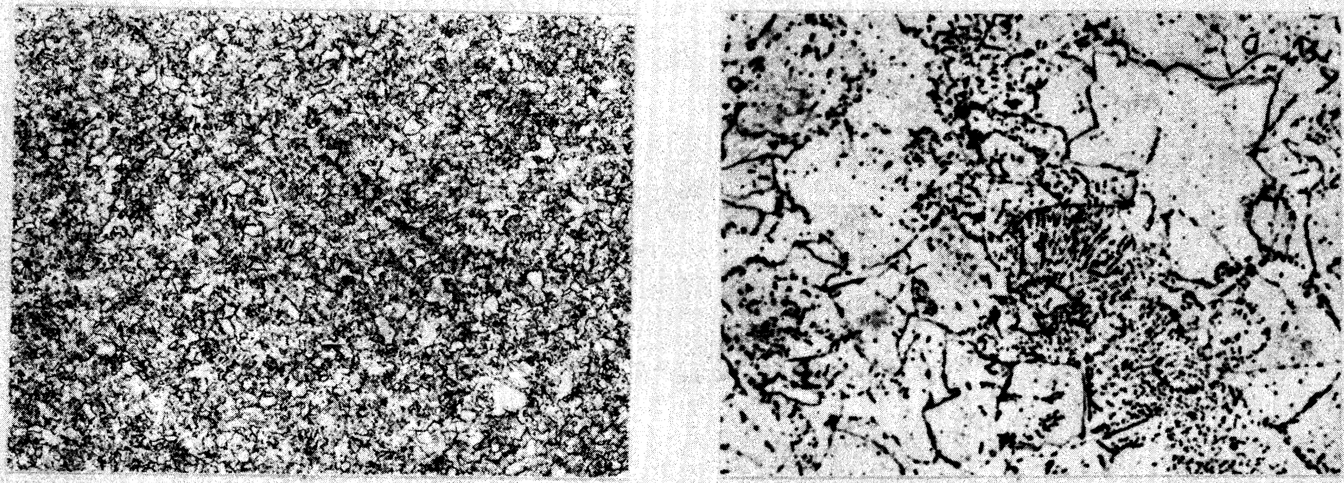
(a) Normalized 1750°F - 361 BHN

(b) Normalized 1750°F + tempered 10 hrs at 1200°F - 302 BHN.

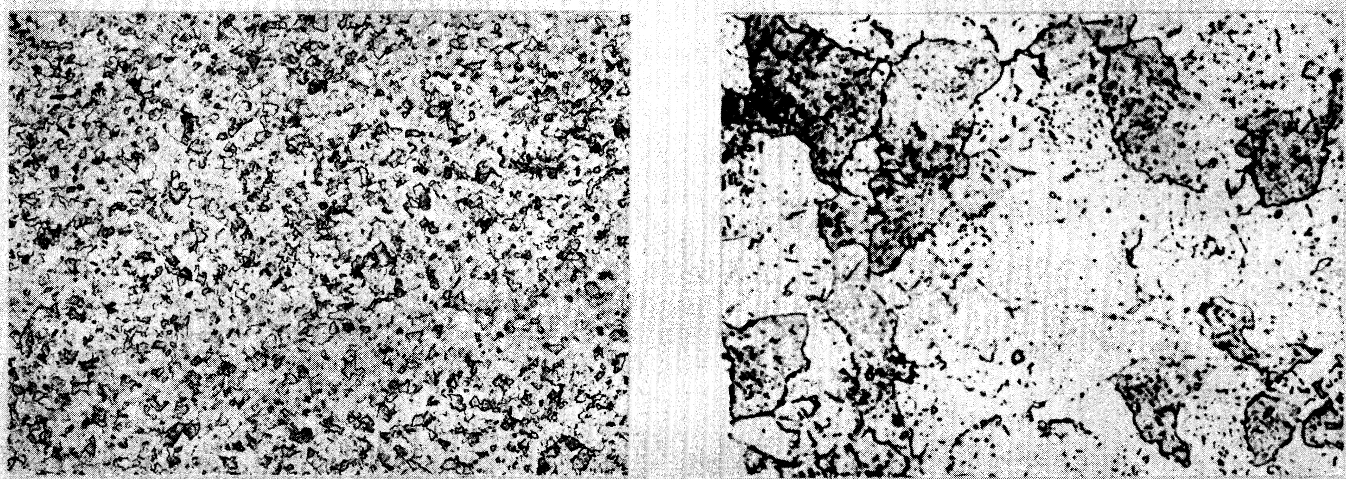
(c) Normalized 1750°F + tempered 10 hrs at 1200°F + creep-rupture tested 773 hrs at 1100°F and 20,000 psi - 268 BHN.

Figure 20 "17-22A"S Bar Stock (a) As Normalized, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

X100D X1000D



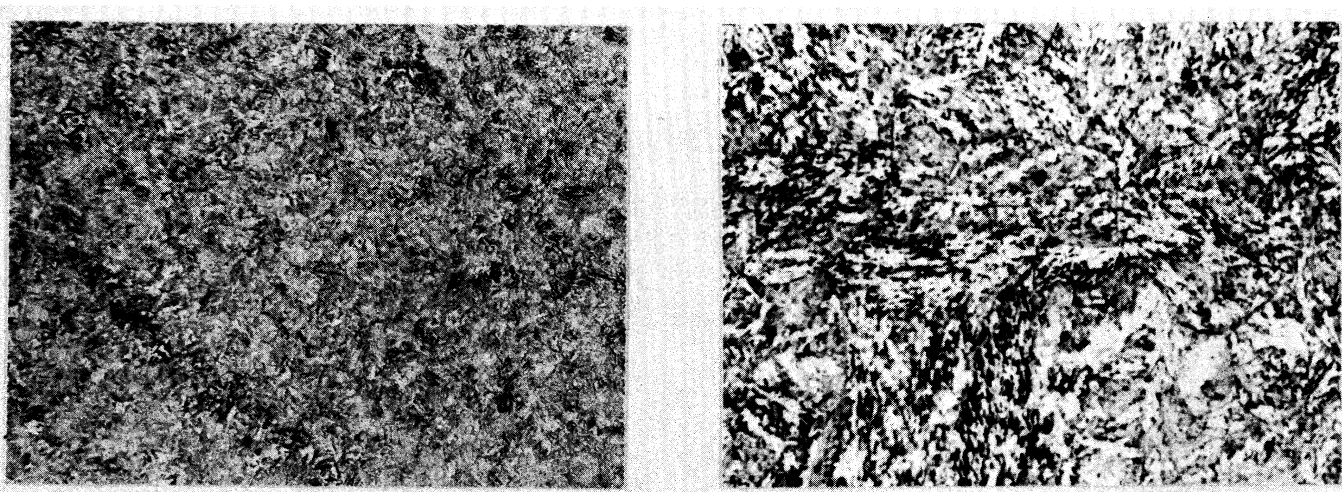
(a) Austenitized 1950°F + 24 hrs at 1300°F - 193 BHN.



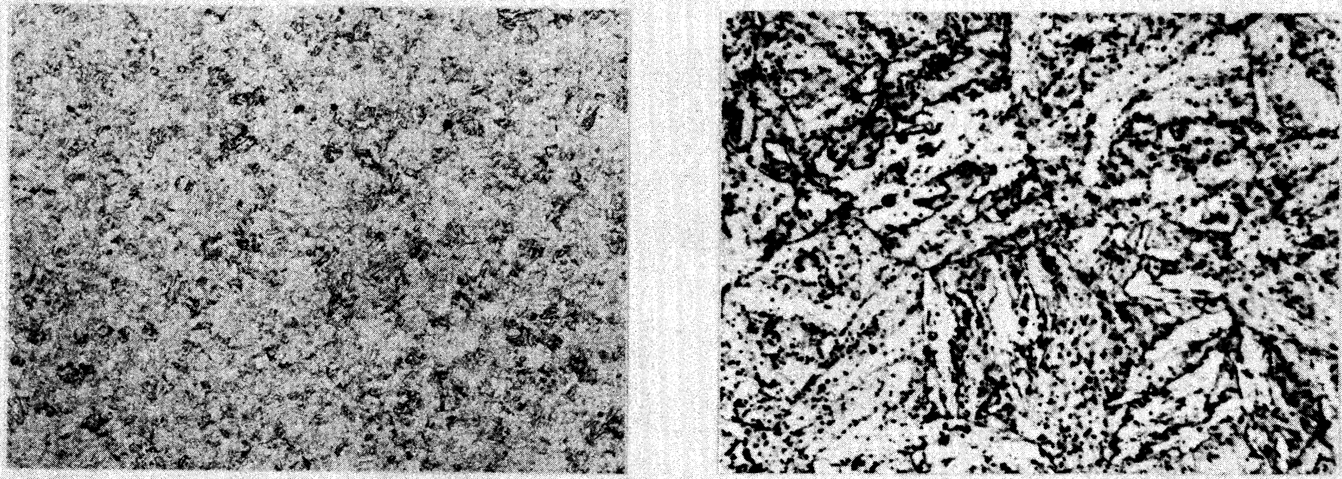
(b) Austenitized 1950°F + 24 hrs at 1300°F + rupture tested 23 hrs at 1100°F and 30,000 psi - 186 BHN.

Figure 21. H-40 Bar Stock (a) As Transformed to Pearlite and (b) after Rupture Testing at 1100°F.

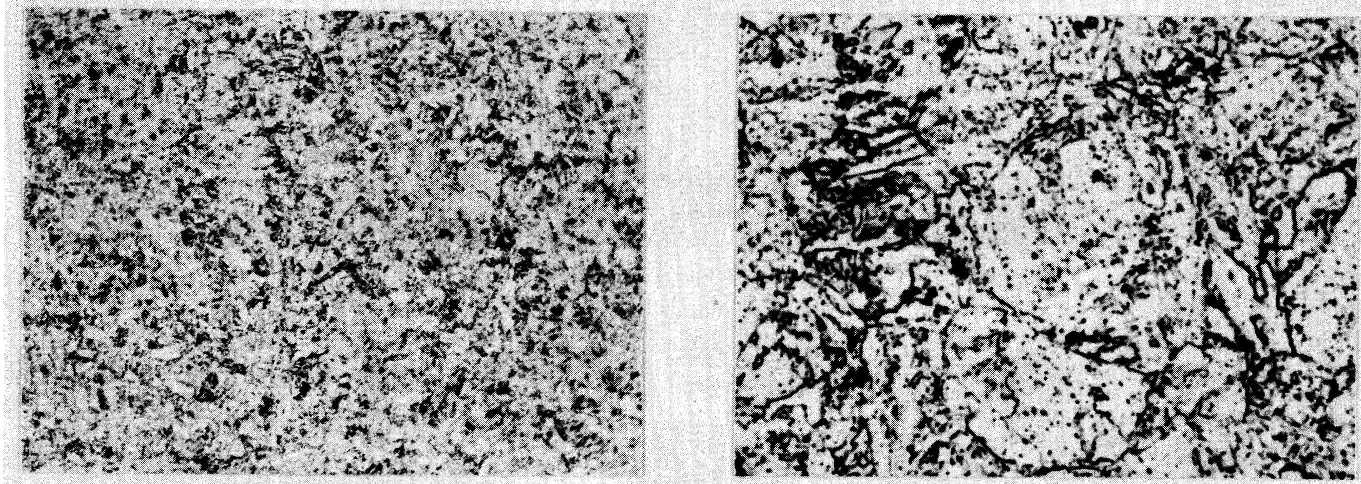
X100D X1000D



(a) Austenitized 1950°F + 10 hrs at 750°F - 478 BHN.



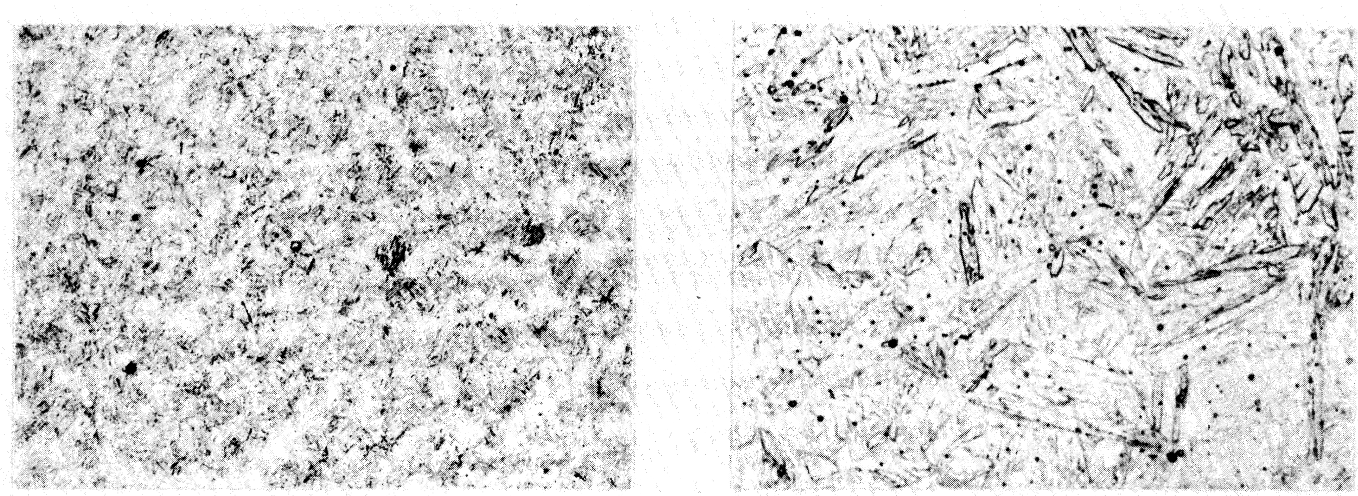
(b) Austenitized 1950°F + 10 hrs at 750°F + tempered 1 hr at 1300°F - 310 BHN.



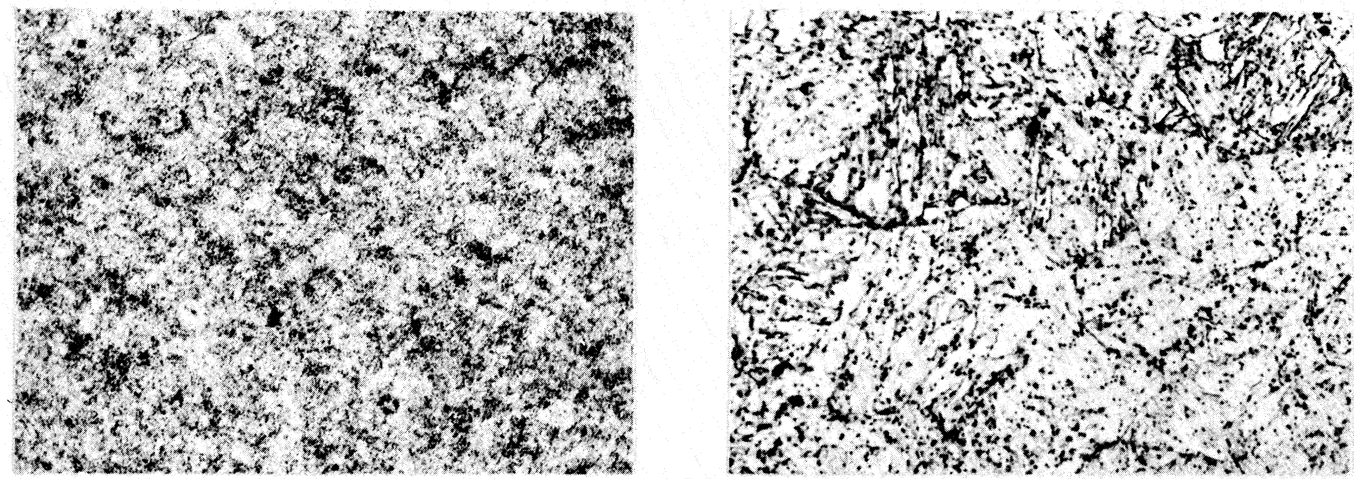
(c) Austenitized 1950°F + 10 hrs at 750°F + tempered 1 hr at 1300°F + creep tested 1005 hrs at 1100°F and 28,000 psi - 255 BHN.

Figure 22. H-40 Bar Stock (a) As Transformed to Bainite, (b) As Tempered to 300 BHN, and (c) after Creep Testing at 1100°F.

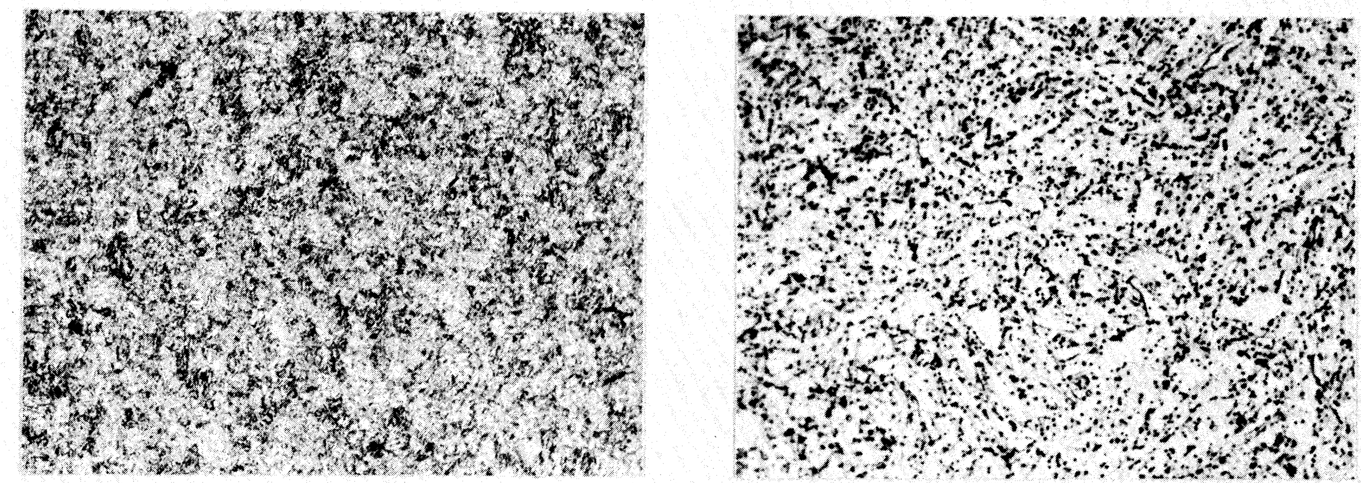
X100D X1000D



(a) Oil quenched 1950°F - 523 BHN.



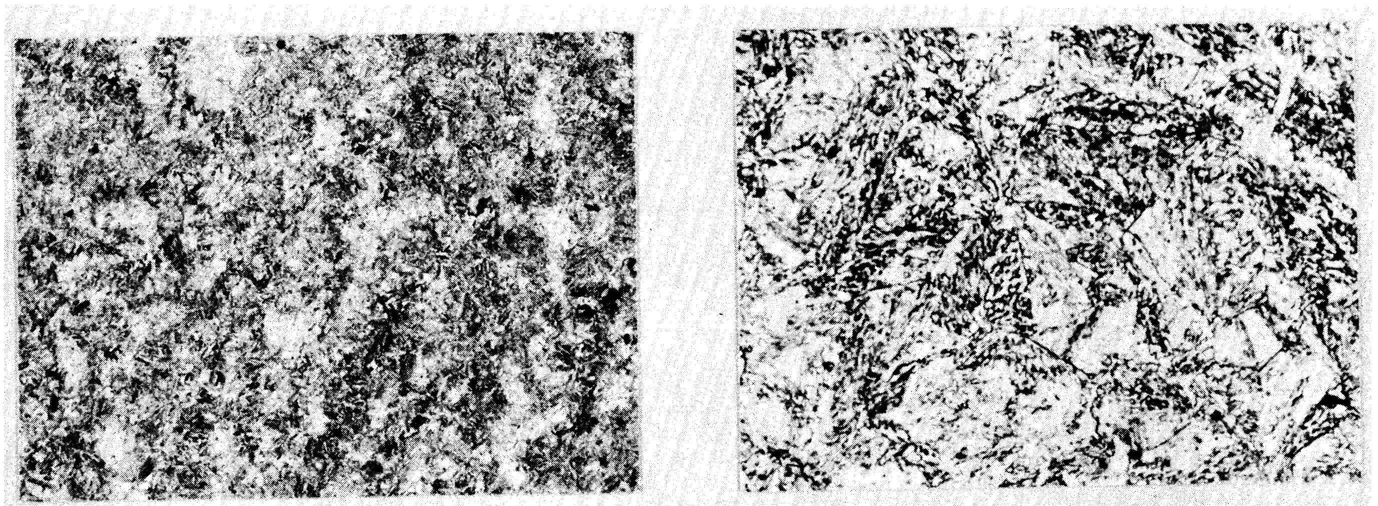
(b) Oil quenched 1950°F + tempered 12 hrs at 1200°F - 320 BHN.



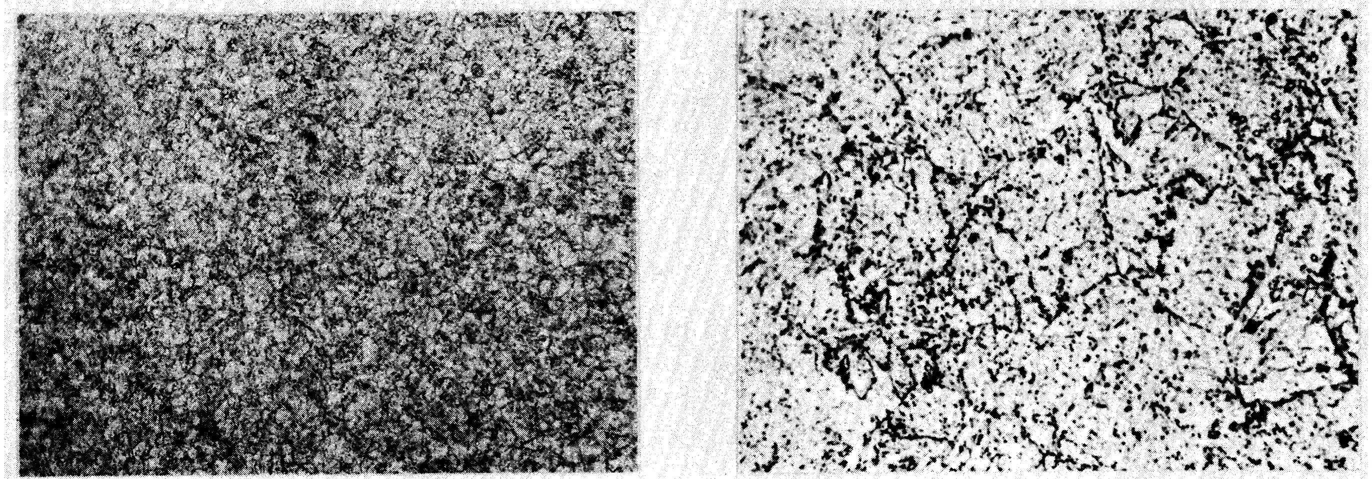
(c) Oil quenched 1950°F + tempered 12 hrs at 1200°F + creep-rupture tested 865 hrs at 1100°F and 30,000 psi - 272 BHN.

Figure 23. H-40 Bar Stock (a) As Oil Quenched, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

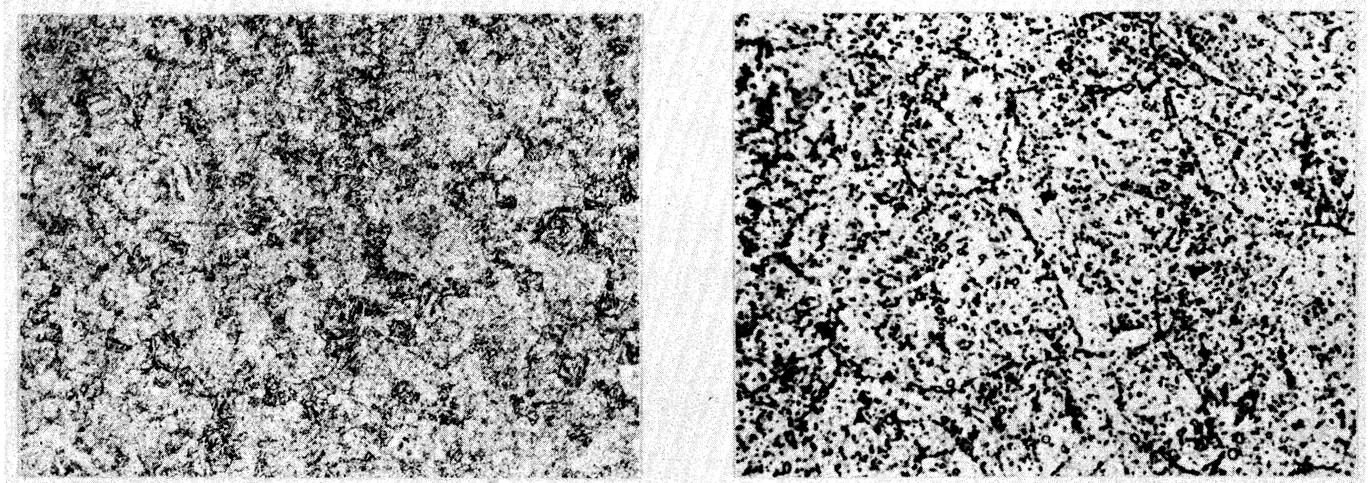
X100D X1000D



(a) Normalized 1950°F - 435 BHN.



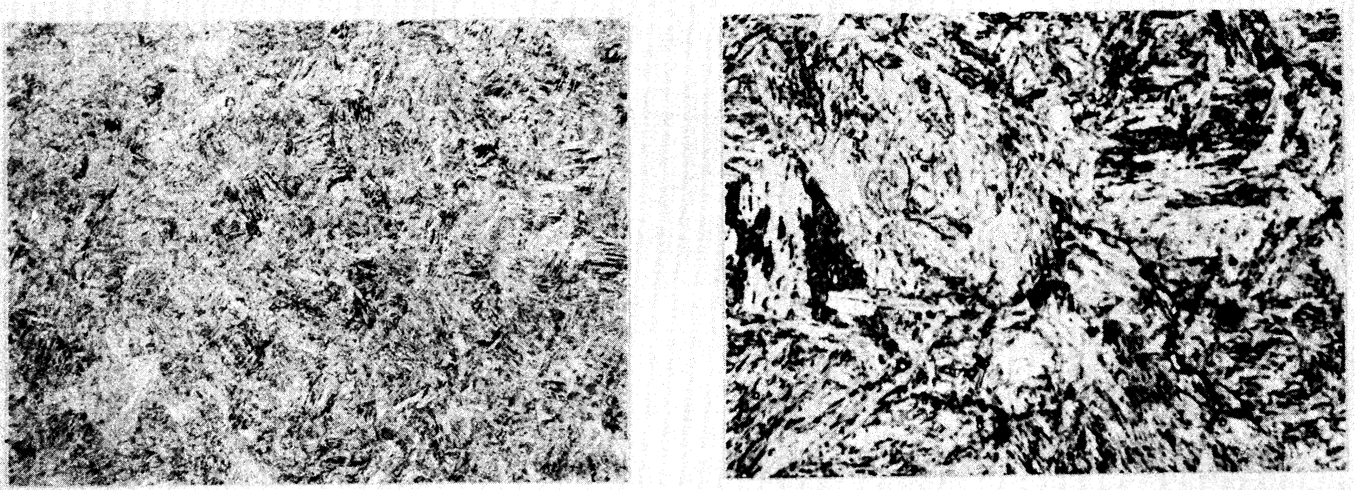
(b) Normalized 1950°F + tempered 18 hrs at 1200°F - 316 BHN.



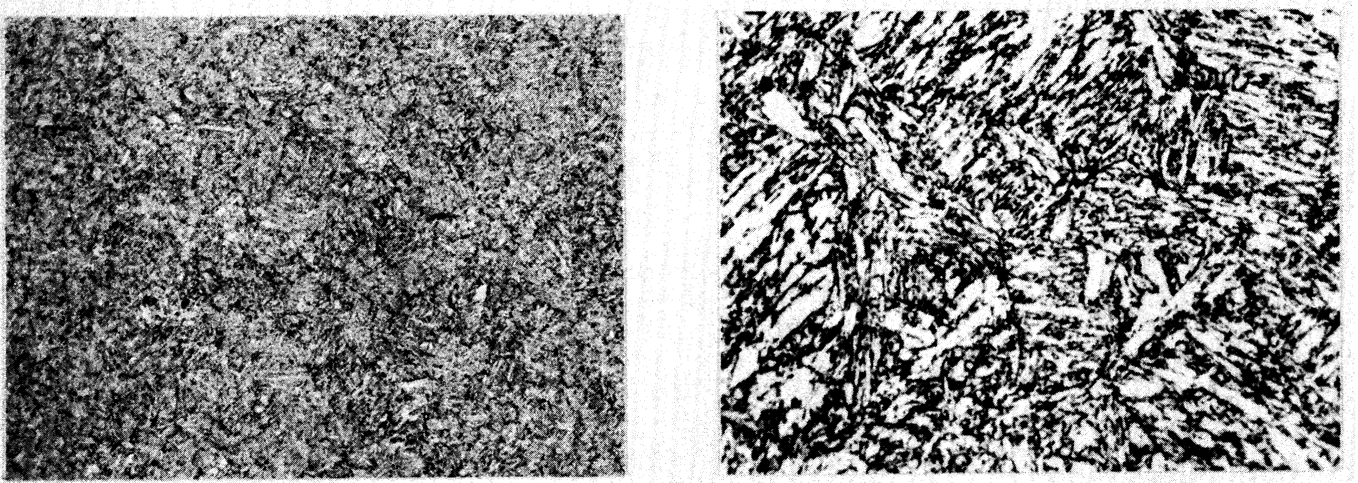
(c) Normalized 1950°F + tempered 18 hrs at 1200°F + creep-rupture tested 272 hrs at 1100°F and 34,000 psi - 285 BHN.

Figure 24. H-40 Bar Stock (a) As Normalized, (b) As Tempered to 300 BHN, and (c) As Creep-Rupture Tested at 1100°F.

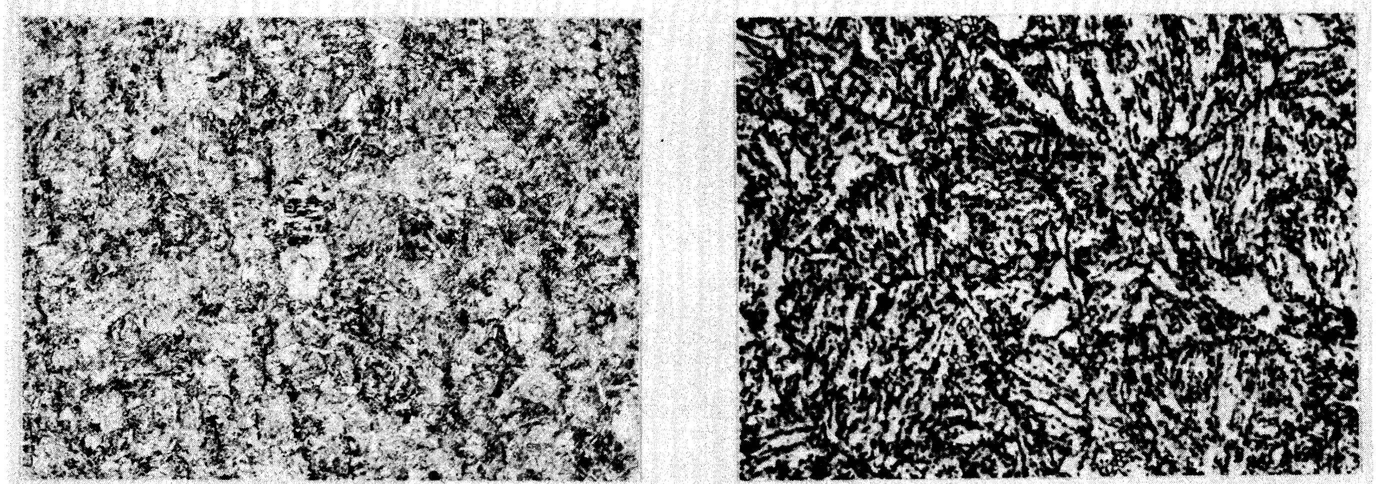
X100D X1000D



(a) Oil quenched 1900°F - 510 BHN.



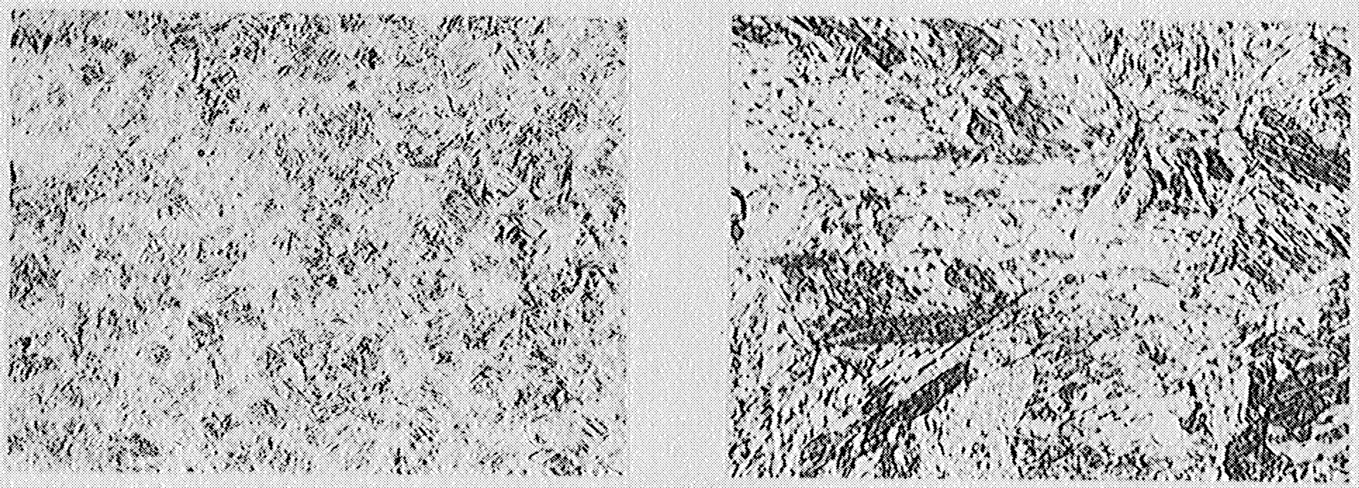
(b) Oil quenched 1900°F + tempered 4 hrs at 1200°F - 310 BHN.



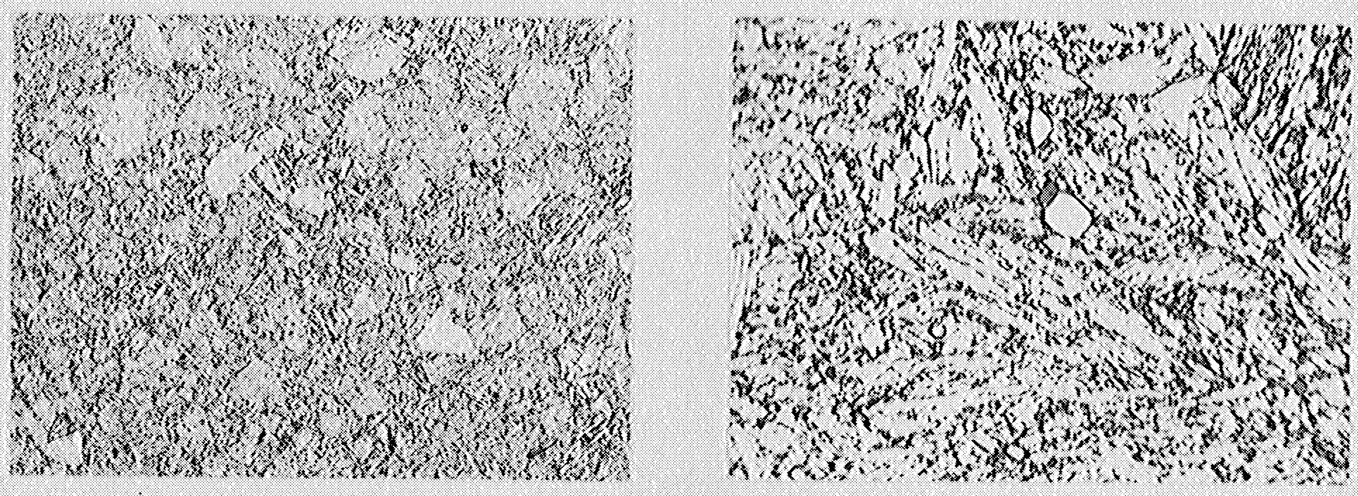
(c) Oil quenched 1900°F + tempered 4 hrs at 1200°F + creep tested 1003 hrs at 1100°F and 30,000 psi - 285 BHN.

Figure 25. C-422 Bar Stock (a) As Oil Quenched, (b) As Tempered to 300 BHN, and (c) after Creep Testing at 1100°F.

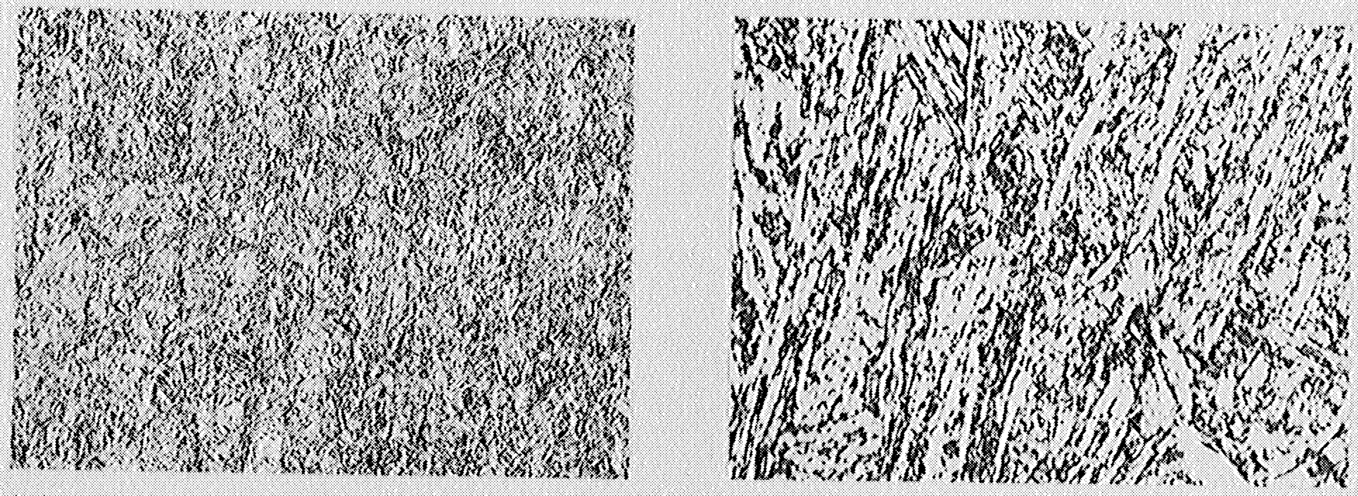
X100D X1000D



(a) Normalized 1900°F - 485 BHN.



(b) Normalized 1900°F + tempered 24 hrs at 1200°F - 302 BHN.



(c) Normalized 1900°F + tempered 24 hrs at 1200°F + creep-rupture tested 366 hrs at 1100°F and 39,000 psi - 281 BHN.

Figure 26. C-422 Bar Stock (a) As Normalized, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

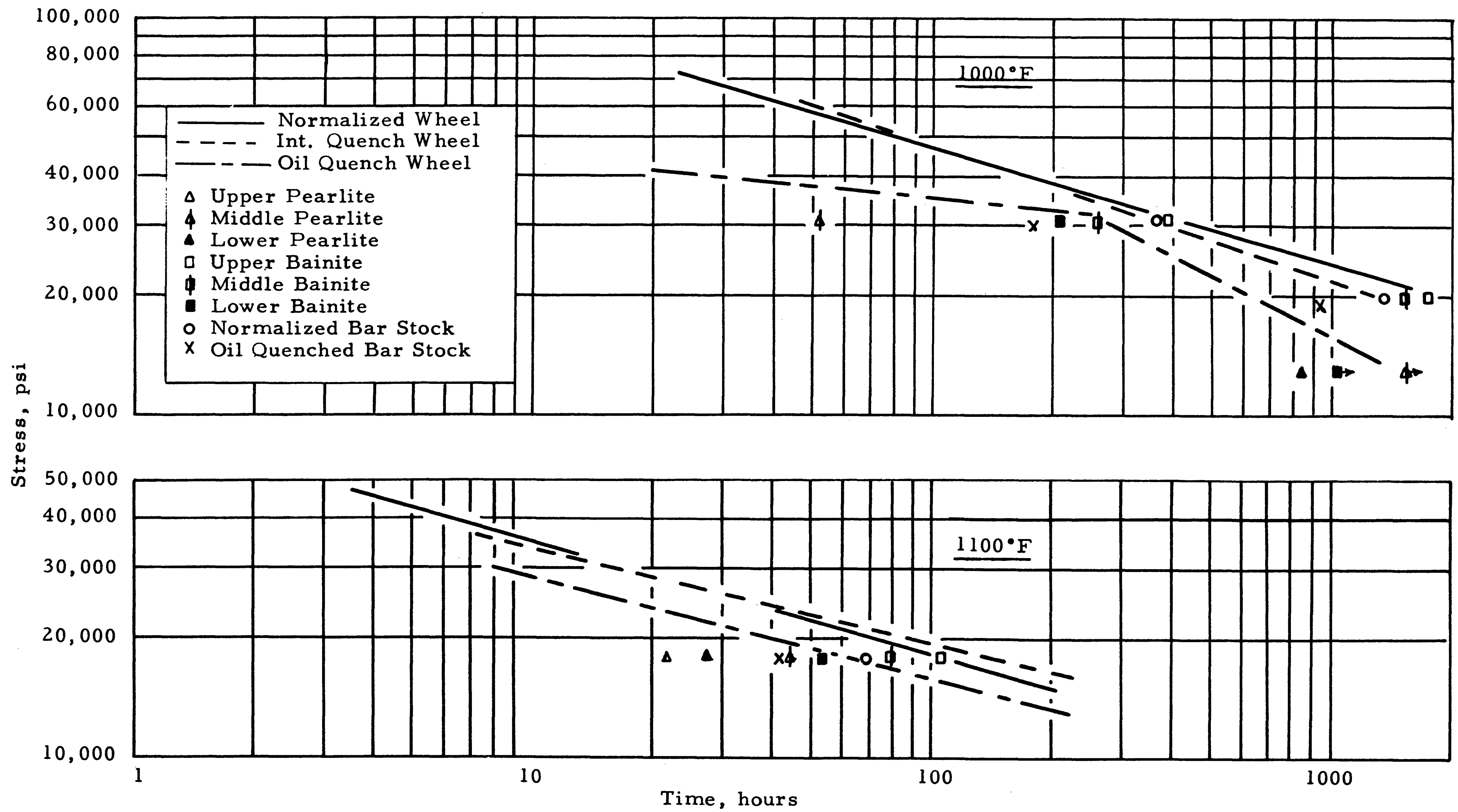


Figure27. Comparison of Stress-Rupture Data at 1000° and 1100°F between Isothermally Transformed Structures and Variously Heat Treated Turbine Wheels of SAE 4340 Steel.

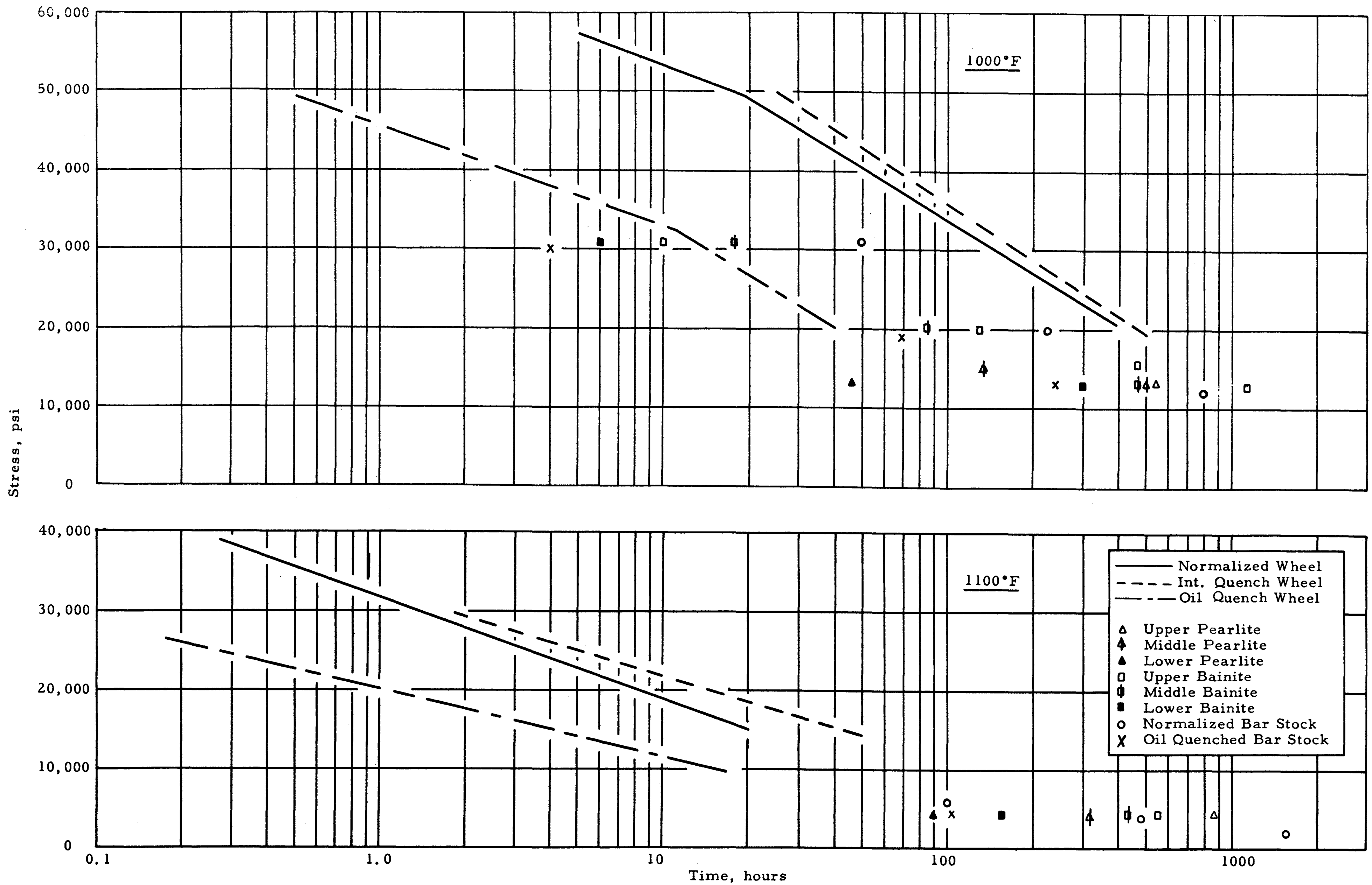


Figure 28. Comparison of 0.5-Percent Total Deformation Data at 1000° and 1100°F between Isothermally Transformed Structures and Various Heat Treated Turbine Wheels of SAE 4340 Steel.

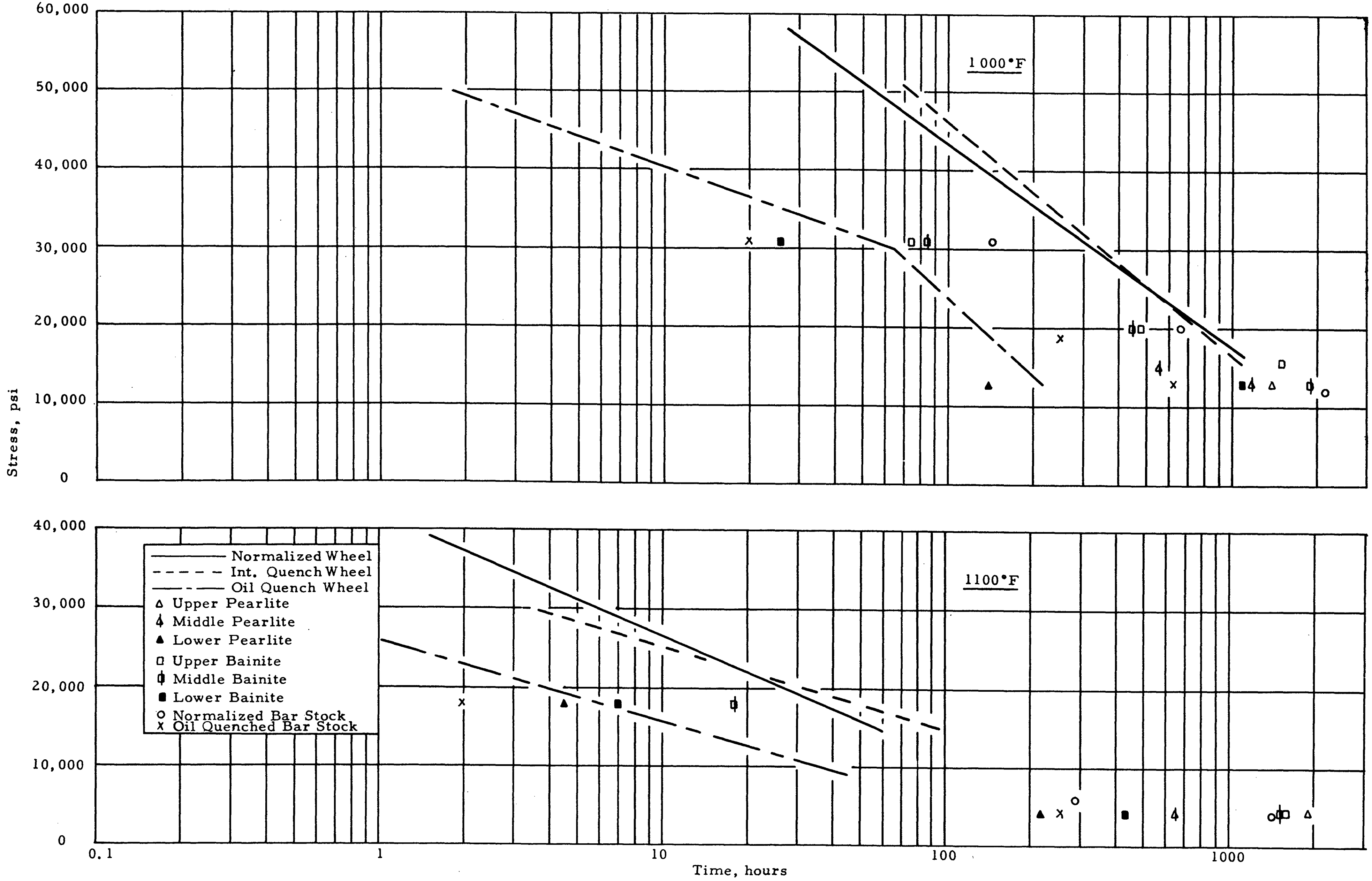


Figure 29. Comparison of One-Percent Total Deformation Data at 1000° and 1100°F between Isothermally Transformed Structures and Variously Heat Treated Turbine Wheels of SAE 4340 Steel.

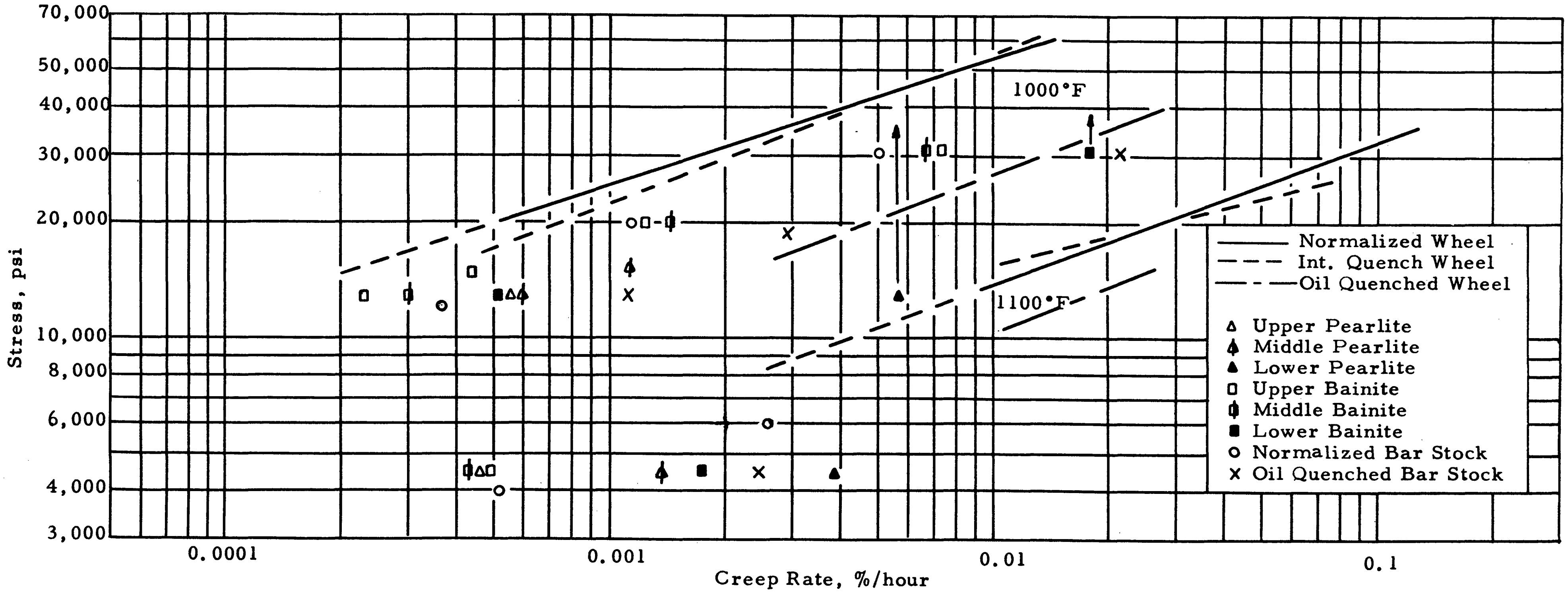


Figure 30. Comparison of Stress - Creep Rate Data at 1000° and 1100°F between Isothermally Transformed Structures and the Variously Heat Treated Turbine Wheels of SAE 4340 Steel.

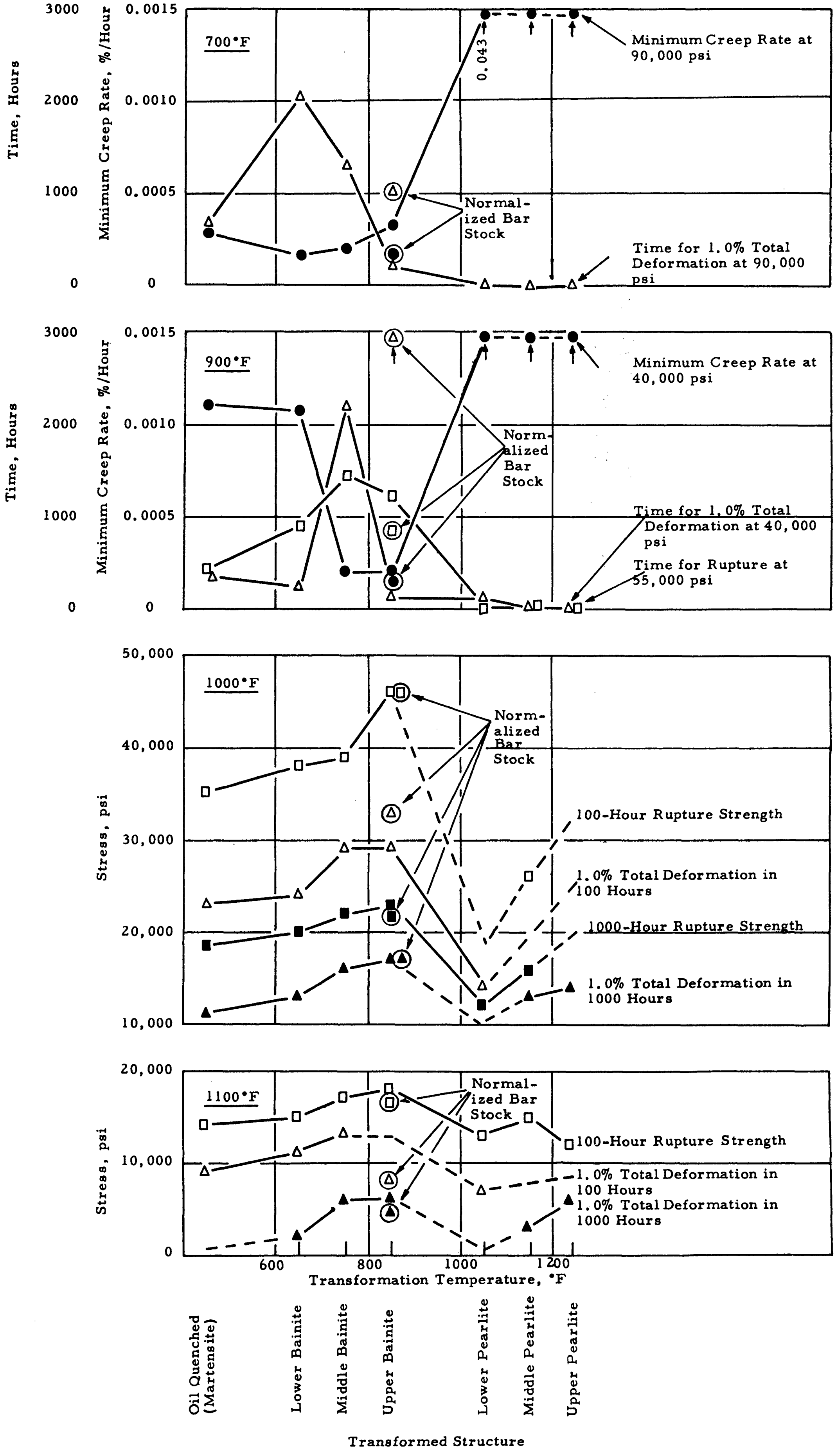


Figure 31. Relationship between Properties at 700°, 900°, 1000°, and 1100°F of Isothermally Transformed Structures of SAE 4340 and Temperature of Transformation. (NOTE: Properties of Normalized Bar have been inserted at isothermal transformation temperature yielding structure most similar to normalized bar.)

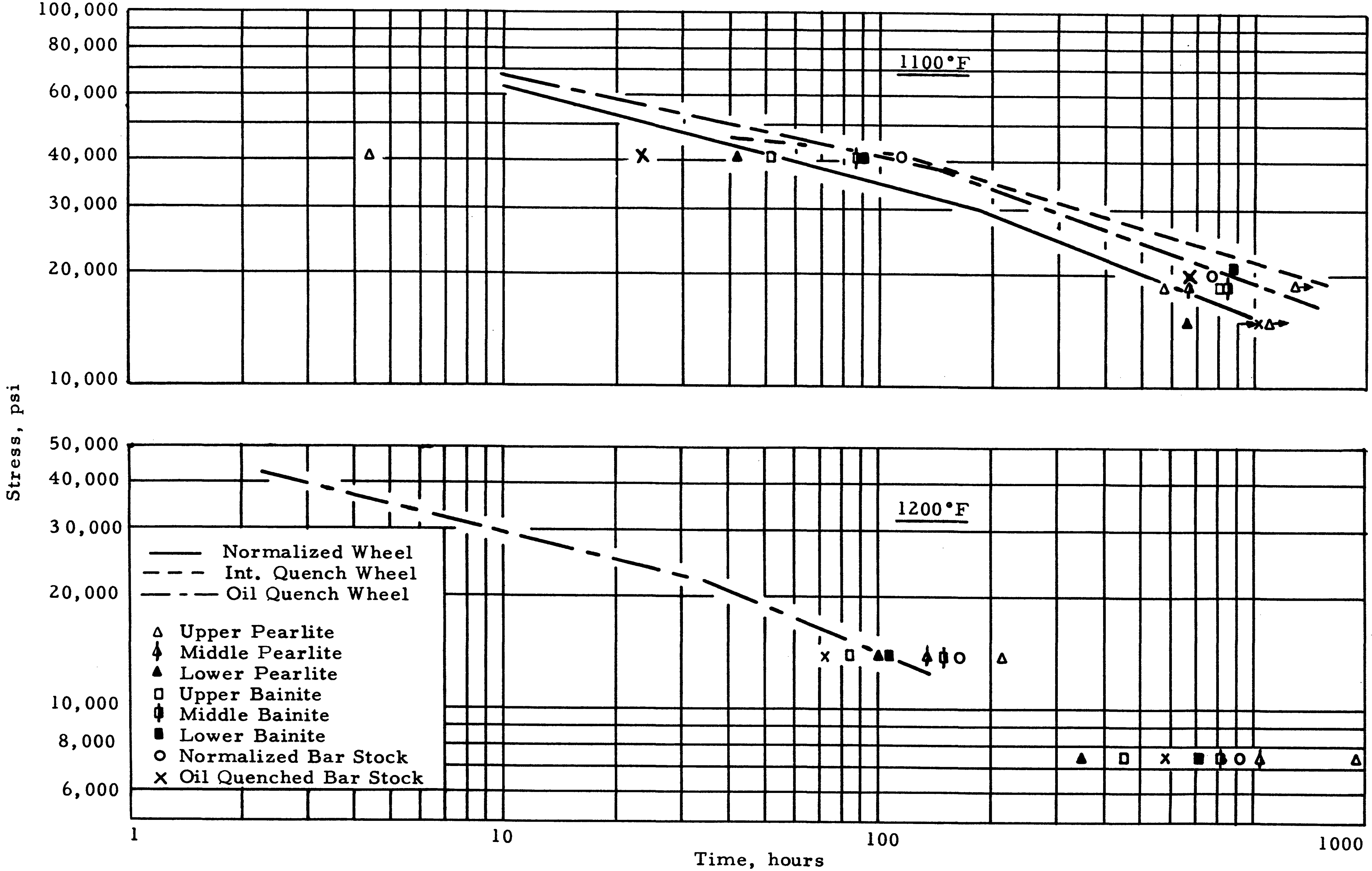


Figure 32. Comparison of Stress-Rupture Data at 1100° and 1200°F between Isothermally Transformed Structures and Variously Heat Treated Turbine Wheels for "17-22A"S Steel.

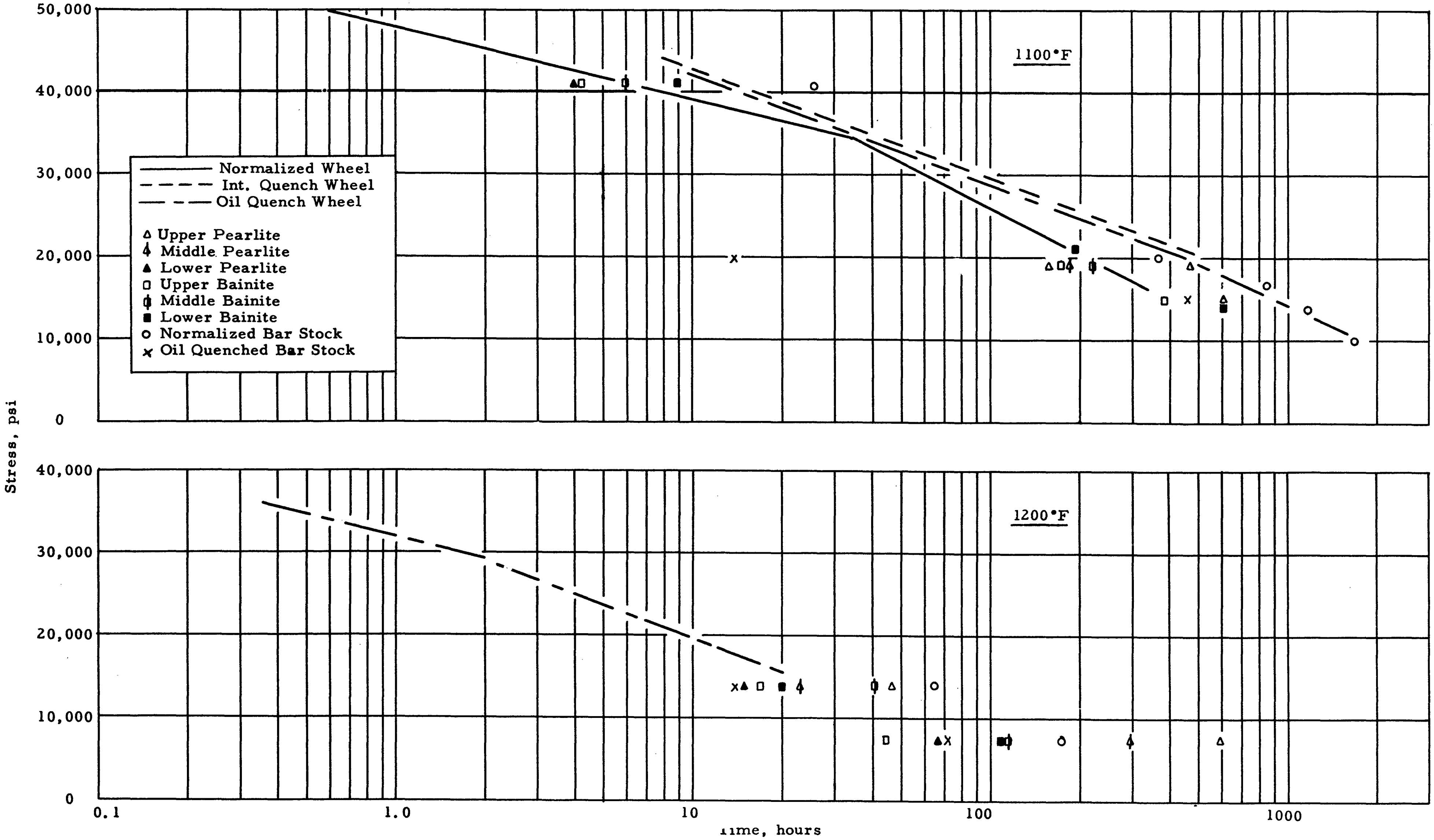


Figure 33. Comparison of 0.5-Percent Total Deformation Data at 1100° and 1200°F between Isothermally Transformed Structures and Variously Heat Treated Turbine Wheels for "17-22A"S Steel.

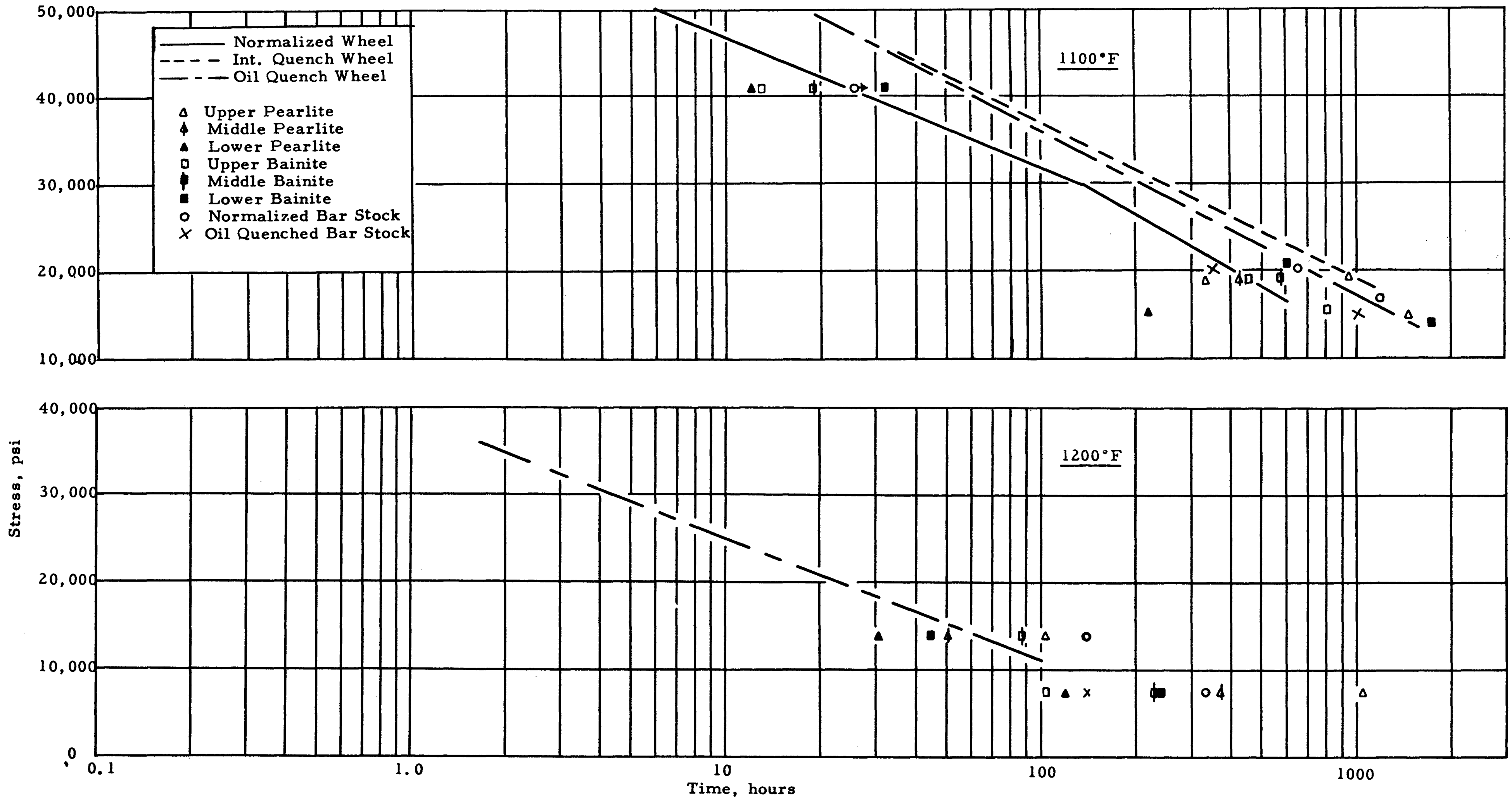


Figure 34. Comparison of One-Percent Total Deformation Data at 1100° and 1200°F between Isothermally Transformed Structures and Variously Heat Treated Turbine Wheels for "17-22A"S Steel.

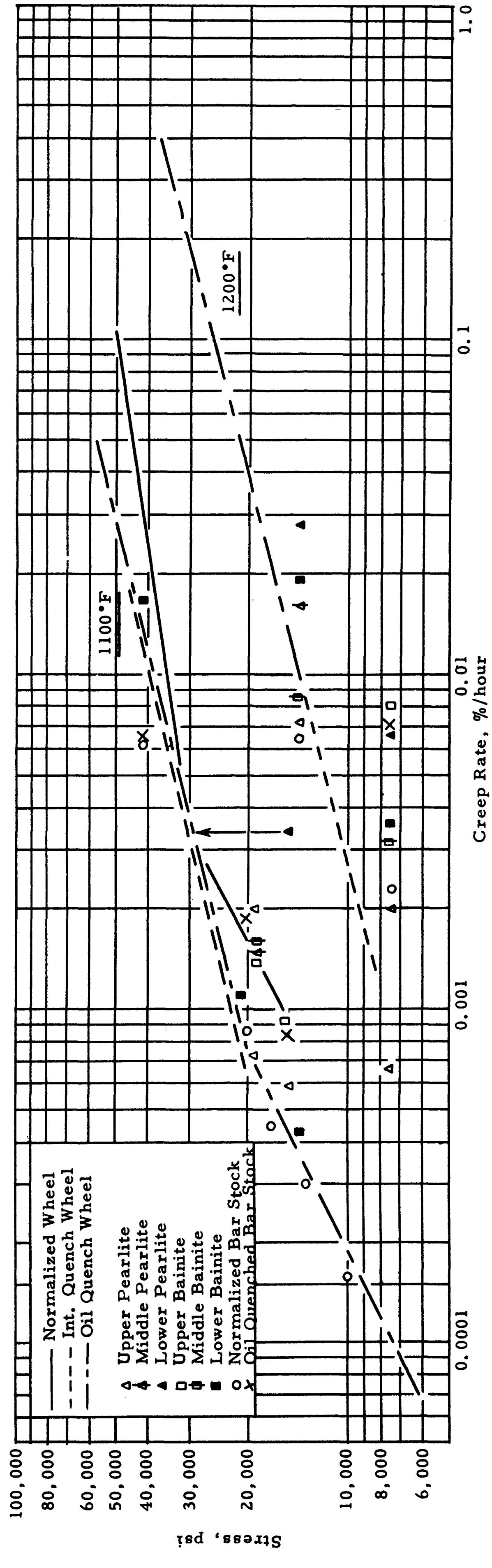


Figure 35. Comparison of Stress - Creep Rate Data at 1100° and 1200°F between Isothermally Transformed Structures and Variously Heat Treated Turbine Wheels for "17-22A"S Steel.

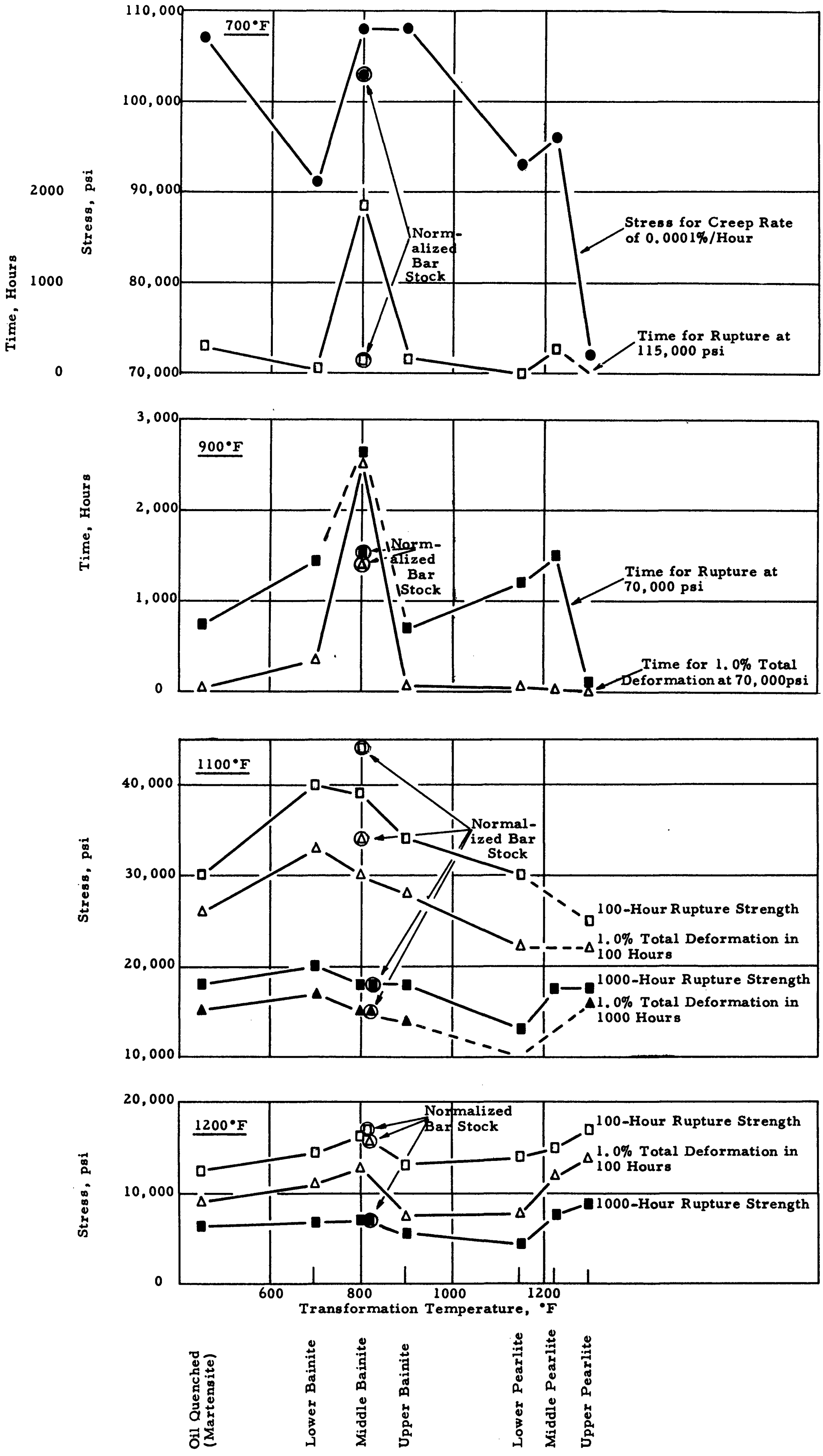


Figure 36. Relationship between Properties at 700°, 900°, 1100°, and 1200°F of Isothermally Transformed Structures of "17-22A"S Steel and Temperature of Transformation. (NOTE: Properties of Normalized Bar have been inserted at isothermal transformation temperature yielding structure most similar to normalized bar.)

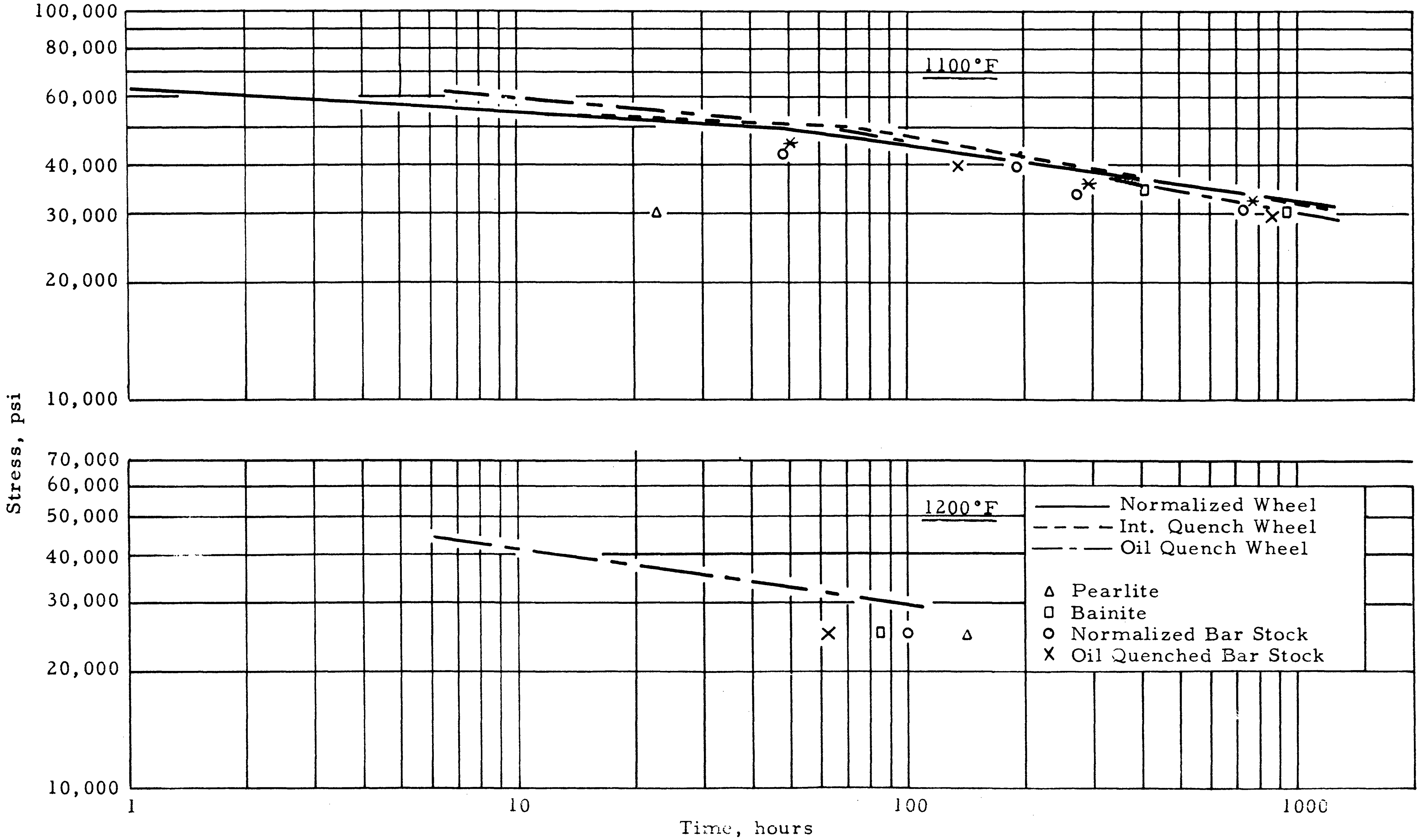


Figure 37. Comparison of Stress-Rupture Data at 1100° and 1200°F between Isothermally Transformed Structures and Variously Heat Treated Turbine Wheels for H-40 Steel.
(Note: * indicates that specimens fractured in shoulder radius or threads.)

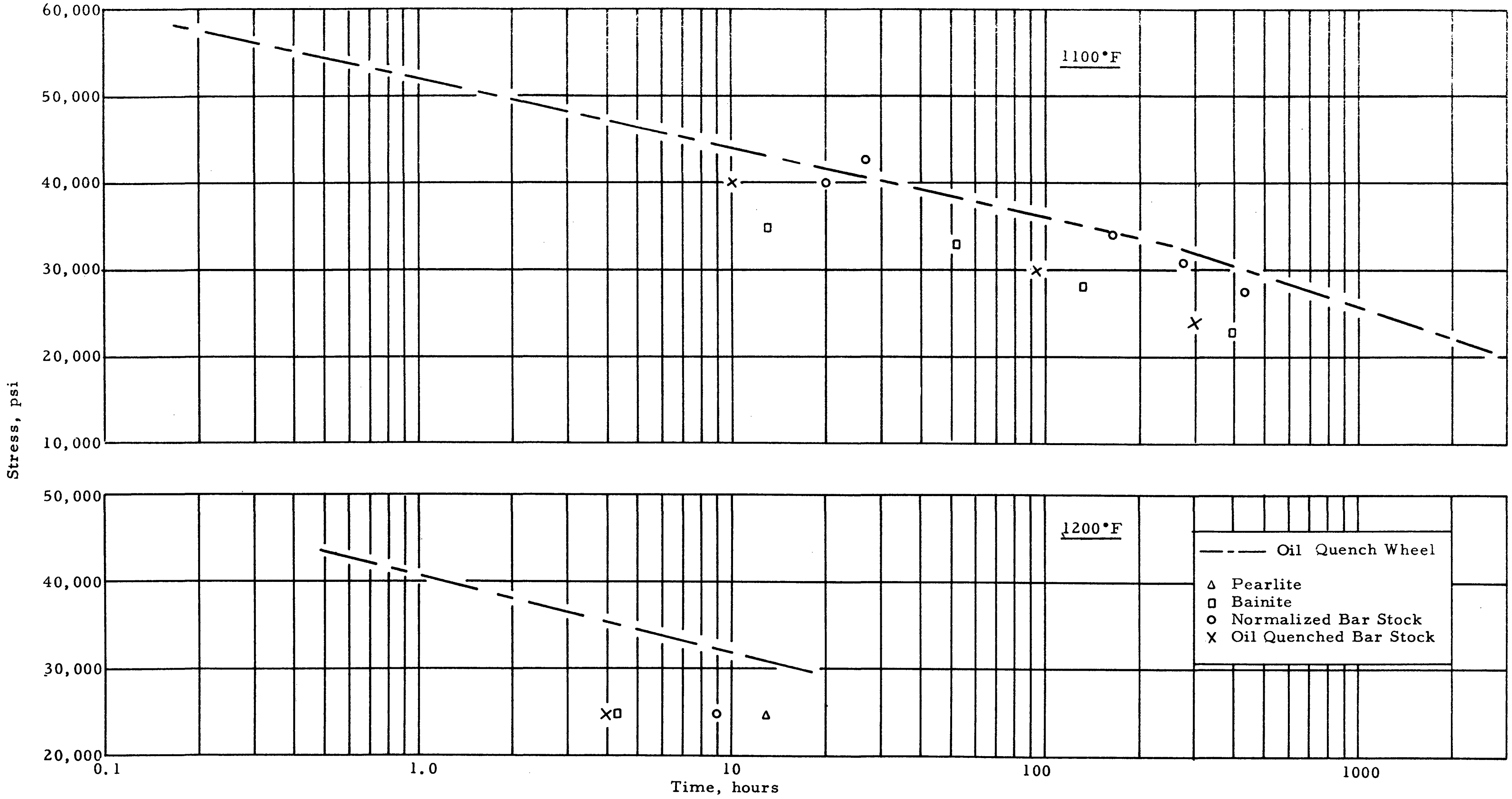


Figure 38. Comparison of 0.5-Percent Total Deformation Data at 1100° and 1200°F between Isothermally Transformed Structures and an Oil Quenched and Tempered Turbine Wheel of H-40 Steel.

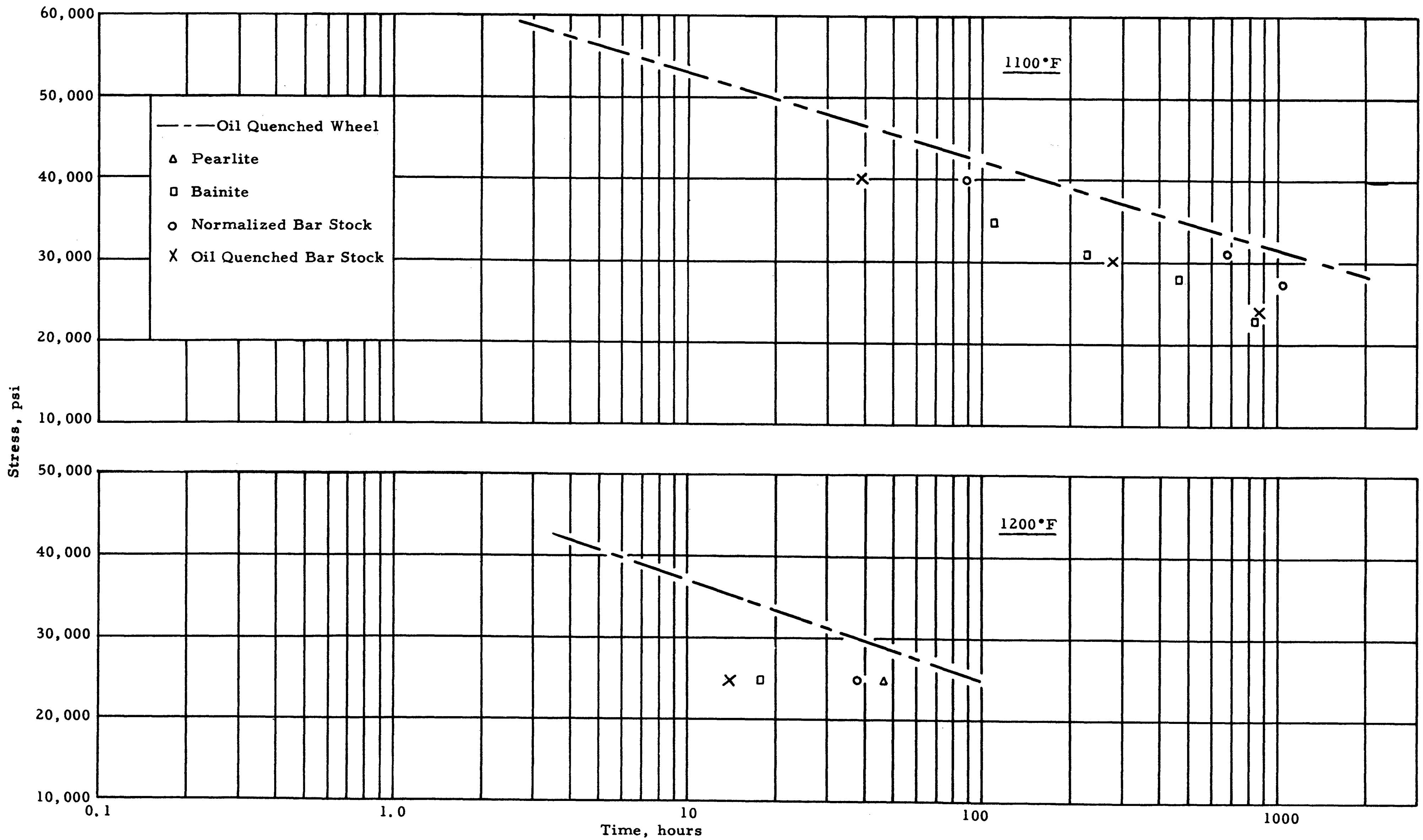


Figure 39. Comparison of One-Percent Total Deformation Data at 1100° and 1200°F between Isothermally Transformed Structures and an Oil Quenched Turbine Wheel of H-40 Steel.

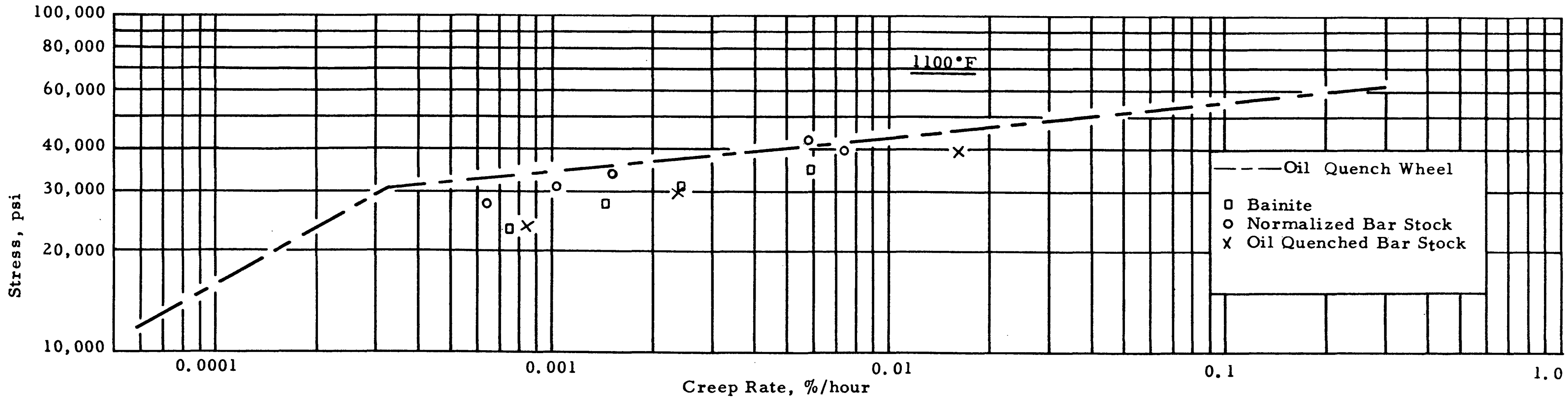


Figure 40. Comparison of Stress - Creep Rate Data at 1100°F between Isothermally transformed Structures and an Oil Quenched and Tempered Turbine Wheel of H-40 Steel.

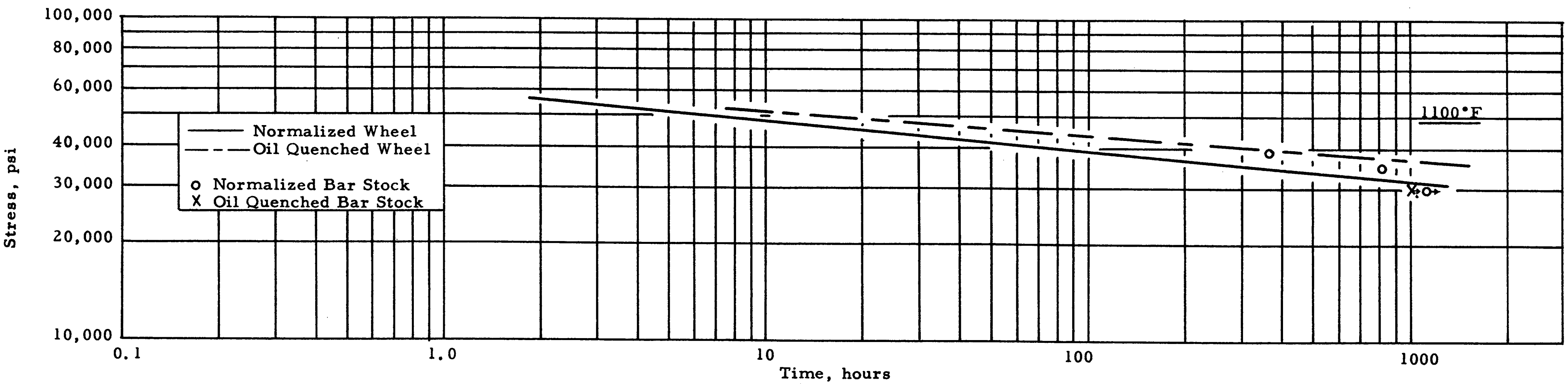


Figure 41. Comparison of Stress-Rupture Data at 1100°F between Normalized and Oil Quenched Bar Stock and Variously Heat Treated Turbine Wheels of C-422 Steel.

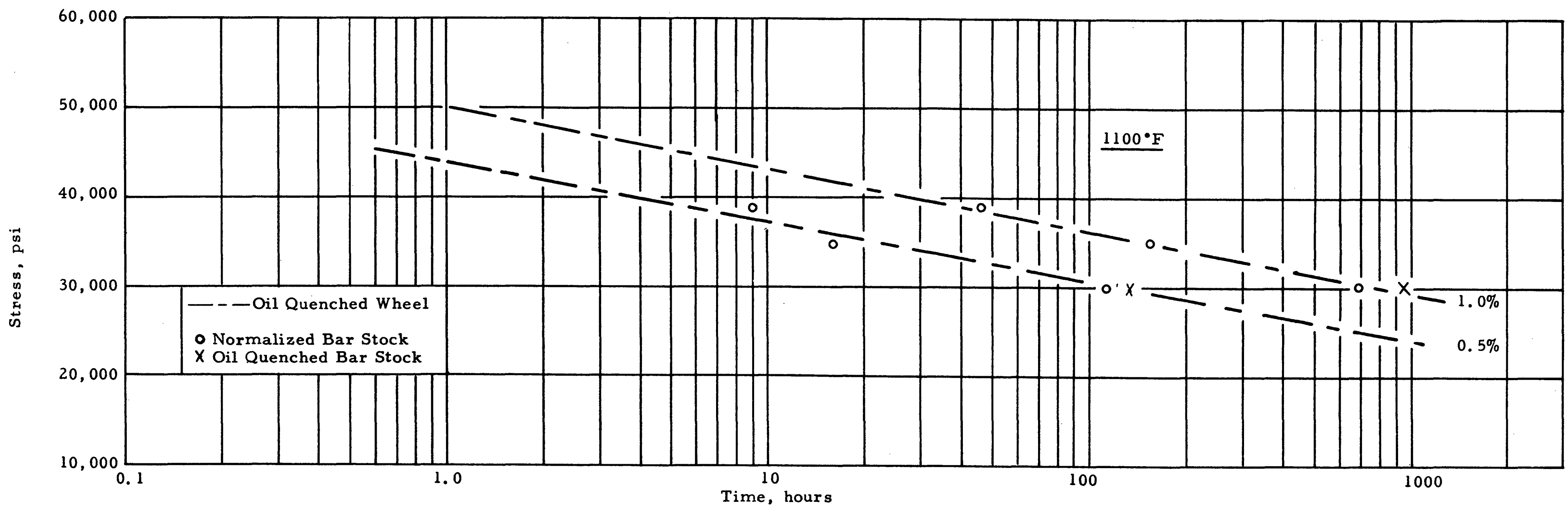


Figure 42. Comparison of 1.0- and 0.5-Percent Total Deformation Data at 1100°F between Normalized and Oil Quenched Bar Stock and an Oil Quenched and Tempered Turbine Wheel of C-422 Steel.

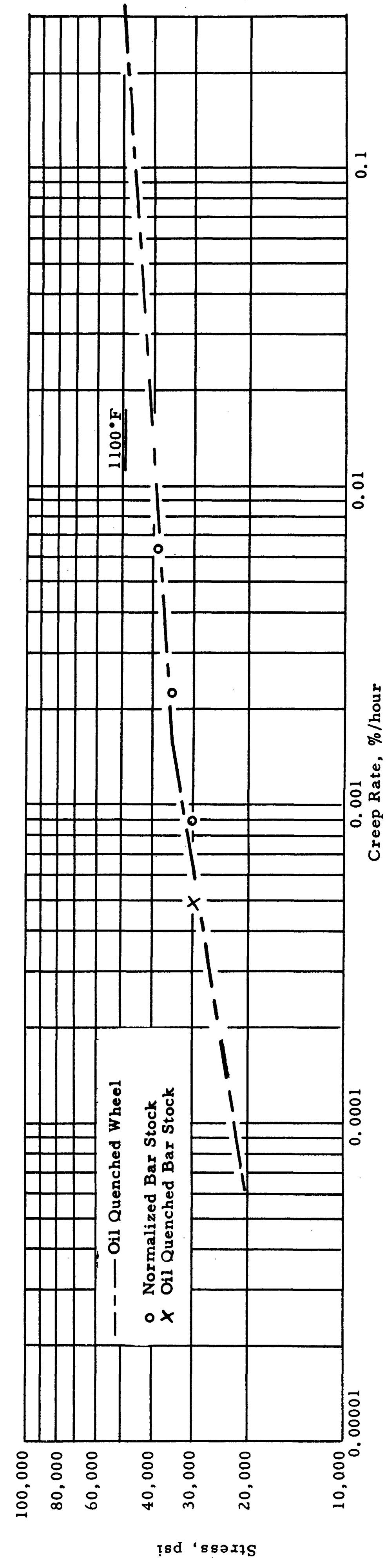


Figure 43. Comparison of Stress - Creep Rate Data at 1100°F between Normalized and Oil Quenched Bar Stock and an Oil Quenched Turbine Wheel of C-422 Steel.

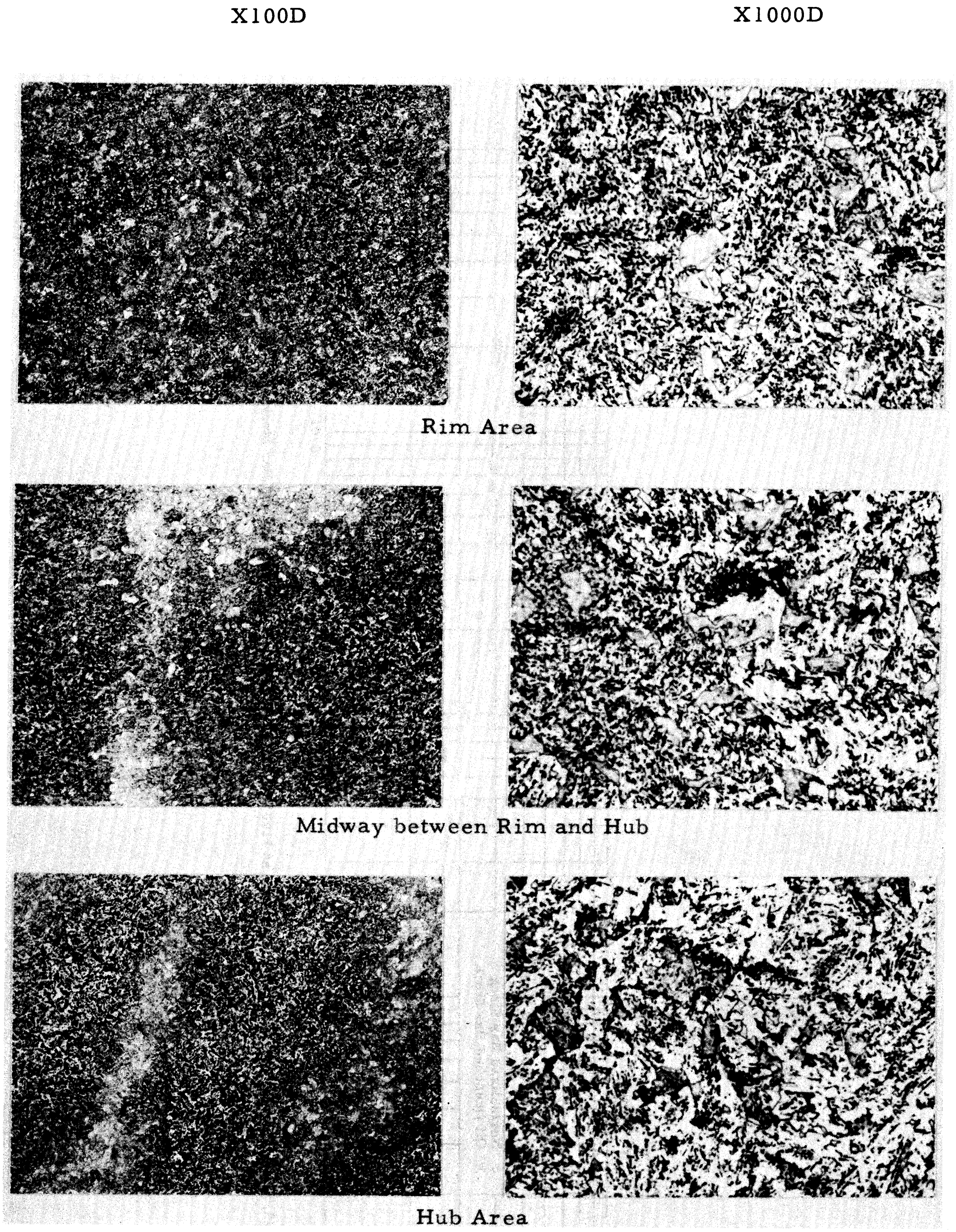


Figure 44. Typical Microstructures of 4340 Disk No. 1. Heat Treatment: (a) Normalized 1750°F + Tempered 2 Hrs at 1200°F, (b) Normalized 1750°F - 297/345 BHN.

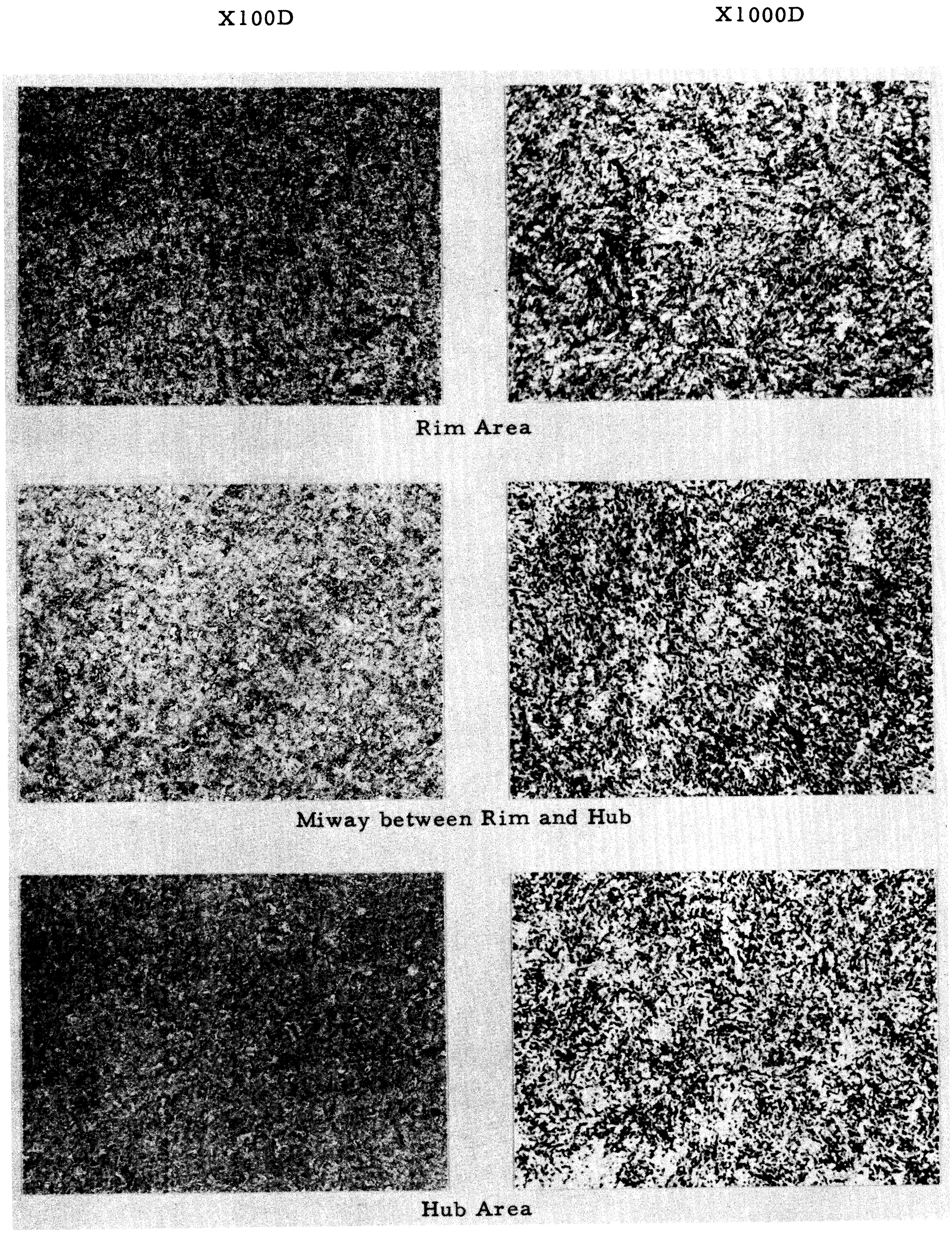


Figure 45. Typical Microstructures of 4340 Disk No. 3. Heat Treatment: (a) Oil Quenched 1750°F + Tempered 8 Hrs at 1200°F, (b) Oil Quenched 1550°F + Tempered at 1050°F - 260/320 BHN.

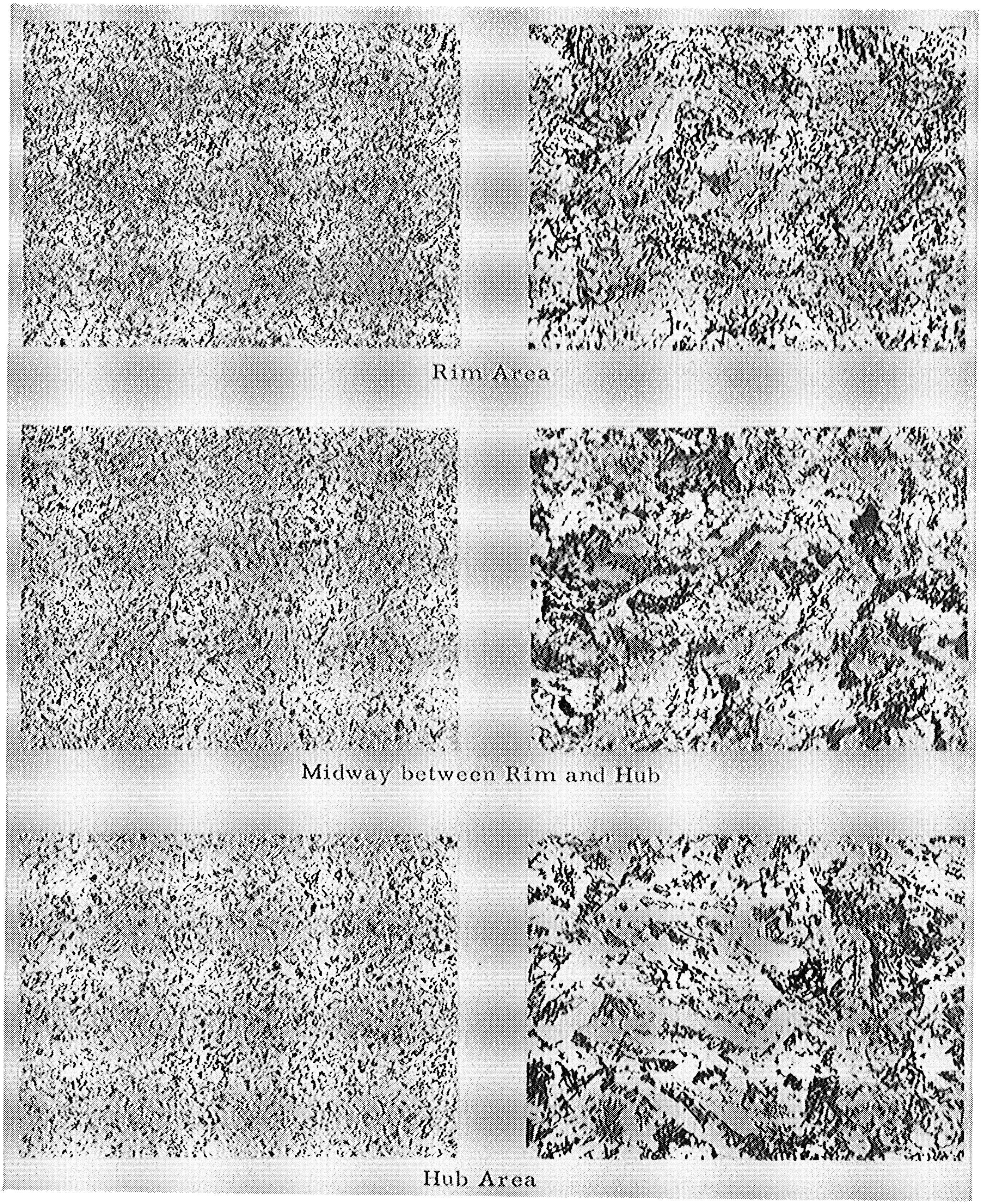
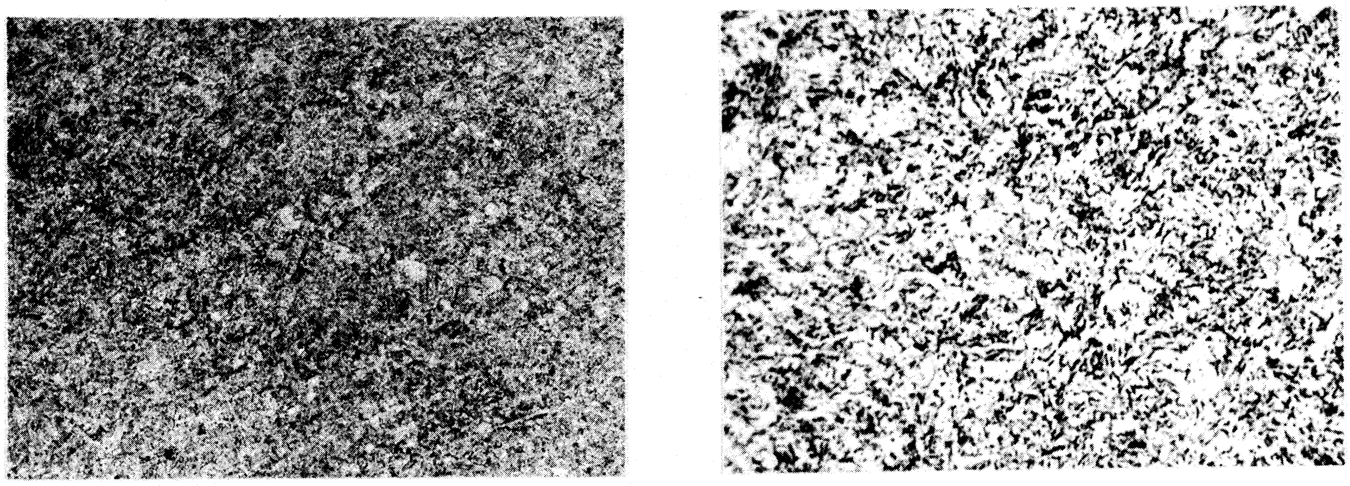
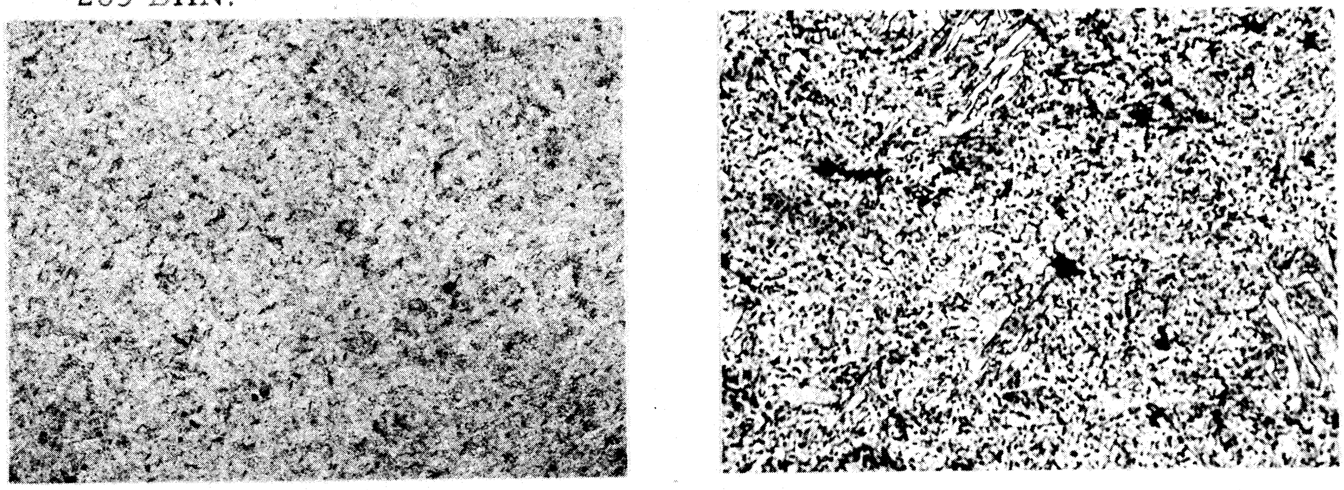


Figure 46. Typical Microstructures of 4340 Disk No. 4. Heat Treatment: Interrupted Quench 1750°F + Tempered 2 Hrs at 1200°F - 280/340 BHN.

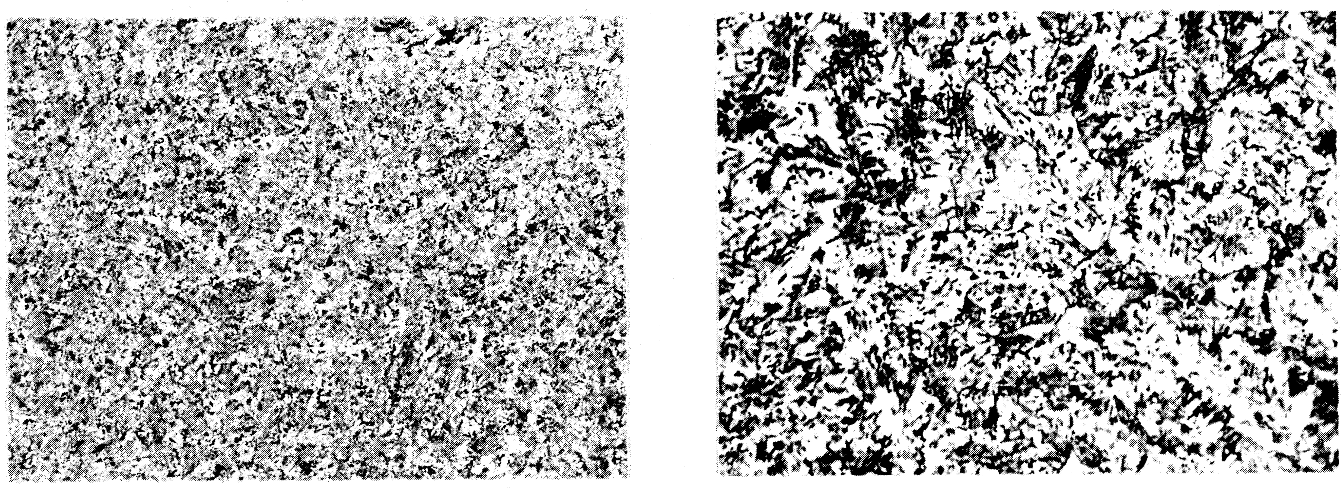
X100D X1000D



(a) 4340 Disk No. 1. Rupture tested 957 hrs at 1000°F and 24,000 psi - 265 BHN.



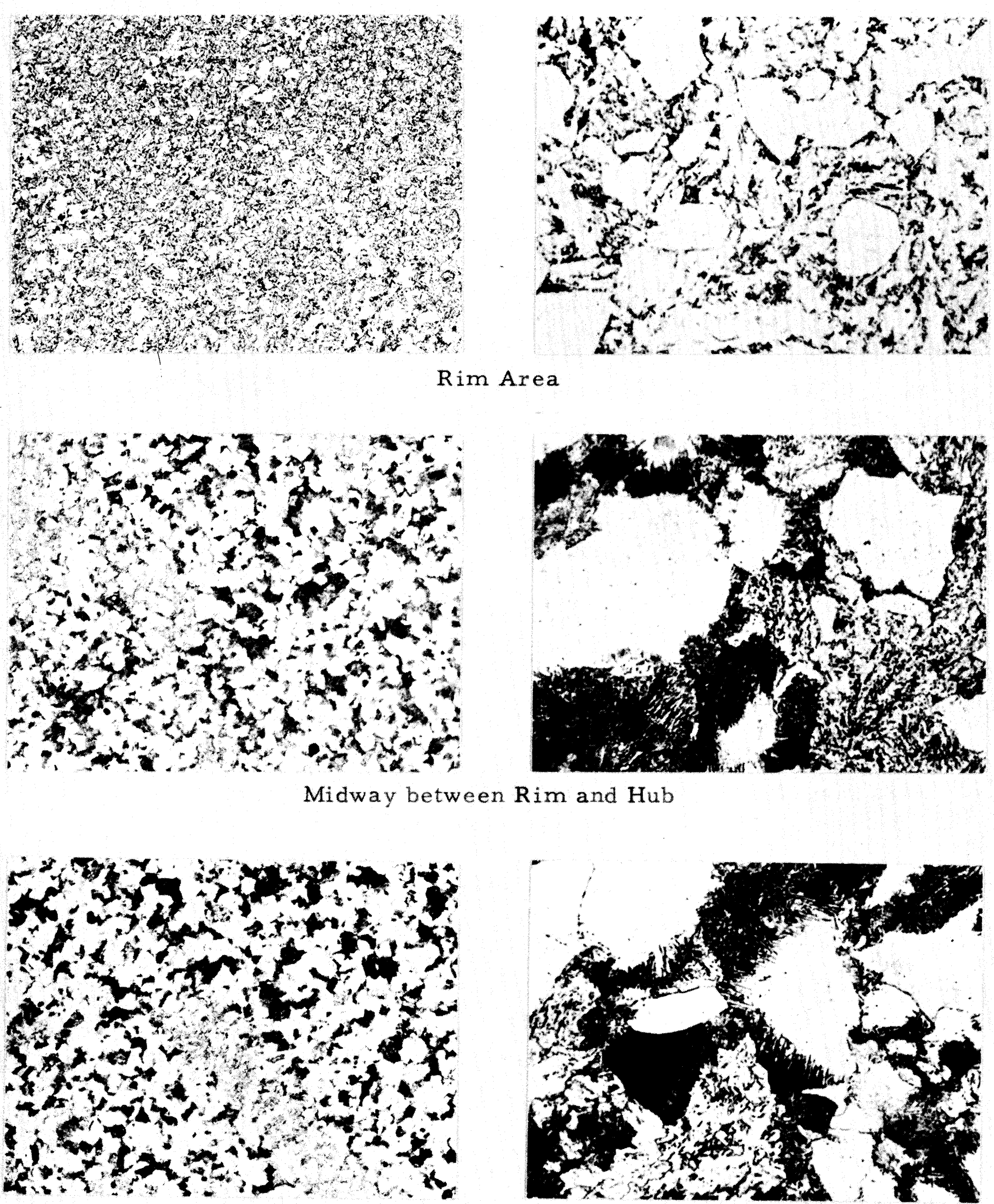
(b) 4340 Disk No. 3. Rupture tested 604 hrs at 1000°F and 20,000 psi - 238 BHN.



(c) 4340 Disk No. 4. Creep tested 1150 hrs at 1000°F and 19,000 psi - 270 BHN.

Figure 47. Microstructures of Creep-Rupture Specimens of 4340 Disks Nos. (a) 1, (b) 3, and (c) 4.

X100D X1000D



Rim Area

Midway between Rim and Hub

Hub Area

Figure 48. Typical Microstructures of "17-22A"S Disk No. 1. Heat Treatment: Normalized 1750°F + Tempered 2 Hrs at 1200°F - 235/330 BHN.

X100D X1000D

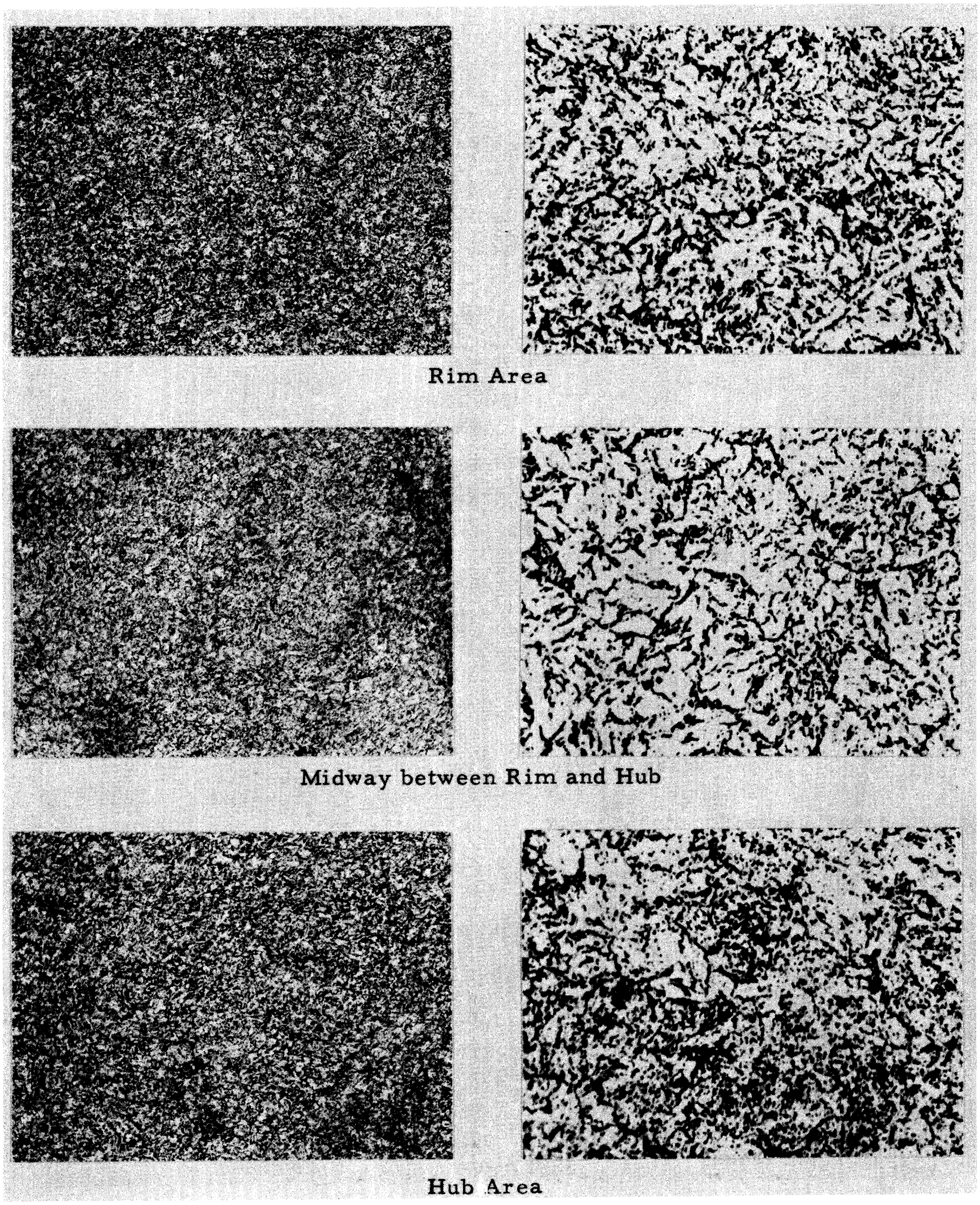


Figure 49. Typical Microstructures of "17-22A"S Disk No. 3. Heat Treatment: Oil Quenched 1750°F + Tempered 8 Hrs at 1200°F - 280/340 BHN.

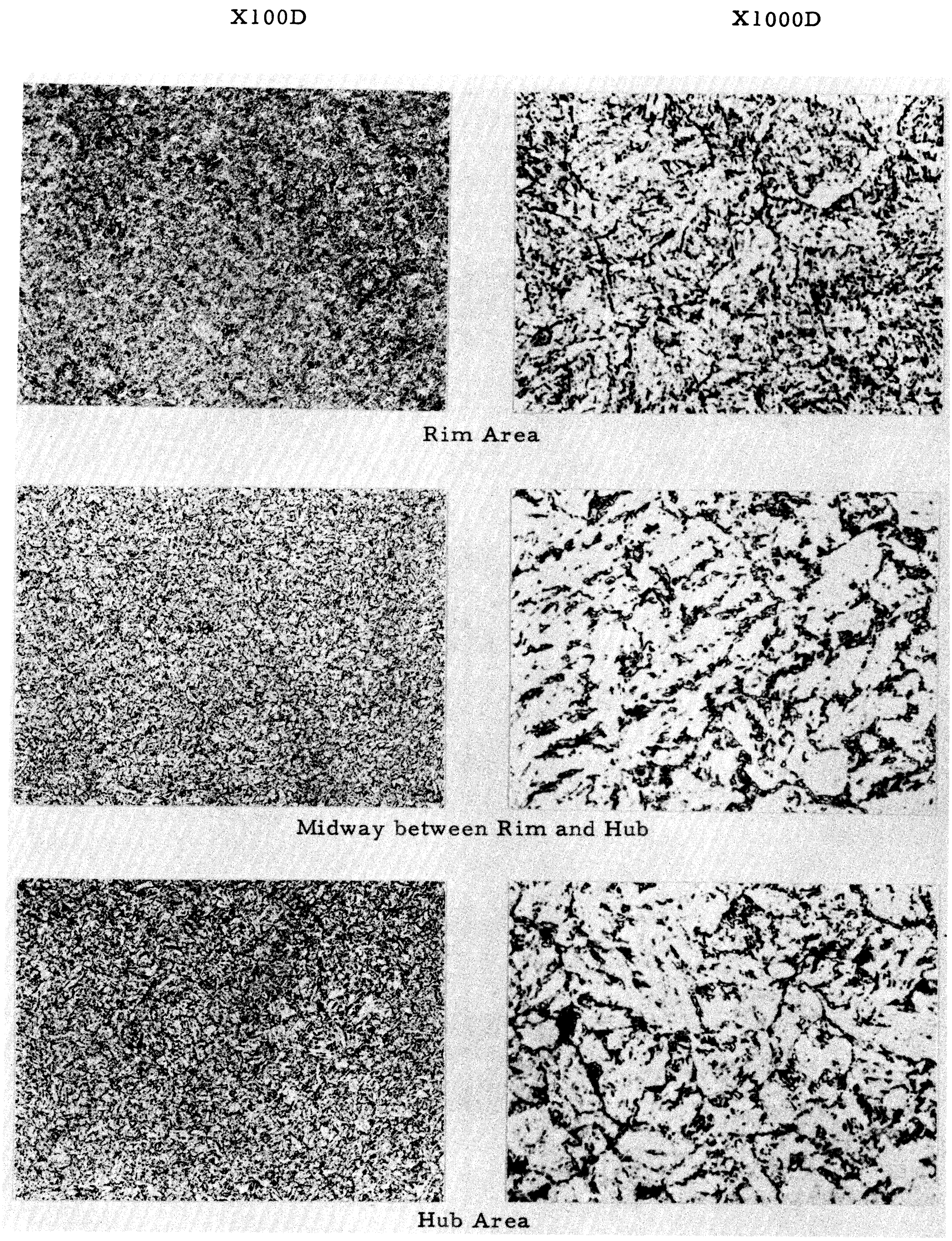
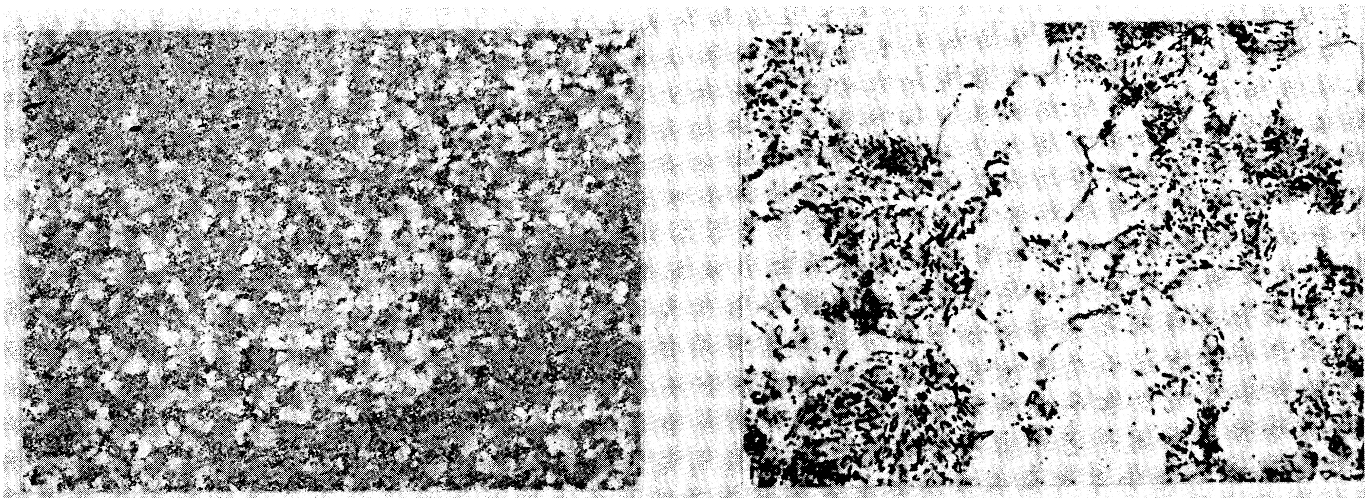
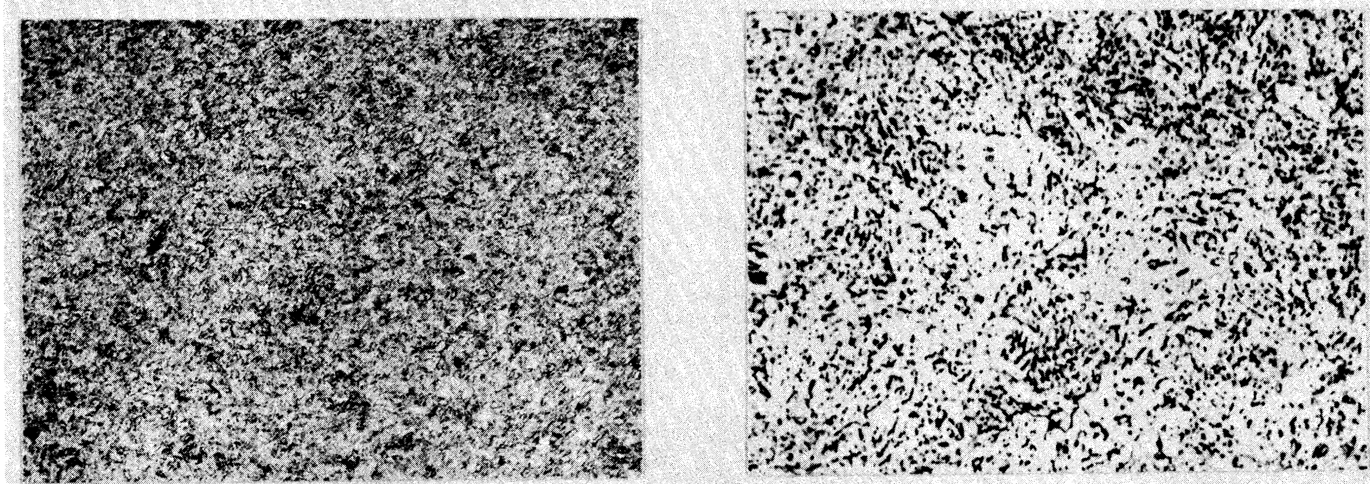


Figure 50. Typical Microstructures of "17-22A"S Disk No. 4. Heat Treatment: Interrupted Quench 1750°F + Tempered 2 Hrs at 1200°F + Tempered 2 Hrs at 1200°F - 280/340 BHN.

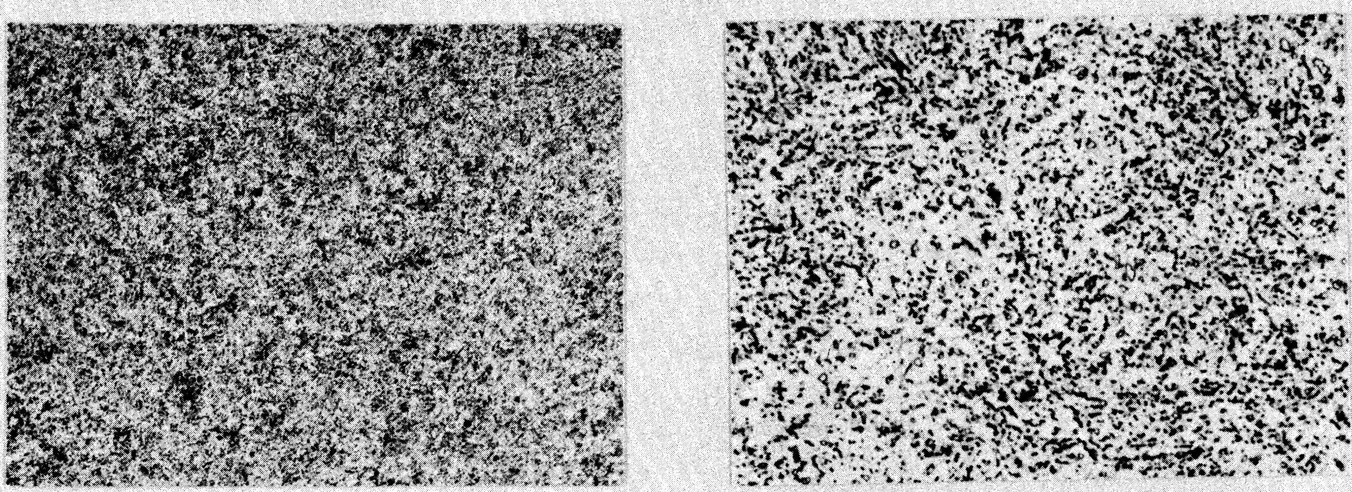
X100D X1000D



(a) "17-22A"S Disk No. 1. Rupture tested 519 hrs at 1100°F and 20,000 psi - 262 BHN.



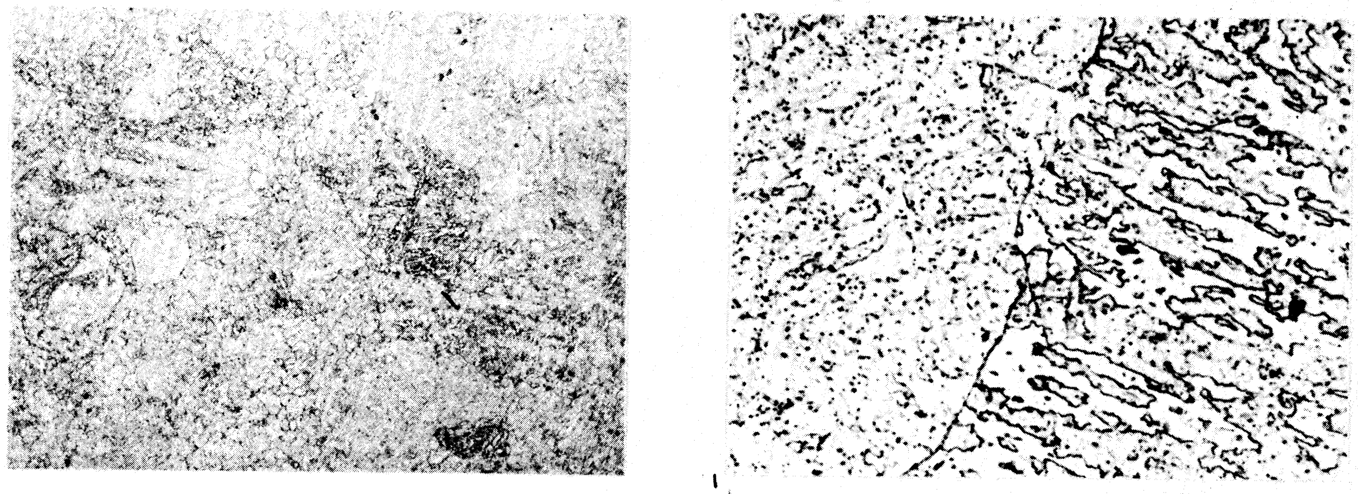
(b) "17-22A"S Disk No. 3. Rupture tested 792 hrs at 1100°F and 20,500 psi - 265 BHN.



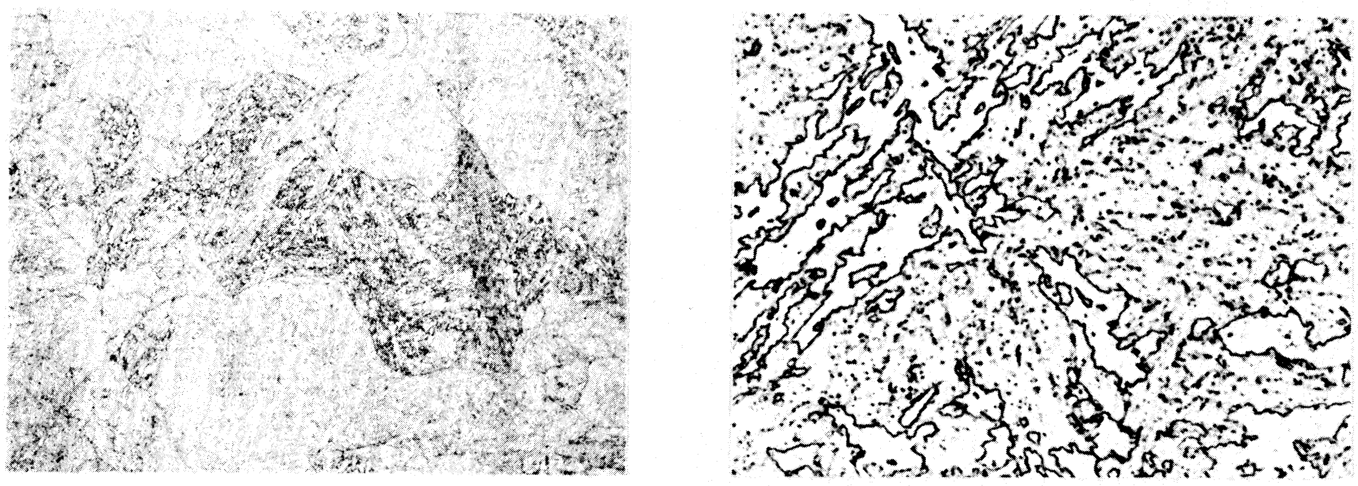
(c) "17-22A"S Disk No. 4. Rupture tested 1233 hrs at 1100°F and 20,500 psi - 262 BHN.

Figure 51. Microstructures of Rupture Specimens of "17-22A"S Disks Nos. (a) 1, (b) 3, and (c) 4.

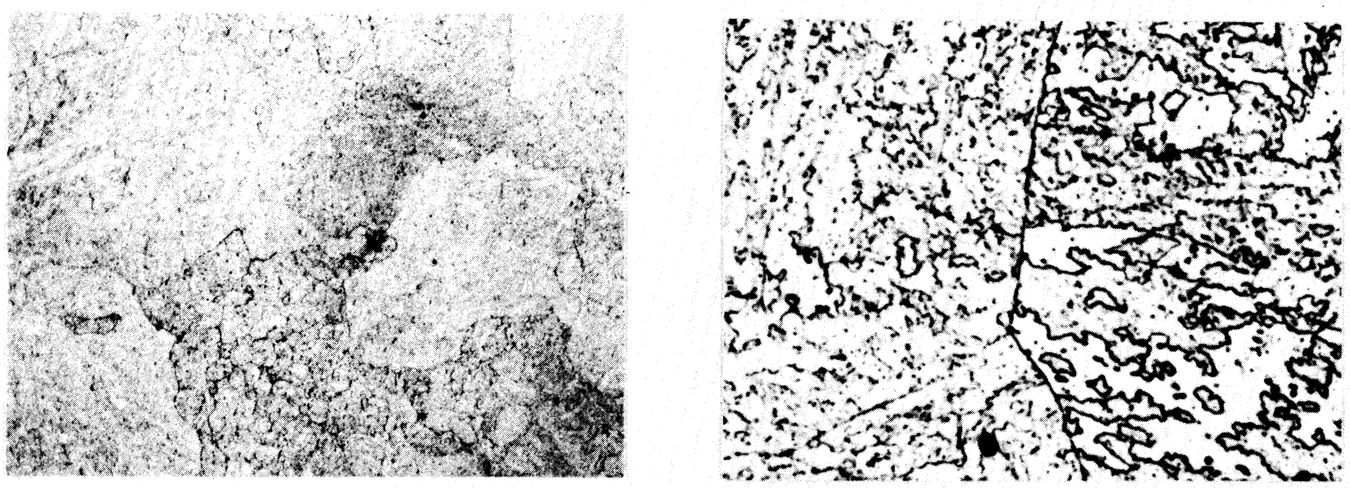
X100D X1000D



Rim Area



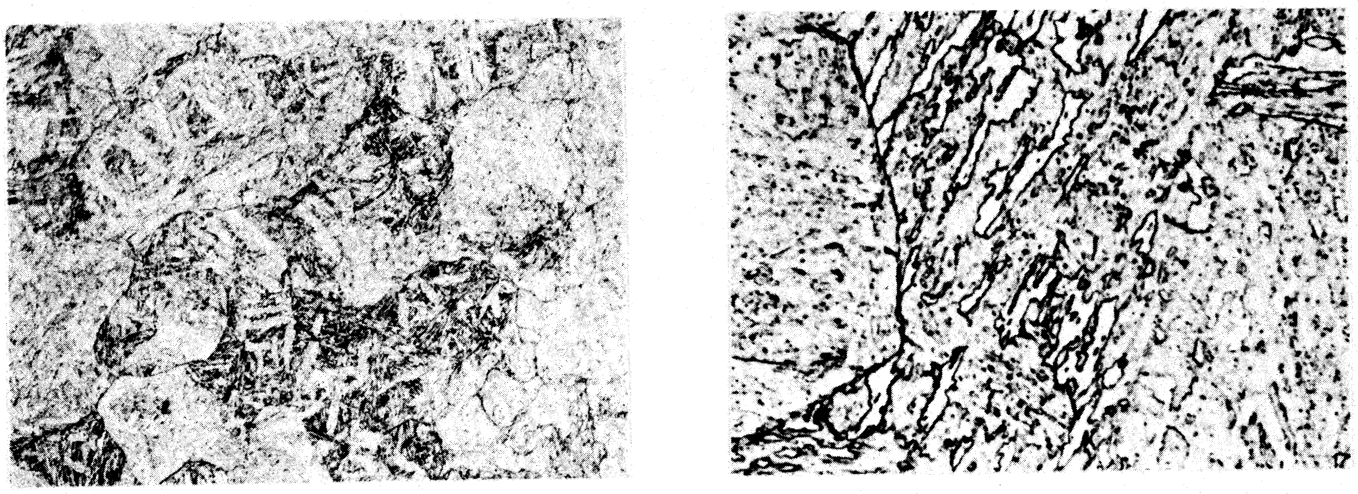
Midway between Rim and Hub



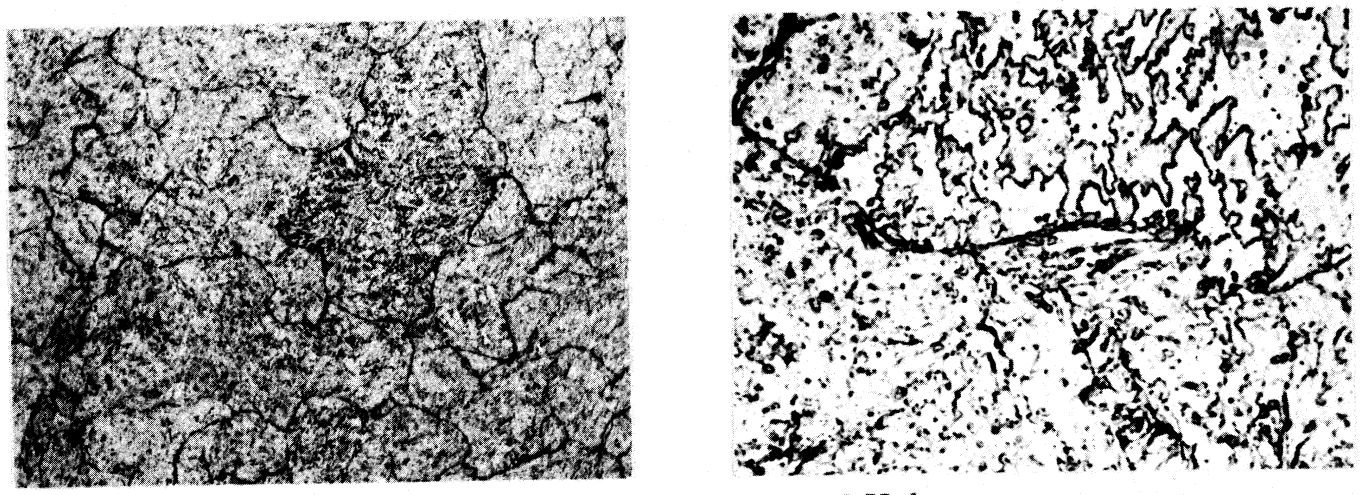
Hub Area

Figure 52. Typical Microstructures of As-Received H-40 Disk No. 1. Heat Treatment: Normalized 1950°F + Tempered 2 Hrs at 1200°F + Tempered 3 Hrs at 1200°F - 315/380 BHN.

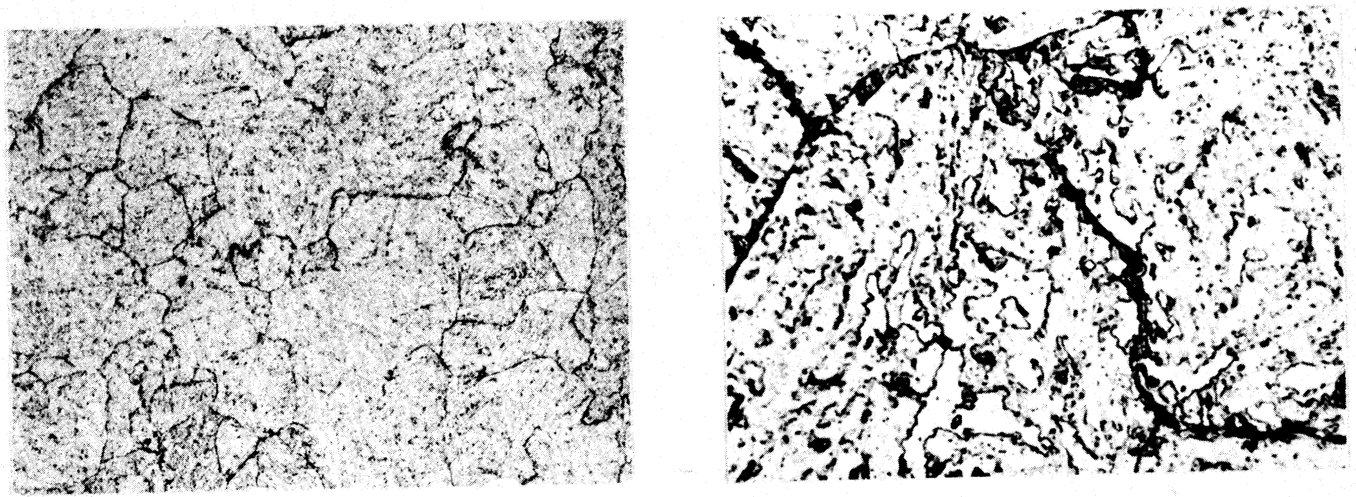
X100D X1000D



Rim Area



Midway between Rim and Hub



Hub Area

Figure 53. Typical Microstructures of As-Received H-40 Disk No. 3. Heat Treatment: Oil Quenched 1950°F + Tempered 8 Hrs at 1200°F + Tempered 3 Hrs at 1200°F - 315/390 BHN.

X100D X1000D

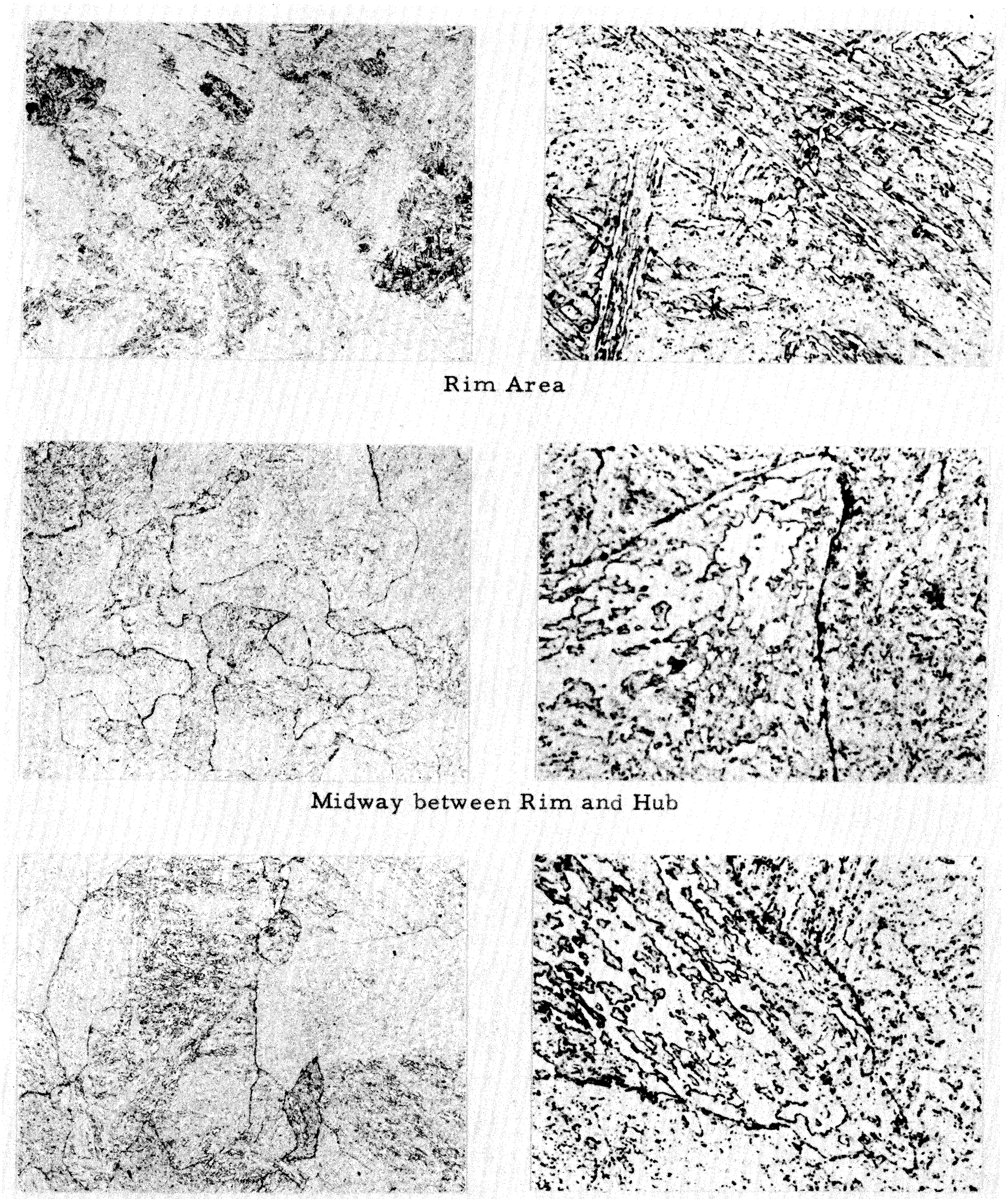
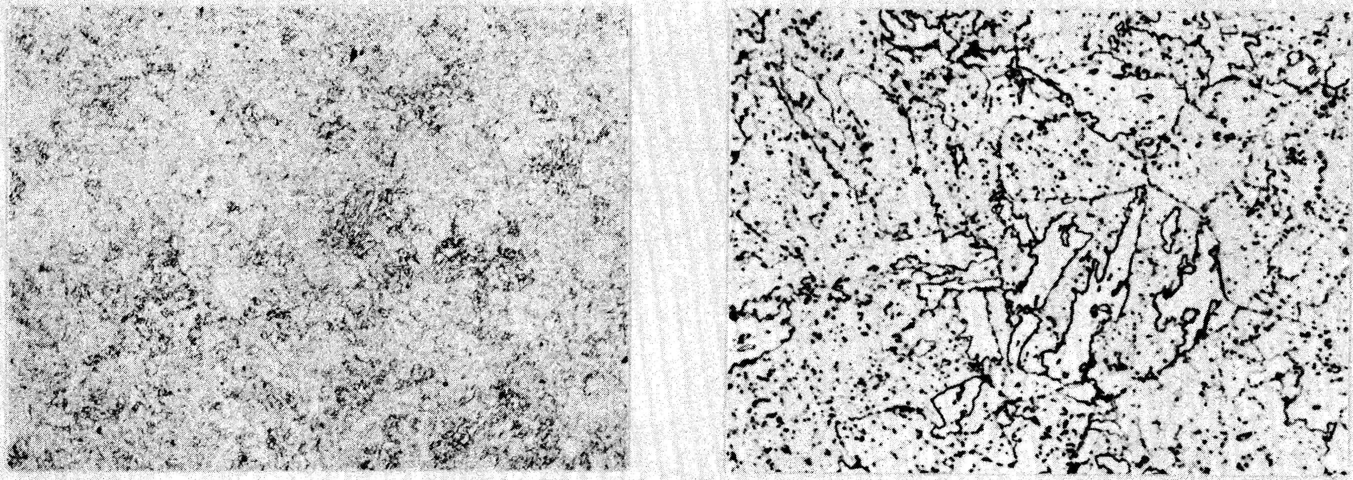
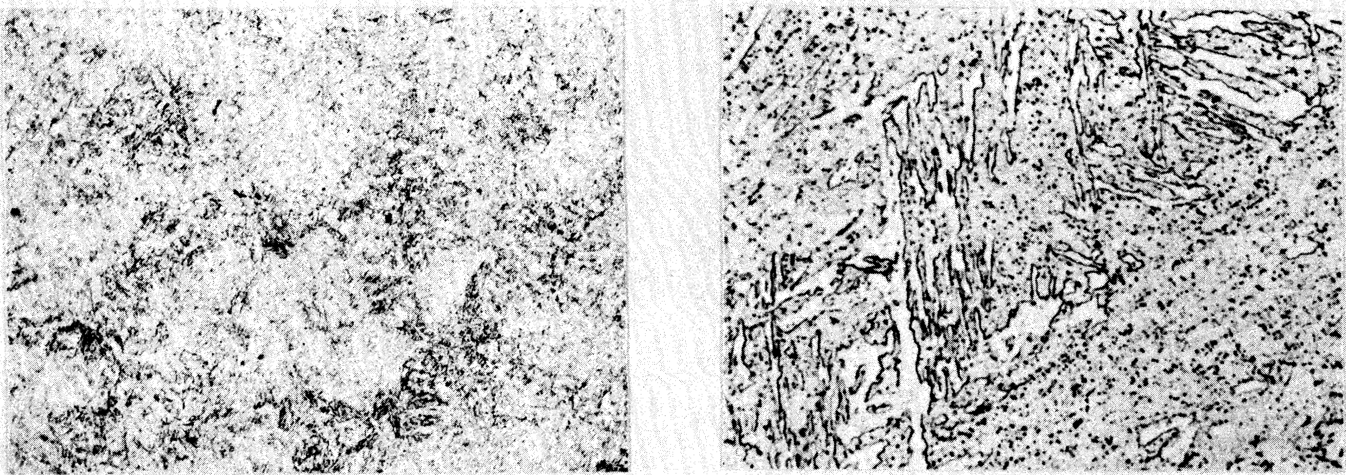


Figure 54. Typical Microstructures of As-Received H-40 Disk No. 4. Heat Treatment: Interrupted Quench 1950°F + Tempered 2 Hrs at 1200°F + Tempered 3 Hrs at 1200°F - 327/393 BHN.

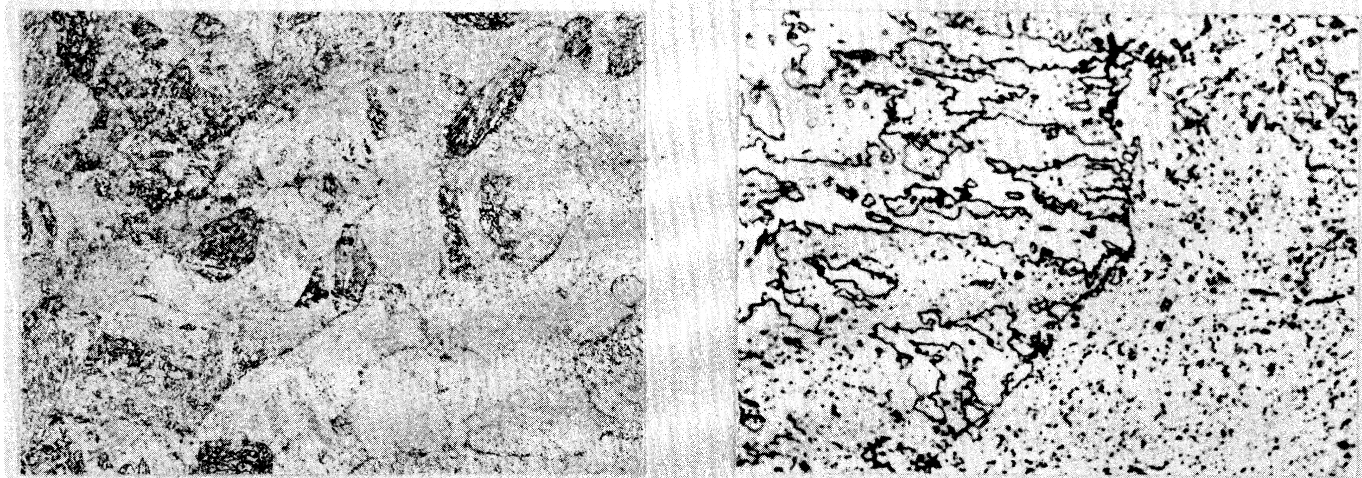
X100D X1000D



(a) H-40 Disk No. 1 - 287/303 BHN.



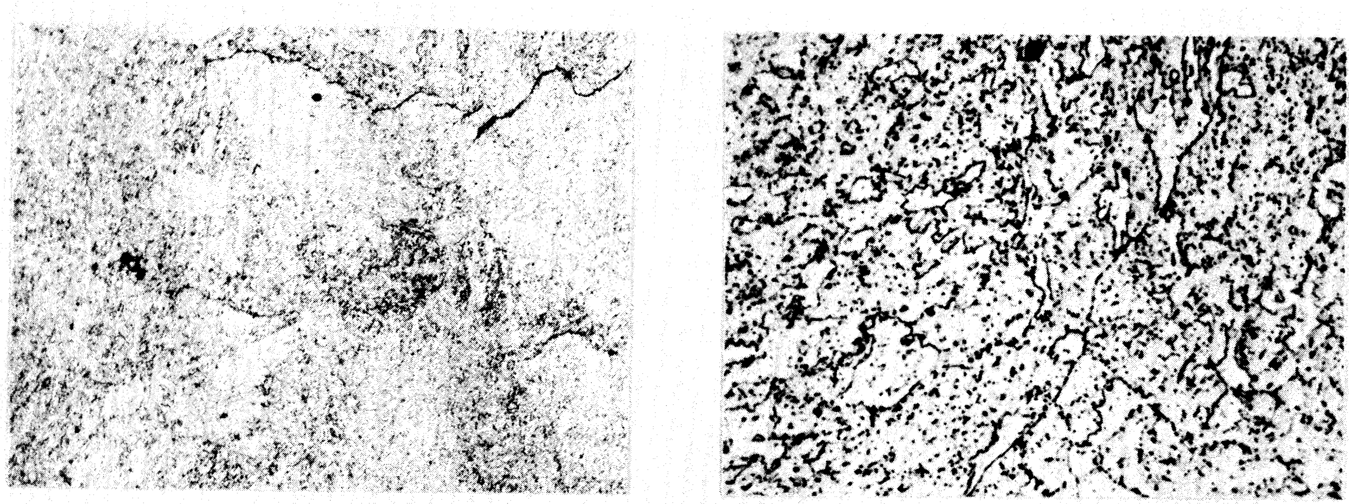
(b) H-40 Disk No. 3 - 295/317 BHN.



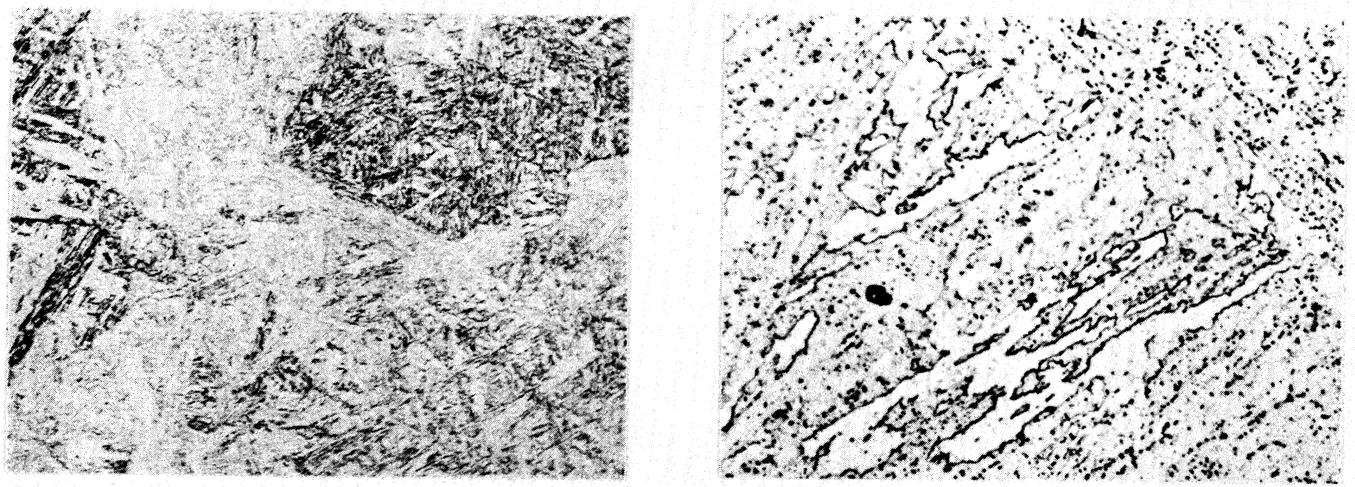
(c) H-40 Disk No. 4 - 287/311 BHN.

Figure 55. Microstructures of H-40 Disks Nos. (a) 1, (b) 3, and (c) 4 after Retempering 4 Hrs at 1250°F.

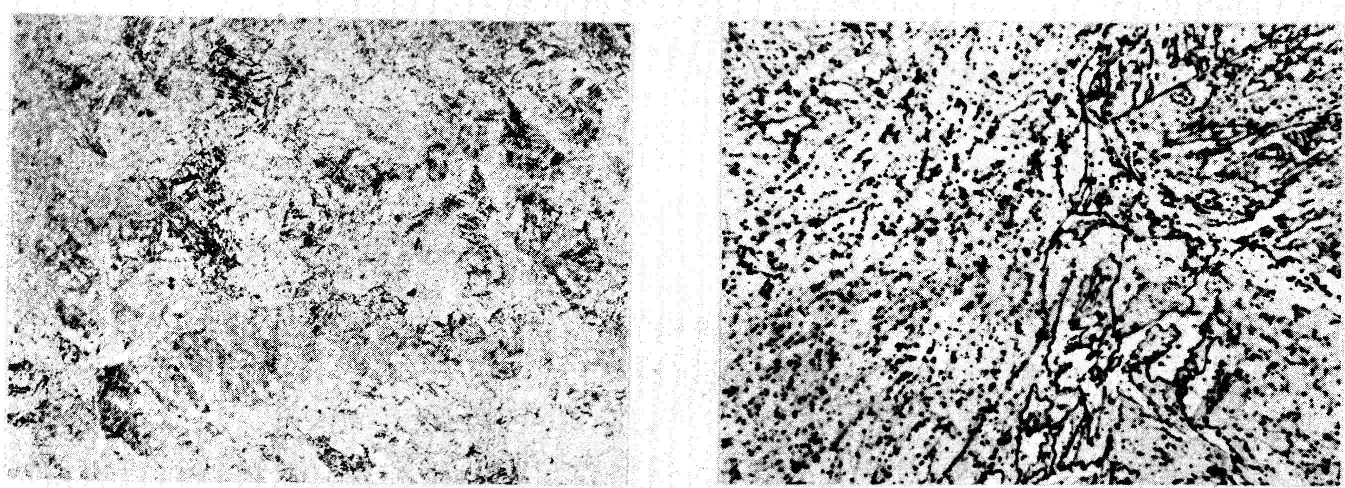
X100D X1000D



(a) As Received H-40 Disk No. 1. Rupture Tested 518 hrs at 1100°F and 37,000 psi - 268 BHN.



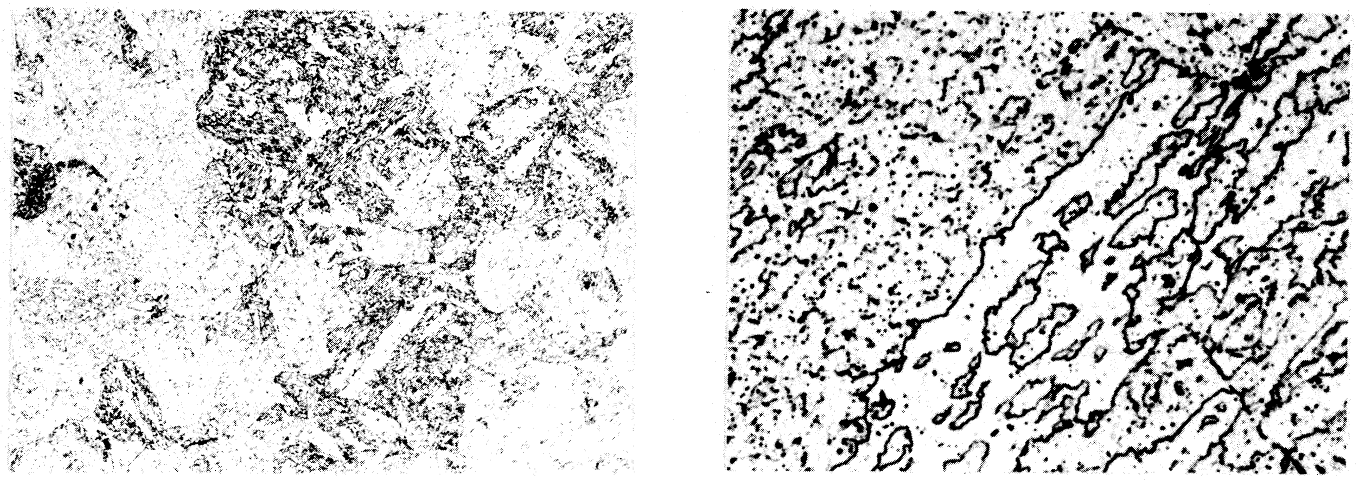
(b) As Received H-40 Disk No. 3. Rupture tested 456 hrs at 1100°F and 39,000 psi - 315 BHN.



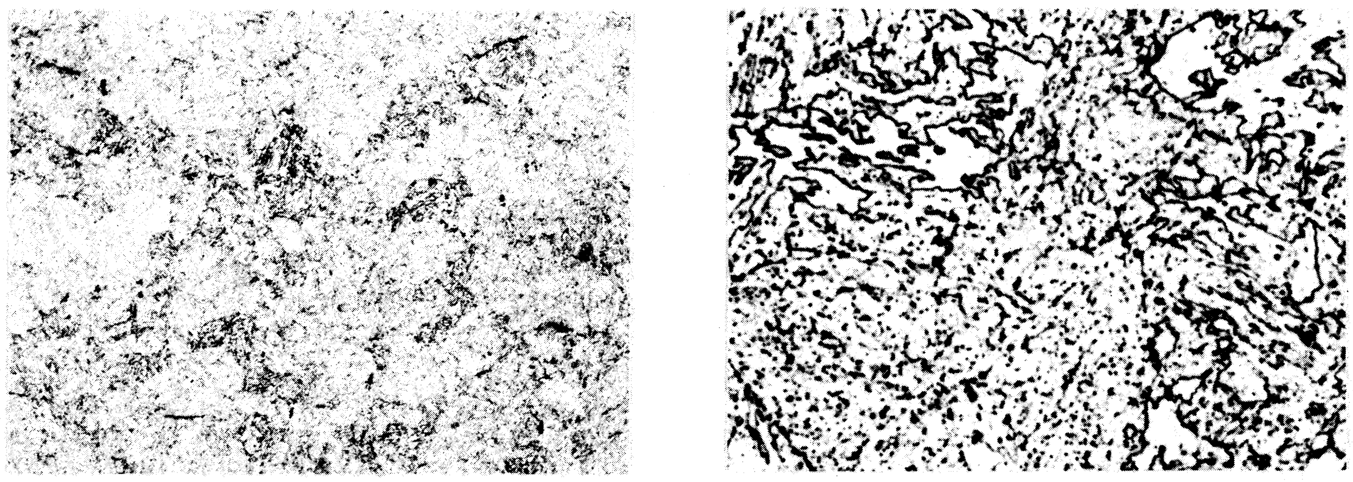
(c) As Received H-40 Disk No. 4. Rupture tested 697 hrs at 1100°F and 35,000 psi - 285 BHN.

Figure 56. Microstructures of Ruptured Specimens of As-Received H-40 Disks Nos. (a) 1, (b) 3, and (c) 4.

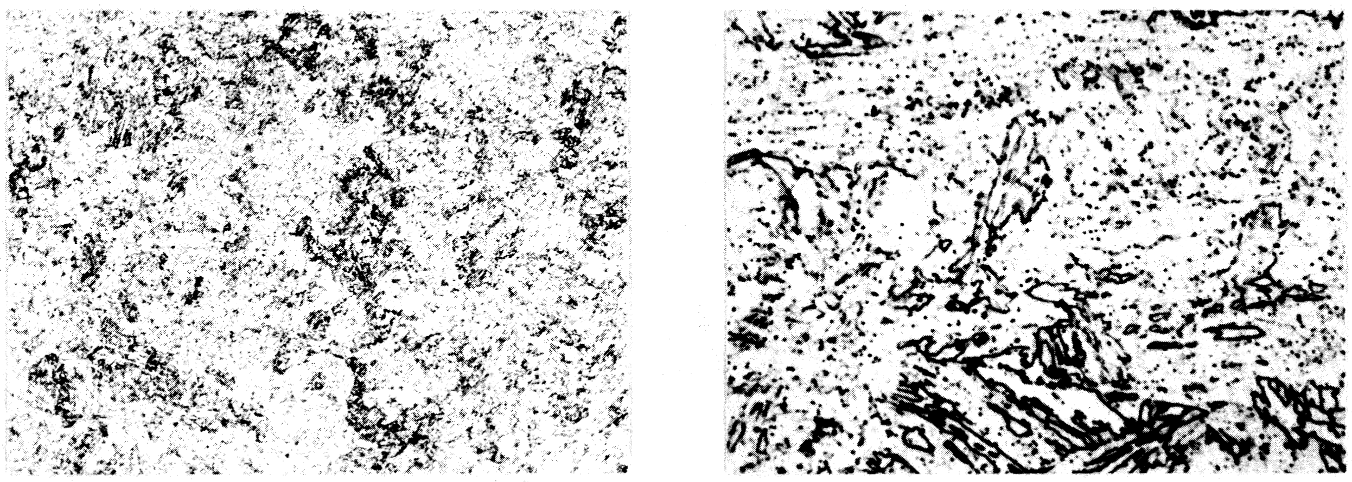
X100D X1000D



(a) Retempered H-40 Disk No. 1. Rupture tested 735 hrs at 1100°F and 34,000 psi - 255 BHN



(b) Retempered H-40 Disk No. 3. Rupture tested 514 hrs at 1100°F and 36,000 psi - 250 BHN.



(c) Retempered H-40 Disk No. 4. Rupture tested 273 hrs at 1100°F and 39,000 psi - 245 BHN.

Figure 57. Microstructures of Rupture Specimens of Retempered H-40 Disks Nos. (a) 1, (b) 3, and (c) 4.

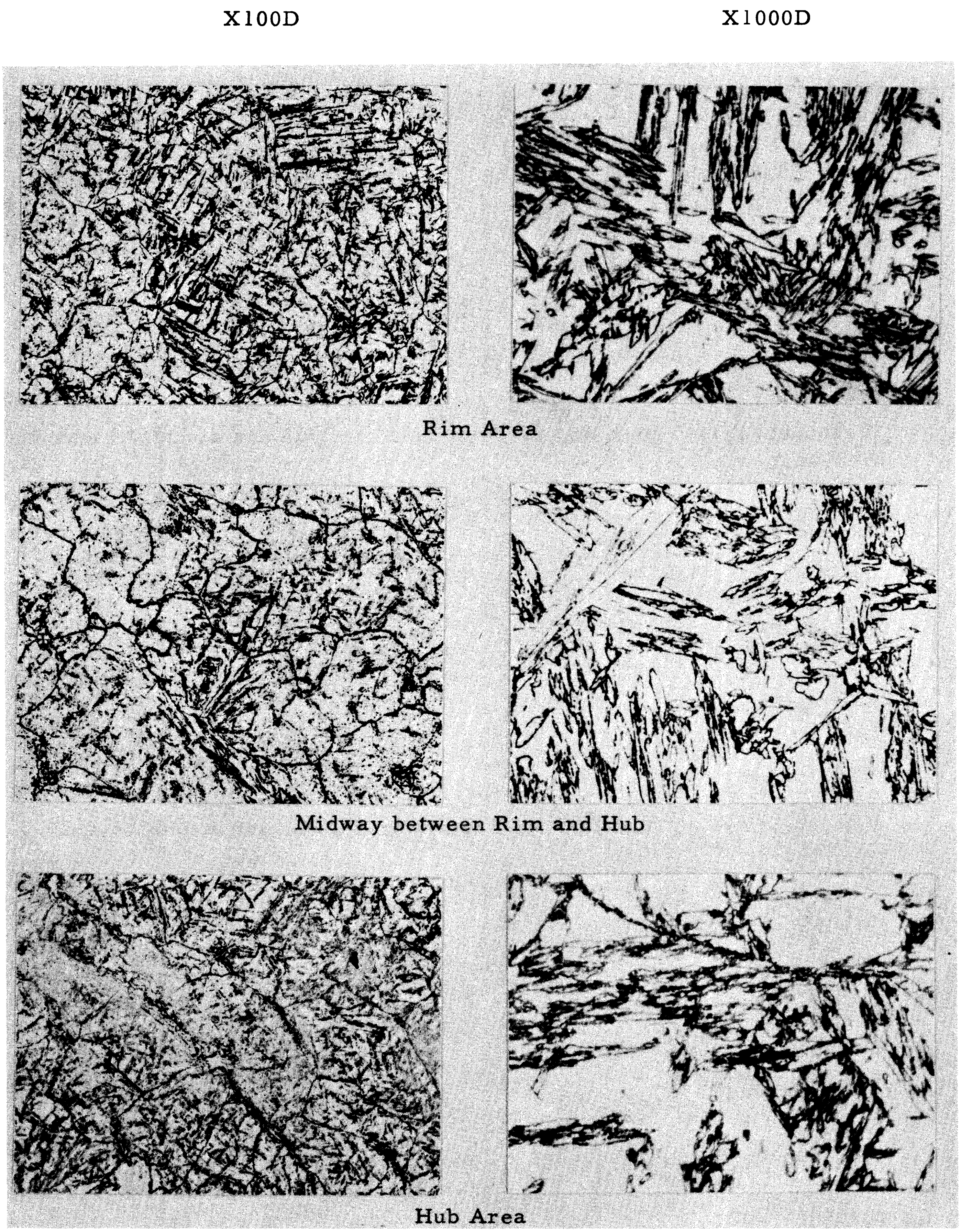


Figure 58. Typical Microstructures of C-422 Disk No. 1. Heat Treatment: (a) Normalized 1900°F + Tempered 2 Hrs at 1200°F, (b) Full Anneal 6 Hrs at 1600°F. Normalized 1900°F + Tempered 2 + 2 Hrs at 1200°F - 283/323 BHN.

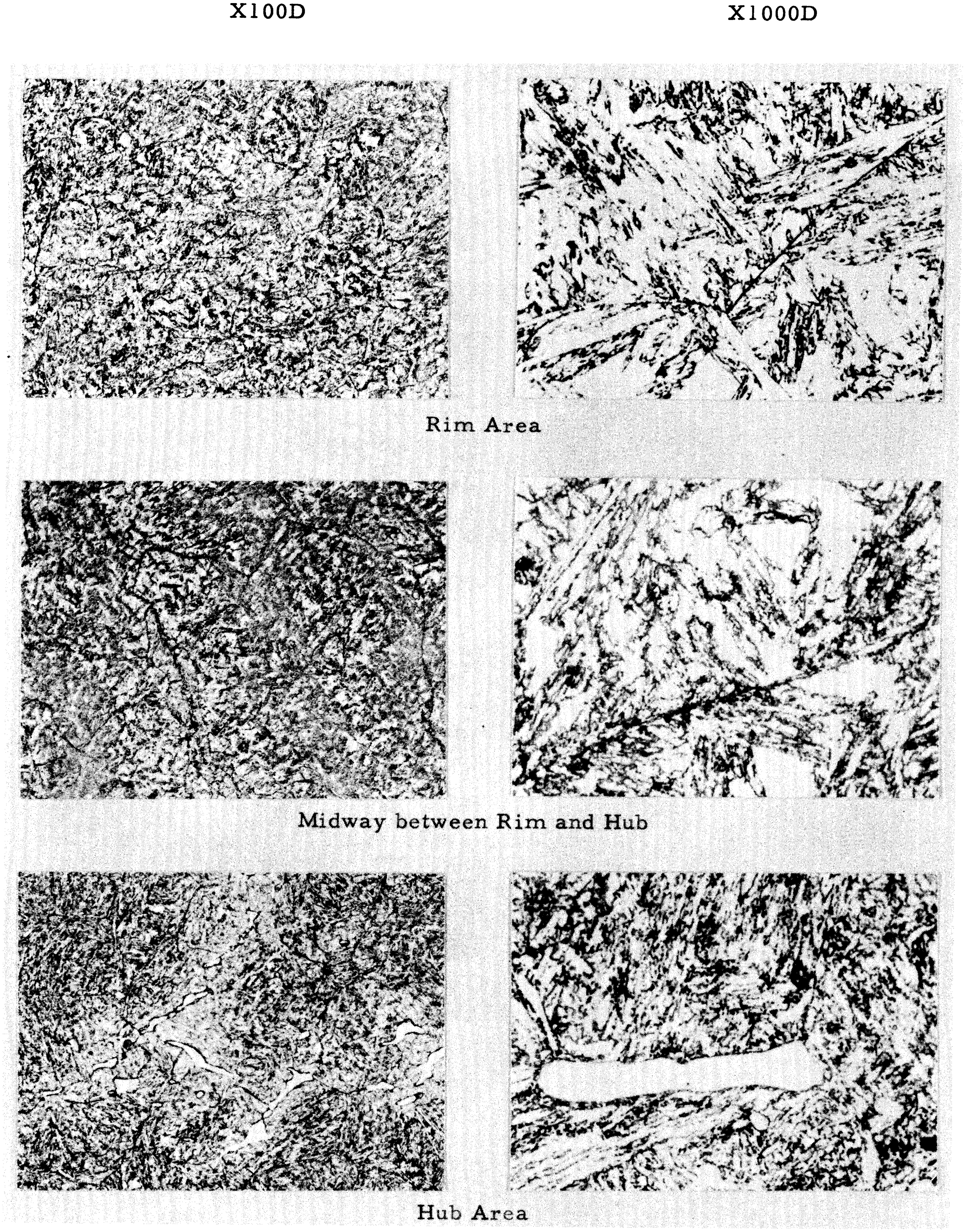
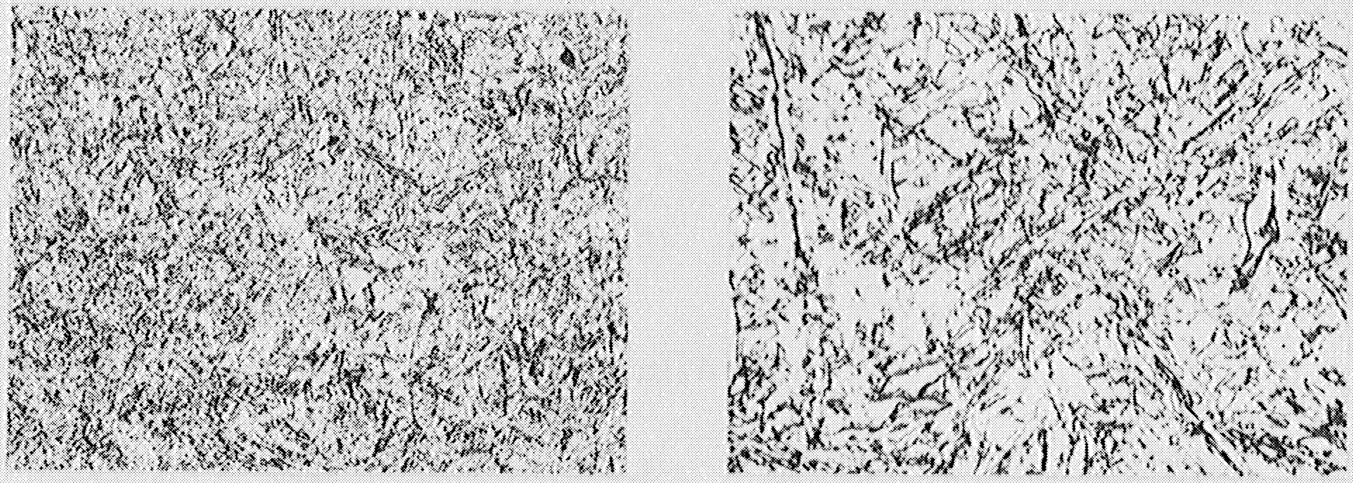
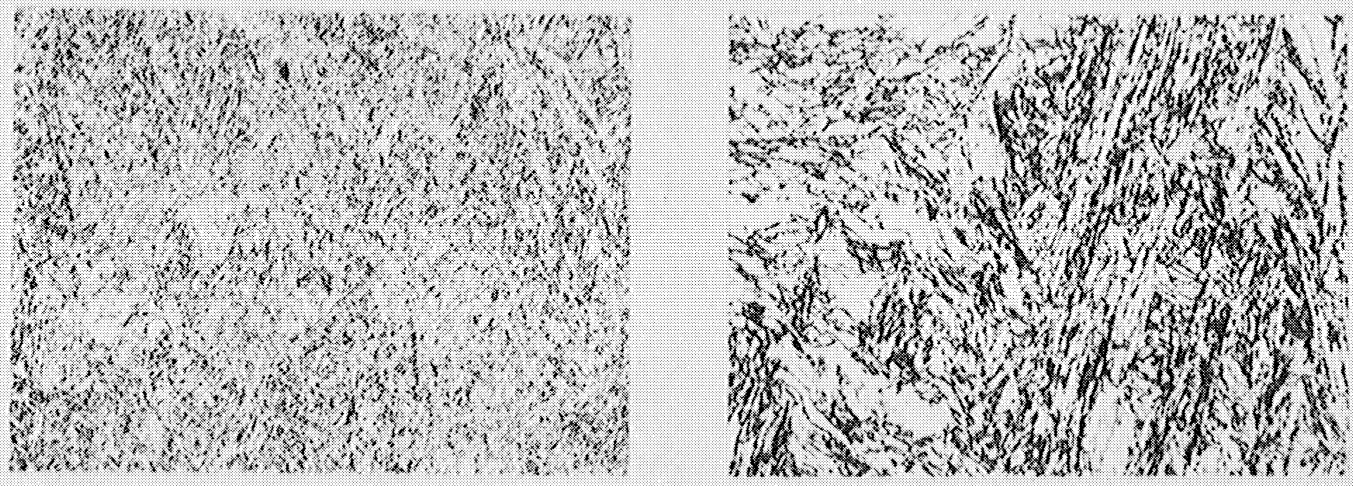


Figure 59. Typical Microstructures of C-422 Disk No. 4. Heat Treatment: (a) Oil Quenched 1900°F + Tempered 8 Hrs at 1200°F, (b) Full Annealed 6 Hrs at 1600°F. Oil Quenched 1900°F + Tempered 2 + 2 Hrs at 1200°F - 275/352 BHN.

X100D X1000D



(a) C-422 Disk No. 1. Rupture tested 1055 hrs at 1100°F and 32,000 psi - 275 BHN.



(b) C-422 Disk No. 4. Rupture tested 399 hrs at 1100°F and 40,000 psi - 290 BHN.

Figure 60. Microstructures of Rupture Specimens of C-422 Disks Nos. (a) 1 and (b) 4.