FINAL REPORT

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WRIGHT AIR DEVELOPMENT CENTER, MATERIALS LABORATORY

ON

A SURVEY OF THE EFFECT OF AUSTENITIZING TEMPERATURE AND RATE OF CONTINUOUS COOLING ON THE STRUCTURE AND 700° TO 1200°F PROPERTIES OF THREE LOW-ALLOYED STEELS

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FOREWARD

This report was prepared by the Engineering Research Institute of the University of Michigan under Contract No. AF 33(038)-13496. The work authorized under this contract involved a survey of the effect of austenitizing temperature and rate of continuous cooling on the structure and 700° to 1200°F properties of three low-alloyed steels.

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A SURVEY OF THE EFFECT OF AUSTENITIZING TEMPERATURE AND RATE OF CONTINUOUS COOLING ON THE STRUCTURE AND 700° TO 1200°F PROPERTIES OF THREE LOW-ALLOYED STEELS

SUMMARY

The relationships between microstructures formed with various cooling rates and austenitizing temperatures and properties at 700° to 1200°F were surveyed for three low-alloyed steels. The steels were Ni-Cr-Mo (SAE 4340), 1.25Cr-Mo-V ("17-22-A"S), and 3Cr-Mo-W-V (H-40). Martensitic, martensitic-bainitic, bainitic, and bainitic-ferritic structures were produced by oil quenching 1-inch rounds and air cooling 1-inch and simulated 3- and 6-inch rounds. Modifications of the oil-quenched and normalized structures of the 1-inch rounds resulted when the austenitizing temperature was raised from 1750° to 2100°F. The hardness level was maintained at 280-320 BHN by tempering the structures which had higher hardnesses in the as-transformed condition.

The results indicated that the fully bainitic structures which were predominantly upper bainite had maximum strength over the range of testing temperature used. In general, such structures were found in the larger, normalized sections and with the higher austenitizing temperature. Since low values of ductility resulted from the higher temperature treatments, however, the best combinations of strength and ductility were obtained when the largest sections were normalized from the lower austenitizing temperatures (1750°F for SAE 4340 and "17-22-A"S, and 1950°F for H-40).

Regarding the effect of varying the cooling rates of normalized bars, it was found that increases in strength occurred for all three steels as the effective bar diameter was increased from 1 inch to 6 inches. The effect of raising the austenitizing temperature from 1750° to 2100°F was to increase the strength, with the H-40 steel being affected the most. Ductility was lowered for all three steels as the heat-treating temperature was raised.

A correlation between the structures and properties of the continuously cooled bars of this investigation and the structures and properties of the continuously cooled turbine wheels studied previously ranged from poor for the SAE 4340 and "17-22-A"S steels to fair for the H-40 steel. The lack of better correlation was assumed to be due to (1) differences between heats and (2) variations in heat-treating conditions.

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INTRODUCTION

There are a considerable number of actual and potential uses at elevated temperatures for heat-treatable low alloyed medium carbon steels in jet engines and air frames. The information covering the basic principles of heat treatment for such service is incomplete. A rather wide range of microstructures and hardness levels are possible in such steels. Control of heat treatment can develop structures with a range of pearlitic and bainitic structures as well as martensite. In many cases, practical considerations dictate a continuous cooling type of heat treatment. The result is a range of structures for a given heat treatment, depending on the actual cooling rates. For instance, normalizing (air cooling) could result in structures ranging from martensite through bainite to pearlite depending on the section size being heat treated. Yet, normalizing is often catagorically stated to give the highest strength at high temperatures. The basic information relating the type of microstructure to the temperature, time and allowable deformation during service was rather meager. The indefinite statement often made is that the maximum strength shifts from martensite to bainite to pearlite as the temperature and time period is increased.

Accordingly, an investigation has been in progress to establish the basic principles of relating type of microstructure to creep-rupture properties at 700° to 1200°F, the potentially useful temperature range where creep-rupture properties could govern performance. The properties of nearly "pure structures" obtained by isothermal transformation in temperature ranges for transformation to the pearlites and bainites have been surveyed (Ref. 1). The results have been correlated with the properties of structures obtained by oil quenching, interrupted quenching and normalizing forged turbine wheels (Ref. 2).

The research reported herein covers two phases extending the knowledge of the relationships of microstructures to creep-rupture properties:

1. The ranges in microstructure resulting from direct cooling over a range of cooling rates down to and including air cooling of a 6-inch round bar. This continuous cooling transformation represents the most widely used method of heat treatment. Transformation under such conditions can occur over a range of temperatures with the possibility of forming mixed microstructures that influence properties.

2. The influence of microstructural changes resulting from increasing the heat-treating temperature for austenitizing during hardening. Creep-rupture strengths are generally considered to increase with austenitizing temperature while ductility deteriorates. However, many apparent anomalies are encountered in practice so that it would be useful to develop a better understanding of the interrelationships of heat-treating temperature and microstructure to service conditions of temperature, stress, time and amount of creep.

Three types of medium carbon, low alloy, heat-treatable steels were used to check the generality of the findings:

Type of Steel	Designation
Cr-Ni-Mo	SAE 4340
1.25Cr-Mo-V	"17-22-A"S
3Cr-Mo-W-V	H-40

Tempering was used to reduce hardnesses to the range of 280 to 320 Brinell. Limited survey creep-rupture tests in the range of 700° to 1200°F were used to develop general trends. The results are correlated with those previously reported in References 1 and 2.

TEST MATERIALS

The chemical compositions of the bar stock material used for this investigation 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
"17-22-A"S	10420	0.29	0.61	0.67	1.30	0.18	0.47	0.26	--	--
H-40	K2509	0.29	0.48	0.26	3.05	0.49	0.49	0.85	0.55	0.15

PROCEDURE

The initial steps in this phase of the program were to establish the range of cooling conditions during which continuous cooling transformations of interest would occur, to establish the range of austenitizing temperature of interest, to prepare specimens heat treated under the selected conditions, and to select suitable survey test conditions.

Continuous Cooling Transformation Conditions

Consideration of the possible section sizes and quenching media involved indicated that the cooling cycles obtained by the oil quenching of 1-inch diameter bars and the air cooling of 1-, 3-, and 6-inch diameter bars should cover adequately the range of structures of major interest; that is, from martensite formed by oil quenching to bainite formed by relatively slow cooling. Since survey data were available from the previously reported work for the oil-quenched and normalized 1-inch bars for "17-22-A"S and SAE 4340 and for 3/4-inch bars of H-40, it was necessary to obtain data only for the 3- and 6-inch diameter bars. However, since only 3/4- and 1-inch diameter bar stock were available, the desired cooling cycles were obtained by the retarded cooling of the 3/4- and 1-inch round bars in a cylinder made from a low heat duty fireclay insulating brick. The general procedure was as follows:

1. To establish the cooling cycles for 3- and 6-inch rounds, the cooling cycles for 1-inch bars of "17-22-A"S and 1- and 3-inch bars of plain carbon steel were obtained during air cooling by means of a thermocouple inserted axially to the center of the bar. Cooling curves were not obtained for 6-inch rounds because of the handling difficulties and the capacity of the laboratory furnaces.

2. From the cooling curves obtained for the 1- and 3-inch rounds, the heat transfer coefficient (h) to the surrounding medium, air in this case, was calculated for the conditions existing in the laboratory. From the value obtained, the cooling curve for the 6-inch round was calculated (Ref. 3).

3. Cooling curves were obtained at the center and surface of 1-inch rounds of SAE 4340 and "17-22-A"S materials and at the same locations for 3/4-inch rounds of H-40 steel during cooling in insulating firebrick cylinders estimated to produce cooling cycles similar to the 3- and 6-inch round bars. After several trials, the thickness of the firebrick cylinder was adjusted to produce cooling cycles equivalent to the experimentally determined cycle for the 3-inch round and the calculated cycle for the 6-inch round.

It was found that the cooling rate at the surface of the enclosed 1- and 3/4-inch diameter bars was essentially the same as that at the center. This observation was confirmed by the uniform microstructure throughout the cross-section of the heat-treated bars.

4. After the necessary thickness of firebrick to produce the desired cooling cycle had been determined, a number of specimens were heat treated by the following procedure:

a. Bar stock of 3/4- or 1-inch diameter was enclosed in the firebrick cyclinder with a thermocouple attached to the surface of the bar at the midpoint.

b. The assembly was inserted in a furnace at the desired temperature and held until the thermocouple indicated that the specimen had been at temperature for 1 hour.

c. The assembly was removed from the furnace and the test bars allowed to cool to room temperature in the insulating firebrick.

5. Samples of the actual cooling curves obtained are shown by Figures 1 and 2.

Austenitizing Temperature

Experience with alloys of the same type as those being studied has indicated that, at least in some instances, better than usual combinations of high temperature strength and ductility may be obtained if the austenitizing temperature is just below the temperature at which coarse-grained, bainitic structures develop. However, this generalization seems to be most applicable to those steels containing carbides which are difficult to dissolve. Heat treatments above the coarsening temperature may or may not improve the strength properties of such steels, but it almost always results in considerable loss in ductility at rupture. Consideration of these facts lead to the belief that the relationships between properties and the structures developed for several austenitizing temperatures should be established for the subject steels.

The method used to evaluate the influence of austenitizing temperature on microstructure was to determine the coarseness of the bainitic structure resulting from normalizing the 1-inch and 3/4-inch round bar stocks between 1750° and

2200°F. The results of this evaluation have been expressed in terms of a "bainitic" grain size. The bainitic grain size coarsened gradually over the range of temperatures as is shown by Figure 3.

It was, therefore, decided to evaluate the high temperature strengths after normalizing over a wide range of temperatures:

a. 4340 and "17-22-A"S at 1950° and 2100°F, supplementing previous data for 1750°F.

b. H-40 at 1750° and 2100°F, supplementing previous data for 1950°F.

The influence of austenitizing temperature on martensitic structures obtained by oil quenching was partially evaluated for 4340 and "17-22-A"S steels. Due to a shortage of stock, oil quenching of the H-40 was not included.

Hardness Level

For the work done on the effect of continuous cooling transformation, and all other previous work, all test bars were tempered to a hardness range of 280 to 320 Brinell when the as-transformed hardness was at a sufficiently high level. In so far as possible, the tempering times and temperatures were the same as, or similar to, those previously employed. However, since the hardness of the 4340 steel as-normalized from 1950° and 2100°F was only slightly above the 320 Brinell maximum and even slight tempering resulted in hardness below the 280 minimum, this steel was tested in the as-normalized condition.

Basis of Evaluation of High Temperature Properties

The general basis of evaluation of the effects of continuous cooling transformation and of austenitizing temperature was the same as previously employed for the isothermally transformed structures (Ref. 2). Only limited survey tests were selected to indicate general trends of the structural variables rather than accumulating complete design data. The basis for selection was as follows:

a. The properties were evaluated for the temperature range over which creep and rupture properties could be the controlling factor. For 4340, this range was set at 700° to 1100°F, while 700° to 1200°F was employed for the "17-22-A"S and H-40 steels. The upper temperature was based on the probable maximum temperature at which hardened structures would have useful properties.

b. The structures were evaluated on the basis of the property which was the controlling factor at the temperature of interest. Thus, at 700° and 900°F, the criteria of comparison were mainly creep rate and total deformation characteristics. At these temperatures, the stresses required to cause rupture in reasonable times would be well above the yield strength, and thus, service stresses would be limited to those below which rupture would occur.

However, approximately 100-hour rupture tests were conducted for 4340 steel at 900°F because the relatively low strength of this material at that temperature indicated that a knowledge of its stress-rupture properties was desirable.

c. At 1000°F for 4340 and at 1100°F for "17-22-A"S and H-40, the temperatures of major interest for these steels, stress-rupture, creep, and total deformation data from relatively long time rupture tests were obtained.

d. The property considered to be of most interest at 1100°F for the 4340 steel and at 1200°F for the "17-22-A"S and H-40 Steels was the 100-hour rupture strength. However, 1000-hour creep tests were conducted for the 4340 and "17-22-A"S steels to permit better correlation between structural variations and temperature of testing.

RESULTS

The interrelations between steel composition, microstructure and proper- are fairly complex. Hence, it is necessary to use several test temperatures measures of strength at high temperatures to cover the effects of temperature-time-amount of creep.

Two main variables were studied: (1) Influence of Rate of Continuous Cooling; and (2) Influence of Austenitizing Temperature. In analyzing the results, it seemed best to consider the two together for each steel. Actually, microstructures were the real variable and it is easiest to grasp the data when composition is not a variable. For this reason, all the photomicrographs illustrating the structures are presented together as Figures 4 through 25. The graphical presentation of the creep and rupture data are also kept together as Figures 26 through 43.

The results are presented in the following sections as general trends. In most cases, the details should also be considered by those attempting to apply the results. It is also important to recognize that the data are sparse and are only intended for general survey purposes. To aid in the evaluation of the influence of stress from the sparse data, complete curves showing the stress dependency of creep rate, rupture time, and total deformation time for the turbine wheels(Ref. 1) have been included in the appropriate figures. It is also to be noted that specific hardness values are given with the photomicrographs, whereas, average hardness values are used in some of the tables.

Cr-Ni-Mo (SAE 4340) Steel

Influence of Rate of Continuous Cooling

Reducing the cooling rate changed the as-transformed structures from martensite to bainites plus 35 to 20% martensite (Table I and Figures 9,4,5, and 6). The hardness also decreased. In the normalized 1-inch round the lower hardness was apparently due to the appearance of large amounts of relatively soft bainite. In the 3- and 6-inch rounds, both lesser amounts of martensite and tempering of the martensite present were involved. Other than the degree of tempering, there seemed to be little to distinguish the three normalized structures.

To meet the requirement of approximately 300 BHN for high temperature testing, it was necessary to temper the martensite (oil-quenched) structure for 10 hours at 1100°F and the mixed martensitic plus bainitic structure formed after normalizing the 1-inch round for 1 hour at 1100°F. The resulting microstructures (Figures 9 and 4) were quite similar. The normalized structures for the larger sizes (Figures 5 and 6) could not be tempered without reducing hardness below the desired range. The structures tested, therefore, represent the spheroidization and agglomeration accompanying tempering during reheating in the first two cases and the structures resulting from direct transformation in the latter two cases. It should be recognized that there is probably a gradation in the degree of tempering of martensite in the structures. The martensite in the mixed bainitic-martensitic structures was probably harder than in the more drastically tempered, originally oil-quenched material. The mixture of hard martensite and softer bainite gave a hardness equal to that of the tempered martensite.

A review of the high temperature test data (Table IV and Figures 26 through 30)leads to the following generalities:

1. The tempered martensite had the lowest strength at all temperatures in all the tests used to evaluate the strengths at high temperatures.

2. In most cases, there was very little difference in strength between the martensitic plus bainitic structures produced at the centers of bars having diameters of 1, 3 and 6 inches. There was some slight tendency for the short-time rupture strengths to increase with decreasing cooling rate.

3. Data obtained at 700°F were somewhat erratic. There was possibly a slight tendency at 700°F, and even at some of the higher temperatures, which suggested that the less initial self-tempering of the 3-inch round, in comparison to the normalized 1-inch and 6-inch rounds, was detrimental to strength.

4. The data on ductility in the rupture tests is difficult to generalize because increasing rupture time generally reduces ductility and the data are inadequate to evaluate this effect in relation to initial structure due to the variations in rupture time. It appears from Table IV, however, that the tempered martensite was most ductile at 900°F and probably the larger 3- and 6-inch sizes were least ductile. The tempered, mixed bainites plus martensite of the normalized 1-inch round were least ductile at the higher temperatures.

Long duration creep tests at 1000°F showed relatively little change in structure and hardness for the tempered martensite (Figure 9) and tempered, mixed bainite and martensite (Figure 4). However, considerable tempering to a coarser carbide and ferrite structure occurred during testing of the larger, normalized sections (Figures 5 and 6) with a large drop in hardness.

The relatively sparse data in Figures 26 through 30 are, of course, not conclusive but they do indicate that there is relatively little change in the relative slopes of the log-log relationships between the different structures. Thus, the superiority of the normalized structures is maintained to relatively low stresses and long time periods, even though the absolute differences decrease with decreasing stress.

From these results, it can be concluded that the following general relationships between structure and properties at high temperature exist for SAE 4340 steel transformed during continuous cooling over rates ranging from those producing martensite to those producing the mixed, tempered martensite and bainite of air cooling a 6-inch round:

1. At equal, initial hardness levels of 300 BHN, the controlling factor in strength is the presence of considerable bainite (or the presence of bainite indicates some other structural condition controlling strength). Tempered martensite is inferior in strength.

2. The structure seems to be the controlling factor. Large structural changes during testing, as evidenced by large hardness changes of the 3- and 6-inch rounds, did not apparently influence the strength criteria when considered in relation to the initially slightly tempered 1-inch round structure which was more stable. (This should not be applied to very long time period strengths without further tests for proof or disproof).

3. Differences or similarities in strength do not seem to be clearly reflected in microstructures before or after testing. The martensitic structure of the oil-quenched material and the martensitic plus bainitic structures of the normalized 1-inch round were similar as tempered and after testing. They were, however, quite different from the structures of the 3- and 6-inch rounds. Yet, the properties of the normalized 1-inch round were nearly the same as for the 3- and 6-inch rounds while the oil-quenched, tempered martensite was consistently weaker.

Austenitizing Temperature

Increasing the austenitizing temperature before oil quenching increased the coarseness of the martensite and background apparent grain size (Figures 9, 10 and 11). There was also the suggestion that small amounts of bainite were produced. After tempering, there was little difference in structure beyond the size of the background grains (Figures 9, 10 and 11).

Increasing the normalizing temperature apparently reduced the amount of martensite and reduced overall hardness (Figures 4, 7 and 8). When normalized from 1950° and 2100°F, the hardness was too low to allow tempering and still maintain the desired hardness level. Increasing the heat-treating temperature did not produce the apparent coarsening of the grain structure evident in the oil-quenched samples. Apparently, this was due to variation in the orientation effects within the grains so that there was no great contrast from grain to grain.

The increase in austenitizing temperature before oil quenching reduced rupture strength and ductility somewhat (Table IV and Figure 26). There were smaller, similar reductions in strength and ductility for limited deformations and creep rates (Table IV and Figures 27, 28 and 29).

For normalized bars, the increase in temperature of treatment generally raised rupture strengths (Figures 26 and 31). Short-time strengths at 1000°F were an exception. Elongation and reduction of area were also reduced, particularly as the time period for rupture and the testing temperature increased (Table IV). Limited deformations and creep rates generally followed the same trend. The major exception was at 700°F where deformation on loading increased and reduced the time for 1% deformation.

The oil-quenched and tempered martensitic structure retained higher hardness and underwent little change in microstructure during testing at 1000°F. The untempered, normalized structures softened considerably more than the 1-inch round treated at 1750°F and tempered for 1 hour at 1100°F. It seems that even the 1-hour tempering treatment, when it can be applied without too much reduction in hardness, considerably stabilizes the structure.

The results indicate that:

1. For the strength criteria considered, increasing the heat-treating temperature slightly reduced strength at elevated temperatures when quenching was used to develop an originally martensitic structure. The opposite effect was observed for normalizing. In both cases, elongation and reduction of area in the rupture tests were reduced somewhat.

2. The results again indicate that bainites (or treatments which produce bainites) are necessary for highest strength.

3. Any coarsening of the structure resulting from increased heat-treating temperature had opposite effects in that tempered martensitic was weakened while bainitic structures were strengthened.

In considering these results, it should be recognized that the lowest temperature of treatment, 1750°F, is the highest temperature recommended on the basis of experience with the alloy. It is possible that the lower temperatures commonly used might have different effects.

1.25Cr-Mo-V ("17-22-A"S) Steel

Influence of Rate of Continuous Cooling

The structures obtained ranged from martensite, bainites plus martensite, bainites, to bainites plus a small amount of ferrite (Table II and Figures 17, 12, 13 and 14) as the cooling rate was reduced. The bainites became coarser as the cooling rate was reduced.

Hardness values decreased with decreased cooling rate as would be expected from the changes in structure.

The severity of the temper had to be reduced with reduced cooling rate in order to maintain the hardness level at about 300 BHN. It should be noted, however that secondary hardening permitted a 6-hour temper at 1200°F after air cooling a 6-inch round to an as-normalized hardness of 325 BHN.

The structures after tempering varied (Figures 17, 12, 13 and 14). The martensite from oil quenching and the bainitic plus martensitic structure of the normalized 1-inch round resulted in a heavy dispersion of carbides with the carbides being coarser in the latter. The bainites of the larger rounds underwent considerable alteration of the ferrite as well as spheroidization of the carbides.

The tempered structures all had strengths at high temperatures which showed the tempered martensite from oil quenching to be weakest (Table V and Figures 32 through 37). The strengths of the normalized and tempered structures tended to increase as the section size increased, although this effect definitely decreased with increasing test temperature. The evaluations on the basis of time and creep rate at a specific stress at 700° and 900°F exaggerate the effect since the probable stress-time for deformation and stress-creep rate curves have very little slope at these temperatures. In other words, wide differences in these values at a specific stress represent very little effect on the stress for a given deformation or creep rate.

Elongation and reduction of area values in the rupture tests were low at 1100° and 1200°F for all initially normalized structures and apparently tended to be slightly lower for the slower initial cooling rates. Even the tempered martensitic structure had quite low ductility for the longer times at 1100°F.

Some softening and spheroidization occurred during creep testing at 1100°F. However, there was very little difference in this respect between any of the four initial structures.

The data are essentially similar to those for SAE 4340 steel. Originally martensitic structures are weaker than originally bainitic structures at 700° to 1200°F. The strengths generally increase slightly with decreased cooling rate so long as essentially bainitic structures form initially. This relationship existed after drastic tempering.

Influence of Austenitizing Temperature

Oil quenching from 1950°F produced a somewhat coarser martensitic structure than from 1750°F (Table II, Figures 17 and 18). When the heat-treating temperature was raised to 2100°F, however, the structure contained about 50% of what appeared to be bainite in very coarse grains of martensite (Figure 19). The as-transformed hardness decreased with increasing temperature of heat treatment.

After tempering 1 hour at 1300°F, the degree of carbide spheroidization decreased with increasing hardening temperature (Figures 17, 18 and 19). The hardness differences were, however, small in comparison to the initial hardness values.

The strengths at high temperature (Table V and Figures 32 through 35) were generally higher for those samples originally quenched from the higher temperatures. The 1950°F treatment generally had the highest strength, except for the lower stress tests at 1200°F. The 1950°F treatment produced structures which were probably inferior in strength at 700°F to those produced by the 1750°F treatment. Increasing the austenitizing temperature before oil quenching reduced ductility in the rupture tests (Table V and Figure 32), particularly at the shorter time periods.

It appears that increasing the austenitizing temperature did increase the strength of originally martensitic structures somewhat. The appearance of considerable, fine bainite-appearing structure in the material quenched from the highest temperature, however, did not result in a substantial increase in strength.

Increasing the normalizing temperature to 1950° and 2100°F prevented the formation of any martensite and gave increasingly coarse 100% bainitic structures (Table II and Figures 12, 15 and 16). The hardness decreased accordingly. Less tempering was necessary for the structures formed from the higher temperatures to obtain 300 BHN. The spheroidized carbides were less evident and the background ferritic structure more prominent after tempering the structures formed from the higher normalizing temperatures.

The strength properties increased with normalizing temperature at 700°, 900°, 1100° and 1200°F, except for short-time rupture strength at the latter two temperatures (Table V, Figures 32, 33, 34, 35 and 37). The changes were not particularly large in any case. The apparent, large changes at 700° and 900°F would not be nearly so prominent on the basis of stress for a given deformation or creep rate. Ductility dropped off in the rupture tests as a result of increasing the normalizing temperature (Table V).

The structures were somewhat less stable with increasing normalizing temperatures as judged by hardness after testing at 1100°F (Figures 12, 15 and 16). Some spheroidization occurred during testing, possibly being least in the material normalized from 1950°F.

Increasingly coarse bainite resulting from increasing the normalizing temperature was accompanied by moderately increased strengths at high temperatures. The rather low ductility in rupture tests accompanying a normalize from 1750°F was lowered still further. The strengths were substantially higher than those obtained by oil quenching from the same temperatures. Raising the austenitizing temperature, in some cases, produced strengths in oil-quenched, martensitic structures slightly higher than those obtained by normalizing at 1750°F. It thus appears that some effects accompanying increased austenitizing temperature are effective in increasing strength regardless of whether martensite or bainites are formed on cooling. A bainitic structure will, however, generally be superior to a martensitic structure provided both are formed from the same austenitizing temperature.

3Cr-Mo-W-V (H-40) Steel

Influence of Rate of Continuous Cooling

Reducing the cooling rate altered microstructure mostly between oil quenching and normalizing of 3/4-inch rounds by changing from martensite to a predominately bainitic structure (Table III and Figures 25, 20, 21 and 22). Completely bainitic structures were formed in the 3- and 6- inch sections. The bainitic structures in the normalized samples were not greatly different, possibly becoming somewhat coarser with decreasing cooling rate. There was a substantial increase in the background apparent grain size with decreasing cooling rate. There was a small decrease in as-transformed hardness of the bainitic structures with decreased cooling rate.

The as-transformed structures varied considerably in their resistance to tempering (Table III and Figures 25, 20, 21 and 22). The normalized 3/4-inch round was the most resistant, while the 3- and 6-inch sections were least resistant. The structures after tempering were not greatly different as viewed at high magnification. The difference in background grain size was quite prominent at low magnification.

Changing from an originally martensitic to predominately bainitic structure by changing from oil quenching to normalizing 3/4-inch rounds had little benefit in the tests at 700° and 900°F (Table VI and Figure 42). The 3- and 6-inch rounds were, however, substantially stronger at these two temperatures. At 1100°F, improvement was obtained by normalizing. The structures giving improvement, however, varied between the 3/4- and 3-inch normalized rounds (Table VI and Figures 38 through 42). Apparently, at 1200°F, there would be a steady improvement with decreasing cooling rate.

Ductility in the rupture tests decreased as the result of normalizing to form bainitic structures (Table VI). The 3-inch section samples were least ductile with some evidence that the 6-inch round was not reduced as much in ductility.

The alteration of structure during creep testing at 1100°F was relatively small microscopically (Figures 25, 20, 21 and 22). The 3- and 6-inch sections, however, underwent considerably more softening than the two smaller section sizes.

Influence of Increased Austenitizing Temperatures

Reducing the normalizing temperature to 1750°F produced a 100% fine bainitic structure. The two higher temperatures resulted in a small amount of martensite plus fine acicular bainite with somewhat increased hardness (Table III and Figures 24, 13 and 25). The resistance to tempering increased with normalizing temperature (Table III and Figures 23, 20 and 24). Tempering produced spheroidized carbides and alteration of the ferrite.

The strengths at high temperatures of the tempered structures generally increased with normalizing temperature to a pronounced extent (Table VI and Figures 38, 39, 40, 41 and 43). The only exception might be 700°F although additional tests should be made to verify the apparent strength of the material normalized at 1750°F. In most cases, the increases in strength were large in comparison to the other two steels considered.

Ductility in the rupture tests decreased markedly when the austenitizing temperature was raised from 1750° to 1950°F (Table VI). A further decrease resulted from raising the temperature to 2100°F.

The structure obtained by normalizing from 1950°F was far more stable than those of either the 1750° or 2100°F treatments (Figures 23, 20 and 24) as judged by hardness drops during creep testing at 1100°F. The material treated at 1750°F may have undergone recrystallization during testing.

The low strength after a 1750°F normalize indicates that a bainitic structure alone is not sufficient to obtain high strength at high temperatures. There was also more effect of heat-treating temperature in this more highly alloyed steel.

DISCUSSION

From a practical heat treating viewpoint, the data obtained lead to the following important generalizations:

1. Increasing the section size (up to 6 inches) of bars normalized from the established austenitizing temperatures did not substantially weaken any of the steels. In most cases, it actually increased strengths even when the structures could not be tempered without reducing hardness below 300 BHN. The larger section sizes often softened more during testing, but this evidence of structural instability did not seem to adversely affect the strengths considered.

2. Increasing the austenitizing temperature above the established heat-treating temperatures did not give marked improvement in strength for either SAE 4340 or "17-22-A"S. The influence was greater in the case of the H-40 steel which contained vanadium, suggesting that more complete solution and diffusion of vanadium compounds was somewhat beneficial. In the 1.25Cr-0.5Mo-0.25V ("17-22-A"S)steel both martensitic and bainitic structures were somewhat increased in strength by increasing the austenitizing temperature. This would probably have been true also for the 3Cr-Mo-W-V (H-40) steel although only the bainitic structures were tested. Martensitic structures in SAE 4340 steel were not improved but the bainitic structures obtained by normalizing were.

3. Too low a temperature of austenitizing for complete solution is very detrimental as judged by the results for H-40 steel.

4. Increased austenitizing temperature or decreased cooling rate generally reduced ductility in the rupture tests.

Correlation of the Structures and Properties of the Continuously Cooled Bars and Turbine Wheels

The figures showing the stress dependency of strength properties included curves for forged turbine wheels previously established (Ref. 2). One reason for this was to indicate probable stress dependency effects for the sparse survey data from this investigation. In addition, it permits, in conjunction with the microstructures, an appraisal of the agreement in properties for the continuously cooled samples of this investigation with those which existed in the wheels examined for Reference 2.

Cr-Ni-Mo (SAE 4340) Wheels and Continuously Cooled Bar Stock

The oil-quenched wheel was treated at 1550°F and tempered at 1050°F to 280/320 BHN. This produced a uniformly tempered, martensitic structure which appeared to be similar to the bar stock oil quenched from 1750°F for this investigation. References to Figures 26 through 29 show that the two had approximately the same properties, except that the bar stock had lower strength at short time periods, and higher strength at longer time periods. Apparently, the bar stock material did not exhibit the breaks in the curves that the wheel did. There are a number of possible reasons for this. One is that the wheel was actually cooled at a somewhat slower rate than the bar. It will be noted that the slower cooled, normalized disk did not show the breaks. It is, however, equally possible, in view of the lack of confirming data, that the lower austenitizing temperature of the wheel was responsible.

The normalized wheel was treated at 1750°F and was not tempered. The section size of the disk ranged from about 3-inches to 6-inches. The structures of the disk did not perfectly match those of the samples simulating the centers of 3- and 6-inch rounds. The restriction of cooling rate to more closely simulate that of the wheel did not improve the agreement in strengths over that obtained with the 1-inch normalized bar stock (Figures 26 through 29). It appears that either differences between the heats of the wheel and bar stock materials or the double normalize of the wheel resulted in the different response to heat treatment.

1.25Cr-Mo-V ("17-22-A"S) Wheels and Continuously Cooled Bar Stock

The oil-quenched wheel had properties which were in general superior to the normalized wheel. In Reference 2, it was concluded that the retarded cooling rate from the mass of the forging gave lower bainite plus martensite on oil quenching. The normalized wheel had varying tempered bainitic-ferritic structures near the rim, and bainitic-pearlitic structures near the hub. Again, the mass of the forging was presumed to have retarded cooling rate and allowed higher temperature transformation products to form. Unfortunately, as-transformed structures for the wheel were not available. However, the structures resulting from the simulated rates of continuous cooling were compared with the tempered wheel structures. The simulated center of the 6-inch round gave a structure resembling the rim of the normalized wheel. In no case was the predominantly pearlitic type structure of the wheel found. The structure of the oil-quenched wheel was not reproduced in the bar stock experiments.

The strengths of all three normalized section sizes were superior to the oil-quenched wheel in most cases, as is shown by Figures 32 through 35. The oil-quenched bar stock was generally inferior. It is therefore presumed that the oil-quenched wheel had structures in between the martensite formed by oil quenching and the bainitic-martensitic structure formed by normalizing the 1-

inch diameter bar stock.

The large amount of pearlite in the normalized wheel has always been a mystery because the alloy should not have formed pearlite on air cooling a 6-inch section. Secondly, the oil-quenched wheel should have been largely martensite. Differences between the two heats could be involved. Prior history effects also could have been a factor. The most probable explanation, however, is in unrecorded variations in the thermal conditions during heating and cooling of the wheels.

3Cr-Mo-W-V (H-40) Wheels and Continuously Cooled Bar Stock

In Reference 2, it was observed that there was little difference in structure between the oil-quenched and normalized wheels of H-40 steel after tempering. The properties were also similar. In so far as could be determined, the wheels apparently had a coarse-grained, tempered bainitic structure. Good agreement in rupture strength was found between the bainitic bar stock structures and the wheels in spite of the apparent difference in grain size. Total deformations, however, were less. Normalized and tempered 3/4-inch bar stock, even though it did not have a similar structure, came closer to the wheels for limited deformations.

The structures of the continuously cooled bar stock from this investigation were compared with those of the wheels even though it was difficult to draw conclusions from the tempered structures of the wheels. The structures of the 3- and 6-inch rounds were quite close to those of the wheels. The 3-inch round normalized specimens matched the properties of the oil-quenched wheel somewhat closer than the normalized 3/4-inch round. It seems somewhat surprising that the center of a normalized 3-inch round should match the 3-inch section of an oil-quenched wheel.

The wheel apparently had a coarse grain size. The results of the present investigation indicated that the retarded cooling rate developed the appearance of the coarse grains. Since the wheels and bars were from the same heat, this points to the wheels, even when oil quenched, having been cooled at rates similar to those of the simulated 3- and 6-inch rounds.

General Comments on Correlation of Structures and Properties of Wheels and Continuously Cooled Bars

One of the reasons the correlation between bar stock and wheels of the 4340 and "17-22-A"S steels was not better could be that different heats were involved. There was also a difference in austenitizing temperature for 4340 steel. The questionable aspects of the structures of the "17-22-A"S and H-40 wheels previously mentioned leaves questions regarding the conditions of treatment of the wheels.

It must be recognized, however, that there were differences in heating rates, and therefore, times at temperature, between the bar stock and the wheels as well as differences in prior history. The results of the tests involving variation in austenitizing temperature showed some sensitivity to this factor for both the "17-22-A"S and H-40 steels. It is, therefore, entirely possible that the heating condition during forging combined with the final heat-treating conditions were sufficiently different to cause the observed differences in structure and properties.

Structures of Continuously Cooled Bars

In an attempt to better define the structures of the continuously cooled specimens, they were compared with those obtained by isothermal transformation in Reference 2.

Cr-Ni-Mo (SAE 4340) Steel

As far as could be judged, the three normalizing conditions produced mainly upper bainite and martensite, with the greatest effect being the increasing amount of tempering of the martensite as the cooling rate decreased. There was some gradation of the fine mass of the bainite, with the 1-inch stock having the greatest predominance of fine bainite. This follows the general trend of properties as set forth in Figure 30 and the shift in relative properties towards superior properties for upper bainite with increasing test temperatures (Ref. 2).

Increasing the normalizing temperature apparently altered transformation conditions so that the bainite which formed more nearly approached the softer middle bainitic structures. This also is consistent with the correlation of properties of Ref. 2 where increasing amounts of middle bainite gave superior properties in the 900° to 1000°F range.

1.25Cr-Mo-V ("17-22-A"S) Steel

As far as could be judged, normalizing the 1-inch section gaved mixed middle bainite and martensite. Increasing the section size resulted in a shift towards upper bainite. Apparently, increasing the normalizing temperature had the same effect. This is not too generally consistent with the properties versus structure relationship of Reference 2 where the middle bainitic structure generally had the highest strengths. It would appear that a more thorough knowledge of the factors involved in continuous cooling transformation is needed.

3Cr-Mo-W-V (H-40) Steel

Only one temperature of isothermal transformation to bainite was reported in Reference 2 due to the narrow temperature range in which bainite would form in a reasonable time. The three slower cooling rates of this investigation all gave similar structures, except for the apparent grain size of the bainite, and the properties were not too far different. The major difference was decreased resistance to tempering with attendant decreased retention of hardness during testing as the cooling rate was decreased. The "bainite" formed isothermally for Reference 2 did not closely resemble the structures formed in this investigation. It is concluded that there are differences between structures formed isothermally and structures formed over a range of temperature on continuous cooling which must be studied in greater detail if a completely satisfying correlation is to be made between the present work and the work reported in Reference 2.

CONCLUSIONS

1. All of the data showed predominantly bainitic structures to have the highest strength in the range from 700° to 1200°F.

2. Sufficiently rapid cooling rates to produce essentially martensitic structures result in lower strength. When the cooling rate was reduced from oil-quenching to normalizing of 1-inch rounds, changing the structure from martensitic to predominantly bainitic gave a substantial increase in strength with loss in rupture-test ductility. Further reductions in cooling rate to those equivalent to the centers of air-cooled round bars 3 and 6 inches in diameter still resulted in bainitic structures, with a further increase in strength and some loss in ductility.

3. The increase in strength from reducing the cooling rate from that of the centers of air-cooled 1-inch rounds to that of the centers of 6-inch rounds appeared to be due to the development of complete bainitic structures similar to middle to upper bainite. The strengths approached those of the strongest structures developed by isothermal treatment. The correlation between observed structures of this phase of the investigation and previous studies for isothermally transformed structures was fairly good for 4340 steel, not as good for "17-22-A"S and poor for H-40 steel. The assumption is that there is need for more detailed information concerning the relationships between structures formed on continuous cooling and structures formed isothermally, as well as the relationship between these two types of structures and high-temperature properties. The estimation of properties of structures formed by continuous cooling is still uncertain for this reason.

4. Increasing heat-treating temperature for 1-inch rounds generally increased strength and reduced ductility. The largest effect was obtained from H-40 steel. This was true for martensitic as well as bainitic structures, except for 4340 steel where the martensitic structures were not increased in strength.

5. The range of austenitizing temperature (1750° to 2100°F) was at or above the usual temperature of treatment of 1750°F for 4340 and "17-22-A"S while 1750°F was below the established temperature of 1950°F for H-40. This probably accounts for the much greater apparent effect for H-40 steel.

6. Increasing the austenitizing temperature generally increased the coarseness of the background grain size. The effect on the basic structure was less, although there was a tendency on normalizing for increasing coarseness of the bainite with increased austenitizing temperature.

7. The correlation of the structures of the continuously cooled structures and properties with those of forged wheels previously investigated ranged from poor for 4340 and "17-22-A"S to fair for H-40 steel. The lack of better correlation was assumed to be due to the materials being from different heats and differences in prior thermal history.

8. The trends shown by the data are believed to be quite reliable. However, it should be recognized that survey-type tests were used - necessarily limiting the dependability of the exactness of the levels of the strength criteria.

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TABLE I

Influence of Austenitizing Temperature, Section Size, and Cooling Medium on the Microstructure and Hardness of SAE 4340 Steel

Austenitizing Temp. (°F)	Quenching Medium	Bar Diameter (inches)	Microstructure Obtained	Average BHN	Tempering Conditions		Average BHN
					Temp (°F)	Time (hrs)	
1750	Oil (a)	1	100% martensite	585	1100	10	307
	Air (a)	1	35% martensite + 65% bainites	374	1100	1	306
	Air	3 (b)	25% martensite + 75% bainites	329	None	--	329
	Air	6 (b)	20% martensite + 80% bainites	322	None	--	322
1950	Oil	1	100% martensite	560	1100	10	302
	Air	1	15% martensite + 85% bainites	328	None	--	328
2100	Oil	1	100% martensite	534	1100	10	298
	Air	1	15% martensite + 85% bainites	333	None	--	333

(a) Previously reported in WADC TR 53-277 Part II

(b) 1-inch diameter bars were air cooled in insulating cylinders of firebrick to simulate the cooling cycles of normalized 3- and 6-inch diameter bar stock.

TABLE II

Influence of Austenitizing Temperature, Section Size, and Cooling Medium on the Microstructure and Hardness of "17-22-A"S Steel

Austenitizing Temp (°F)	Quenching Medium	Bar Diameter (inches)	Microstructure Obtained	Average BHN	Tempering Conditions Temp (°F)	Tempering Conditions Time (hrs)	Average BHN
1750	Oil (a)	1	100% martensite	525	1300	1	291
	Air (a)	1	15% martensite + 85% coarse bainites	355	1200	10	307
	Air	3 (b)	100% bainite	325	1200	6	302
	Air	6 (b)	98% bainite + 2% ferrite	325	1200	6	306
1950	Oil	1	100% martensite	470	1300	1	300
	Air	1	100% bainite	335	1200	6	298
2100	Oil	1	50% martensite + 50% lower bainite	412	1300	1	290
	Air	1	100% bainite	313	1200	6	306

(a) Previously reported in WADC TR 53-277 Part II

(b) 1-inch diameter bars were air cooled in insulating cylinders of firebrick to simulate the cooling cycles of normalized 3- and 6-inch diameter bar stock.

TABLE III

Influence of Austenitizing Temperature, Section Size, and Cooling Medium on the Microstructure and Hardness of H-40 Steel

Austenitizing Temp (°F)	Quenching Medium	Bar Diameter (inches)	Microstructure Obtained	Average BHN	Tempering Conditions		Average BHN
					Temp (°F)	Time (hrs)	
1750	Air	3/4	100% fine bainites	409	1200	4	310
1950	Oil (a)	3/4	100% martensite	523	1200	12	306
	Air (a)	3/4	20% martensite + 80% bainites	435	1200	18	316
	Air	3 (b)	100% bainites	400	1200	4	308
	Air	6 (b)	100% bainites	390	1200	4	309
2100	Air	3/4	20% martensite + 80% bainites	429	1250	4 + 2	319

(a) Previously reported in WADC TR 53-277 Part II

(b) 1-inch diameter bars were air cooled in insulating cylinders of firebrick to simulate cooling cycles of normalized 3- and 6-inch diameter bars.

TABLE IV

Rupture, Total Deformation, and Creep Data at 700°, 900°, 1000°, and 1100°F for SAE 4340 Steel for Several Austenitizing Temperatures and Cooling Cycles

Austenitizing Temp. (°F)	Quenching Medium	Bar Diam (inches)	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in)	Reduction of Area (%)	Deformation on Loading (%)	Time to Reach Specified Total Deformation (hours)				Minimum Creep Rate (%/hour)
									0.1%	0.2%	0.5%	1.0%	
							700°F						
1750	Oil(b)	1	304	90,000	1350(d)	--	--	0.430	a	a	2	675	0.00027
	Air(b)	1	300	90,000	1294(d)	--	--	0.467	a	a	1	1000	0.00016
	Air	3(c)	327	90,000	1342(d)	--	--	0.463	a	a	~3	668	0.00021
	Air	6(c)	315	90,000	1342(d)	--	--	0.450	a	a	~5	1000	0.00021
1950	Air	1	328	90,000	1293(d)	--	--	0.542	a	a	a	440	0.00014
2100	Oil	1	294	90,000	1584(d)	--	--	0.511	a	a	a	215	0.00032
	Air	1	336	90,000	1293(d)	--	--	0.547	a	a	a	565	0.00015
							900°F						
1750	Oil(b)	1	306	55,000	381	19.5	39.5	0.269	a	a	2	13	0.01480
	Air(b)	1	300	55,000	842	12.0	22.3	0.260	a	a	8	64	0.00414
	Air	3(c)	327	55,000	1536	6.0	6.3	0.305	a	a	3	30	0.00130
	Air	6(c)	315	55,000	1951	5.0	5.5	0.290	a	a	3	45	0.00085
1950	Air	1	336	55,000	1660	4.0	4.7	0.307	a	a	5	263	0.00056
2100	Oil	1	296	55,000	324	10.0	12.7	0.300	a	a	~3	12	0.01000
	Air	1	328	55,000	1975	2.0	4.7	0.285	a	a	5	277	0.00065
1750	Oil(b)	1	302	40,000	2338	4.0	5.5	0.175	a	-	50	355	0.00111
	Air(b)	1	300	40,000	1919(d)	--	--	0.164	a	5	1160	>3000(e)	0.00015
	Air	3(c)	331	40,000	1464(d)	--	--	0.185	a	~2	82	1800(e)	0.00024
	Air	6(c)	315	40,000	1483(d)	--	--	0.175	a	~4	430	>3000(e)	0.00015
1950	Air	1	336	40,000	1461(d)	--	--	0.163	a	2.5	475	(f)	0.00013
2100	Air	1	328	40,000	1650(d)	--	--	0.194	a	a	425	(f)	0.00012
							1000°F						
1750	Oil(b)	1	310	31,000(g)	160	11.0	15.0	0.149	a	~1	~3.5	16	0.02500
	Air(b)	1	290	31,000	371	5.5	7.4	0.126	a	~5	50	145	0.00505
	Air	3(c)	331	31,000	259	12.5	15.7	0.148	a	~1	16	39	0.01140
	Air	6(c)	315	31,000	362	11.0	11.1	0.157	a	~1	19	94	0.00650
1950	Oil	1	302	31,000	111	9.0	9.5	0.173	a	<1	3	18	0.02800
	Air	1	321	31,000	283	6.0	4.5	0.148	a	~2	35	142	0.00420
2100	Oil	1	296	31,000(g)	130	10.0	11.4	0.158	a	<1	3	18	--
	Air	1	328	31,000	490	4.5	4.0	0.148	a	~2	50	220	0.00280
1750	Oil(b)	1	309	20,000(g)	780	12.0	15.0	0.099	a	7	47	190	0.00380
	Air(b)	1	300	20,000	1392	5.0	4.0	0.090	~1	20	228	650	0.00114
	Air	3(c)	327	20,000	1310	8.5	6.6	0.101	a	5	110	387	0.00170
	Air	6(c)	315	20,000	1488	6.0	6.6	0.092	~1	12	145	534	0.00120
1950	Oil	1	302	20,000(g)	480	7.5	9.5	0.110	a	3	33	130	0.00520
	Air	1	325	20,000	1425	2.5	3.0	0.093	<1	~2	120	768	0.00073
2100	Oil	1	301	20,000	548	8.5	9.8	0.091	<1	10	58	166	0.00440
	Air	1	328	20,000	2257(d)	--	--	0.116	a	18	285	1300	0.00043
							1100°F						
1750	Oil(b)	1	293	18,000	43.5	20.0	25.2	0.148	a	-	--	--	---
	Air(b)	1	293	18,000	69.6	7.0	11.7	0.116	a	-	--	--	---
	Air	3(c)	328	18,000	78.6	17.5	22.5	0.107	a	<1	2.5	--	---
	Air	6(c)	321	18,000	77.2	18.0	21.8	0.112	a	<1	3	--	---
1950	Oil	1	302	18,000	36.3	12.0	14.8	0.106	a	-	--	--	---
	Air	1	321	18,000	105.0	5.5	7.0	0.093	<1	2	12	45	---
2100	Oil	1	284	18,000	67.2	19.5	18.9	0.215	a	a	--	--	---
	Air	1	328	18,000	123.0	5.5	4.9	0.105	a	2.5	14	40	---
1750	Oil(b)	1	309	4,500	1080(d)	--	--	0.027	5	22	104	258	0.00316
	Air(b)	1	311	4,500(g)	1100(d)	--	--	0.020	12	56	300	900	0.00150
	Air	3(c)	327	4,500	815(d)	--	--	0.022	15	60	268	725	0.00108
	Air	6(c)	315	4,500	839(d)	--	--	0.030	15	60	305	822	0.00100
1950	Air	1	325	4,500	2740(d)	--	--	0.040	17	165	1148	(f)	0.00019
2100	Air	1	330	4,500	1897(d)	--	--	0.035	50	250	1810	(f)	0.00015

(a) Specimen reached indicated deformation on loading
(b) Data previously reported in WADC TR 53-277 Part II
(c) 1-inch diameter bars were air cooled in insulating firebrick cylinders to simulate cooling cycles of normalized 3- and 6-inch diameter bars.
(d) Test discontinued at indicated time
(e) Extrapolated value
(f) Deformation not obtained during testing period and to indicate time would have required excessive extrapolation
(g) Interpolated values

TABLE V

Rupture, Total Deformation, and Creep Data at 700°, 900°, 1100°, and 1200°F for "17-22-A"S Steel for Several Austenitizing Temperatures and Cooling Cycles

Austenitizing Temp. (°F)	Quenching Medium	Bar Diam. (inches)	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in)	Reduction of Area (%)	Deformation on Loading (%)	Time to Reach Specified Total Deformation (hours) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hr)
						700°F							
1750	Oil(b)	1	298	107.000	1145(d)	--	--	0.550	a	a	a	1000	0.00010
	Air(b)	1	307	102,000	1194(d)	--	--	0.465	a	a	~1	>2000(e)	0.00007
	Air	3(c)	291	102,000	1793(d)	--	--	0.620	a	a	a	150	0.00016
	Air	6(c)	294	102,000	1324(d)	--	--	0.660	a	a	a	f	0.00001
1950	Oil	1	294	102,000	1733(d)	--	--	0.715	a	a	a	75	0.00008
	Air	1	302	102,000	1757(d)	--	--	0.550	a	a	a	f	0.00003
2100	Air	1		102,000	1897(d)	--	--	0.653	a	a	a	f	0.000016
						900°F							
1750	Oil(b)	1	272	70,000	756	30.0	64.0	0.378	a	a	3	50	0.00384
	Air(b)	1	303	70,000	1482(d)	--	--	0.335	a	a	24	1400	0.00030
	Air	3(c)	302	70,000	1223(d)	--	--	0.288	a	a	235	>2000	0.00014
	Air	6(c)	297	70,000	1152(d)	--	--	0.285	a	a	525	>2000	0.00008
1950	Oil	1	300	70,000	714	6.0	17.5	0.370	a	a	22	215	0.00180
	Air	1	300	70,000	1277(d)	--	--	0.355	a	a	60	f	0.00008
2100	Air	1		70,000	2020(d)	--	--	0.350	a	a	263	f	0.00004
						1100°F							
1750	Oil(b)	1	293	41,000	23.4	28.0	27.5	0.173	a	-	-	-	0.0065
	Air(b)	1	309	41,000	112	2.5	3.1	0.212	a	a	26	-	0.00614
	Air	3(c)	291	41,000	110	2.0	h	0.206	a	a	34	-	0.00523
	Air	6(c)	293	41,000	115	2.0	3.5	0.221	a	a	29	-	0.00420
1950	Oil	1	294	41,000	29	5.5	10.0	0.213	a	a	-	-	-
	Air	1	298	41.000	75	2.5	1.2	0.172	a	<1	16.5	-	-
2100	Oil	1	290	41,000	29	8.0	14.5	0.215	a	a	-	-	-
	Air	1	317	41.000	79	1.0	1.0	0.205	a	a	54	-	-
1750	Oil(b)	1	306	19,000(g)	850	4.0	--	0.105	a	17	170	420	0.00152
	Air(b)	1	311	19,000(g)	900	2.0	--	0.085	5	80	580	800	0.00063
	Air	3(c)	295	19,000	1220	2.0	h	0.090	15	193	1045	1500(e)	0.00026
	Air	6(c)	291	19,000	1309	1.0	2.0	0.091	5	183	994	1400(e)	0.00028
1950	Oil	1	298	19,000	1081	2.5	2.0	0.090	~2	62	597	~1070	0.00047
	Air	1	294	19,000	1205	1.5	1.0	0.080	10	150	940	-	0.00028
2100	Oil	1	290	19,000	1001	3.0	3.9	0.105	a	40	328	888	0.00068
	Air	1	317	19,000	1653	0.5	h	0.090	~1	425	~1650(i)	(i)	0.00012
						1200°F							
1750	Oil(b)	1	298	14,000	73	8.0	14.9	0.096	a	4	14	-	-
	Air(b)	1	304	14,000	167	4.0	5.0	0.066	5	22	65	~140	0.0064
	Air	3(c)	290	14,000	158	2.0	2.8	0.072	5	22	91	~130	0.0040
	Air	6(c)	295	14,000	152	1.5	h	0.070	5	22	93	~127	0.0041
1950	Oil	1	294	14,000	157	4.5	8.1	0.080	2	11	42	92	0.0084
	Air	1	302	14,000	129	3.5	3.5	0.073	2	16	87	-	0.0052
2100	Oil	1	302	14,000	129	6.0	9.5	0.089	~1	7	24	57	0.0150
	Air	1	294	14,000	214	1.5	3.9	0.080	~1	61	213	-	0.00155
1750	Oil(b)	1	310	7,500	575	30.0	39.8	0.058	6	17	69	144	0.0066
	Air(b)	1	313	7,500	918	10.0	14.9	0.046	6	46	176	333	0.0023
	Air	3(c)	313	7,500	1079(d)	--	--	0.029	45	160	532	945	0.00085
	Air	6(c)	322	7,500	1125(d)	--	--	0.037	37	155	568	1030	0.00068
1950	Oil	1	286	7,500	937	5.0	14.4	0.052	8	31	153	347	0.00218
	Air	1	294	7,500	1757	2.5	7.5	0.037	37	196	717	1320	0.00056
2100	Oil	1	286	7,500	1073	6.0	4.9	0.045	45	103	317	620	0.00134
	Air	1	294	7,500	2313	4.0	7.5	0.035	82	360	1500	~2300	0.00022

(a) Specimen reached indicated deformation on loading
(b) Data previously reported in WADC TR 53-277 Part II
(c) 1-inch diameter bars were air cooled in insulating firebrick cylinders to simulate cooling cycles of normalized 3- and 6-inch diameter bars.
(d) Test discontinued at given time
(e) Extrapolated value
(f) Deformation not obtained during testing period, and to indicate time would have required excessive extrapolation
(g) Interpolated values
(h) Fractured in shoulder radius
(i) Failed with only 0.5% elongation

TABLE VI

Rupture, Total Deformation, and Creep Data at 700°, 900°, 1100°, and 1200°F for H-40 Steel for Several Austenitizing Temperatures and Cooling Cycles

Austenitizing Temp. (°F)	Quenching Medium	Bar Diam. (inches)	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in)	Reduction of Area (%)	Deformation on Loading (%)	Time to Reach Specified Total Deformation (hours)				Minimum Creep Rate (%/hour)
									0.1%	0.2%	0.5%	1.0%	
						700°F							
1750	Air	3/4	311	90,000	1369(d)	--	--	0.375	a	a	100	f	0.00006
1950	Oil(b)	3/4	290	90,000	1514(d)	--	--	0.410	a	a	15	~2000(e)	0.00019
	Air(b)	3/4	310	90,000	1292(d)	--	--	0.416	a	a	13	1770(e)	0.00017
	Air	3(c)	313	90,000	1272(d)	--	--	0.390	a	a	135	f	0.00008
	Air	6(c)	322	90,000	1124(d)	--	--	0.410	a	a	60	f	0.00008
2100	Air	3/4	319	90,000	1897(d)	--	--	0.458	a	a	20	f	0.00005
						900°F							
1750	Air	3/4	323	65,000	699	24.0	70.0	0.355	a	a	4	77	0.0556
1950	Oil(b)	3/4	290	65,000	917	31.0	68.0	0.359	a	a	1	50	0.00463
	Air(b)	3/4	320	65,000	1052	18.0	36.0	0.301	a	a	10	85	0.00328
	Air	3(c)	313	65,000	1131(d)	--	--	0.390	a	a	20	1500(e)	0.00011
	Air	6(c)	322	65,000	1131(d)	--	--	0.414	a	a	15	~2200(e)	0.00008
2100	Air	3/4	319	65,000	1897(d)	--	--	0.283	a	a	625	f	0.00005
						1100°F							
1750	Air	3/4	321	40,000	34.7	39.0	77.0	0.253	a	a	--	--	--
1950	Oil(b)	3/4	320	40,000	136	12.5	46.0	0.232	a	a	10	39	0.0160
	Air(b)	3/4	310	40,000(g)	110	5.0	13.6	0.231	a	a	30	89	0.0054
	Air	3(c)	304	40,000	213	4.0	9.5	0.230	a	a	15	107	0.0047
	Air	6(c)	297	40,000	149	10.5	31.0	0.230	a	a	9	44	0.0134
2100	Air	3/4	319	40,000	427	5.0	5.5	0.238	a	a	125	~400	0.0014
1750	Air	3/4	301	30,000	83.7	54.0	79.5	0.187	a	~1	6	21	0.0336
1950	Oil(b)	3/4	321	30,000	865	20.0	26.0	0.150	a	2	94	279	0.00237
	Air(b)	3/4	320	30,000(g)	850	h	--	--	a	10	290	720	0.00090
	Air	3(c)	313	30,000	1317(d)	--	--	0.201	a	a	160	725	0.00079
	Air	6(c)	322	30,000	1318(d)	--	--	0.205	a	a	215	910	0.00068
2100	Air	3/4	319	30,000	1922(d)	--	--	0.215	a	a	317	1600	0.00037
						1200°F							
1750	Air	3/4	298	25,000	13.8	56.0	84.0	0.276	a	a	--	--	--
1950	Oil(b)	3/4	300	25,000	62	45.0	74.0	0.185	a	<1	4	14	--
	Air(b)	3/4	315	25,000	100	17.0	45.0	0.142	a	1	9	38	--
	Air	3(c)	304	25,000	188	10.5	11.7	0.170	a	1	24	71	--
	Air	6(c)	297	25,000	205	11.0	9.4	0.172	a	1	29	72	--
2100	Air	3/4	319	25,000	244	7.0	7.5	0.197	a	~6	31	119	0.0064

(a) Specimen reached indicated deformation on loading
(b) Data previously reported in WADC TR 53-277 Part II
(c) 1-inch diameter bars were air cooled in insulating firebrick cylinders to simulate cooling cycles of normalized 3- and 6-inch diameter bars
(d) Test discontinued at indicated time
(e) Extrapolated value
(f) Deformation not obtained during testing period and to indicate time would have required excessive extrapolation
(g) Interpolated values
(h) Broken in shoulder radius

TABLE VII

Rupture, Total Deformation, and Creep Strengths at 1000° and 1100°F for SAE 4340 Steel as Influenced by Heat Treatment

Heat Treatment	Bar Diam. (inches)	Rupture Strength (psi)		One-Percent Total Deformation Strength (psi)		0.001%/Hour Creep Strength (psi)
		100-hr	1000-hr	100-hr	1000-hr	
			1000°F			
1750°F - Oil Q.	1	35,000	18,500	22,500	11,000	12,000
1750°F - Norm.	1	46,000	22,000	33,000	17,000	19,000
1750°F - Norm.	3(a)	40,000	21,500	26,500	15,500	17,500
1750°F - Norm.	6(a)	46,000	23,000	30,000	16,000	19,000
1950°F - Oil Q.	1	32,000	16,000	21,500	(8,000)	(11,000)
1950°F - Norm.	1	42,000	22,000	33,000	18,500	21,500
2100°F - Oil Q.	1	33,500	17,000	22,500	(11,000)	(11,000)
2100°F - Norm.	1	45,000	26,000	36,000	22,000	24,000
			1100°F			
1750°F - Oil Q.	1	(14,000)	--	6,000	--	--
1750°F - Norm.	1	16,500	--	8,000	4,500	4,400
1750°F - Norm.	3(a)	17,000	--	(8,000)	4,500	4,500
1750°F - Norm.	6(a)	17,000	--	(8,000)	4,500	4,500
1950°F - Oil Q.	1	(13,000)	--	--	--	--
1950°F - Norm.	1	18,000	--	15,500	(8,000)	(6,800)
2100°F - Oil Q.	1	16,000	--	--	--	--
2100°F - Norm.	1	19,000	--	15,500	(8,000)	(7,100)

(a) 1-inch diameter bars were air cooled in insulating firebrick cylinders to simulate cooling cycles of normalized 3- and 6-inch diameter bars.

( ) Indicates values estimated from insufficient data.

TABLE VIII

Rupture, Total Deformation, and Creep Strengths at 1100° and 1200°F for "17-22-A"S Steel as Influenced by Heat Treatment

Heat Treatment	Bar Diam. (inches)	Rupture Strength (psi) 100-hr	Rupture Strength (psi) 1000-hr	One-Percent Total Deformation Strength (psi) 100-hr	One-Percent Total Deformation Strength (psi) 1000-hr	0.001%/Hour Creep Strength (psi)
			1100°F			
1750°F - Oil Q.	1	30,000	18,000	26,000	15,000	15,000
1750°F - Norm.	1	44,000	18,000	(34,000)	18,000	22,000
1750°F - Norm.	3(a)	42,000	20,500	--	21,000	27,000
1750°F - Norm.	6(a)	43,000	21,000	--	21,000	27,000
1950°F - Oil Q.	1	31,500	19,500	--	19,500	24,000
1950°F - Norm.	1	38,000	20,000	--	(20,000)	(27,000)
2100°F - Oil Q.	1	31,500	19,000	--	18,500	(22,000)
2100°F - Norm.	1	38,000	21,500	--	--	(35,000)
			1200°F			
1750°F - Oil Q.	1	12,500	6,400	9,000	--	--
1750°F - Norm.	1	17,000	7,200	16,000	--	--
1750°F - Norm.	3(a)	16,000	(8,500)	15,000	7,500	--
1750°F - Norm.	6(a)	16,000	(8,500)	15,000	8,000	--
1950°F - Oil Q.	1	17,000	7,400	13,500	3,000	--
1950°F - Norm.	1	15,000	8,600	--	8,500	--
2100°F - Oil Q.	1	15,000	7,600	12,000	6,000	--
2100°F - Norm.	1	17,000	9,400	--	(10,000)	--

(a) 1-inch diameter bars were air cooled in insulating firebrick cylinders to simulate cooling cycle of 3- and 6-inch diameter bars

( ) Indicates values estimated from insufficient data.

TABLE IX

Rupture, Total Deformation, and Creep Strengths at 1100° and 1200°F for H-40 Steel as Influenced by Heat Treatment

Heat Treatment	Bar Diam. (inches)	Rupture Strength (psi) 100-hr	Rupture Strength (psi) 1000-hr	One-Percent Total Deformation Strength (psi) 100-hr	One-Percent Total Deformation Strength (psi) 1000-hr	0.001%/Hour Creep Strength (psi)
			1100°F			
1750°F - Norm.	3/4	29,000	(14,000)	24,000	(17,000)	(17,000)
1950°F - Oil Q.	3/4	42,000	29,000	35,000	23,000	25,000
1950°F - Norm.	3/4	41,000	29,000	39,000	28,000	31,000
1950°F - Norm.	3(a)	44,000	34,000	40,500	29,000	31,000
1950°F - Norm.	6(a)	42,000	32,000	37,500	30,000	31,000
2100°F - Norm.	3/4	(49,000)	36,000	(48,000)	33,000	32,500
			1200°F			
1750°F - Norm.	3/4	(13,000)	--	--	--	--
1950°F - Oil Q.	3/4	23,000	--	--	--	--
1950°F - Norm.	3/4	25,000	--	--	--	--
1950°F - Norm.	3(a)	27,000	--	--	--	--
1950°F - Norm.	6(a)	28,000	--	--	--	--
2100°F - Norm.	3/4	29,000	--	--	--	--

(a) 1-inch diameter bars were air cooled in insulating firebrick cylinders to simulate cooling cycles of normalized 3- and 6-inch diameter bars.

( ) Indicates value estimated from insufficient data.

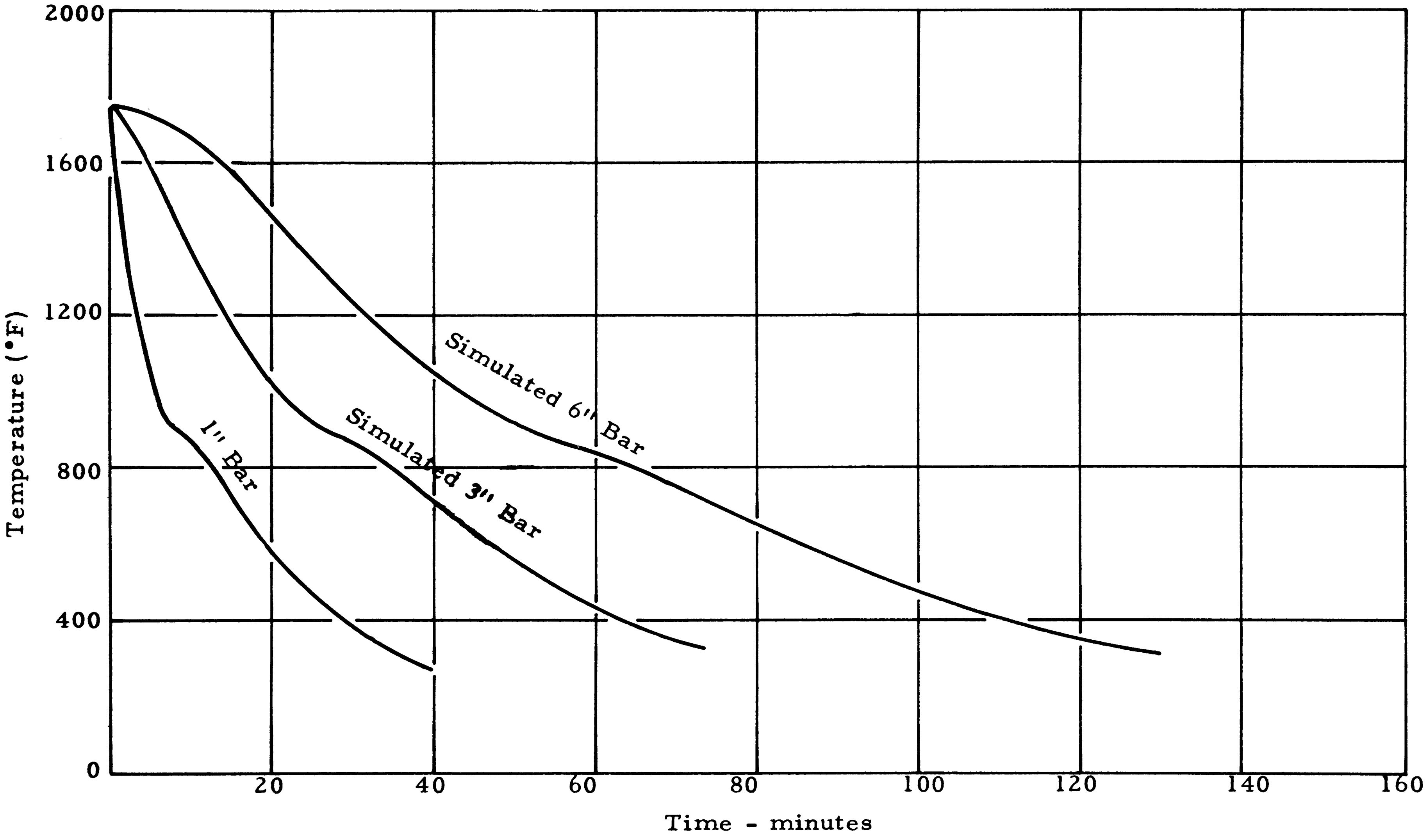


Figure 1.- Cooling Curves for the Centers of 1-inch, Simulated 3-inch, and Simulated 6-inch Rounds of "17-22-A"S Steel Cooled from 1750°F in Air.

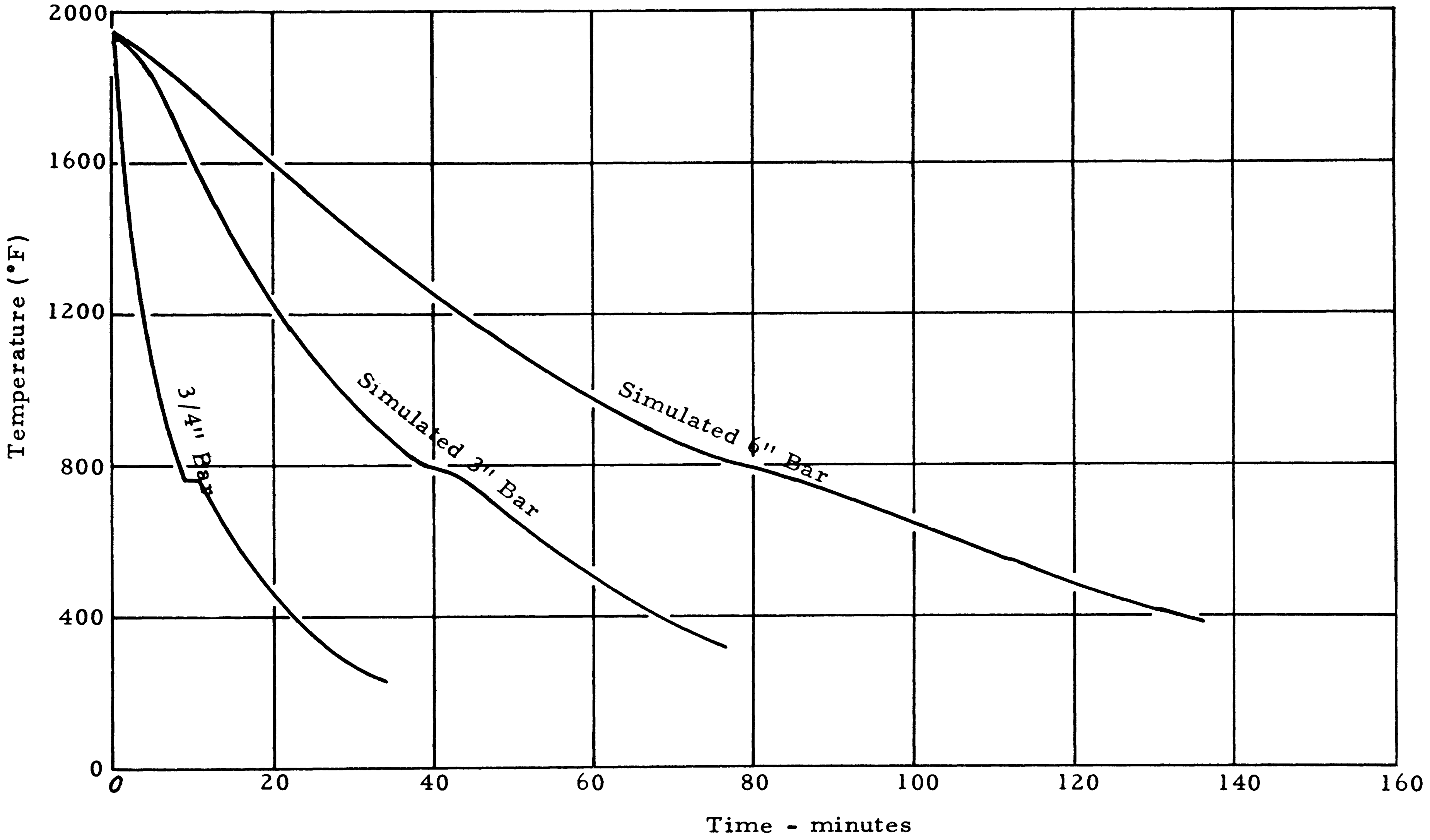


Figure 2. - Cooling Curves for the Centers of 3/4-inch, Simulated 3-inch, and Simulated 6-inch Rounds of H-40 Steel Cooled from 1950°F in Air.

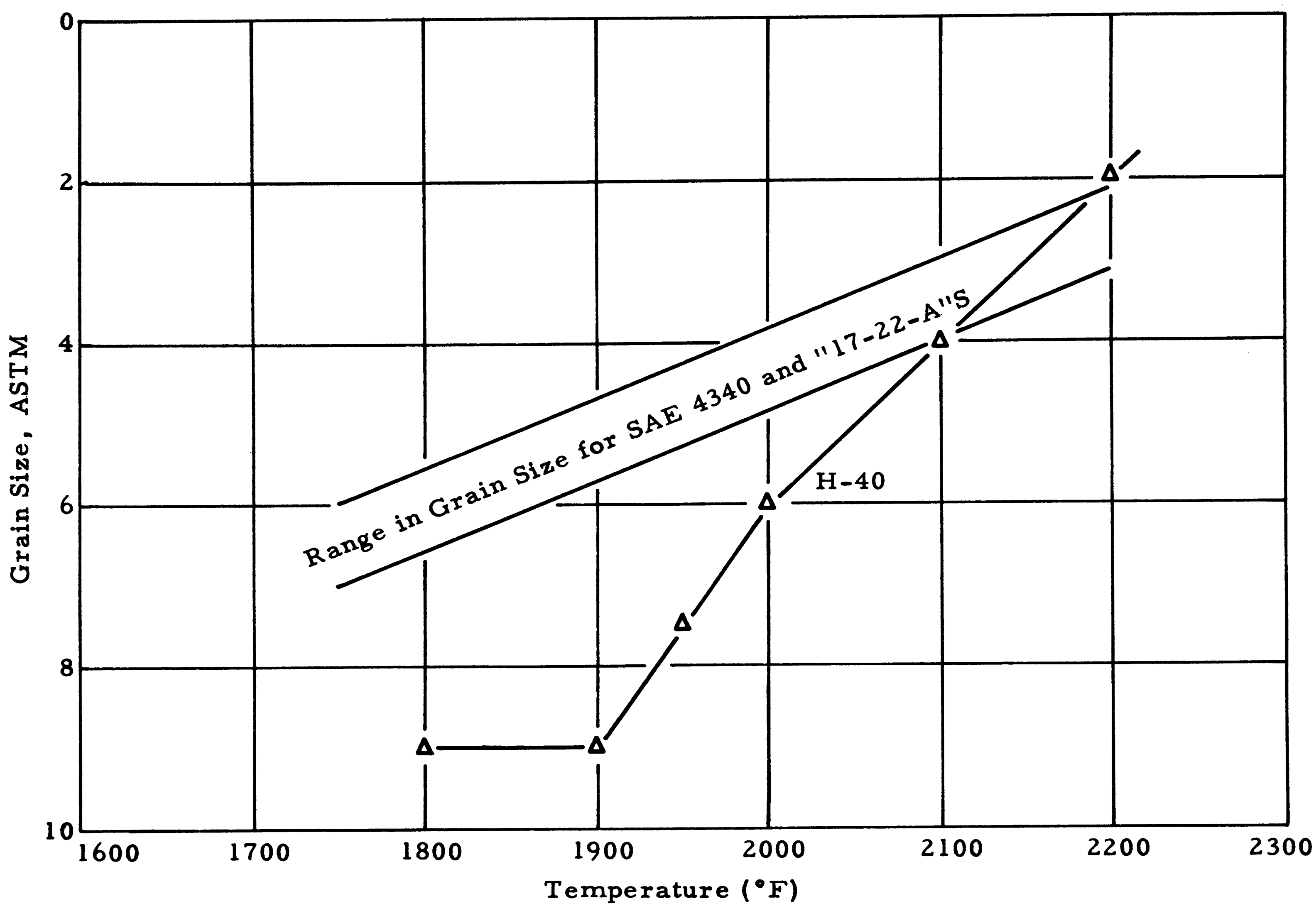
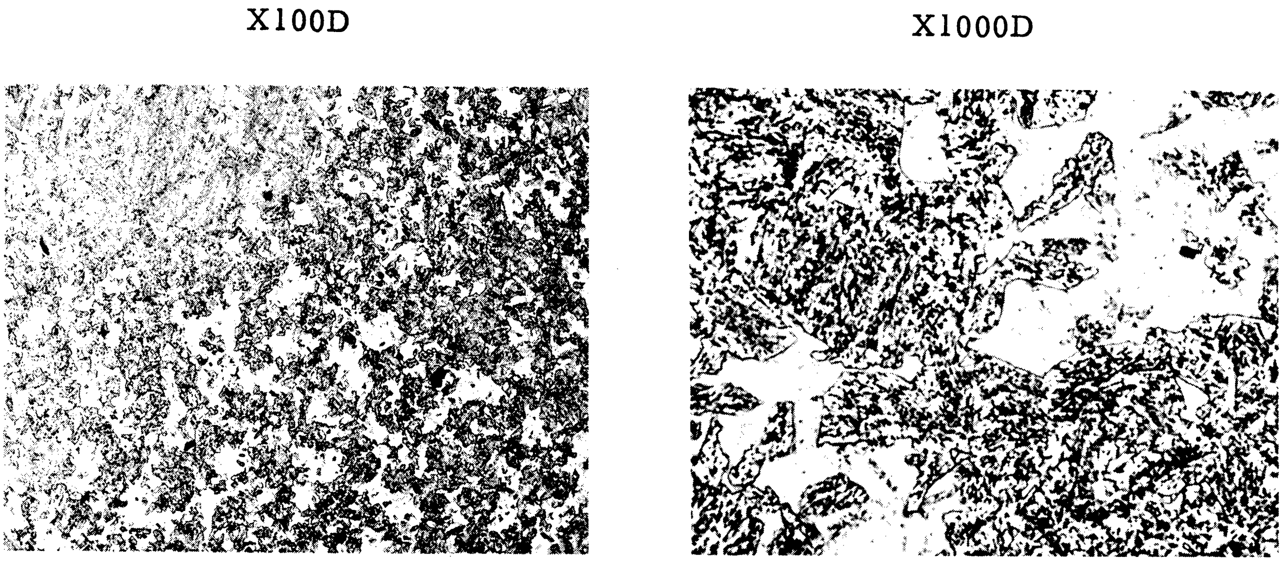
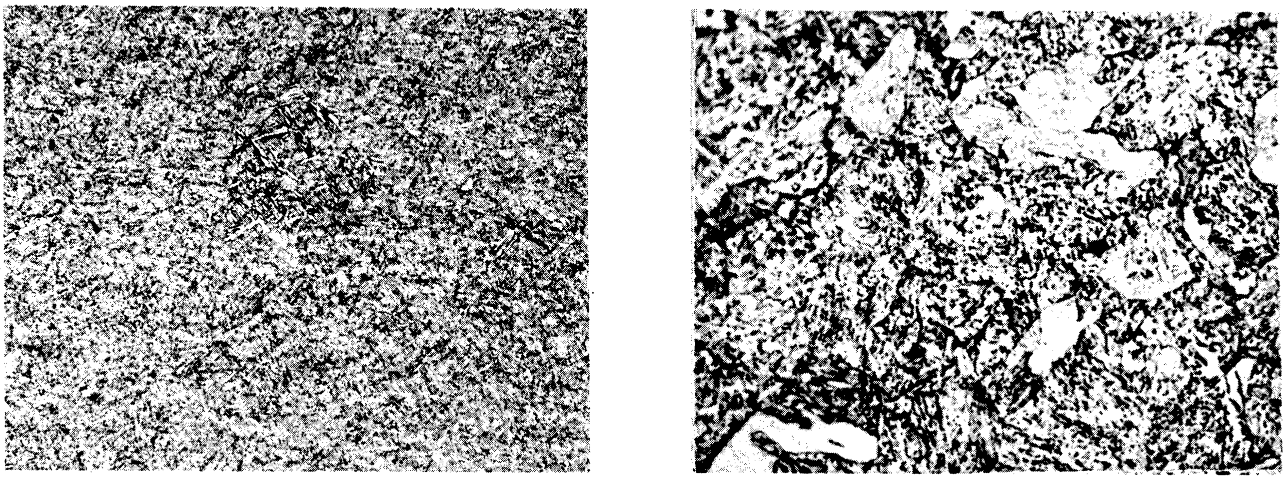


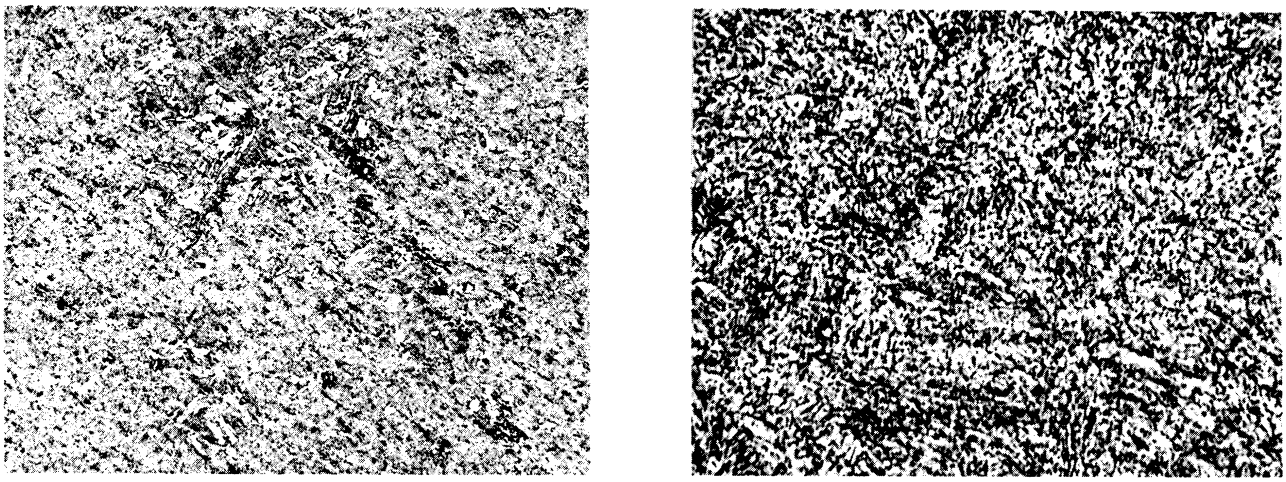
Figure 3.- Effect of Austenitizing Temperature on the Bainitic Grain Size of Normalized 1-inch Diameter Bars of SAE 4340, "17-22-A"S, and H-40 Steels. (Note:- Because of the difficulty in ascertaining the grain size of the "17-22-A"S and 4340 steels in the normalized condition, a band representing the predominant bainitic grain size is shown.)



(a) Normalized from 1750°F as 1-inch diameter bar stock - 390 BHN

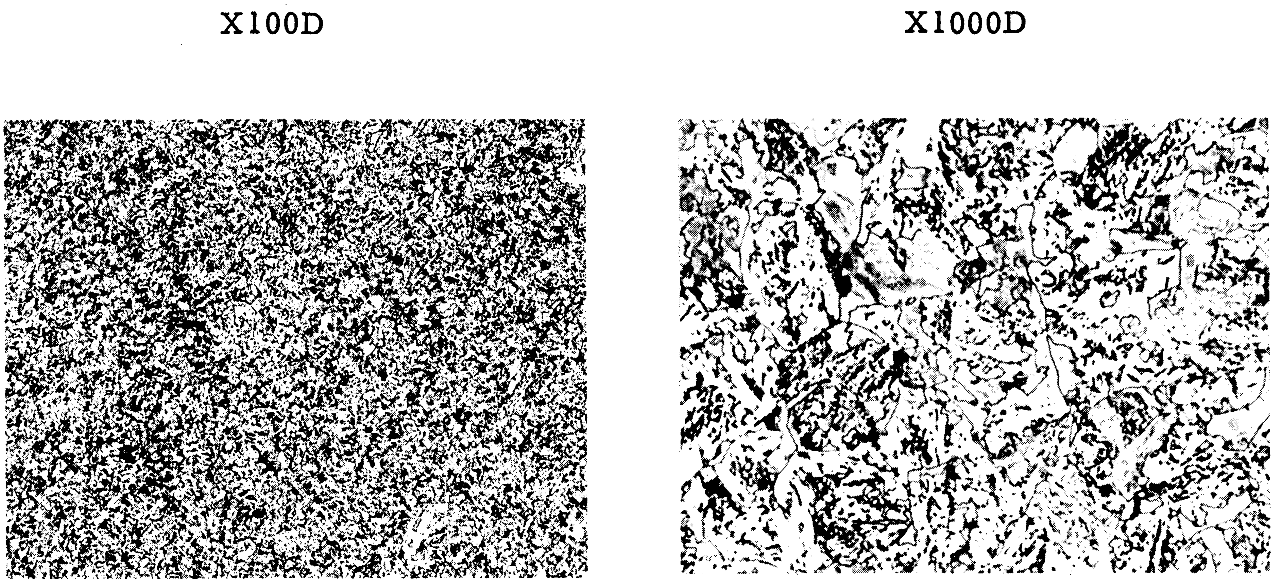


(b) Normalized from 1750°F + tempered 1 hr at 1100°F - 300 BHN

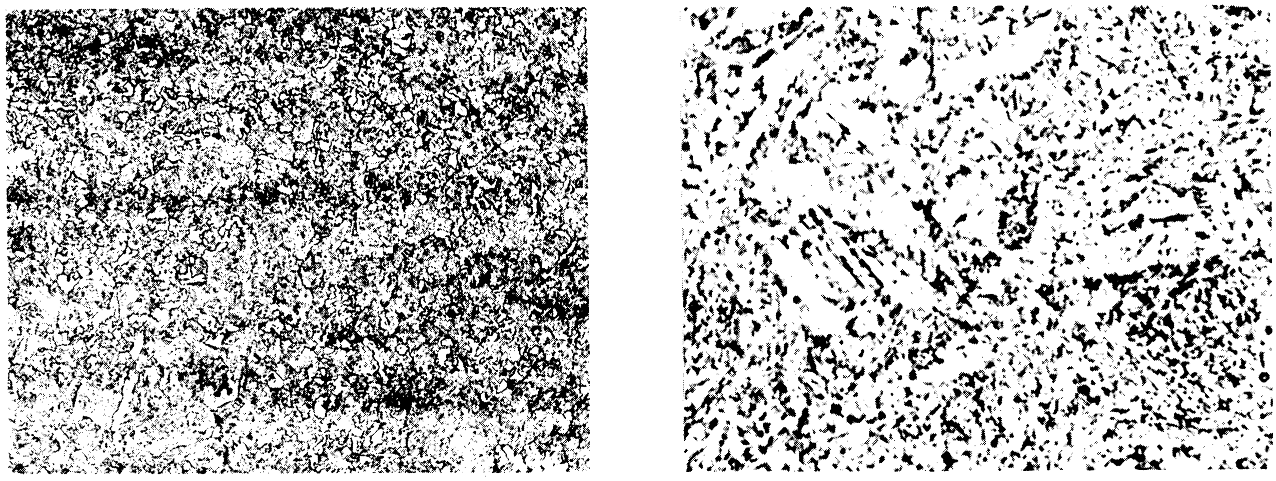


(c) Normalized from 1750°F + tempered 1 hr at 1100°F + creep-rupture tested 1392 hrs at 1000°F and 20,000 psi - 260 BHN

Figure 4. - SAE 4340 Steel. One-inch Diameter Bar Stock (a) As Normalized from 1750°F, (b) As Tempered to 300 BHN, and (c) After Creep-Rupture Testing at 1000°F.

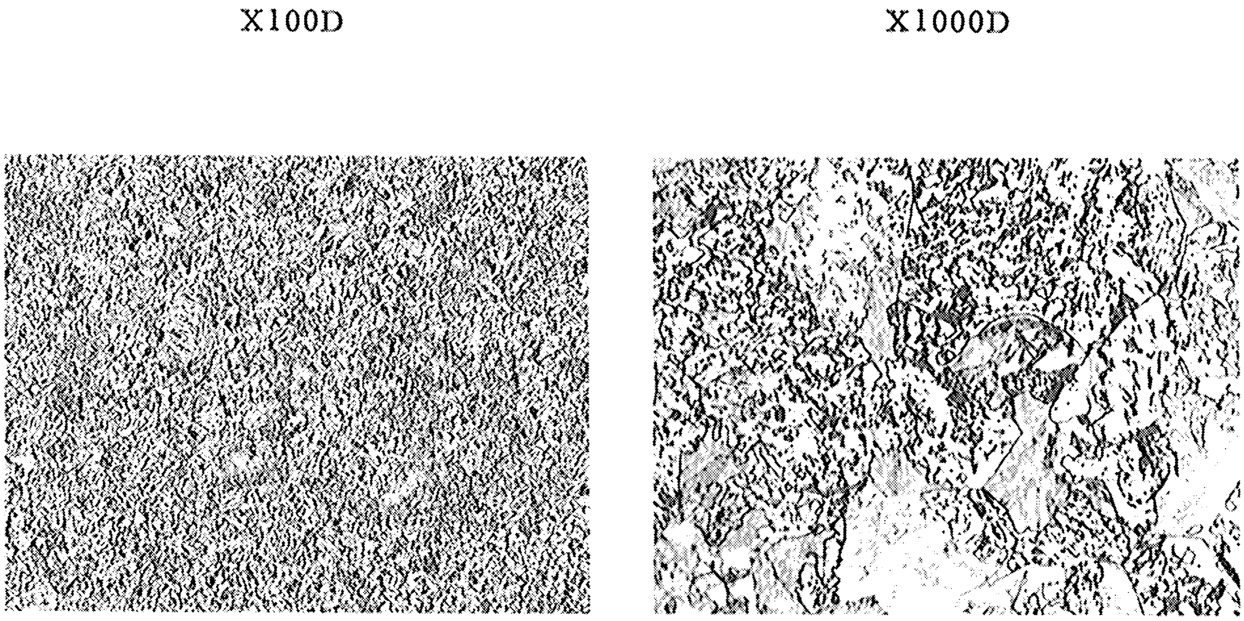


(a) Simulated 3-inch Diameter Bar Stock Normalized from 1750°F - 327 BHN

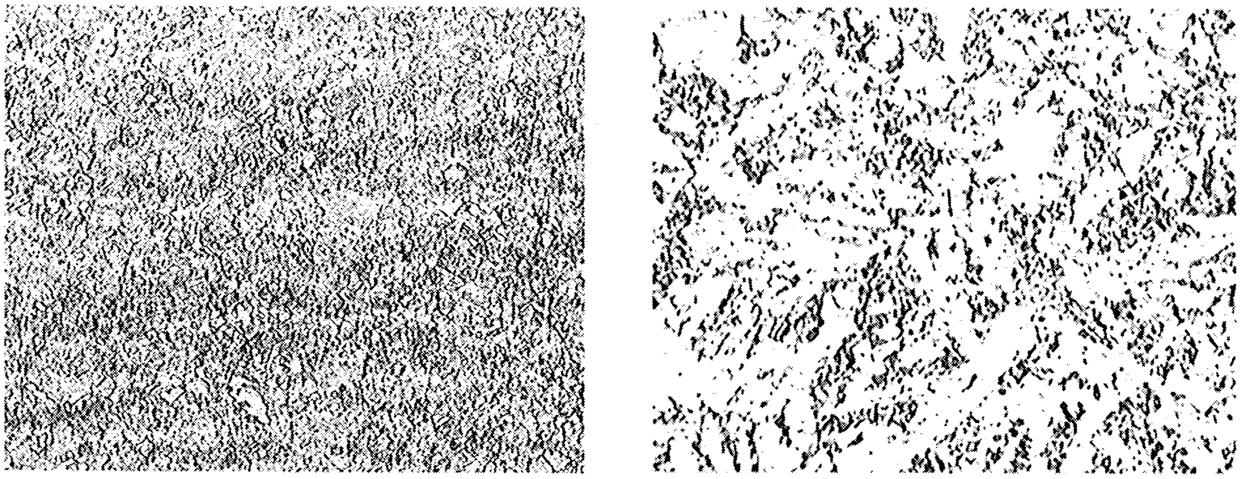


(b) Normalized from 1750°F + creep-rupture tested 1310 hrs at 1000°F and 20,000 psi - 198 BHN

Figure 5. - SAE 4340 Steel. Simulated 3-inch Diameter Bar Stock (a) As Normalized from 1750°F and (b) After Creep-Rupture Testing at 1000°F.

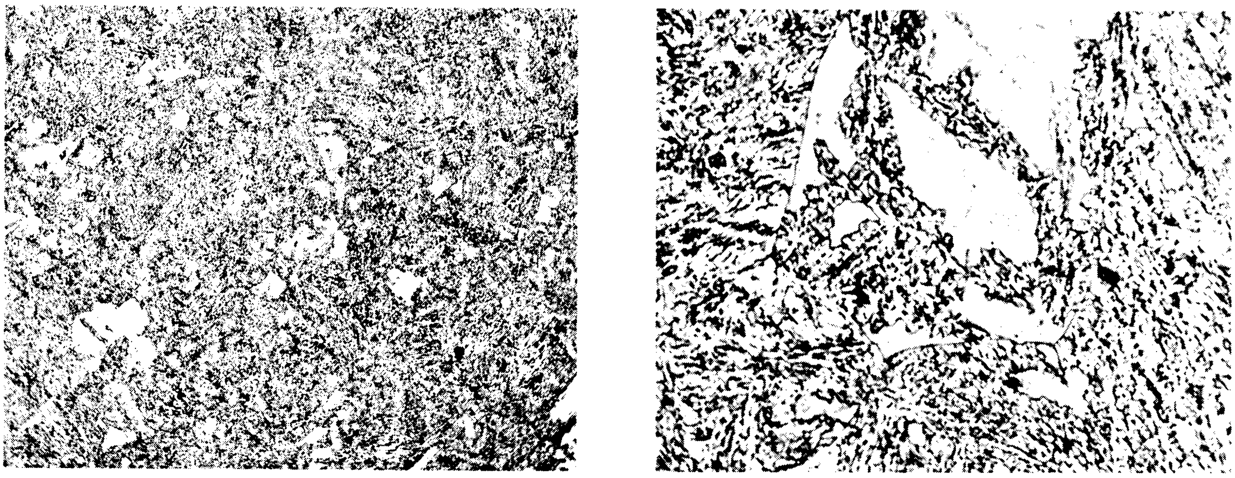


(a) Simulated 6-inch Diameter Bar Stock Normalized from 1750°F - 315 BHN

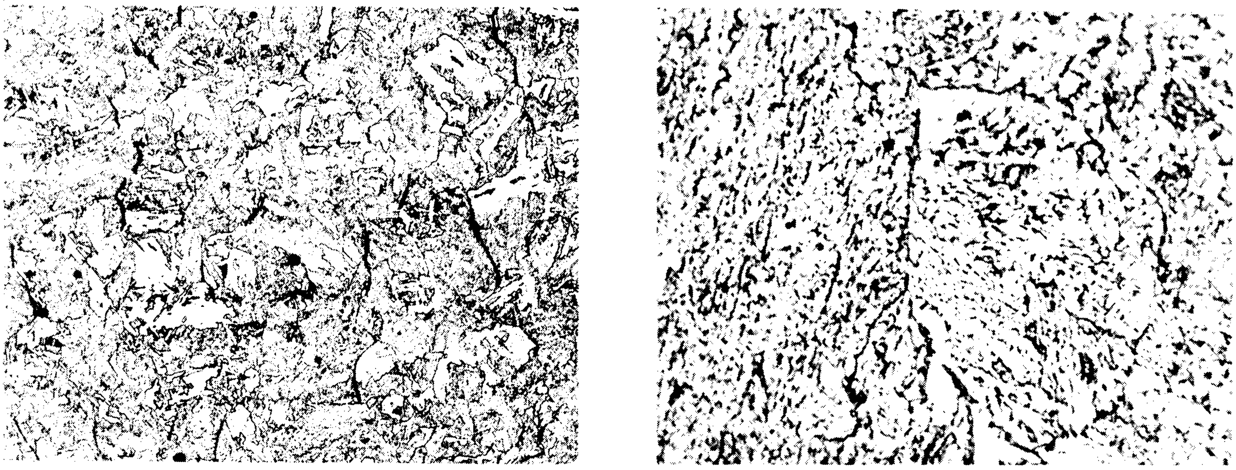


(b) Normalized from 1750°F + creep-rupture tested 1488 hrs at 1000°F and 20,000 psi - 203 BHN

Figure 6. - SAE 4340 Steel. Simulated 6-inch Diameter Bar Stock (a) As Normalized from 1750°F and (b) after Creep-Rupture Testing at 1000°F.

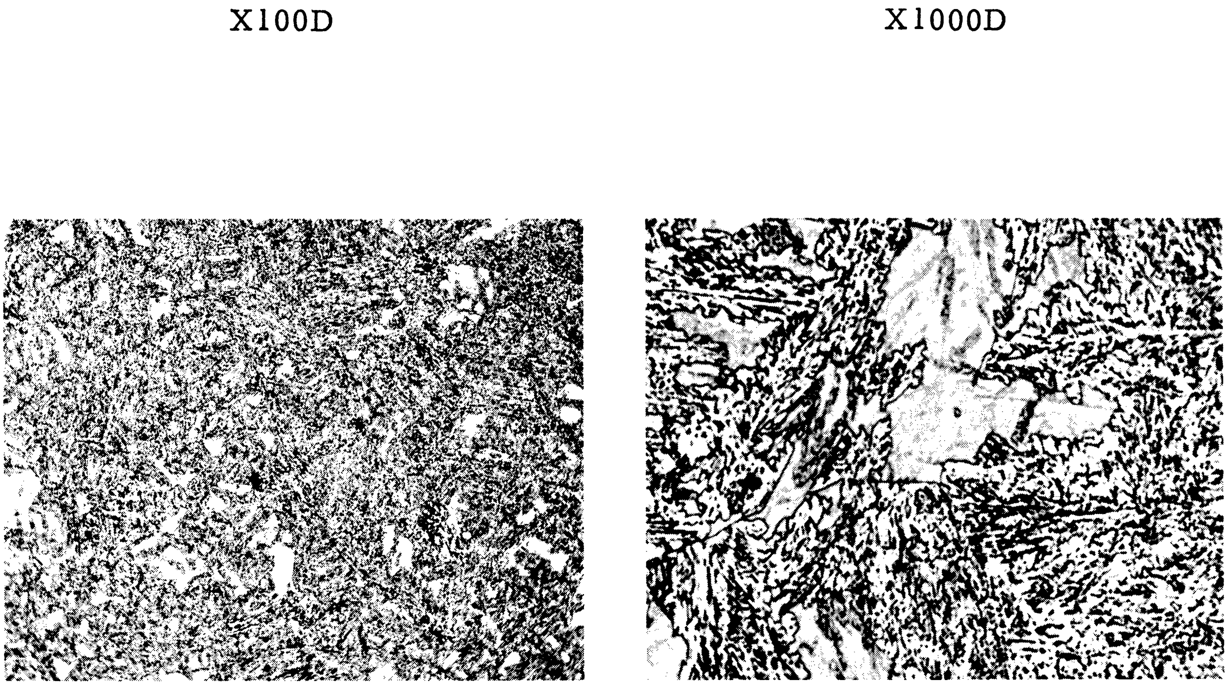


(a) Normalized at 1950°F As 1-inch Diameter Bar Stock - 321 BHN

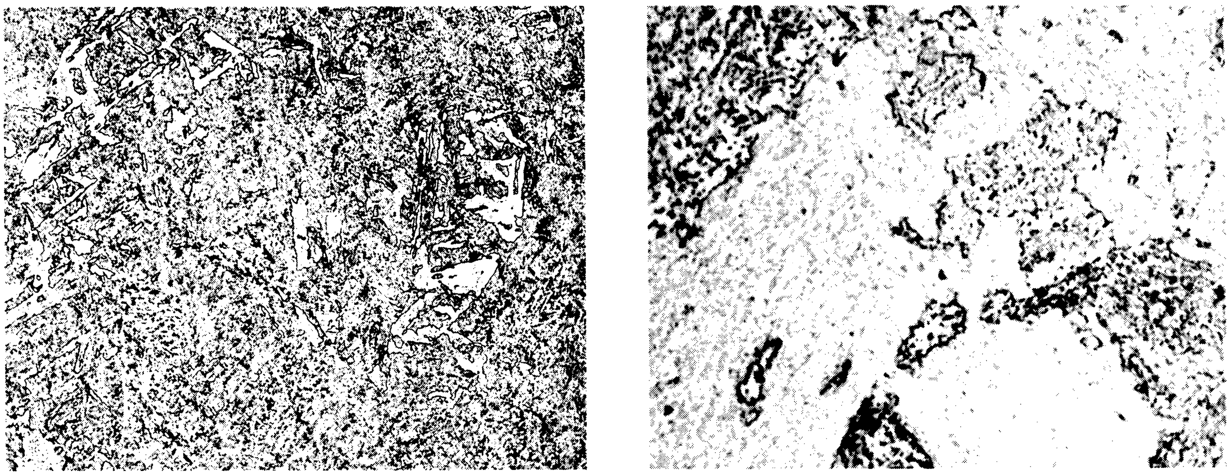


(b) Normalized at 1950°F + Creep-rupture tested 1425 hrs at 1000°F and 20,000 psi - 218 BHN

Figure 7. - SAE 4340 Steel. One-inch Diameter Bar Stock (a) As Normalized at 1950°F and (b) after Creep-Rupture Testing at 1000°F.

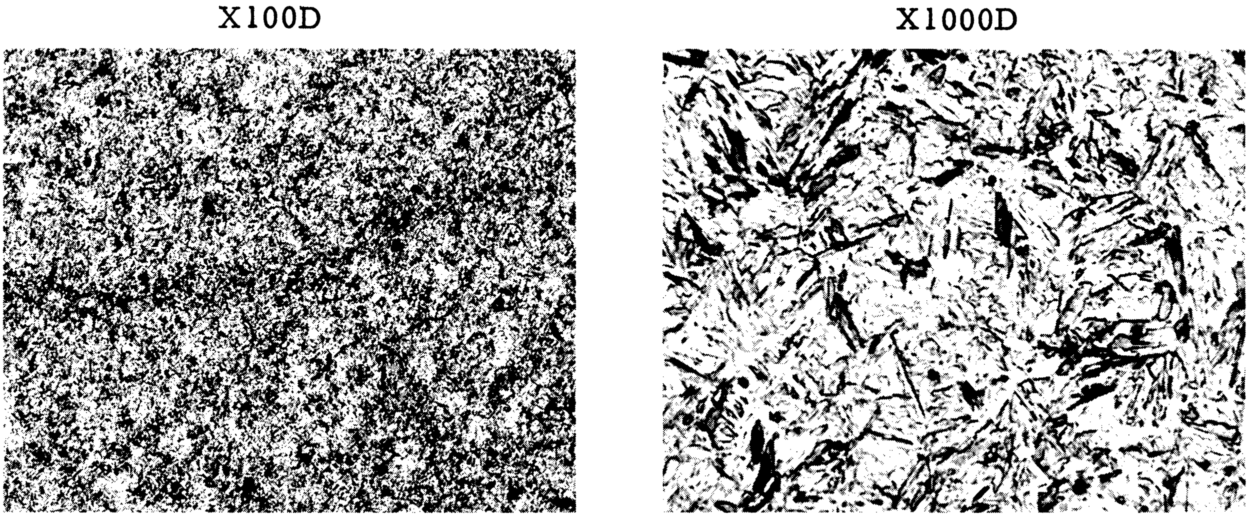


(a) Normalized at 2100°F As 1-inch Diameter Bar Stock - 328 BHN

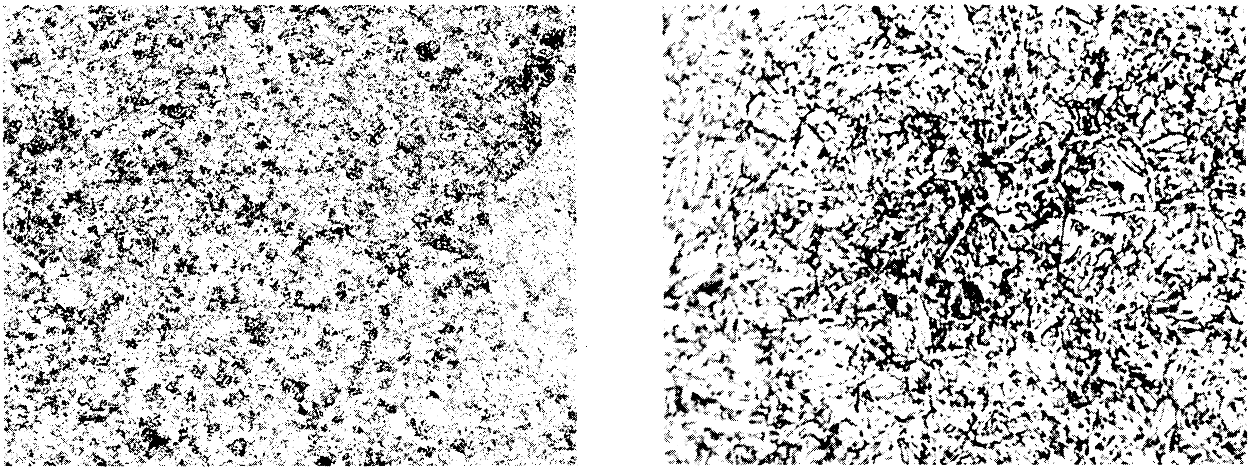


(b) Normalized at 2100°F + creep tested 2257 hrs at 1000°F and 20,000 psi - 222 BHN

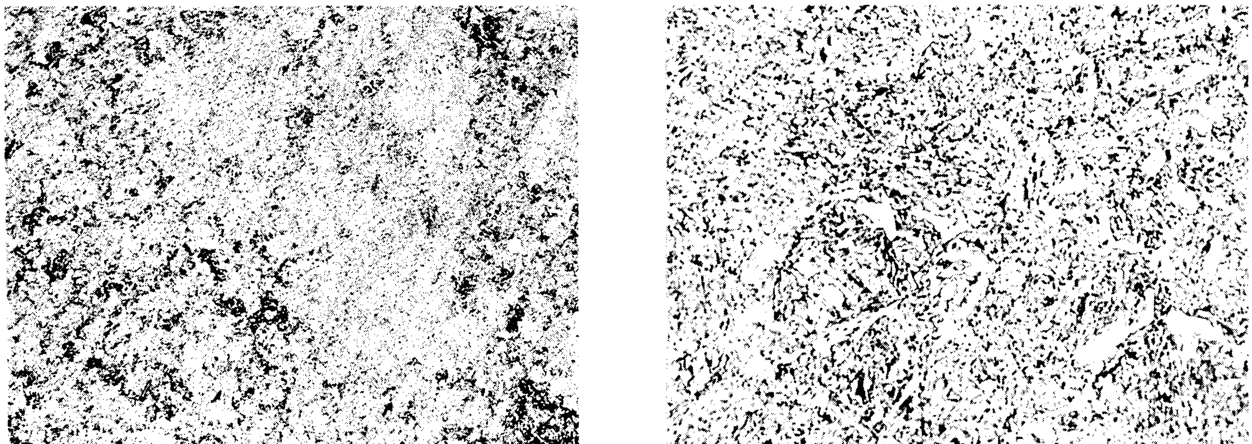
Figure 8. - SAE 4340 Steel. One-inch Diameter Bar Stock (a) As Normalized at 2100°F and (b) after Creep Testing at 1000°F.



(a) Oil-quenched from 1750°F as 1-inch diameter bar stock - 585 BHN

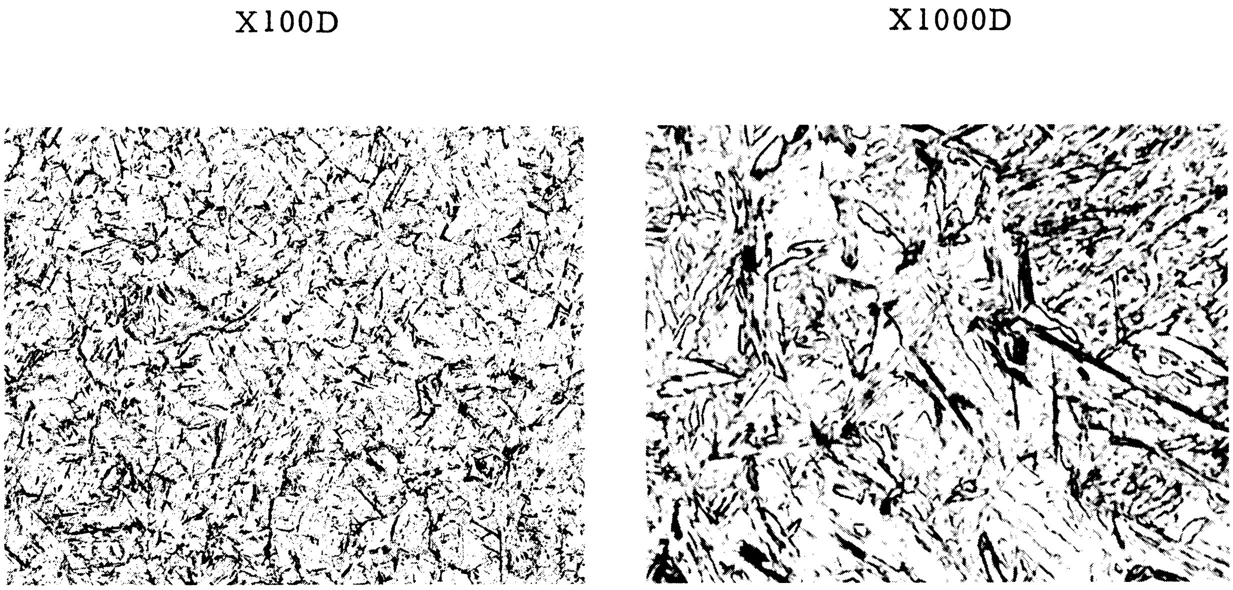


(b) Oil-quenched from 1750°F + tempered 10 hrs at 1100°F - 310 BHN

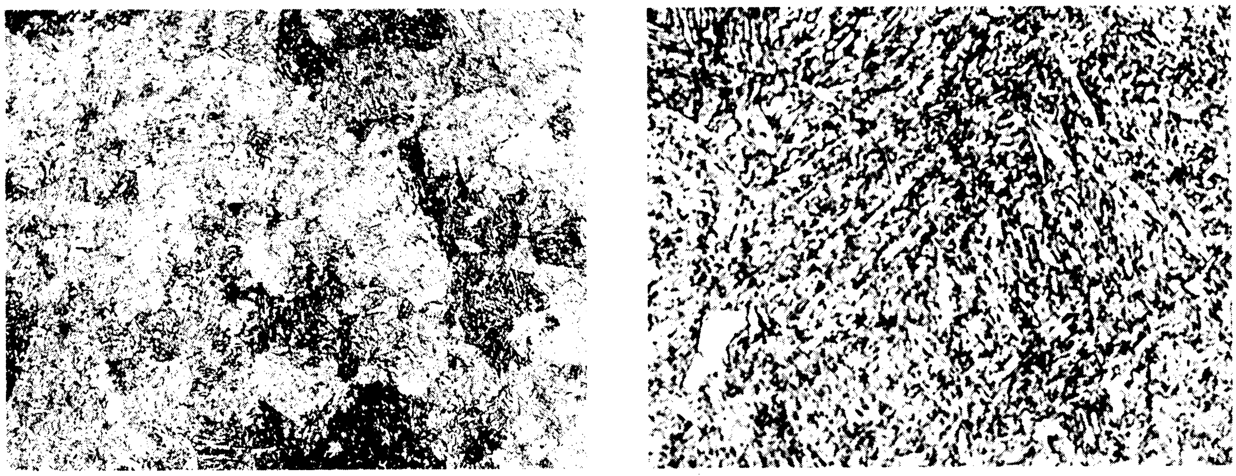


(c) Oil-quenched from 1750°F + tempered 10 hrs at 1100°F + creep tested 1025 hrs at 1000°F and 13,000 psi - 270 BHN

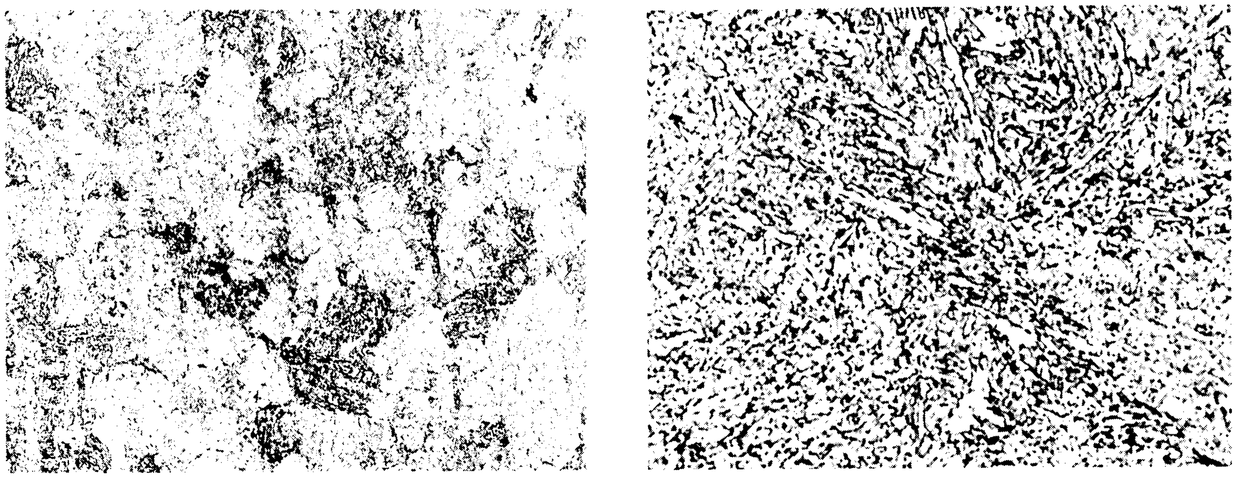
Figure 9. - SAE 4340 steel. One-inch Diameter Bar Stock (a) As Oil-Quenched from 1750°F (b) As Tempered to 300 BHN, and (c) After Creep-Testing at 1000°F.



(a) Oil quenched from 1950°F as 1-inch Diameter Bar Stock - 560 BHN

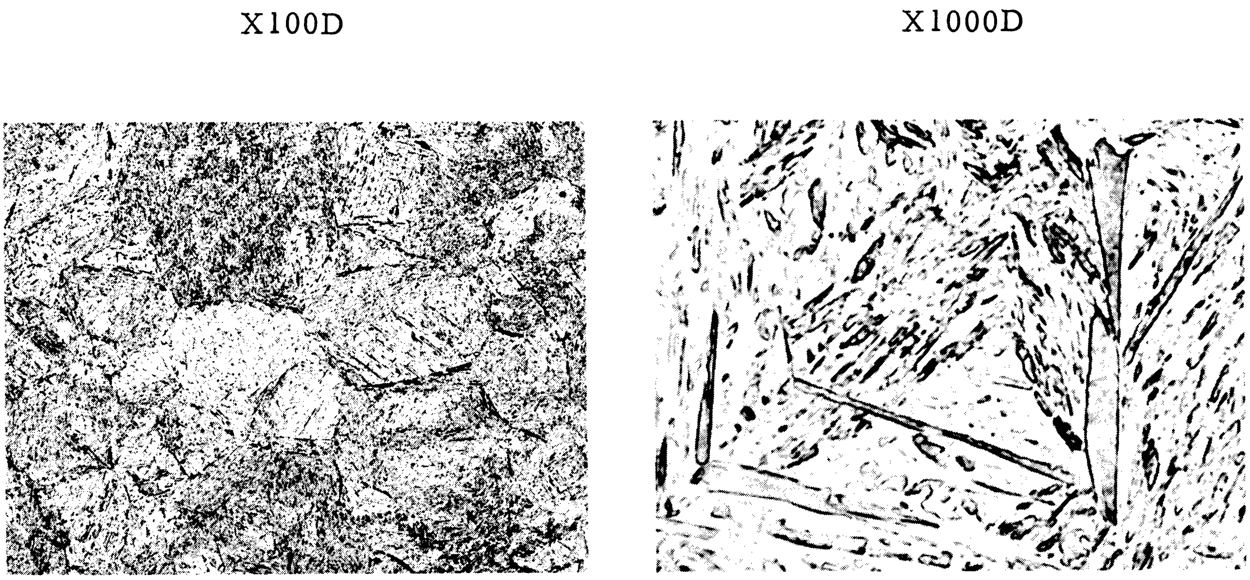


(b) Oil quenched from 1950°F + tempered 10 hrs at 1100°F - 302 BHN

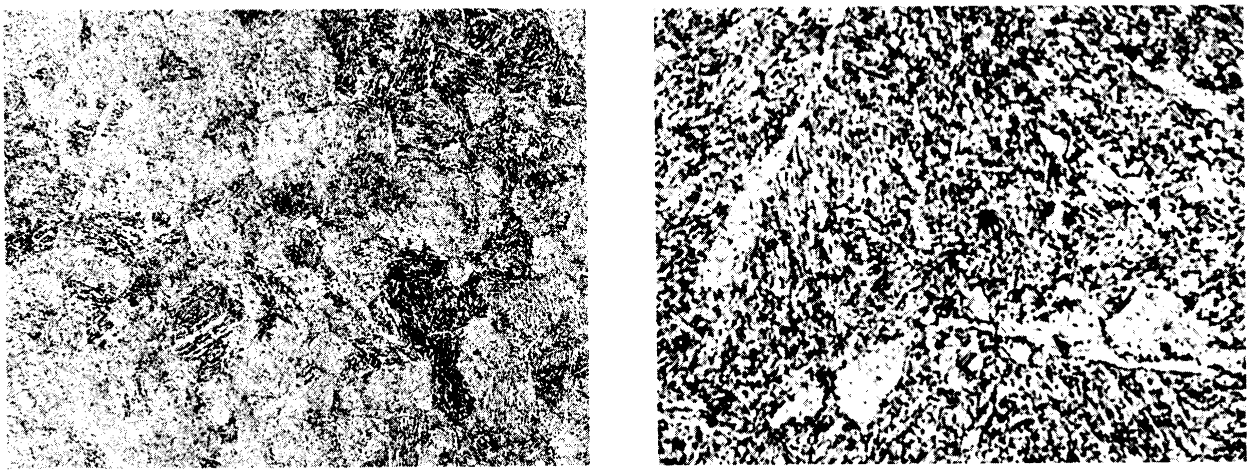


(c) Oil quenched from 1950°F + tempered10 hrs at 1100°F + creep rupture tested 410.1 hrs at 1000°F and 21,000 psi - 255 BHN

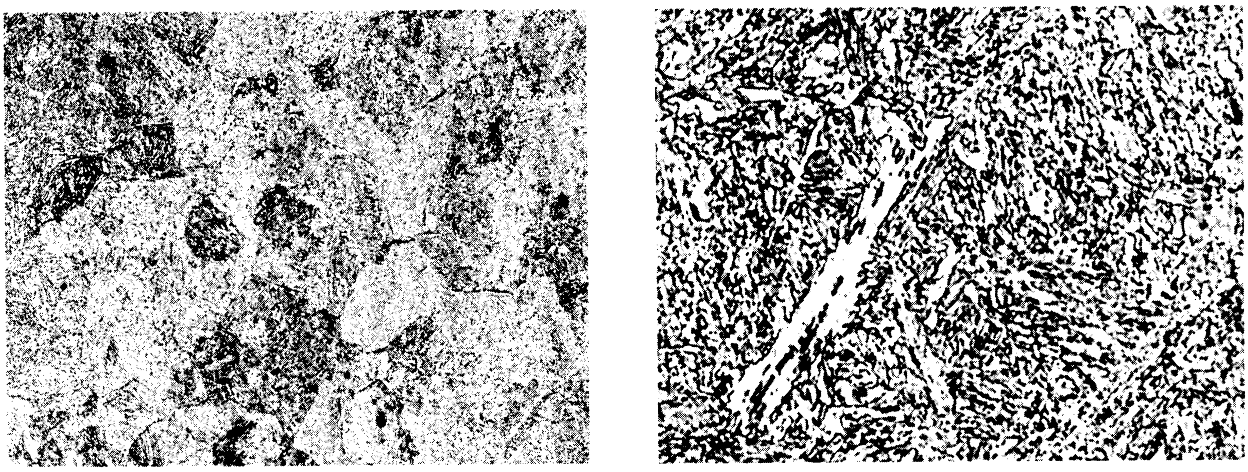
Figure 10. - SAE 4340 Steel. One-inch Diameter Bar Stock (a) As Oil Quenched from 1950°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1000°F.



(a) Oil quenched from 2100°F As 1-inch Diameter Bar Stock - 534 BHN

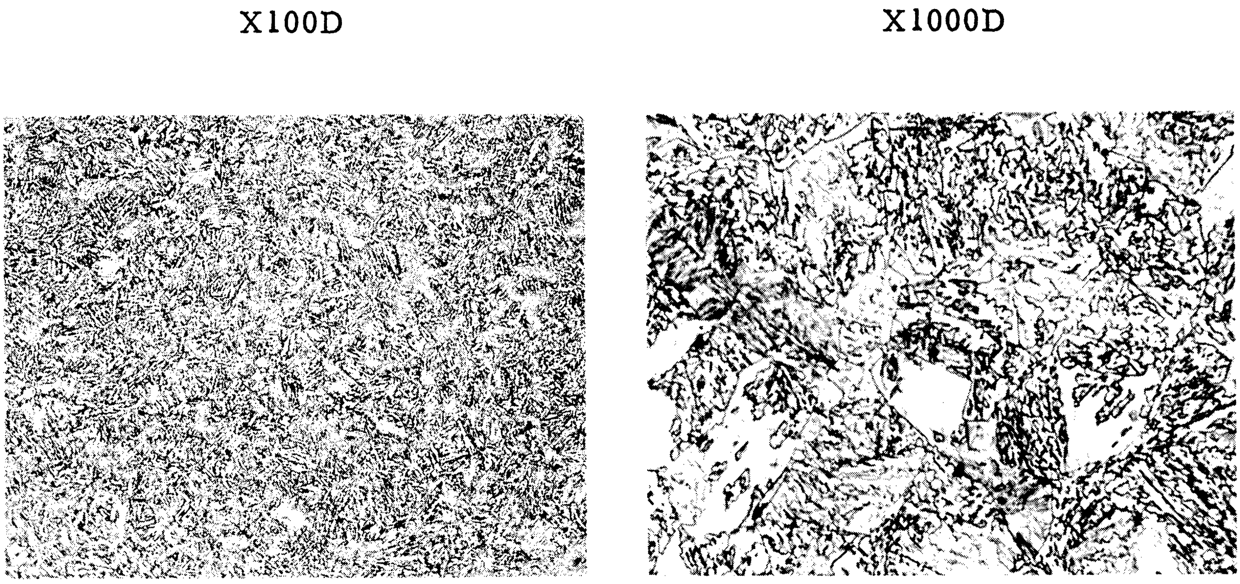


(b) Oil quenched from 2100°F + tempered 10 hrs at 1100°F - 300 BHN

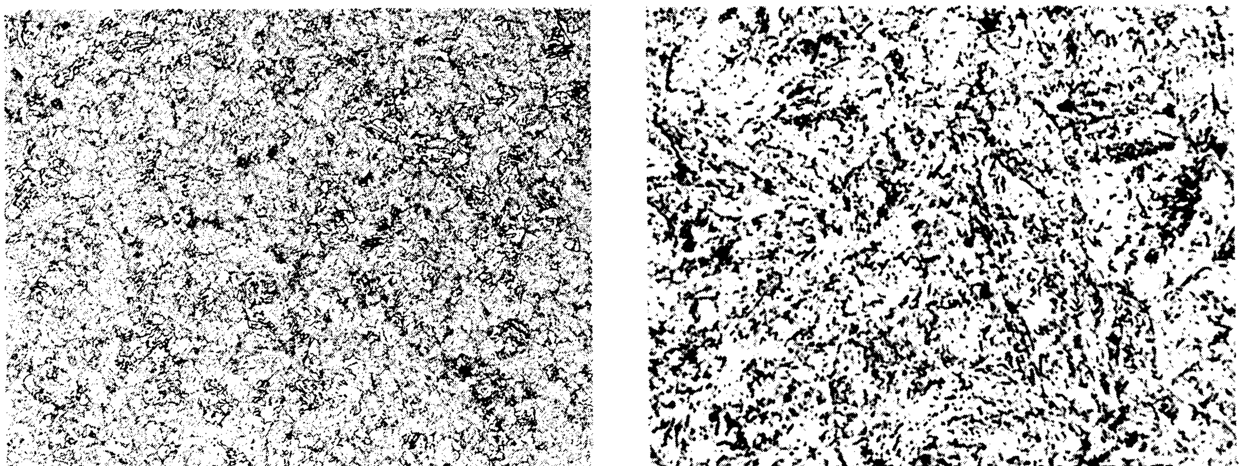


(c) Oil quenched from 2100°F + tempered 10 hrs at 1100°F + creep-rupture Tested 548 hrs at 1000°F and 20,000 psi - 252 BHN

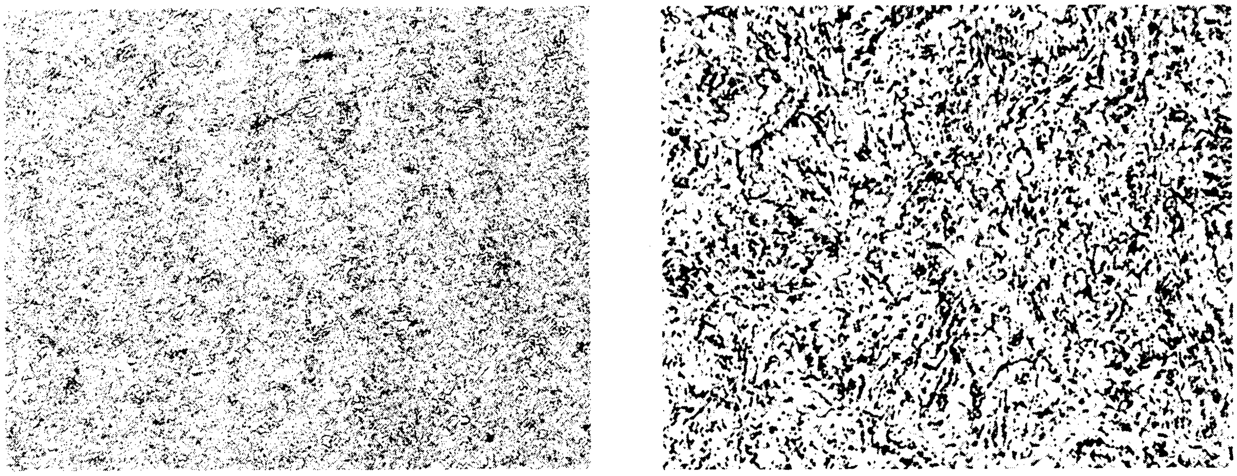
Figure 11. - SAE 4340 Steel. One-inch Diameter Bar Stock (a) As Oil Quenched from 2100°F, (b) As Tempered to 300 BHN, and , (c) after Creep-Rupture Testing at 1000°F.



(a) Normalized from 1750°F as 1-inch diameter bar stock - 352 BHN

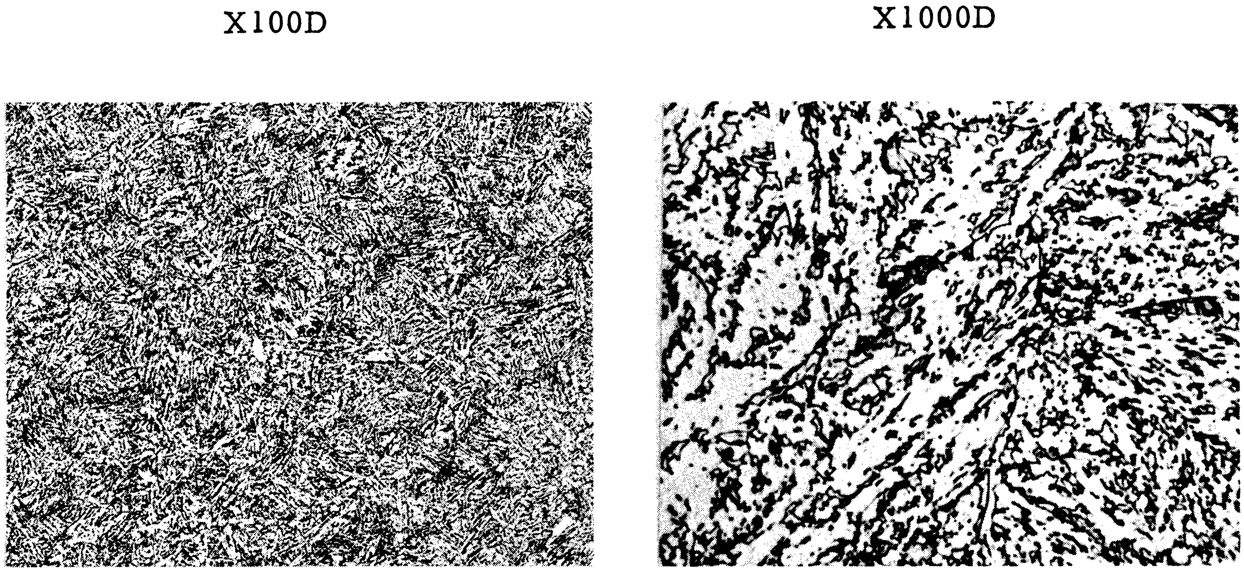


(b) Normalized from 1750°F + tempered 10 hrs at 1200°F - 302 BHN

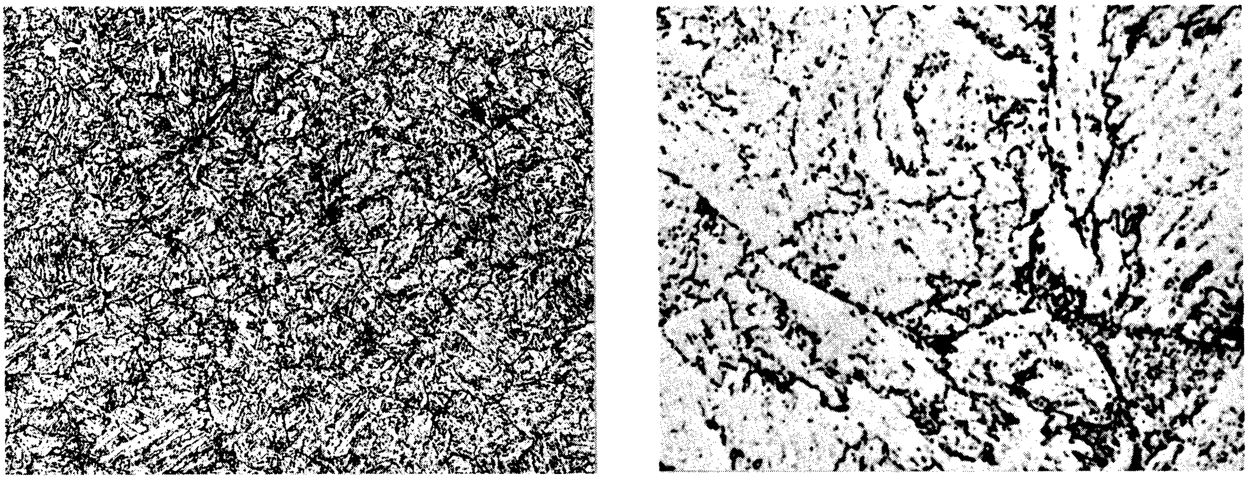


(c) Normalized from 1750°F + tempered 10 hrs at 1200°F + creep-rupture Tested 773 hrs at 1100°F and 19,000 psi - 268 BHN

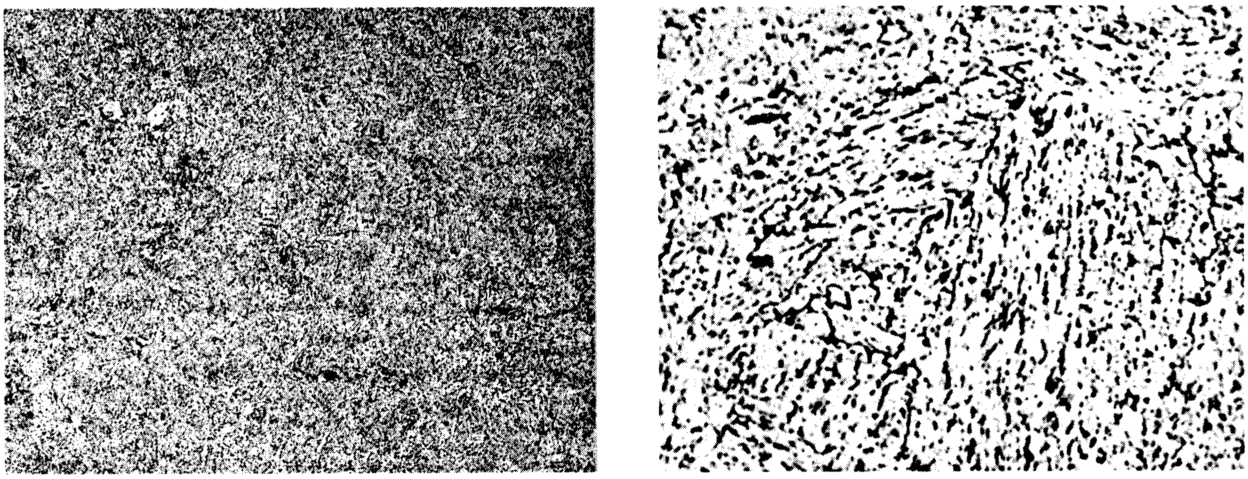
Figure 12. - "17-22-A"S Steel. One-inch Diameter Bar Stock (a) As Normalized (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.



(a) Simulated 3-inch Diameter Bar Stock Normalized from 1750°F - 325 BHN

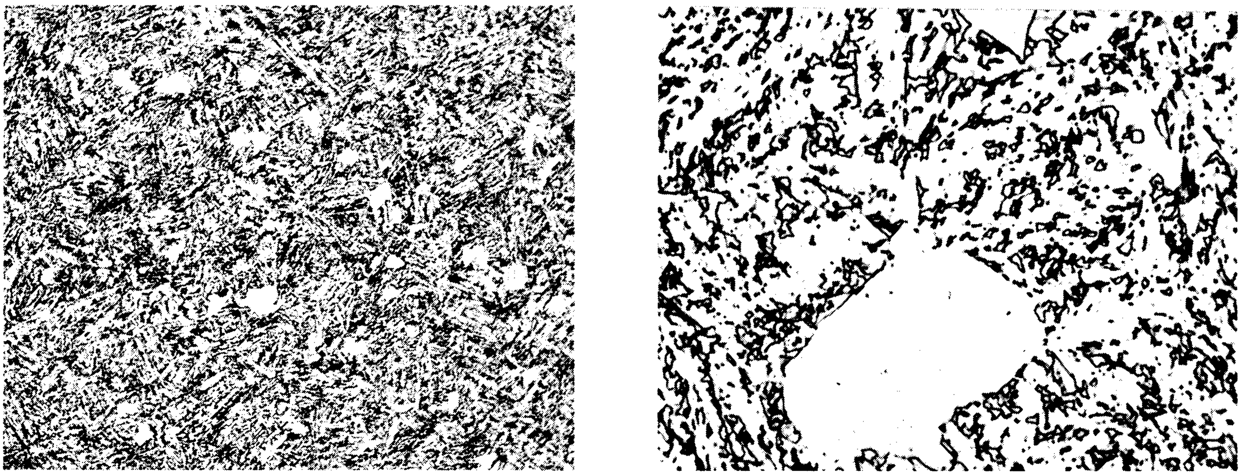


(b) Normalized from 1750°F + tempered 6 hrs at 1200°F - 295 BHN

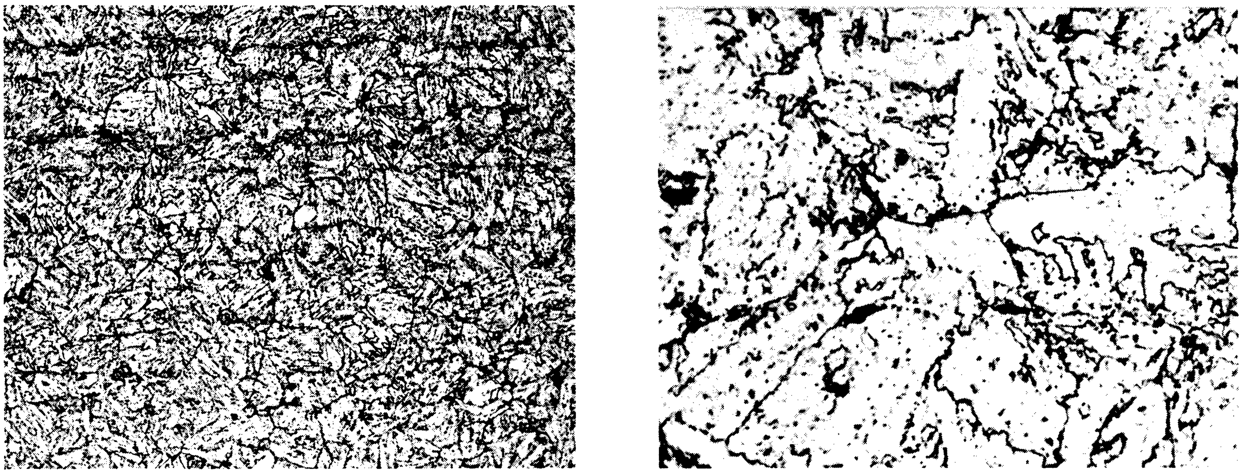


(c) Normalized from 1750°F + tempered 6 hrs at 1200°F + creep-rupture Tested 1220 hrs at 1100°F and 19,000 psi - 257 BHN.

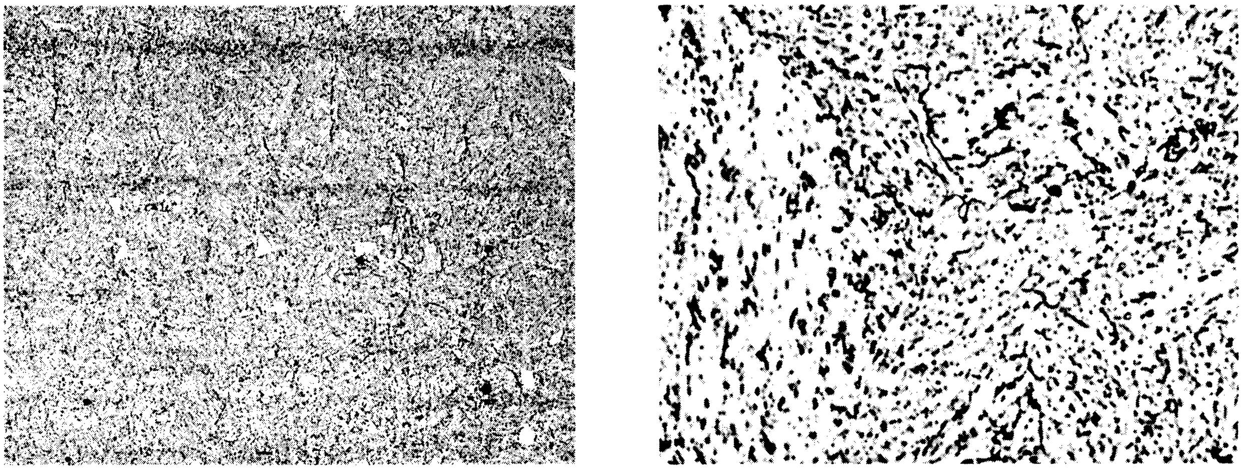
Figure 13. - "17-22-A"S Steel. Simulated 3-inch Diameter Bar Stock (a) As Normalized from 1750°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.



(a) Simulated 6-inch Diameter Bar Stock Normalized from 1750°F -325 BHN



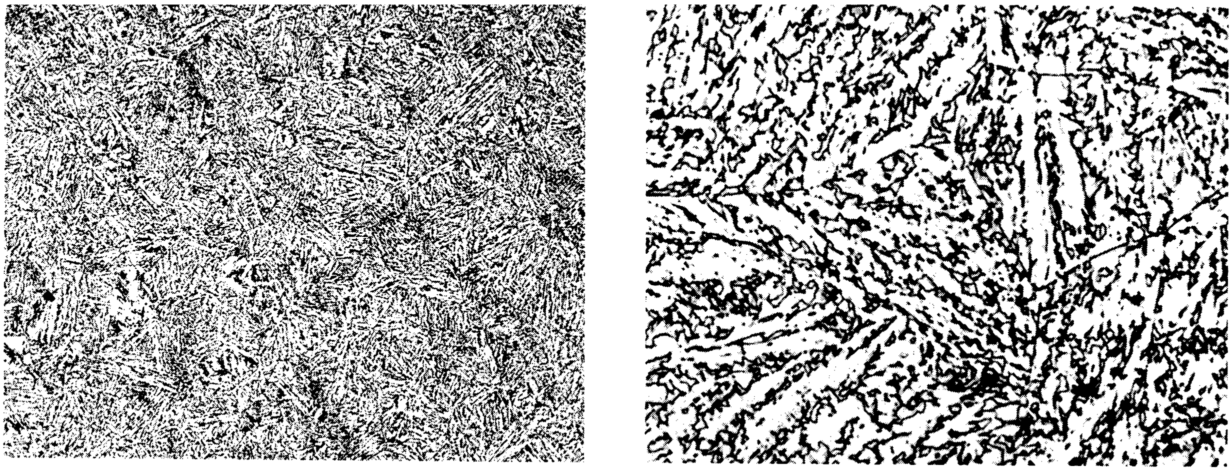
(b) Normalized from 1750°F + tempered 6 hrs at 1200°F - 295 BHN



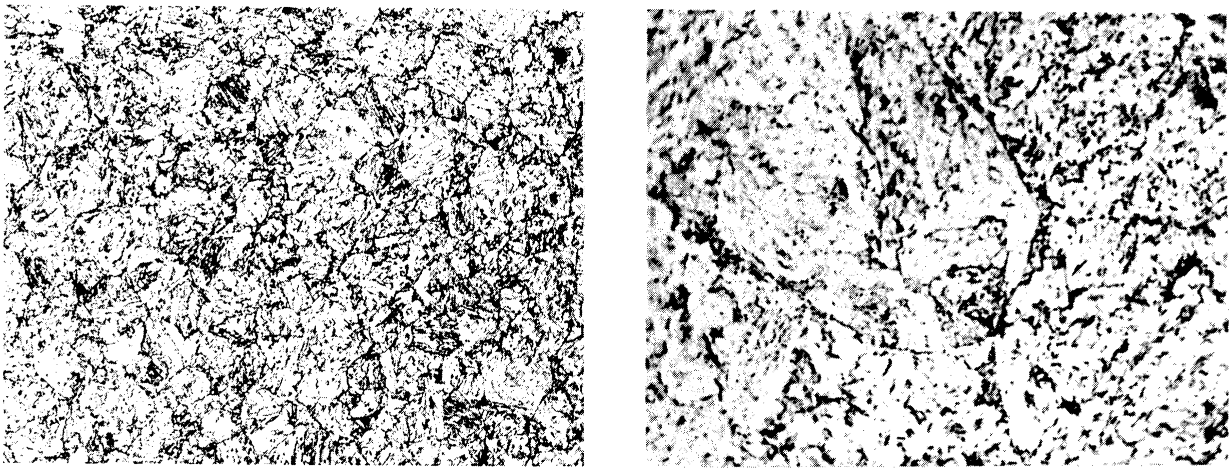
(c) Normalized from 1750°F + tempered 6 hrs at 1200°F + creep-rupture tested 1309 hrs at 1100°F and 19,000 psi - 252 BHN

Figure 14. - "17-22-A"S Steel. Simulated 6-inch Diameter Bar Stock (a) As Normalized from 1750°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

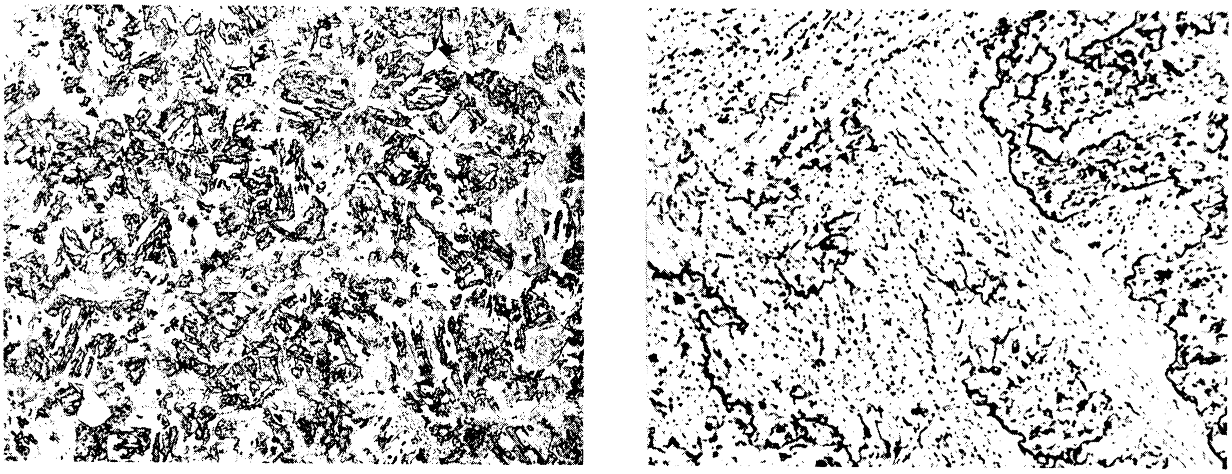
X100D X1000D



(a) Normalized at 1950°F as 1-inch Diameter Bar Stock - 334 BHN

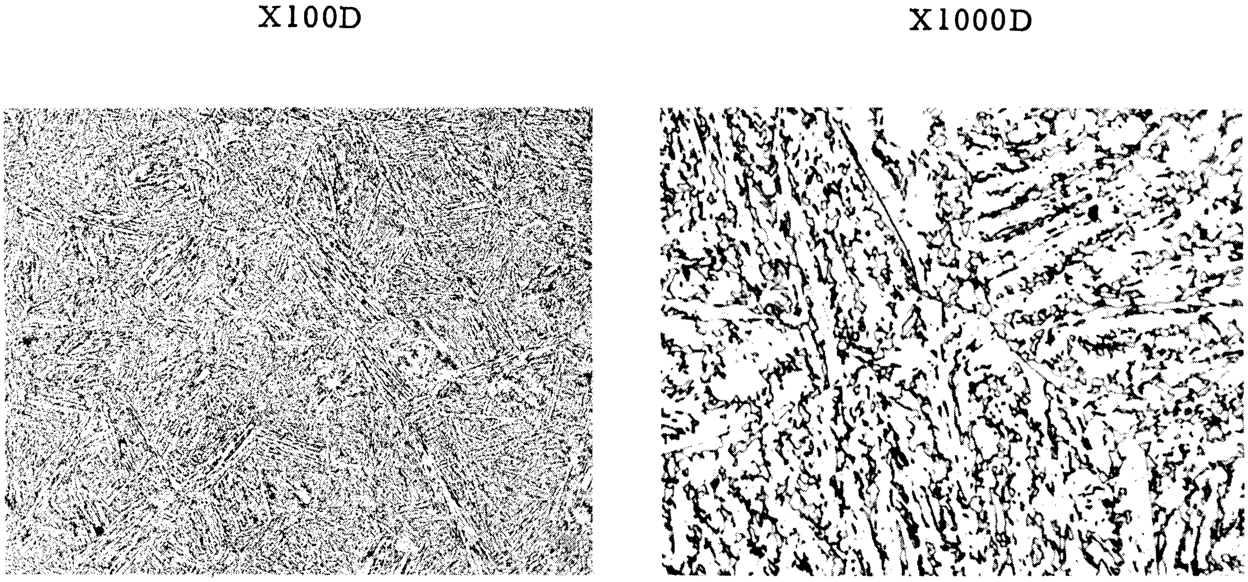


(b) Normalized at 1950°F + tempered 6 hrs at 1200°F - 302 BHN

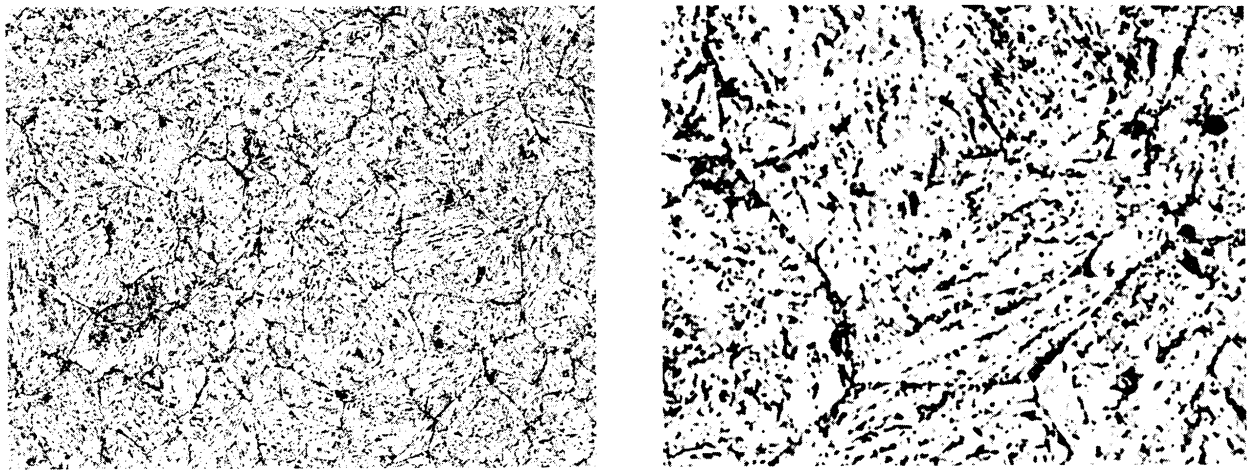


(c) Normalized at 1950°F + tempered 6 hrs at 1200°F + creep-rupture tested 1205 hrs at 1100°F and 19,000 psi - 254 BHN

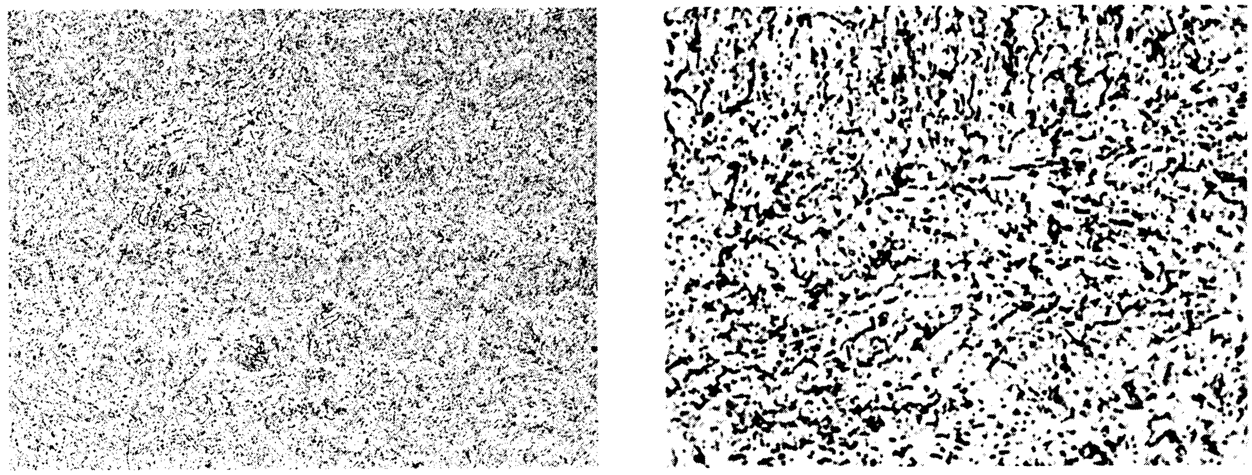
Figure 15. - "17-22-A"S Steel. One-inch Diameter Bar Stock (a) As Normalized at 1950°F (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.



(a) Normalized at 2100°F as 1-inch Diameter Bar Stock - 312 BHN

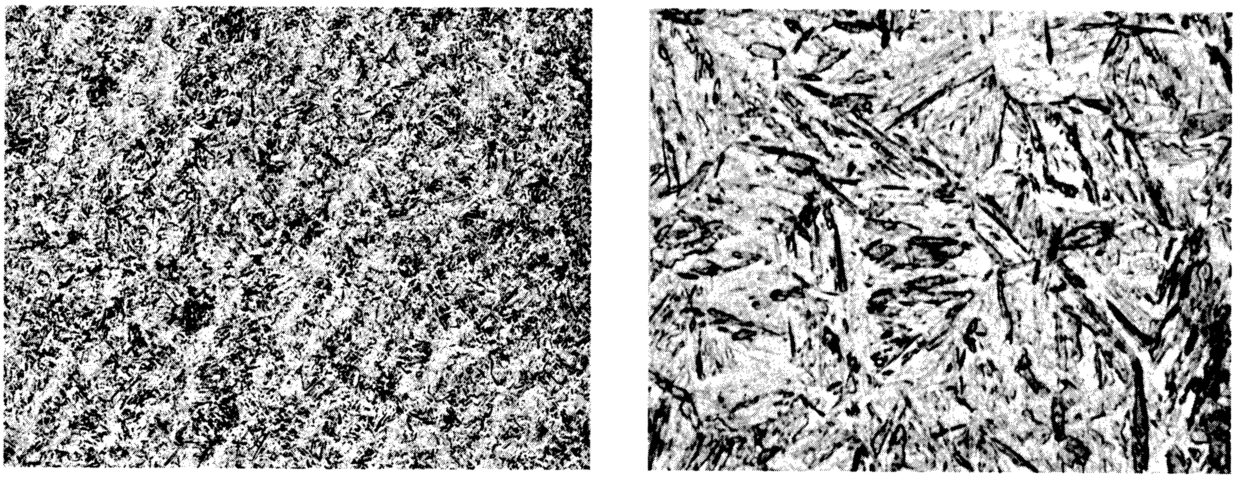


(b) Normalized at 2100°F + tempered 6 hrs at 1200°F - 308 BHN

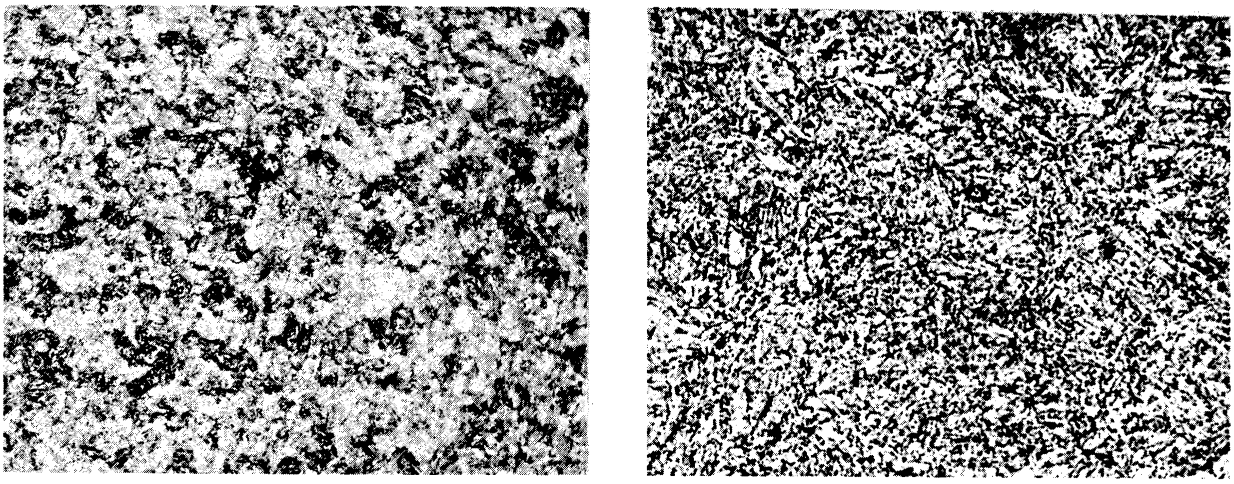


(c) Normalized at 2100°F + tempered 6 hrs at 1200°F + creep rupture tested 1653 hrs at 1100°F and 19,000 psi - 237 BHN

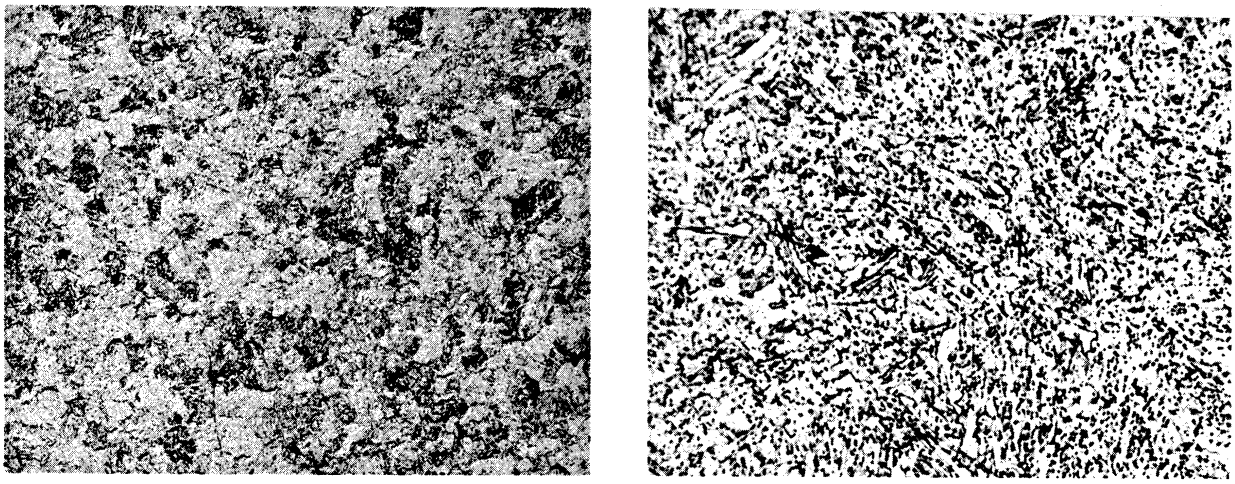
Figure 16. - "17-22-A"S Steel. One-inch Diameter Bar Stock (a) As Normalized at 2100°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.



(a) Oil quenched from 1750°F As 1-inch Diameter Bar Stock - 524 BHN

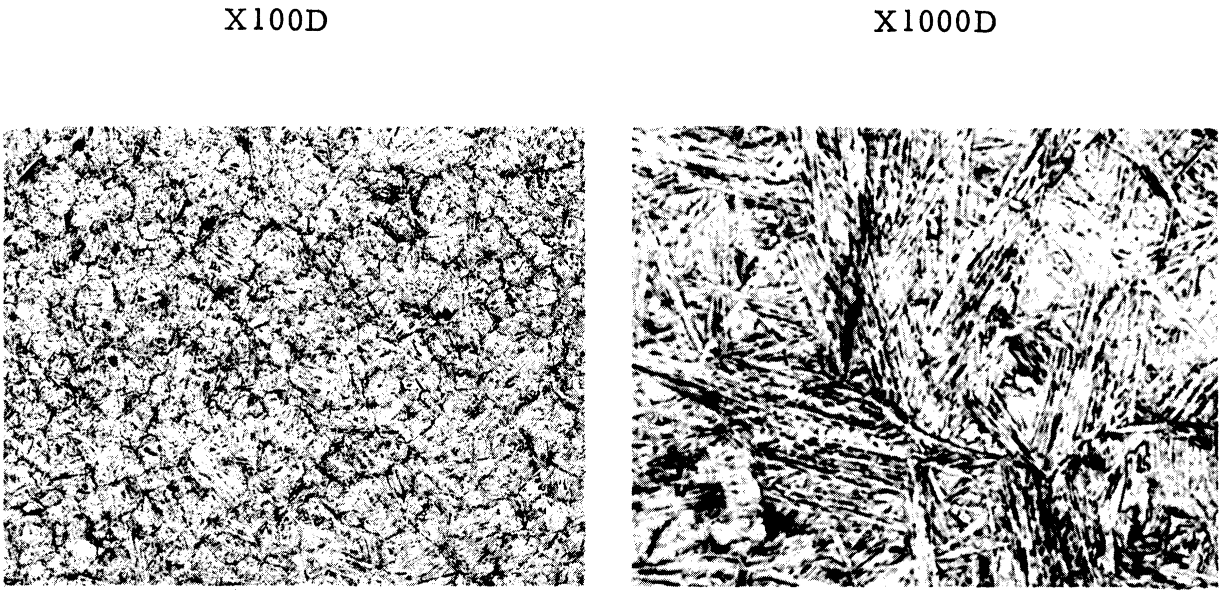


(b) Oil quenched from 1750°F + tempered 1 hr at 1300°F - 305 BHN

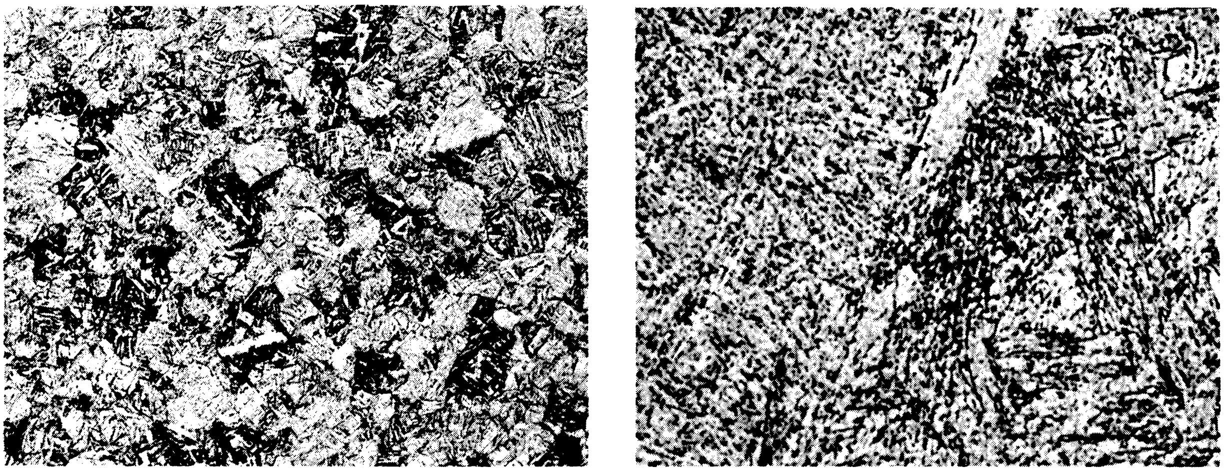


(c) Oil quenched from 1750°F + tempered 1 hr at 1300°F + creep rupture Tested 666 hrs at 1100°F and 20,000 psi - 265 BHN.

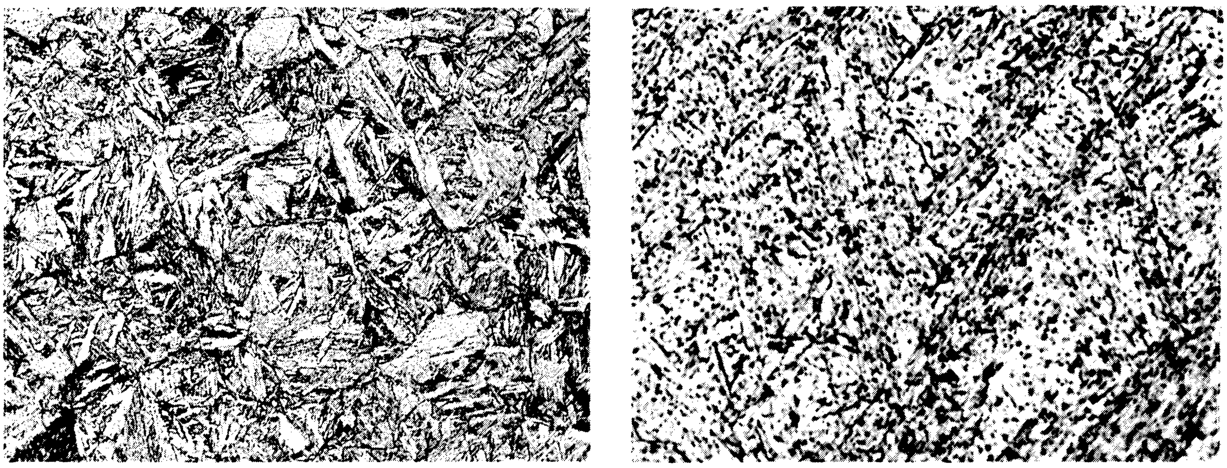
Figure 17. - "17-22-A"S Steel. One-inch Diameter Bar Stock (a) As Oil Quenched from 1750°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.



(a) Oil quenched from 1950°F as 1-inch Diameter Bar Stock - 470 BHN

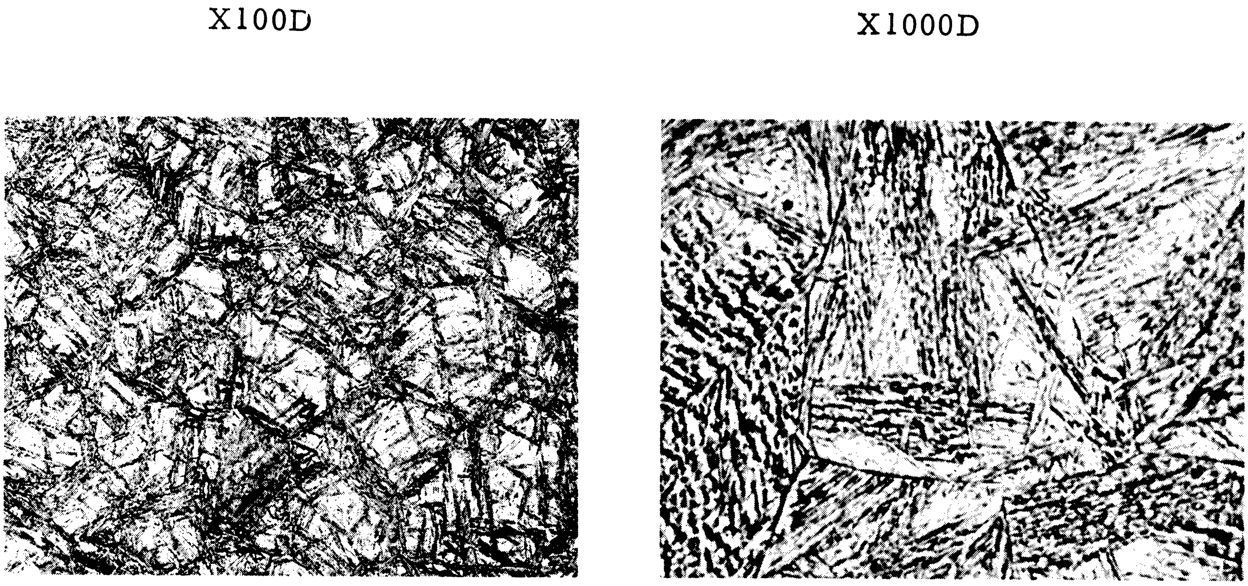


(b) Oil quenched from 1950°F + tempered 1 hr at 1300°F - 300 BHN

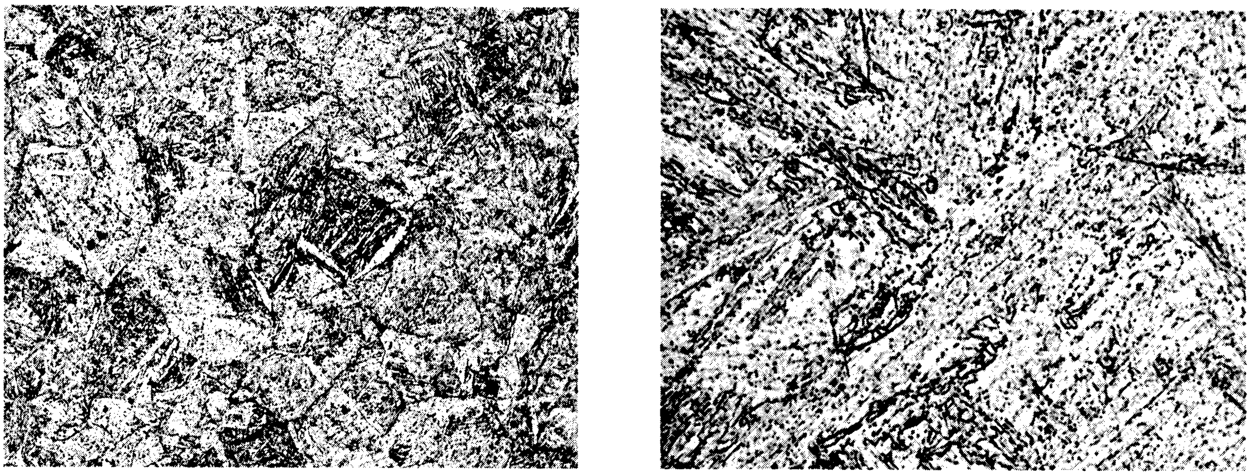


(c) Oil quenched from 1950°F + tempered 1 hr at 1300°F + creep-rupture tested 1081 hrs at 1100°F and 19,000 psi - 240 BHN

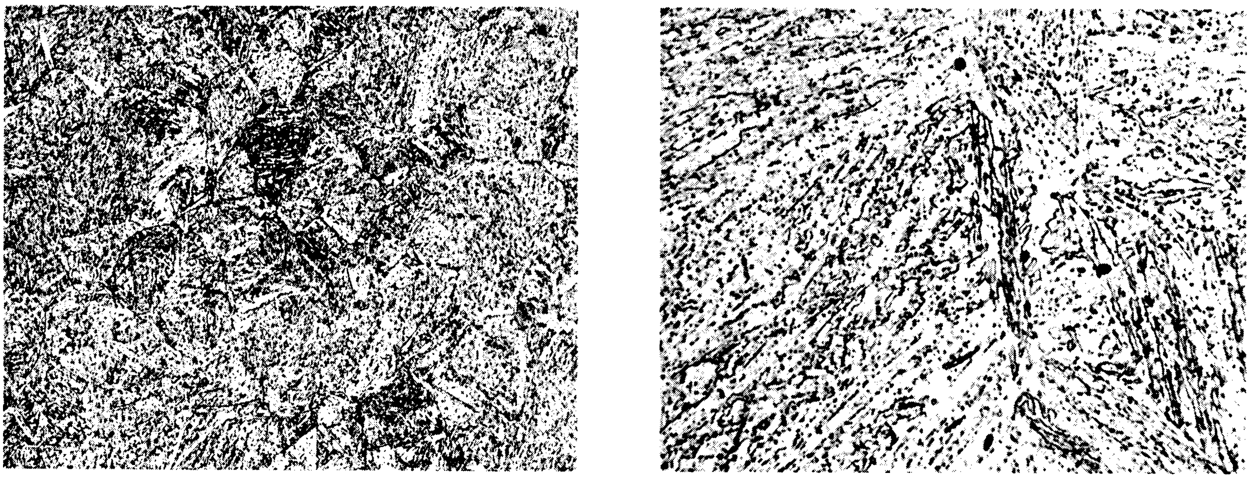
Figure 18. - "17-22-A"S Steel. One-inch Diameter Bar Stock (a) As Oil Quenched from 1950°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.



(a) Oil quenched from 2100°F as 1-inch Diameter Bar Stock - 412 BHN

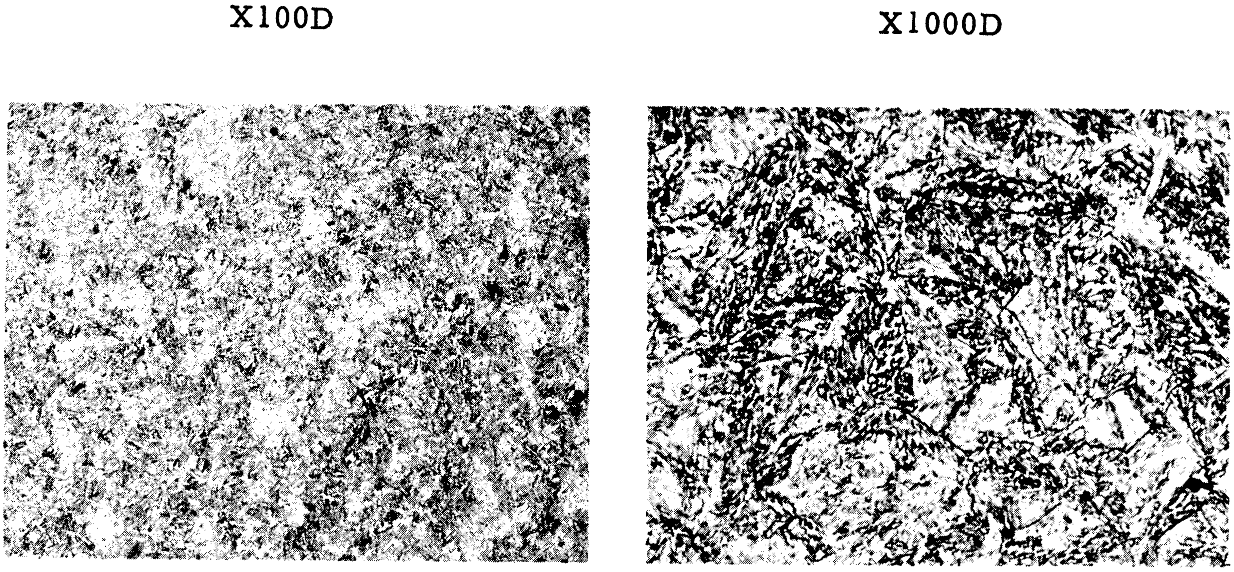


(b) Oil quenched from 2100°F + tempered 1 hr at 1300°F - 290 BHN

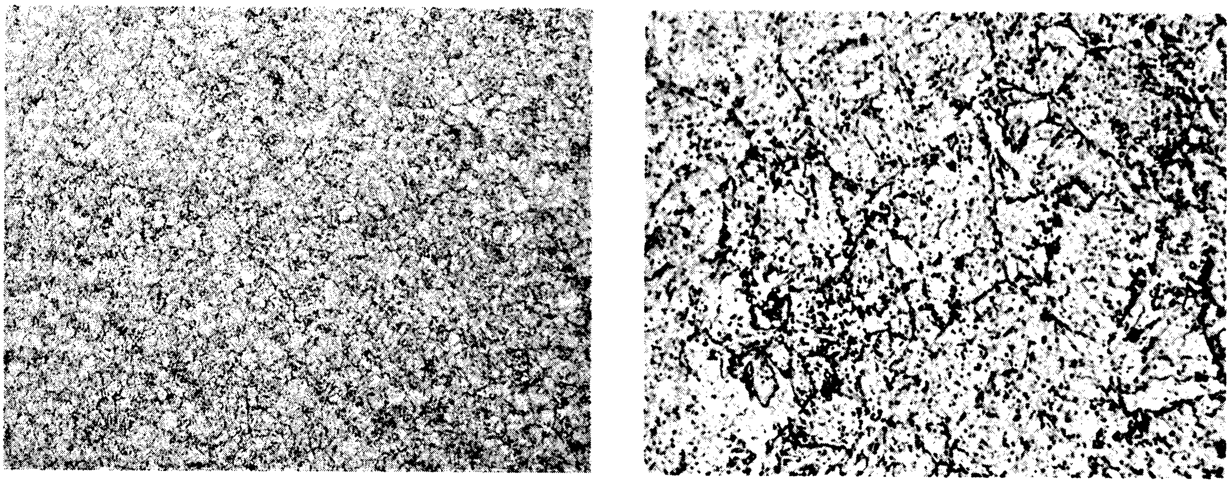


(c) Oil quenched from 2100°F + tempered 1 hr at 1300°F + creep-rupture tested 1001 hrs at 1100°F and 19,000 psi - 250 BHN

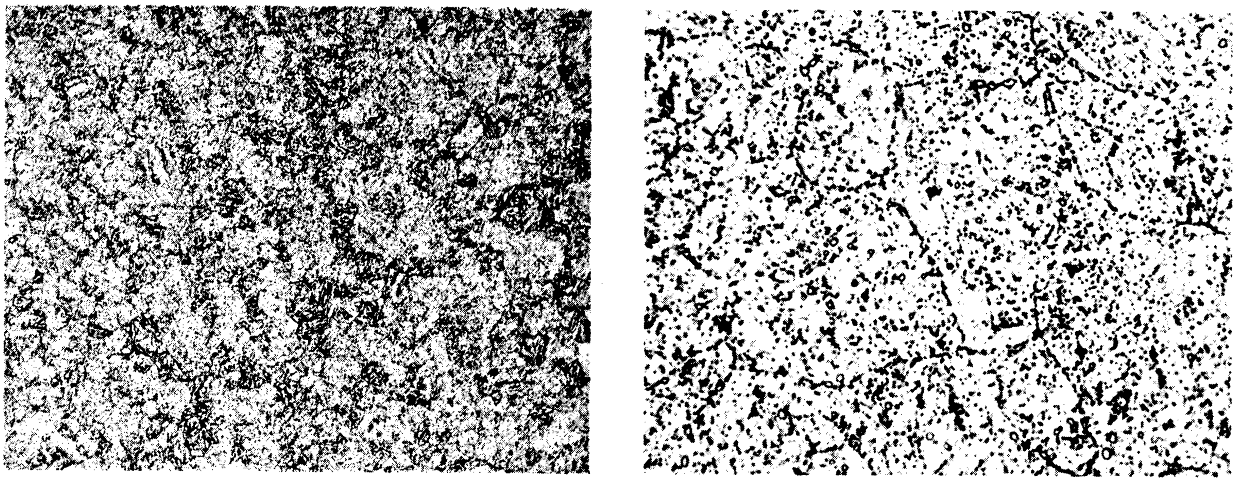
Figure 19. - "17-22-A"S Steel. One-inch Diameter Bar Stock (a) As Oil Quenched from 2100°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.



(a) Normalized from 1950°F as 3/4-inch Diameter Bar Stock - 435 BHN



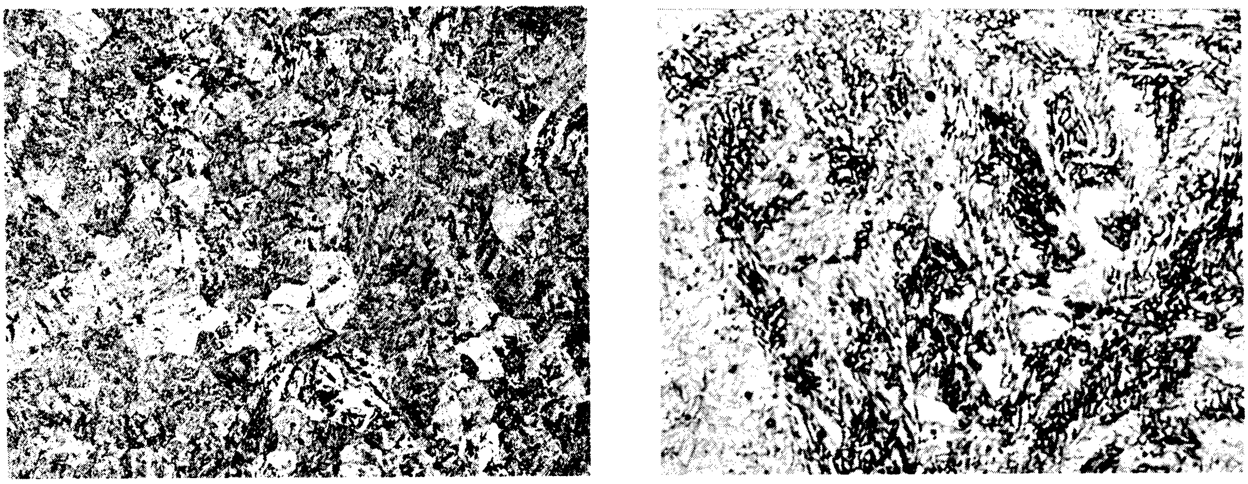
(b) Normalized from 1950°F + tempered 18 hrs at 1200°F - 316 BHN



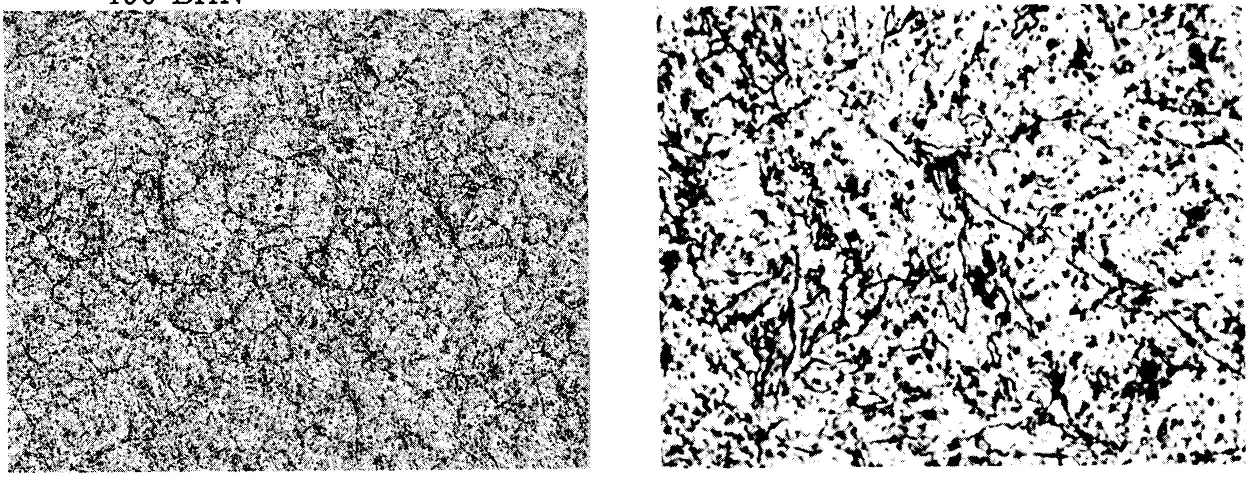
(c) Normalized from 1950°F + tempered 18 hrs at 1200°F + creep-rupture tested 272 hrs at 1100°F and 34,000 psi - 285 BHN

Figure 20. -H-40 Steel. Three-quarter-inch Diameter Bar Stock (a) As Normalized from 1950°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

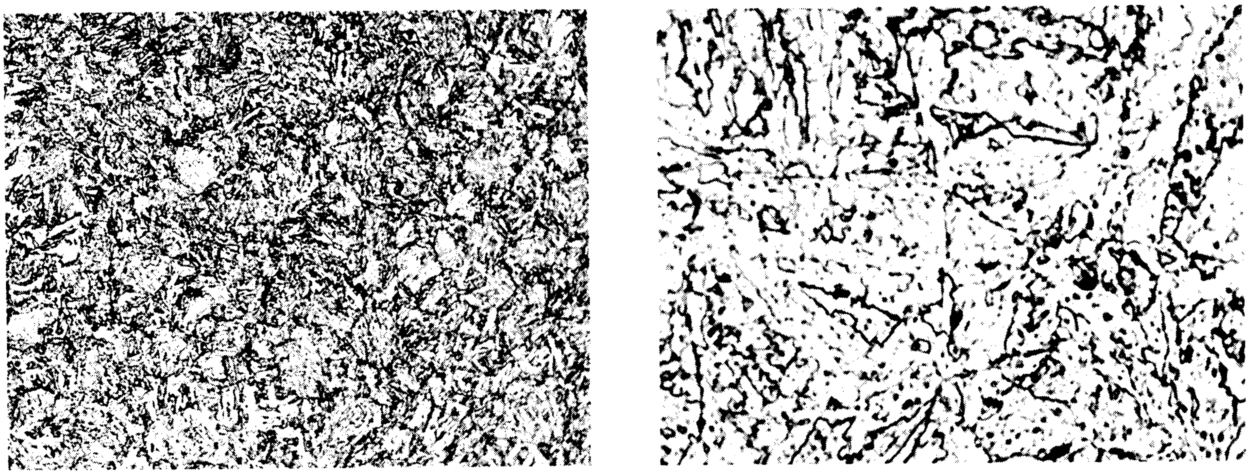
X100D X1000D



(a) Simulated 3-inch Diameter Bar Stock Normalized from 1950°F
400 BHN



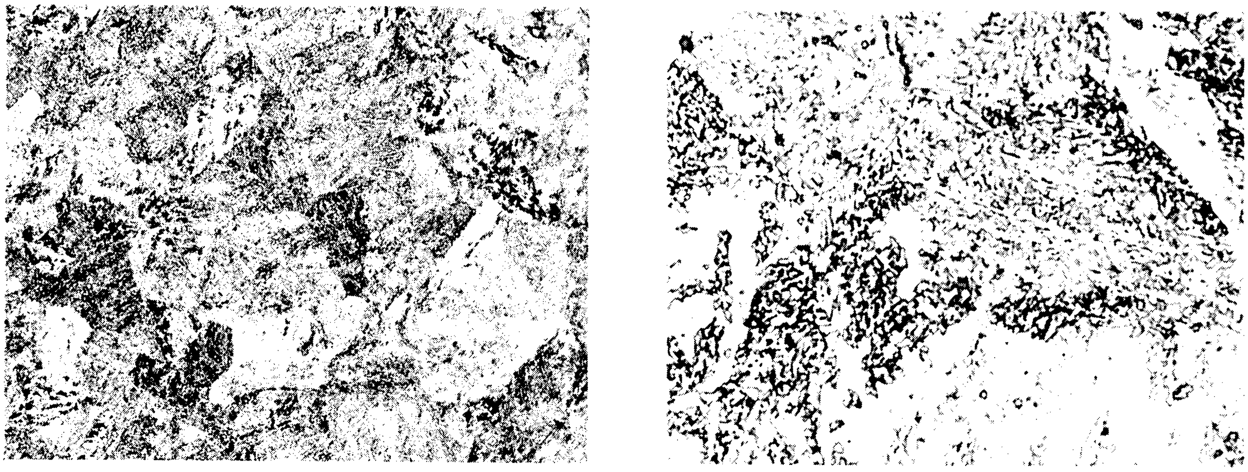
(b) Normalized from 1950°F + tempered 4 hrs at 1200°F - 298 BHN



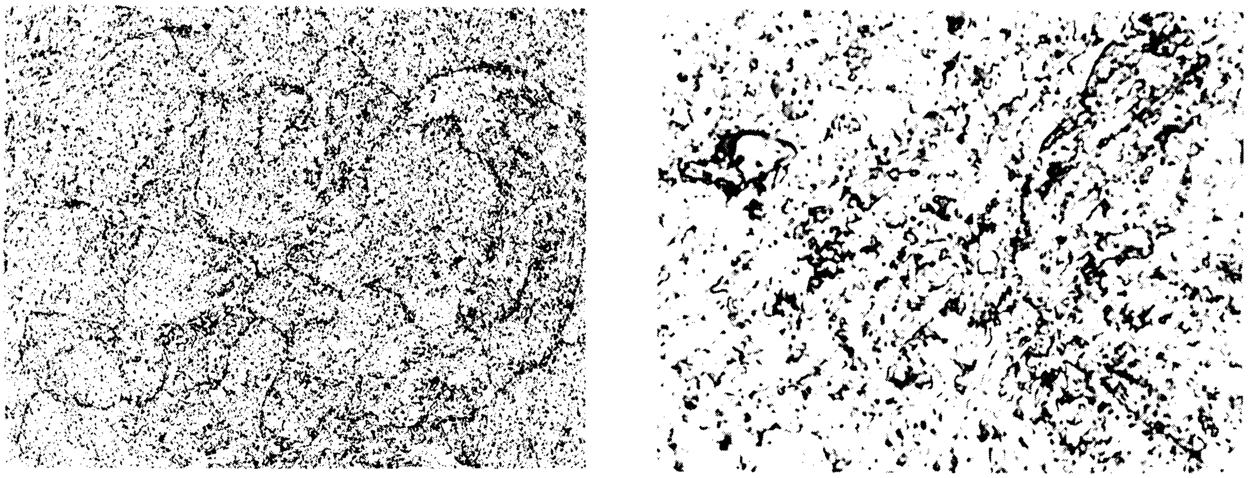
(c) Normalized from 1950°F + tempered 4 hrs at 1200°F + creep tested 1317 hrs at 1100°F and 30,000 psi - 228 BHN

Figure 21. - H-40 Steel. Simulated 3-inch Diameter Bar Stock (a) As Normalized from 1950°F, (b) As Tempered to 300 BHN, and (c) after Creep Testing at 1100°F.

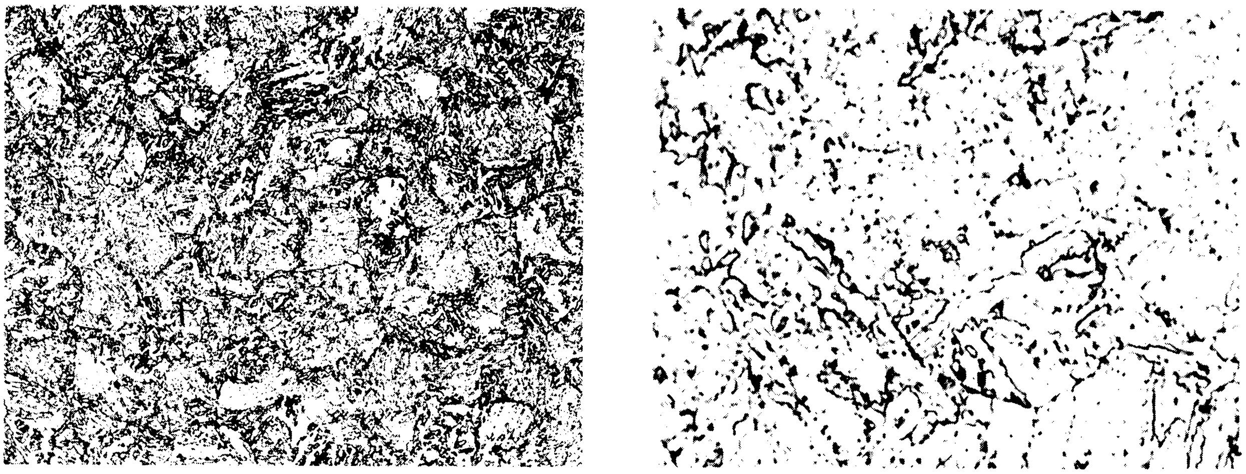
X100D X1000D



(a) Simulated 6-inch Diameter Bar Stock Normalized from 1950°F - 390 BHN



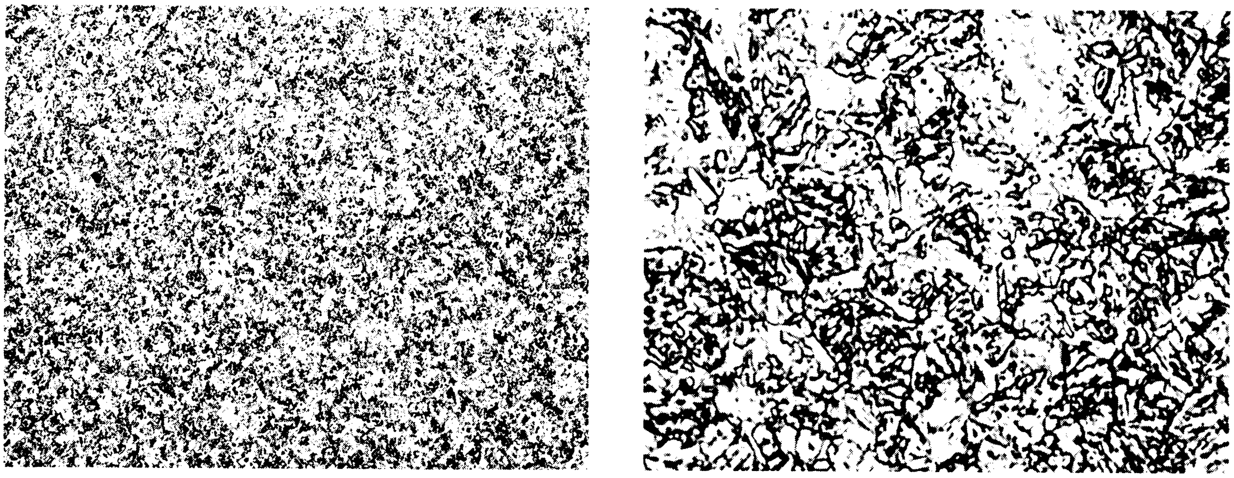
(b) Normalized from 1950°F + tempered 4 hrs at 1200°F - 295 BHN



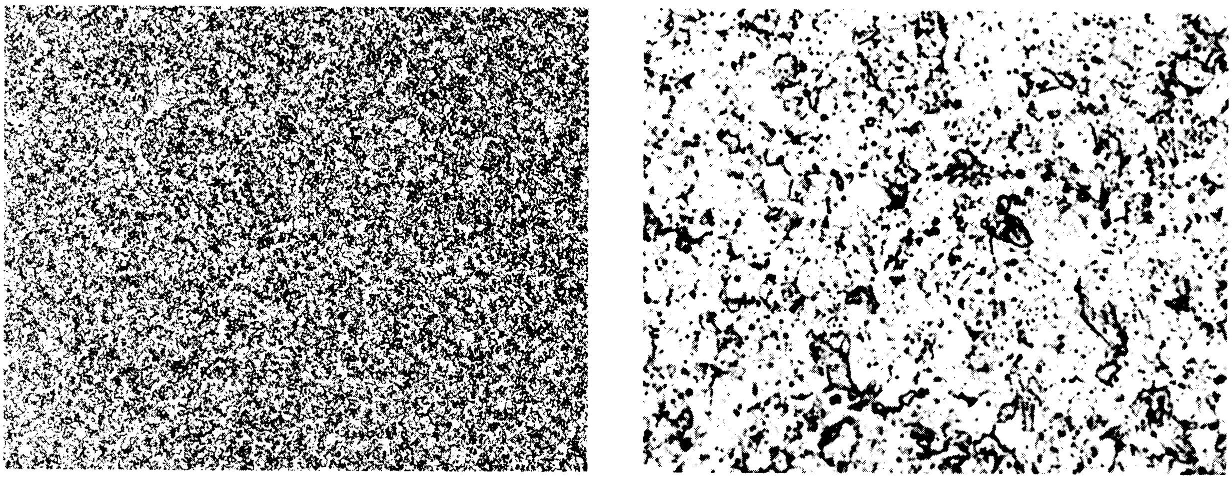
(c) Normalized from 1950°F + tempered 4 hrs at 1200°F + creep tested 1318 hrs at 1100°F and 30,000 psi - 243 BHN

Figure 22. - H-40 Steel. Simulated 6-inch Diameter Bar Stock (a) As Normalized from 1950°F, (b) As Tempered to 300 BHN, and (c) after Creep Testing at 1100°F.

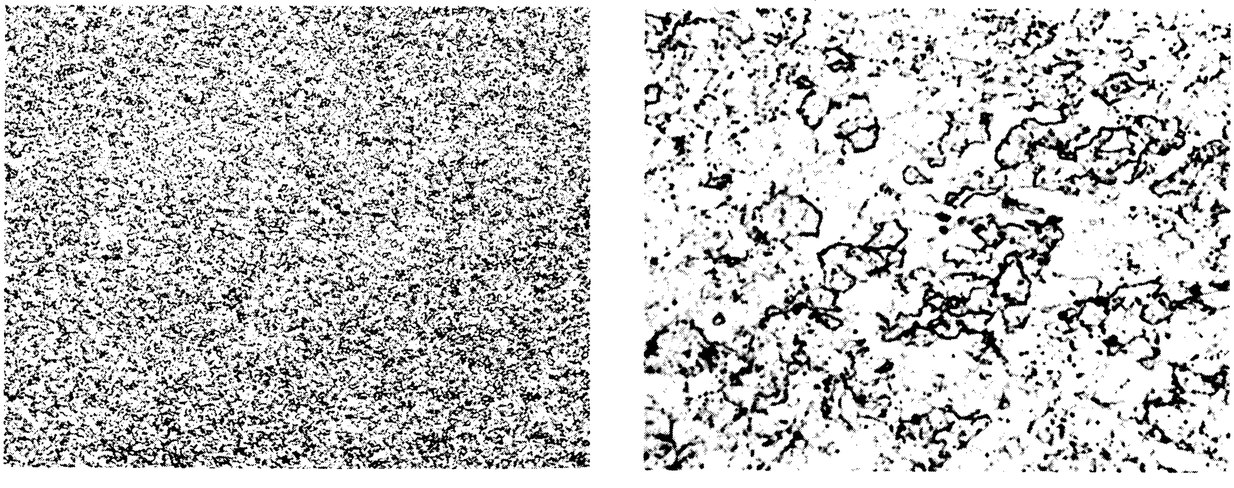
X100D X1000D



(a) Normalized from 1750°F as 3/4-inch Diameter Bar Stock - 408 BHN

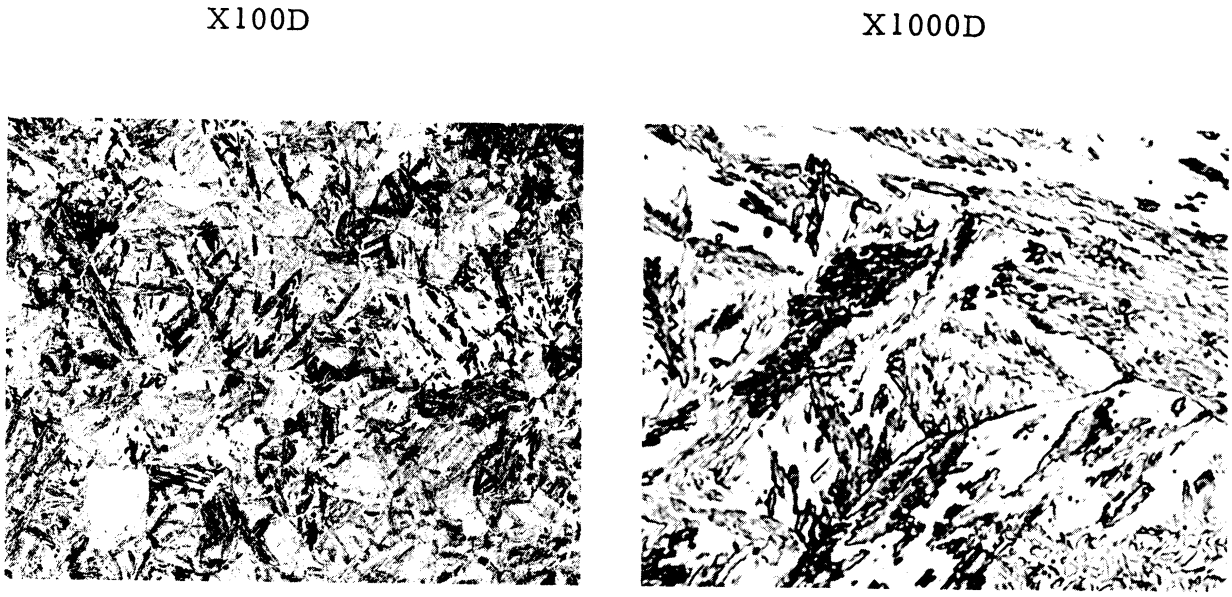


(b) Normalized from 1750°F + Tempered 4 hrs at 1200°F - 313 BHN

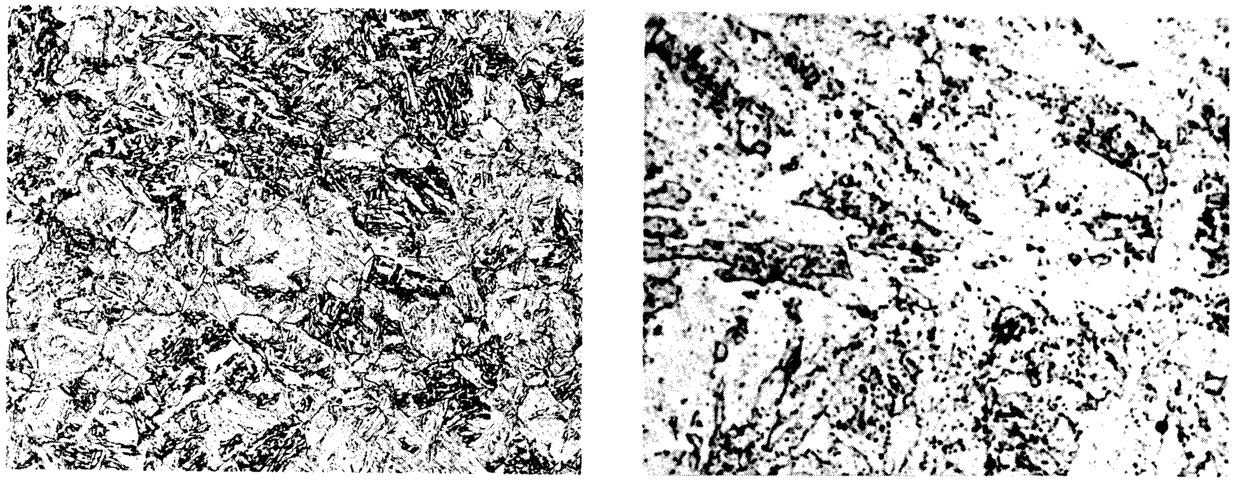


(c) Normalized from 1750°F + tempered 4 hrs at 1200°F + creep rupture tested 83.7 hrs at 1100°F and 30,000 psi - 222 BHN

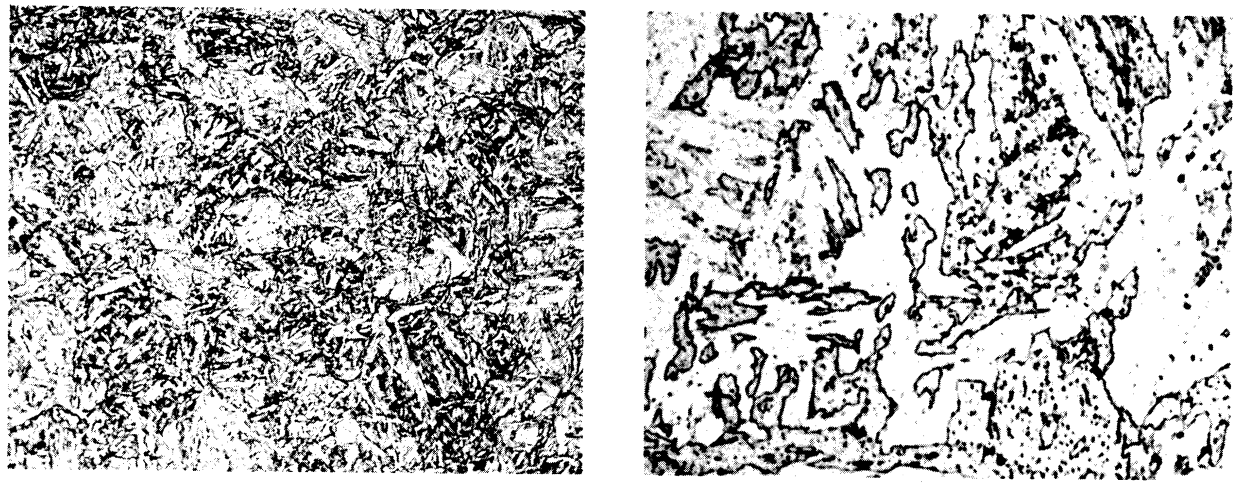
Figure 23. - H-40 Steel. Three-quarter-inch Diameter Bar Stock (a) As Normalized from 1750°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.



(a) Normalized from 2100°F as 3/4-inch Diameter Bar Stock - 429 BHN

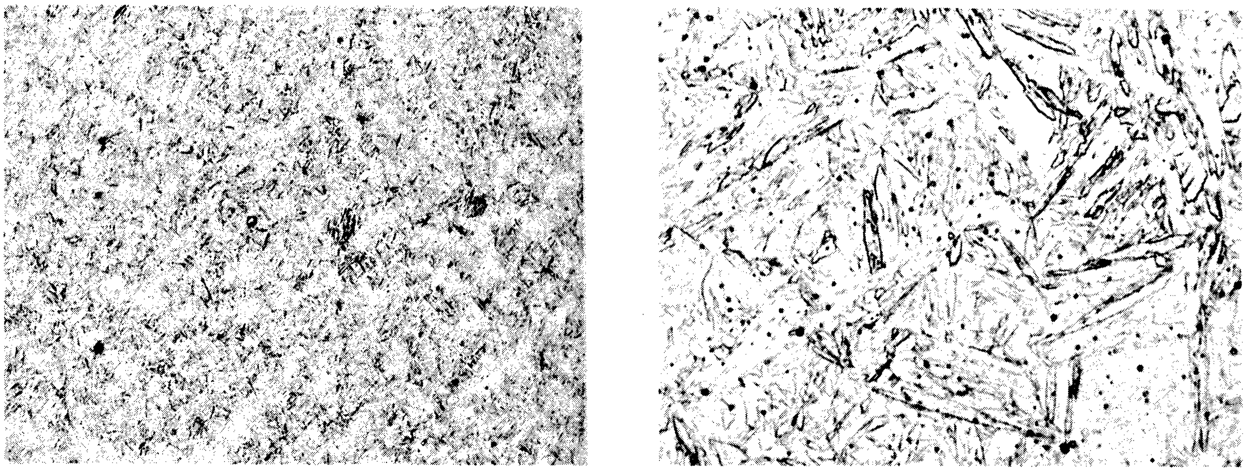


(b) Normalized from 2100°F + tempered 6 hrs at 1250°F - 319 BHN

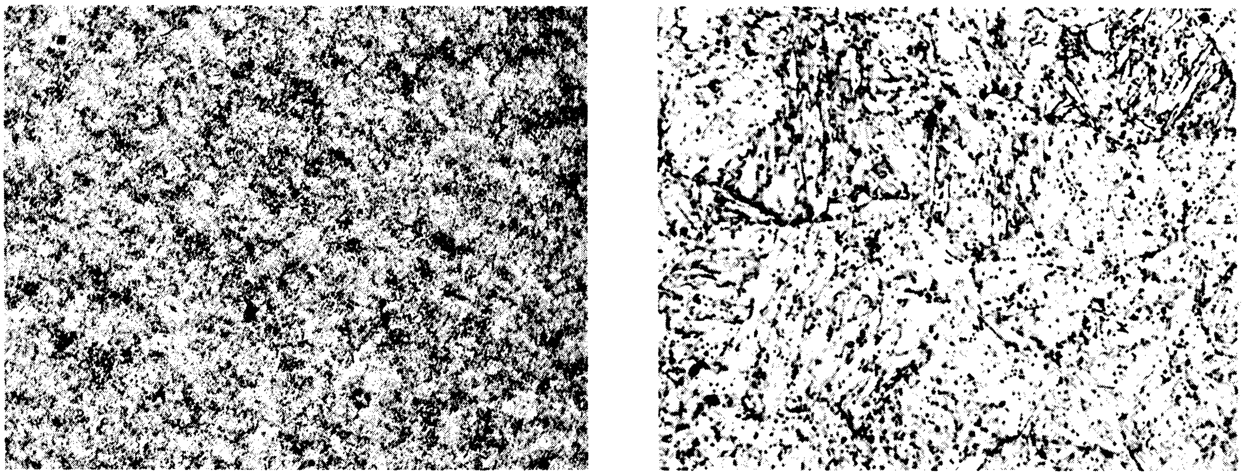


(c) Normalized at 2100°F + tempered 6 hrs at 1250°F + creep tested 1922 hrs at 1100°F and 30,000 psi - 240 BHN

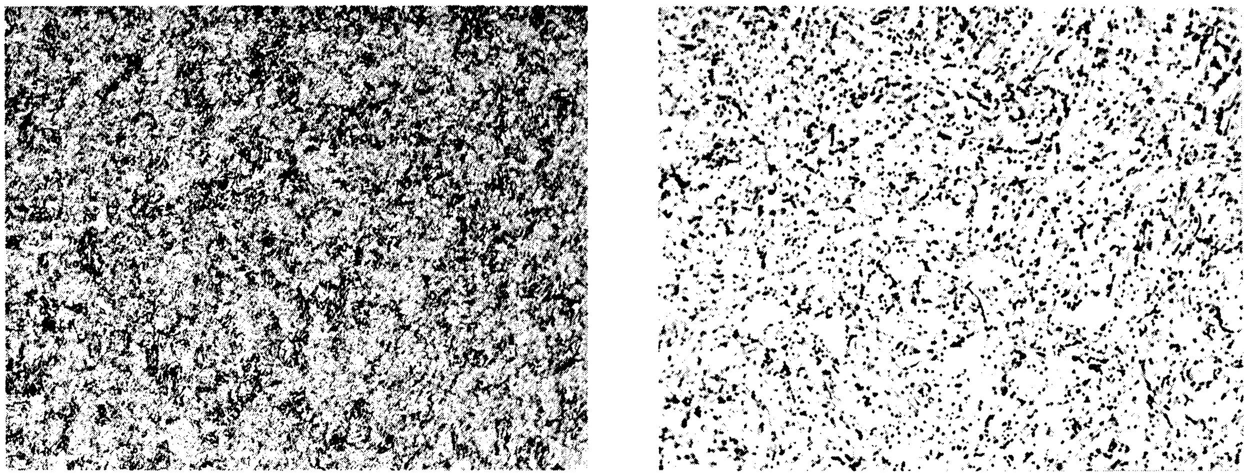
Figure 24. - H-40 Steel. Three-quarter-inch Diameter Bar Stock (a) As Normalized from 2100°F, (b) As Tempered to 300 BHN, and (c) after Creep Tested at 1100°F.



(a) Oil quenched from 1950°F as 3/4-inch Diameter Bar Stock - 523 BHN



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



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

Figure 25. - H-40 Steel. Three-quarter-inch Diameter Bar Stock (a) As Oil Quenched from 1950°F, (b) As Tempered to 300 BHN, and (c) after Creep-Rupture Testing at 1100°F.

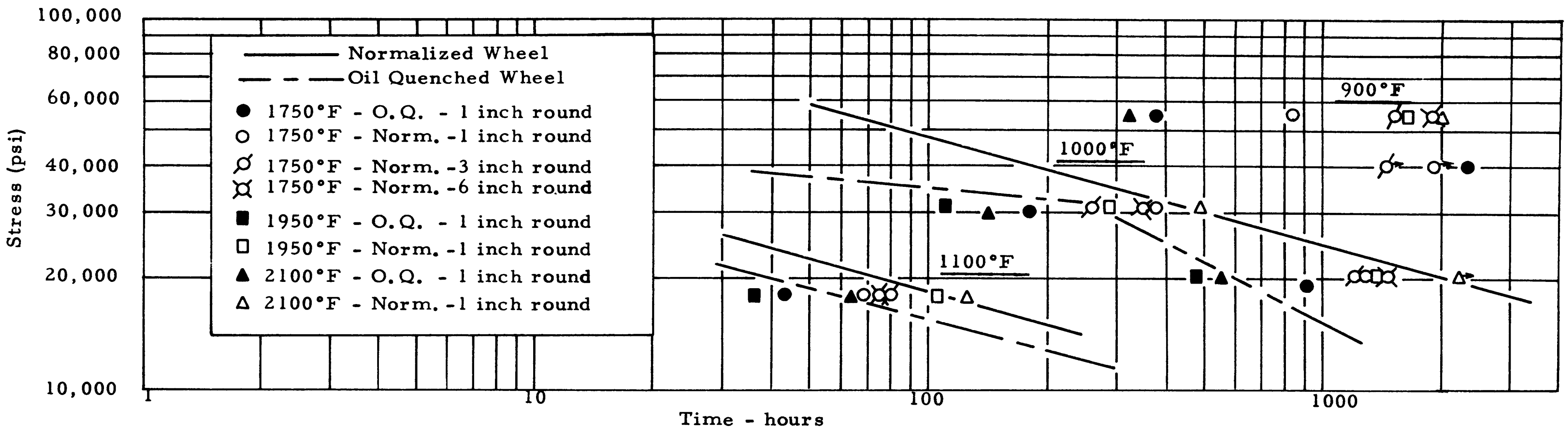


Figure 26. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Stress-Rupture Properties of SAE 4340 Steel at 900°, 1000°, and 1100°F. Curves for SAE 4340 Turbine Wheels Included for Comparison.

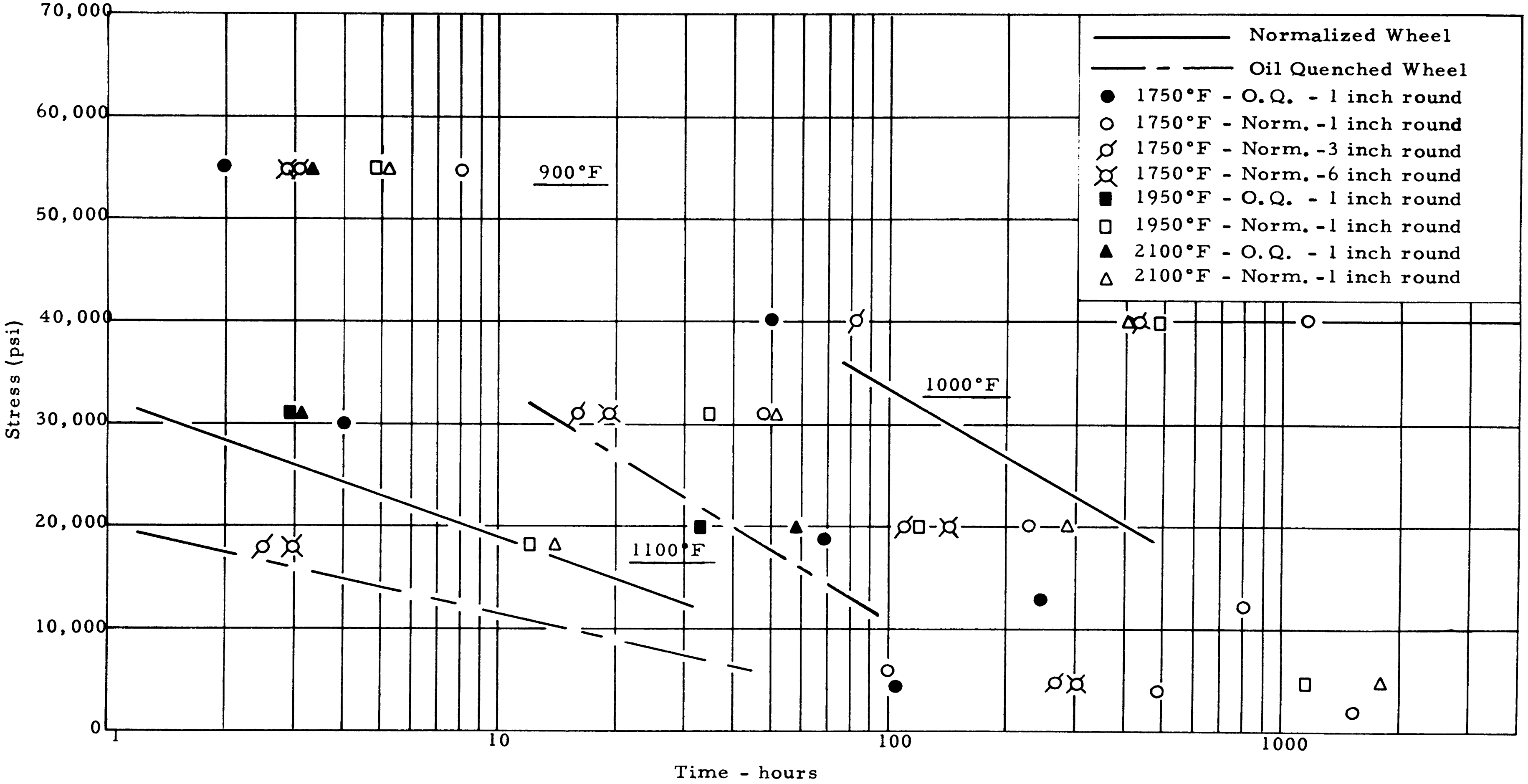


Figure 27. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Time to 0.5 Percent Total Deformation Data for SAE 4340 Steel at 900°, 1000°, and 1100°F. Curves for SAE 4340 Turbine Wheels Included for Comparison.

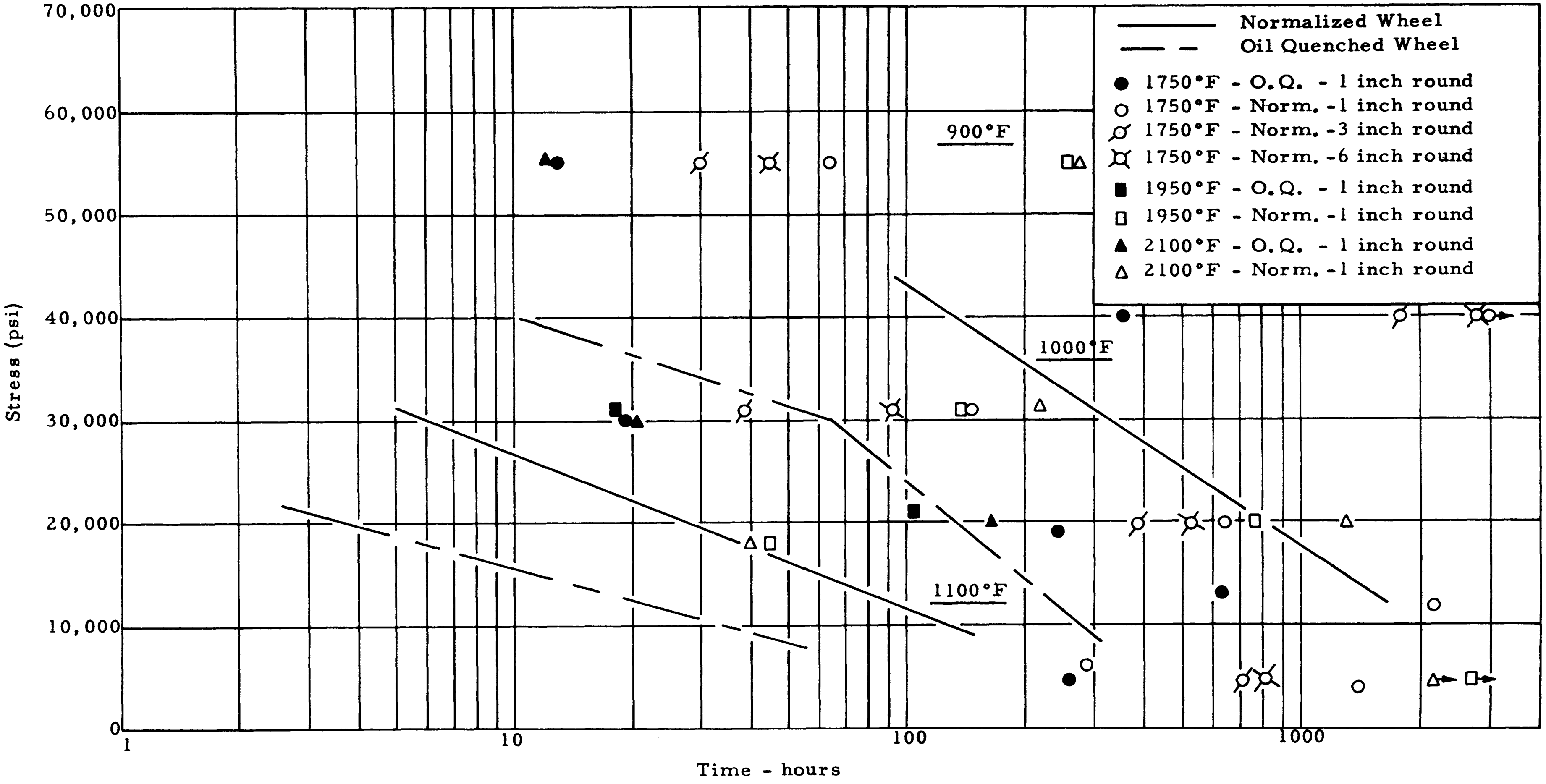


Figure 28. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Time to 1.0 Percent Total Deformation Data for SAE 4340 Steel at 900°, 1000°, and 1100°F. Curves for SAE 4340 Turbine Wheels Included for Comparison.

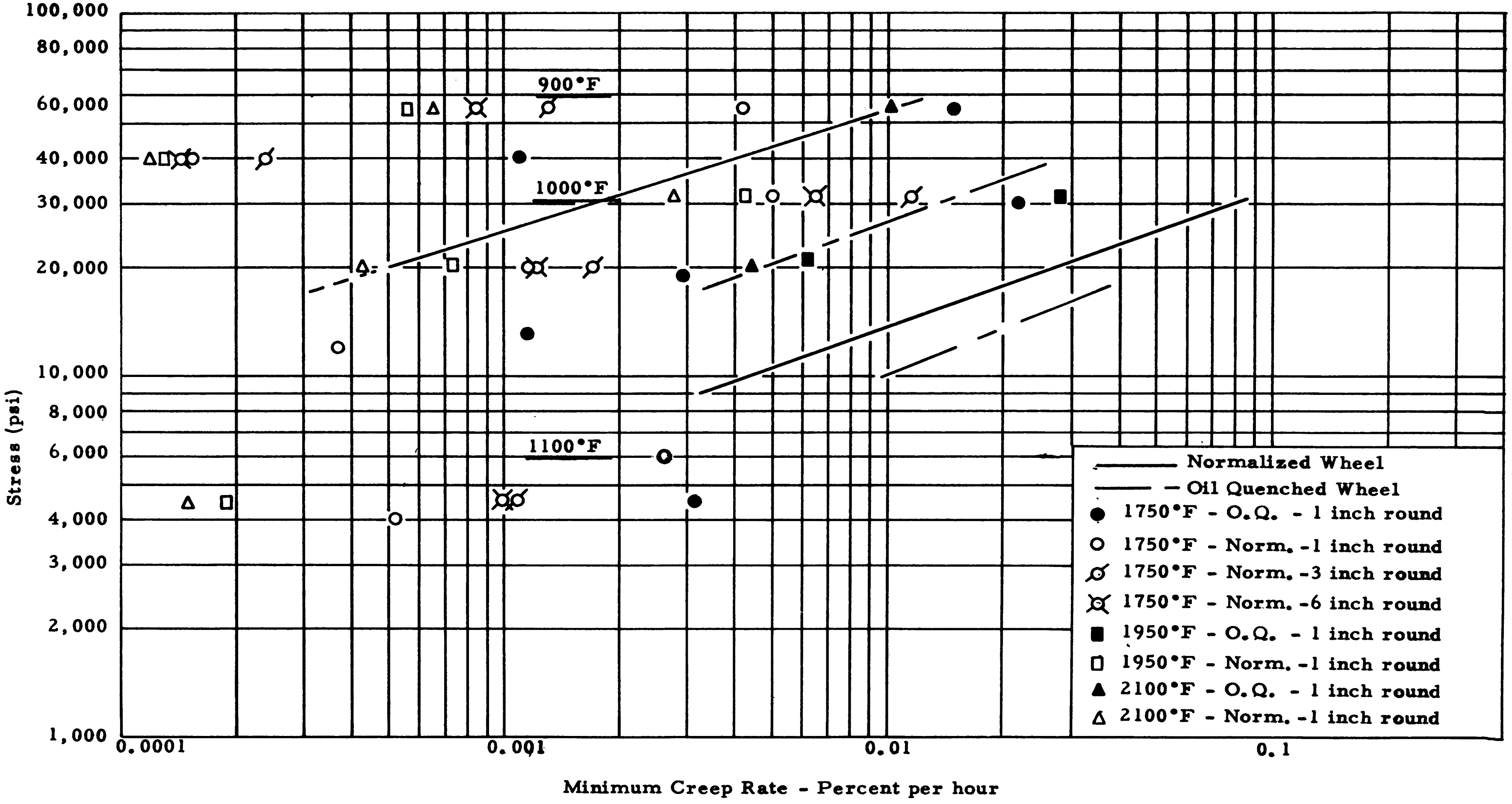


Figure 29. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Stress-Creep Rate Data for SAE 4340 Steel at 900°, 1000°, and 1100°F. Curves for SAE 4340 Turbine Wheels Included for Comparison.

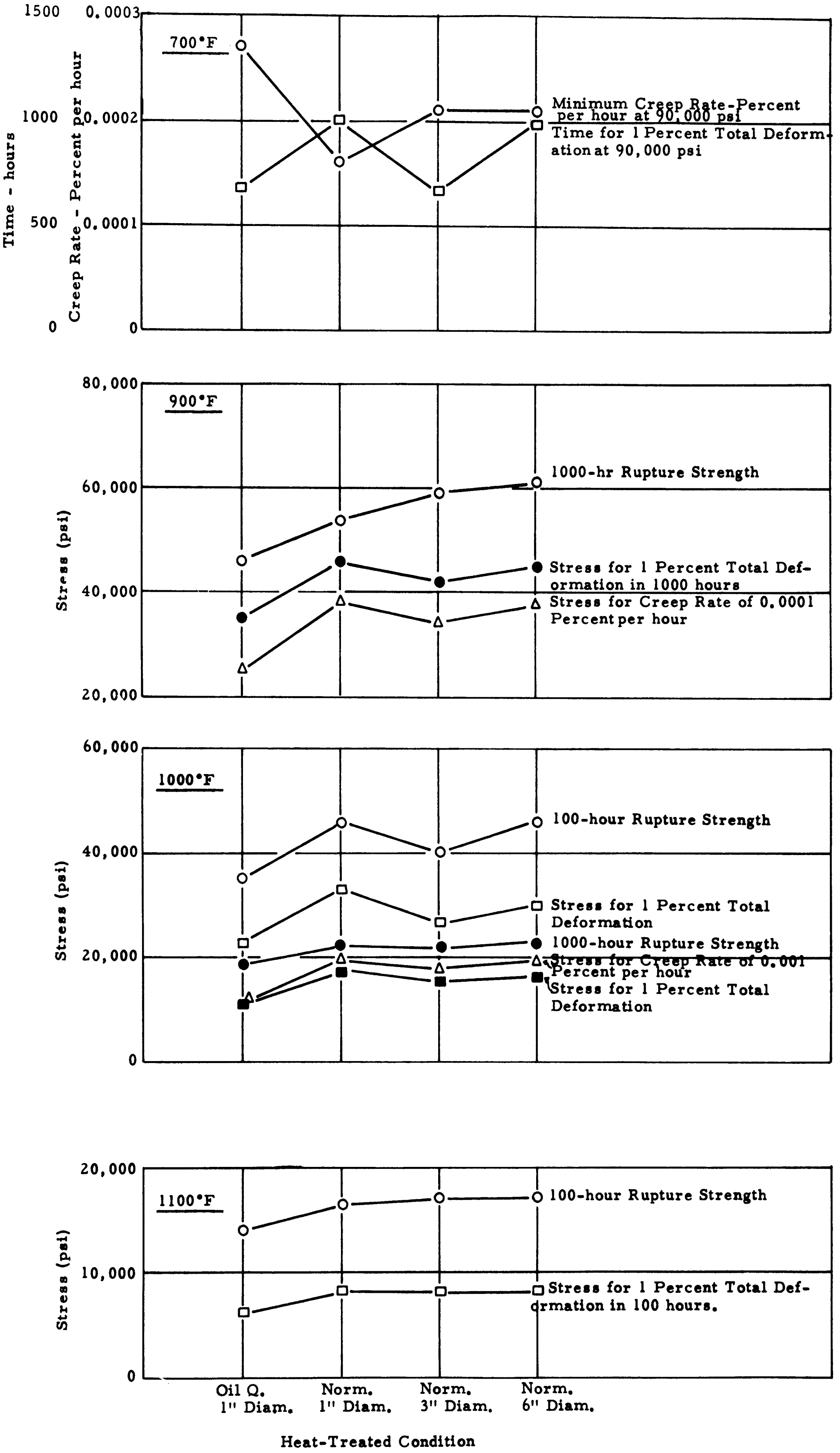


Figure 30. - Influence of Cooling Rate as Controlled by Section Size and Quenching Medium on the High Temperature Properties of SAE 4340 Steel at 700° to 1100°F.

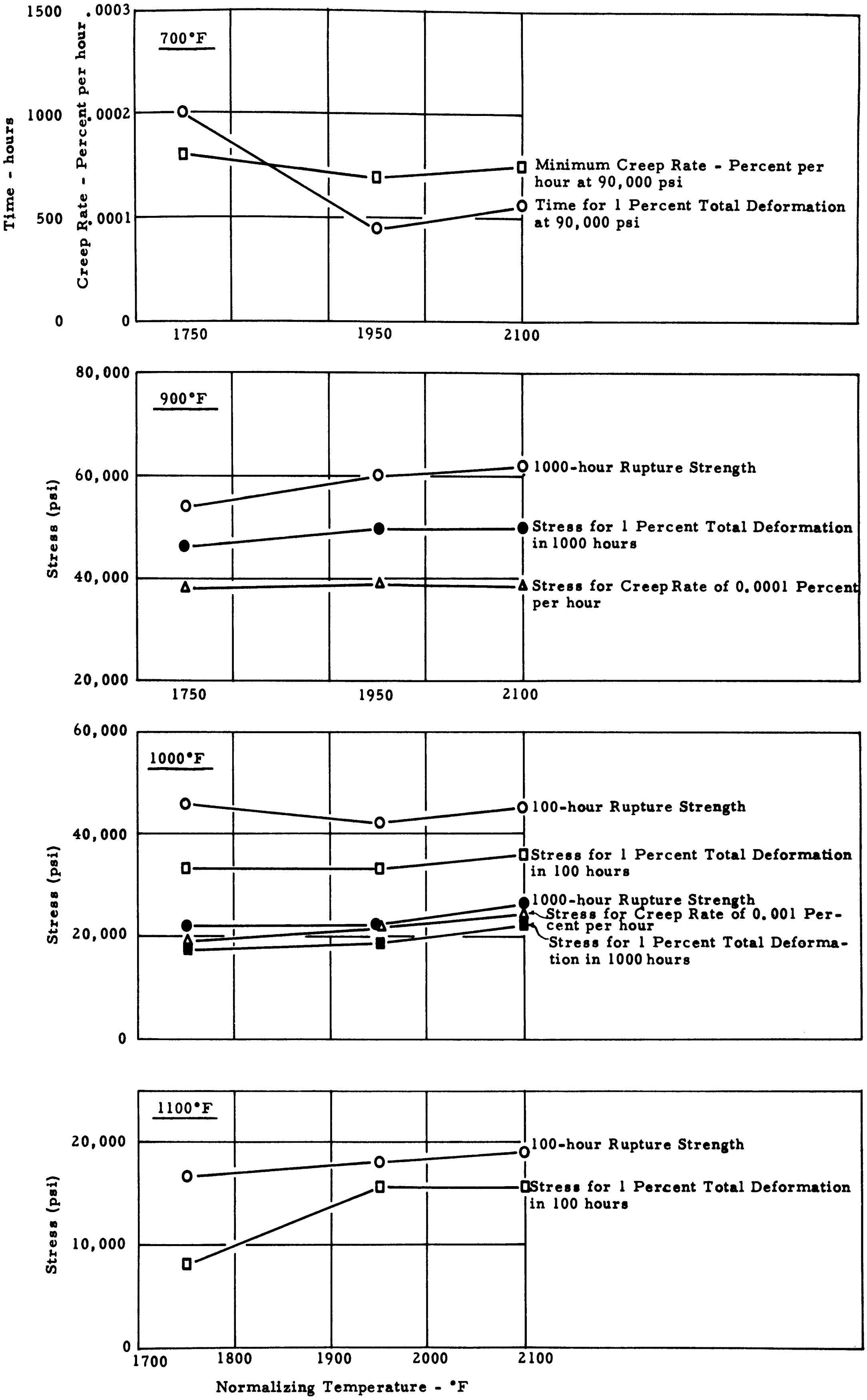


Figure 31. - Influence of Normalizing Temperature on the Elevated Temperature Properties of SAE 4340 Steel at 700° to 1100°F.

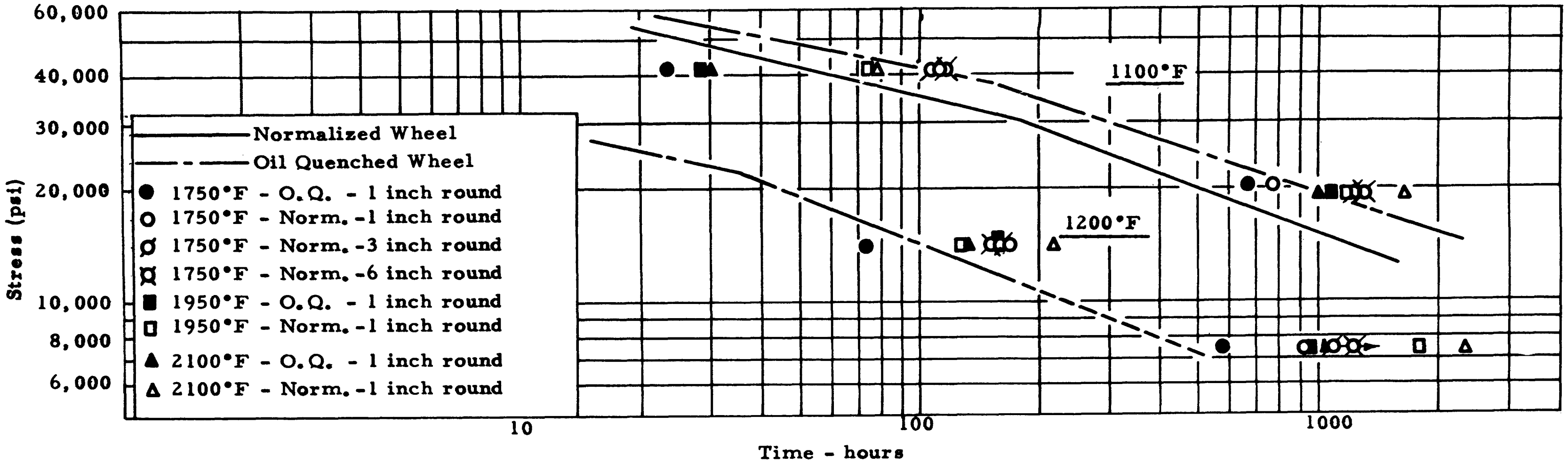


Figure 32. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Stress-Rupture Properties of "17-22-A"S Steel at 1100° and 1200°F. Curves for "17-22-A"S Turbine Wheels Included for Comparison.

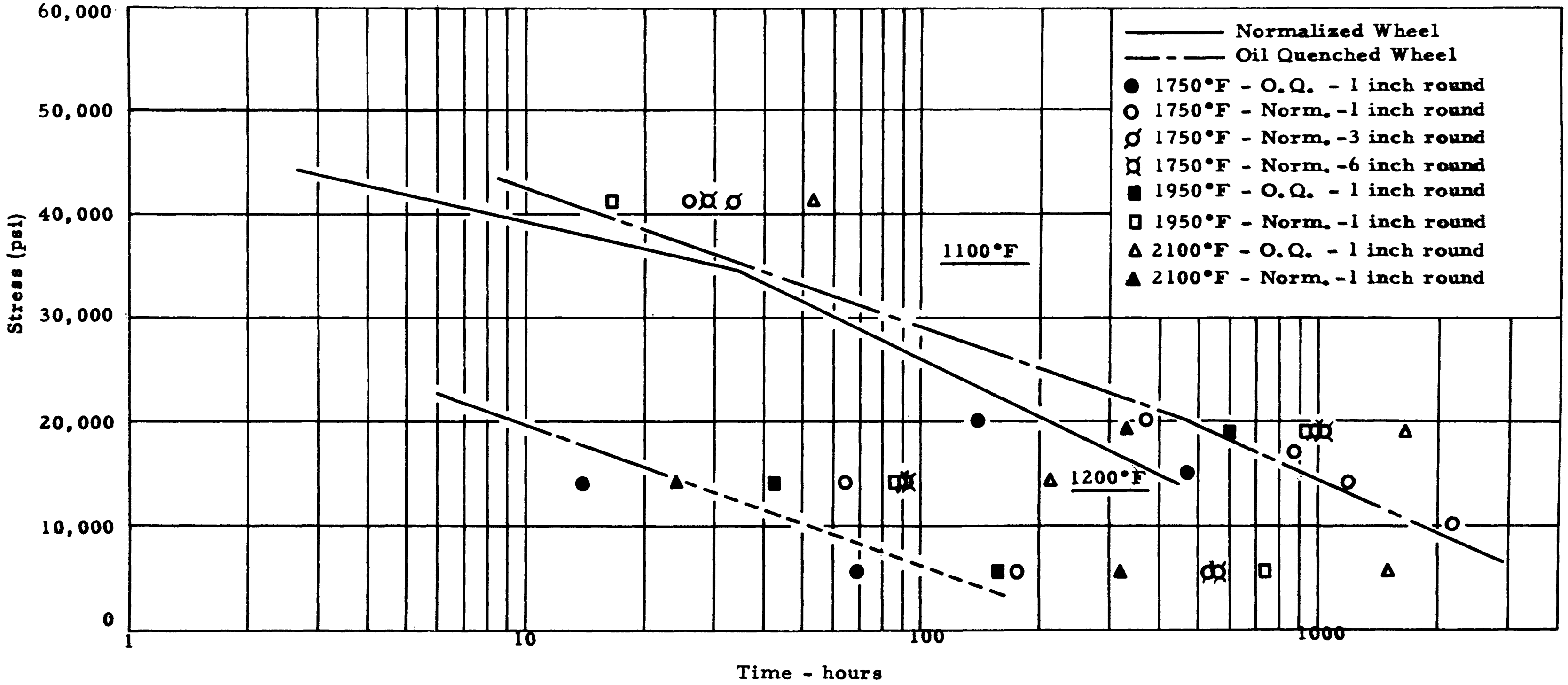


Figure 33. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Time to 0.5 Percent Total Deformation Data for "17-22-A"S Steel at 1100° and 1200°F. Curves for "17-22-A"S Turbine Wheels Included for Comparison.

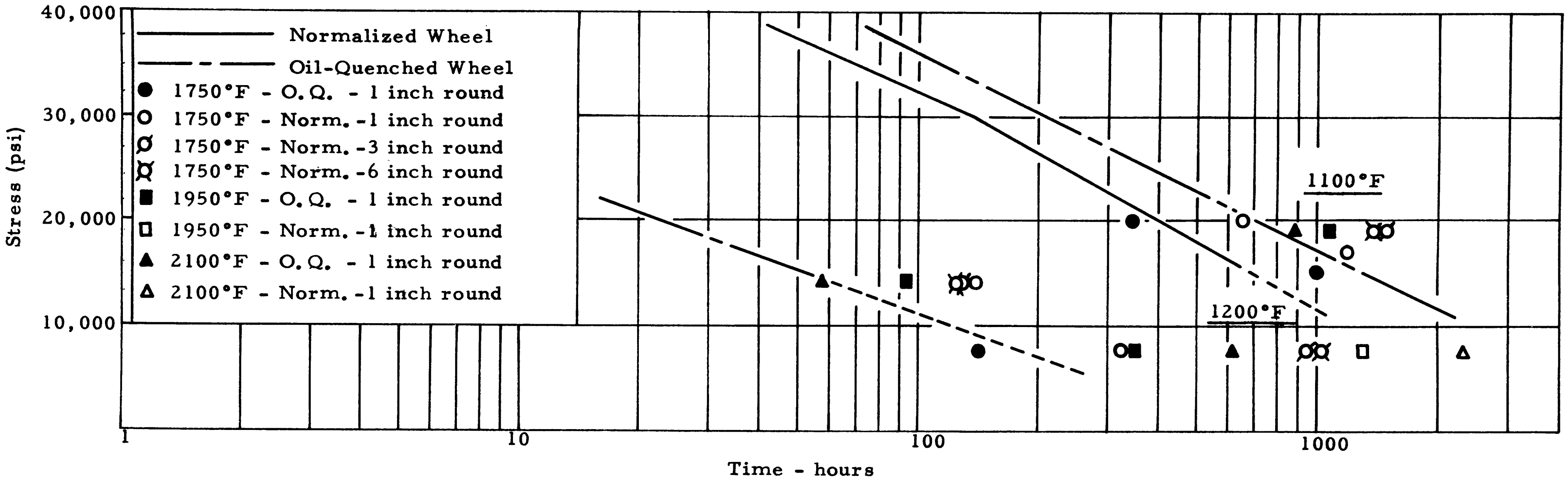


Figure 34. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Time to 1.0 Percent Total Deformation Data for "17-22-A"S Steel at 1100° and 1200°F. Curves for "17-22-A"S Turbine Wheels Included for Comparison.

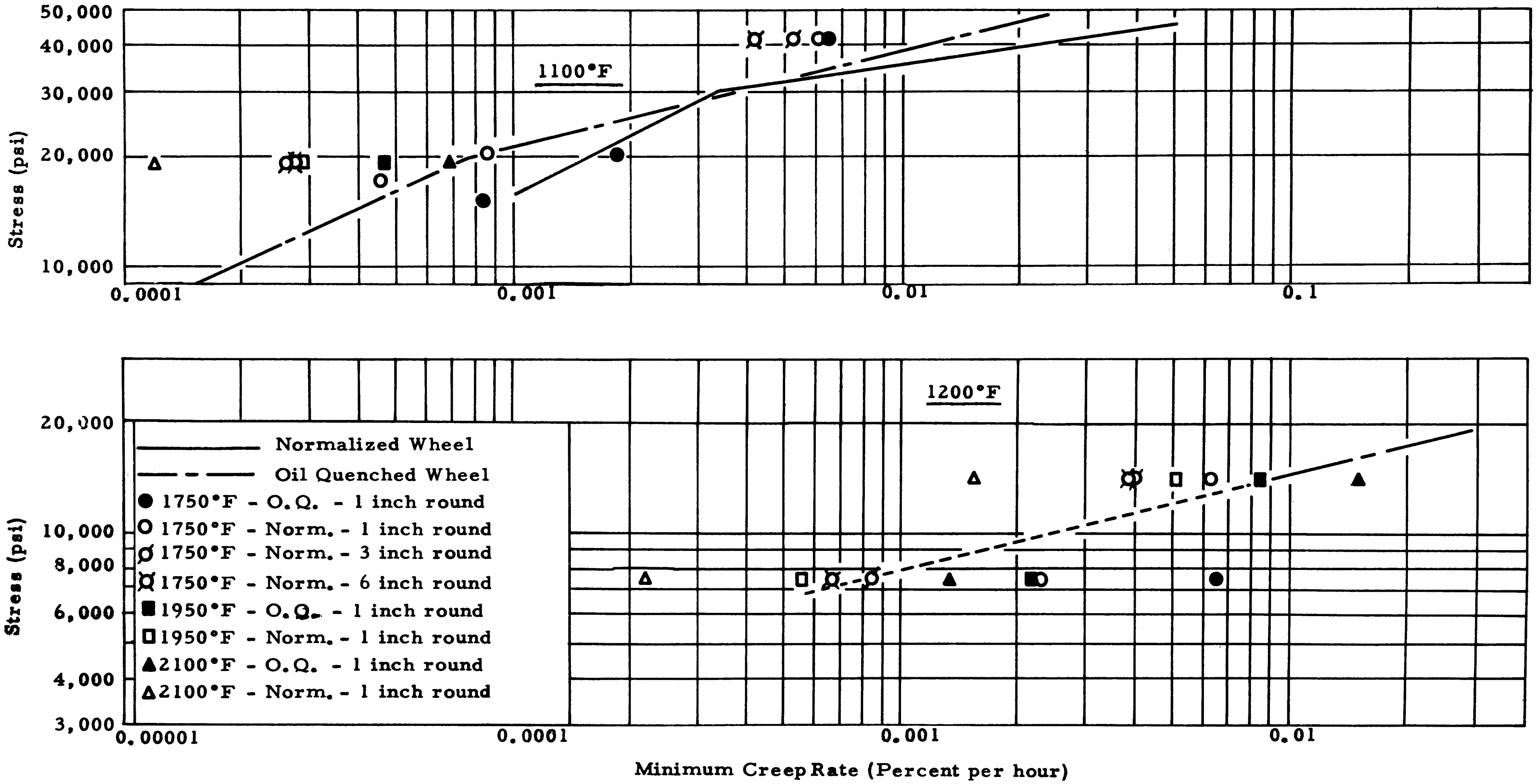


Figure 35. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Stress-Creep Rate Data for "17-22-A"S Steel at 1100° and 1200°F. Curves for "17-22-A"S Turbine Wheels Included for Comparison.

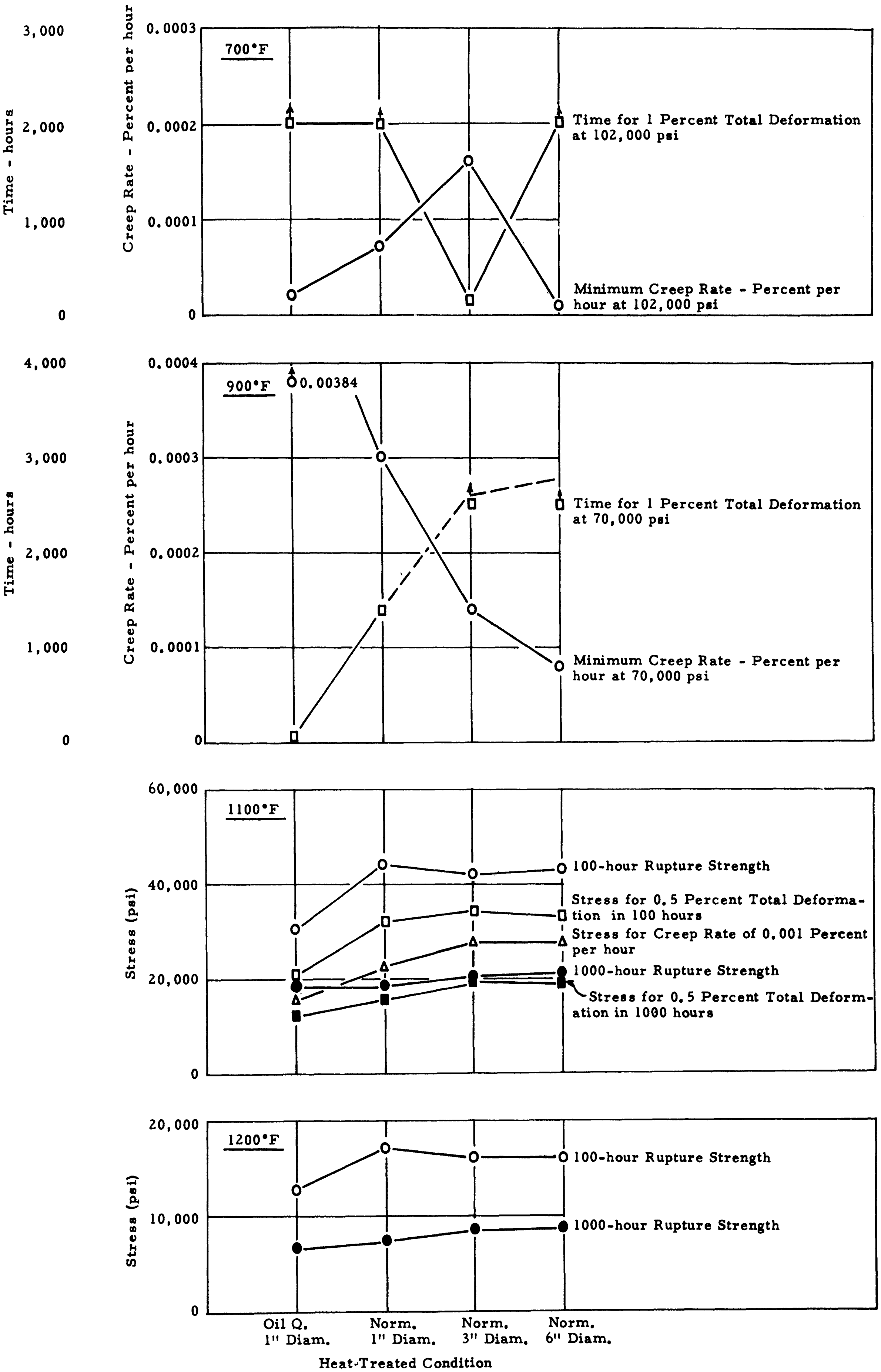


Figure 36. - Influence of Cooling Rate as Controlled by Section Size and Quenching Medium on the High Temperature Properties of "17-22-A"S Steel at 700° to 1200°F.

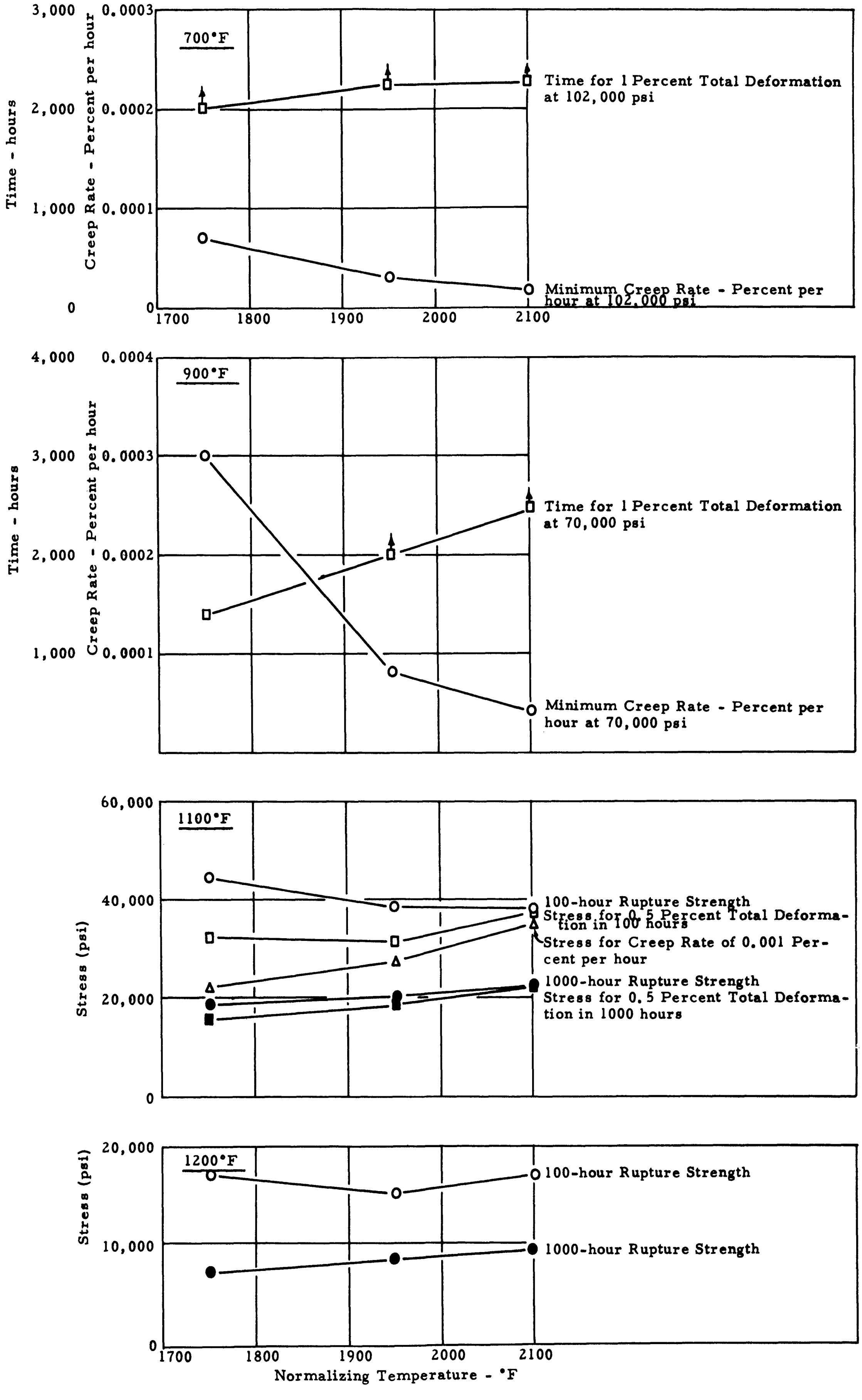


Figure 37. - Influence of Normalizing Temperature on the Elevated Temperature Properties of "17-22-A"S Steel at 700° to 1200°F.

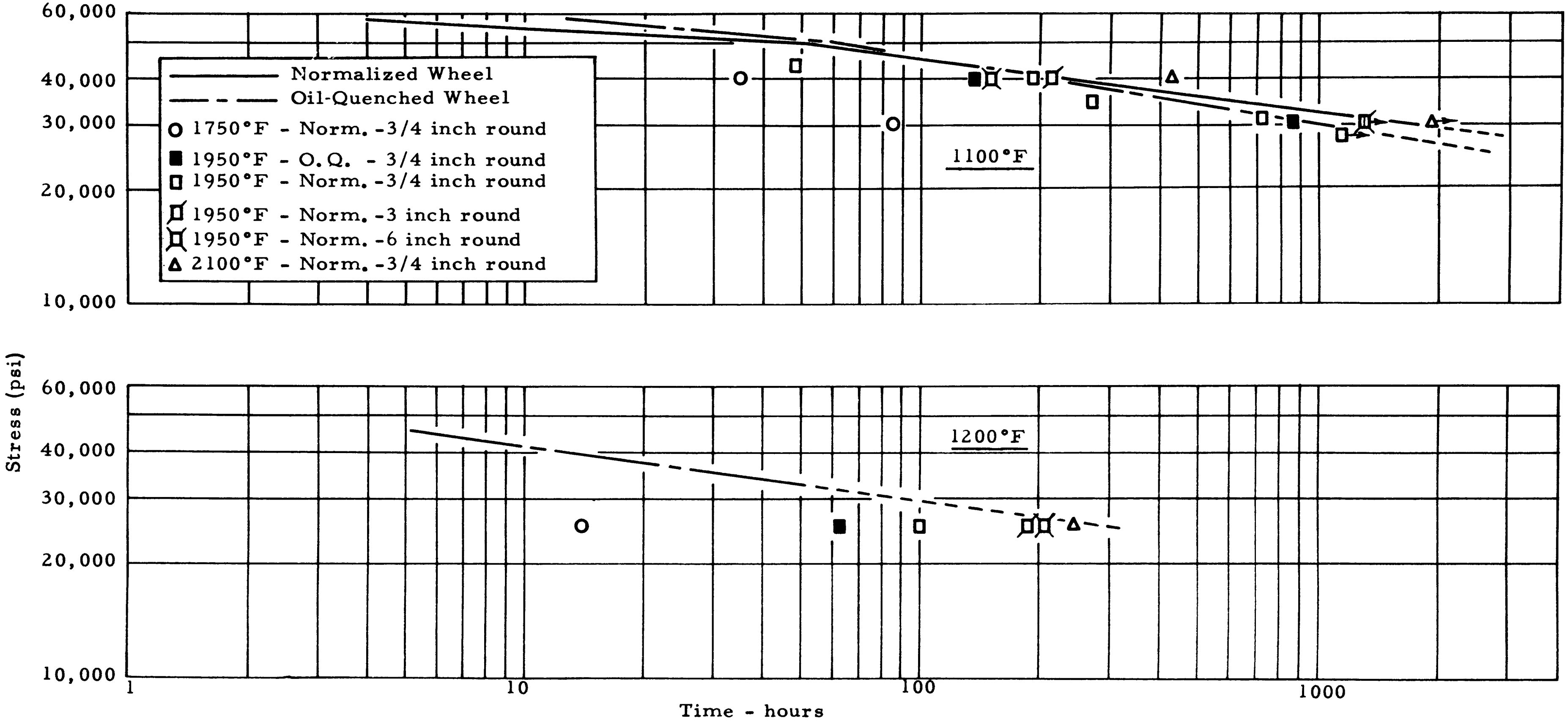


Figure 38. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Stress-Rupture Properties of H-40 Steel at 1100° and 1200°F. Curves for H-40 Turbine Wheels Included for Comparison.

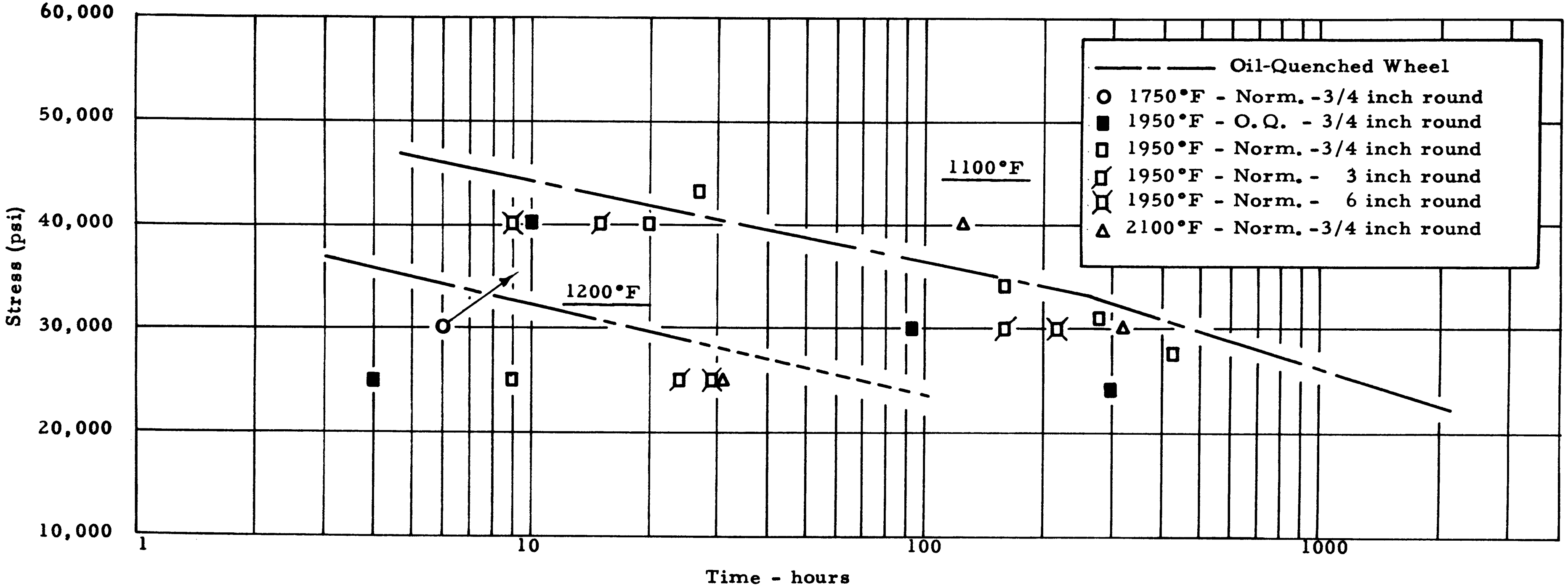


Figure 39. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Time to 0.5 Percent Total Deformation **Data** for H-40 Steel at 1100° and 1200°F. Curves for H-40 Turbine Wheels Included for Comparison.

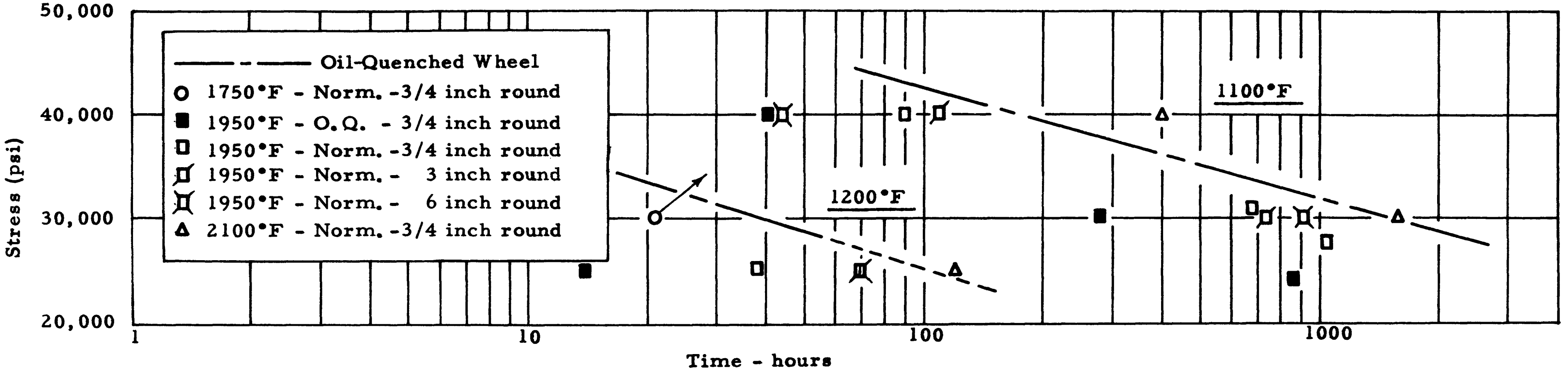


Figure 40. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Time to 1.0 Percent Total Deformation Data for H-40 Steel at 1100° and 1200°F. Curves for H-40 Turbine Wheels Included for Comparison.

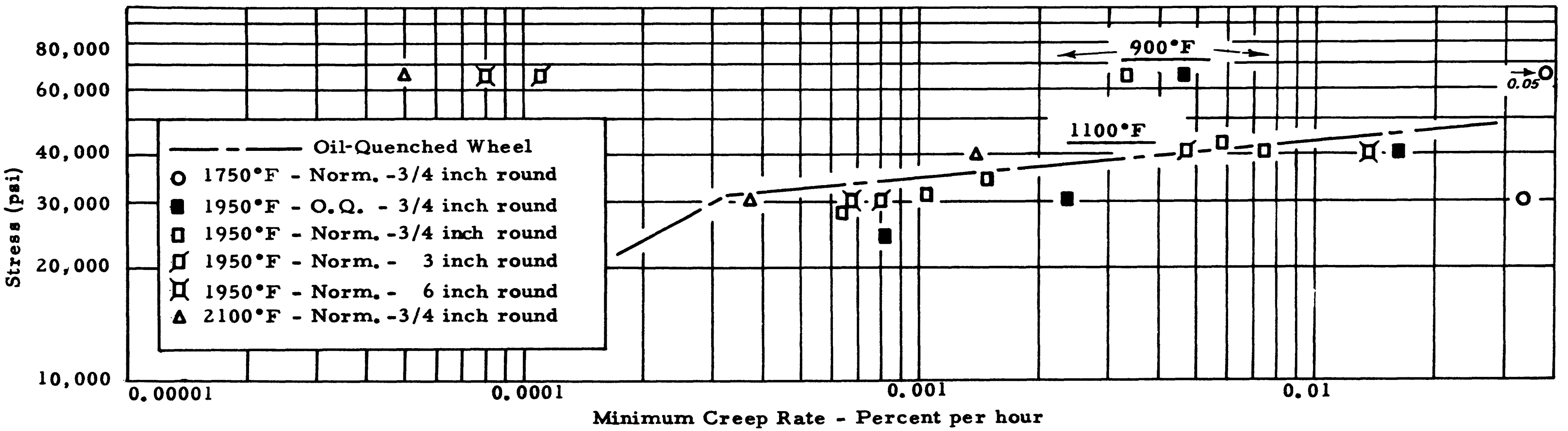


Figure 41. - Effect of Various Cooling Rates and Austenitizing Temperatures on the Stress-Creep Rate Data for H-40 Steel at 900° and 1100°F. Curves for H-40 Turbine Wheels Included for Comparison.

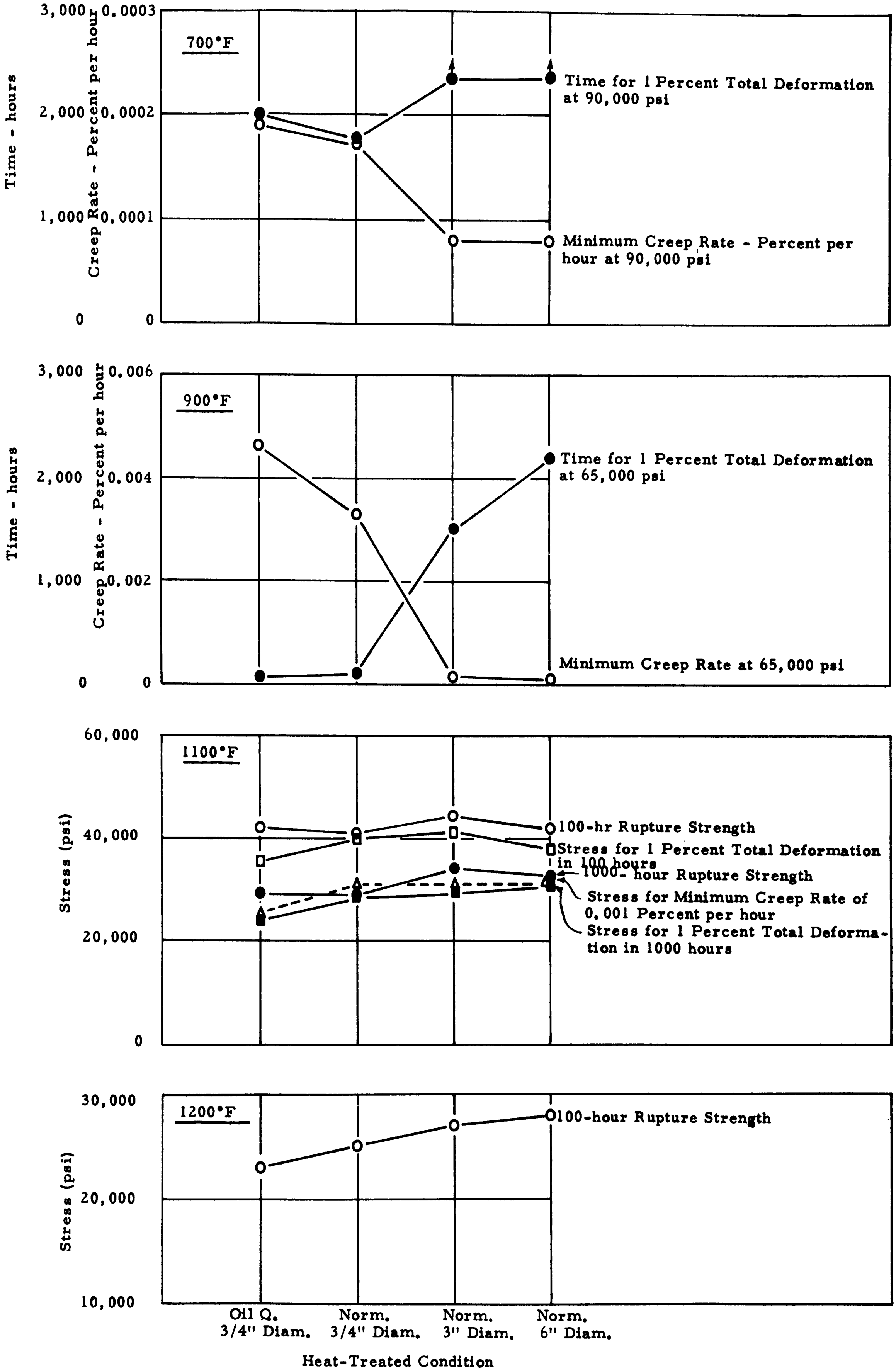


Figure 42. - Influence of Cooling Rate as Controlled by Section Size and Quenching Medium on the High Temperature Properties of H-40 Steel at 700° to 1200°F.

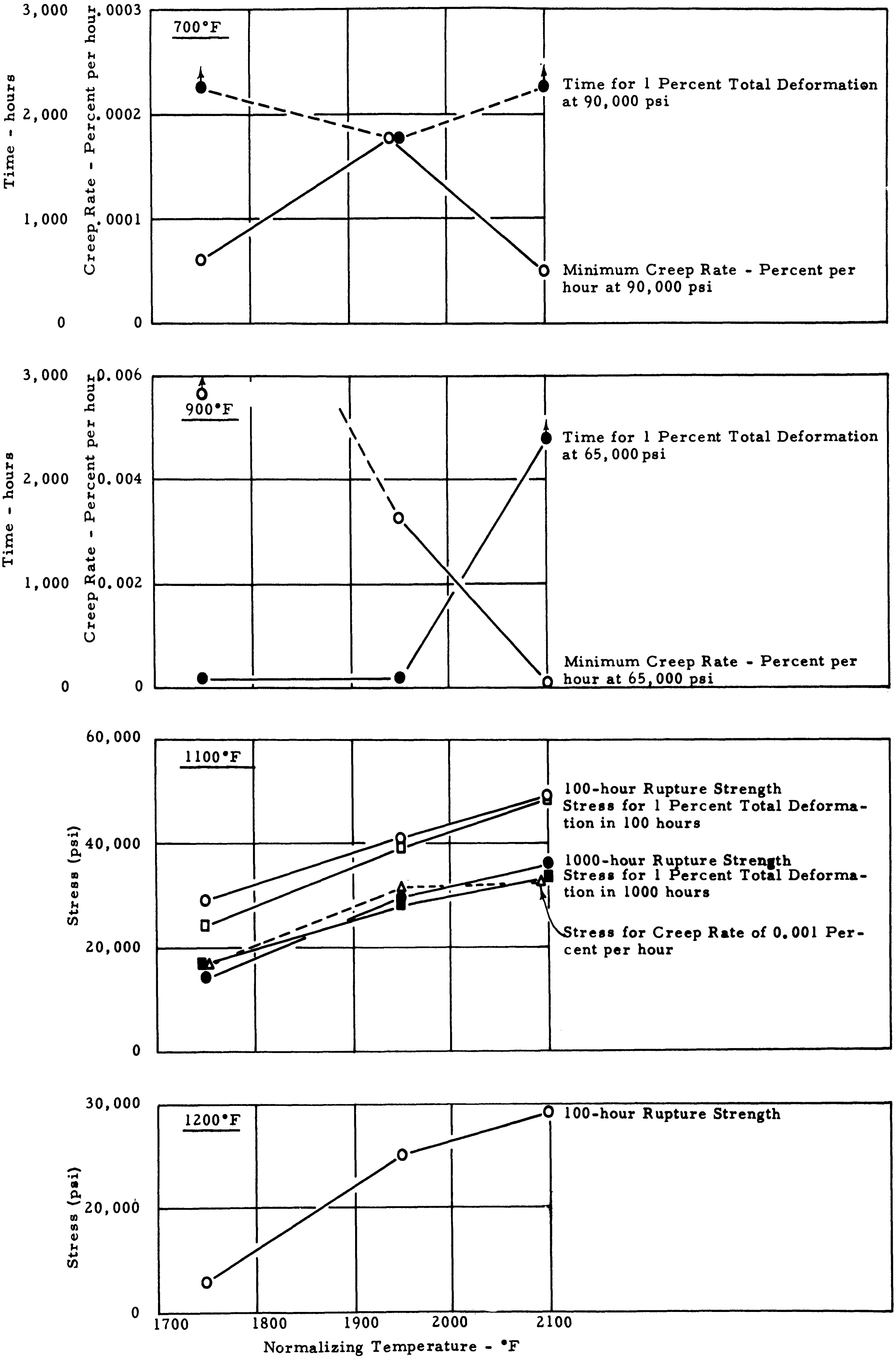


Figure 43. - Influence of Normalizing Temperature on the Elevated Temperature Properties of H-40 Steel at 700° to 1200°F.