NOTICES

FINAL REPORT
TO
MATERIALS LABORATORY
WRIGHT AIR DEVELOPMENT CENTER
ON

AN INVESTIGATION OF THREE FERRITIC STEELS FOR HIGH-TEMPERATURE APPLICATION

by

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FOREWORD

This report was prepared by the Engineering Research Institute of the University of Michigan under USAF Contract Number AF 33 (616)-3239. The contract was initiated under Task Number 73512, with Mr. C. B. Hartley acting as project engineer for the Materials Laboratory, Wright Air Development Center. This report covers work done from ~~September 15,~~ 1955 to ~~December~~ 15, ~~1956~~. December 1, 19..
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The low-alloy steel used in this research was supplied gratis by the Timken Roller Bearing Company, the Universal-Cyclops Steel Corporation, and the Allegheny Steel Corporation.

The A-286 and the "A" Nickel used in this research were supplied gratis by the Allegheny Ludlum Steel Corporation and the International Nickel Company, respectively.

SUMMARY

An investigation was carried out to survey the relationships between microstructure and properties at 700° to 1100°F for low-alloy, hardenable steels. A Ni-Cr-Mo (SAE 4340) and two Cr-Mo-V ("17-22-A"S and "17-22-A"V) steels were studied. The results, together with those presented in References 1 and 2 for previous work on 4340 and "17-22-A"S steels, correlate properties with microstructure for three temperatures of isothermal transformation in the pearlite region and three in the bainite region. Oil-quenched and normalized structures were included for comparison. The properties were evaluated for these structures when tempered to both the 300 and 350 Brinell hardness levels. Data for the "17-22-A"V steel in the form of a TTT diagram obtained to establish heat-treating condition is included.

These data are supplemented by similar studies for continuous cooling down to rates simulating the air cooling of a 6-inch round. The influence of increasing the heat-treating temperature was also studied. Controlled mixed structures were developed by transforming about 50 percent in the upper bainitic range and about 50 percent in the lower bainitic range. The results of a very limited start for a study of hot-working condition effects is included.

The results are correlated and analyzed in the report. Optimum structures (or treatments) vary with both the alloy and test conditions. In general, banitic structures of one type or another gave best properties. However, for the Cr-Mo-V steels; pearlites formed at relatively low temperatures were often as strong or stronger than the bainites. Tempered martensite was never the strongest structure and most often was the weakest.

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INTRODUCTION

An investigation was conducted to determine additional information regarding the basic relationships between type of microstructure and properties at elevated temperatures for low-alloyed, hardenable ferritic steels. Previous research in the same field had been carried out under sponsorship of the Materials Laboratory, Wright Air Development Center. This had shown the relative properties of the possible "pure" types of structures obtainable by heat treatment through studies of isothermally transformed specimens. Further work had related the structures of continuously cooled material to the properties. A study of the effect of austenitizing temperature had also been made.

The investigation covered by this report investigated several additional structural variables which are commonly encountered in heat treating such steels. A number of the same structures previously investigated were studied at a higher hardness level resulting from less tempering. The previous continuous cooling studies were difficult to interpret in terms of the structures developed. Accordingly experiments were carried out in which controlled mixed bainitic structures were developed by isothermal transformation at more than one temperature. Structures of interest were produced in material previously homogenized by a normalize in order to establish how much this factor influenced the properties. There had been some evidence to indicate that prior hot-working conditions could influence properties after a subsequent heat treatment. Furthermore, there were theoretical reasons pointing to the probability that superior properties could be developed by direct transformation from hot-working operations. Accordingly, an investigation of hot-working effects was started.

The studies were conducted using the same 1.75 Ni - 0.80 Cr - .25 Mo (SAE 4340) and 1.25 Cr - 0.50 Mo - .25 V ("17-22-A"S) steels previously used. In addition, a new higher strength, high vanadium 1.25 Cr - 0.50 Mo - 0.80 V steel ("17-22-A"V) was introduced into the program. Most of the structural studies covered in previous investigations of the other steels were included for the "17-22-A"V material. The three steels were included in order to obtain an indication of the general applicability of the conclusions.

There is extensive literature on the relationships between types of microstructures and properties at ordinary temperatures for the types of steels considered. There is, however, very little information available in relation to high-temperature properties.

The practical incentive for the investigation stemmed from several facts. Medium-carbon, low-alloyed steels can be treated to develop rather high strengths for temperatures up to 1000° to 1200°F, depending on the alloy content. Such steels are less expensive, contain only small amounts of strategic metals, and are very much easier to produce and fabricate than heat-resistant alloys. Increasing use of such alloys can be expected in the rotor disks and other lower temperature parts of jet engines. Alloys of this type will also be used increasingly in air frames as aerodynamic heating becomes a greater problem. Successful use of the alloys in such applications will be greatly facilitated by a proper understanding of the optimum types of structures and the heat treatments necessary to provide them.

TEST MATERIALS

The bar stock of the "17-22-A"S and "17-22-A"V steels was supplied gratis by the Timken Roller Bearing Company. The SAE 4340 steel was donated by the Universal-Cyclops Steel Corporation. The chemical analyses were reported by the manufacturers to be as follows:

Steel	Heat No.	C	Mn	Si	Cr	Ni	Mo	V
SAE4340	19053	0.40	0.70	0.30	0.78	1.75	0.26	--
SAE4340	D-14064	0.40	0.80	0.27	0.82	1.67	0.32	--
"17-22-A"S	24797	0.30	0.63	0.60	1.25	0.25	0.52	0.25
"17-22-A"S	10420	0.29	0.61	0.67	1.30	0.18	0.47	0.26
"17-22-A"V	11833	0.29	0.70	0.71	1.43	0.31	0.51	0.81

EVALUATION OF HIGH-TEMPERATURE PROPERTIES

All evaluations of properties at high temperatures were based on a very limited number of tests to survey the general effects. The test conditions were the same for all of the studies. To avoid repeating it for each section a general description applicable to all the studies is given.

Selection of Testing Conditions

All of the studies concerning the SAE 4340 and "17-22-A"S steels involved comparisons with work done in previous years. (References 1 and 2) Therefore, the same temperatures and stresses as in the previous work were used so that direct comparisons of the data could be made. The testing conditions selected for the "17-22-A"V studies were nearly identical with those for "17-22-A"S.

The testing temperatures were selected to cover the range of 700° to 1100°F, the temperature range in which the alloys are mainly used for high-temperature applications. The stresses were selected so that the strength comparisons could be made on the basis of total-deformation-time and creep-rate data at the lower and intermediate temperatures where the rupture strengths are much higher than permissible operating stresses. Rupture data were included with the creep- and total-deformation data at the higher temperatures.

The specific test conditions used and the type of data obtained for the three subject steels in all but the Hot-Working Study were as follows:

Steel	Test Temp (°F)	Stress (psi)	No. of Tests	Type of Data Obtained
SAE 4340	700	90,000	1	Creep Rate and Total Deformation Time
	900	55,000	1	Creep Rate and Total Deformation Time
	1000	31,000	1	Rupture Time, Rupture Ductility, Creep Rate, and Total Deformation Time
	1000	13,000 or 20,000	1	Creep Rate and Total Deformation Time
"17-22-A"S	700	115,000	1	Creep Rate and Total Deformation Time
	900	70,000	1	Creep Rate and Total Deformation Time
	1100	41,000	1	Rupture Time, Rupture Ductility, Creep Rate, and Total Deformation Time
	1100	19,000	1	Creep Rate and Total Deformation Time
"17-22-A"V	700	115,000	1	Creep Rate and Total Deformation Time
	900	70,000	1	Creep Rate and Total Deformation Time
	1100	40,000	1	Rupture Time, Rupture Ductility, Creep Rate, and Total Deformation Time
	1100	19,000	1	Creep Rate and Total Deformation Time

Creep-Rupture Testing Procedure

All creep and rupture tests were of the constant-load type, with the load being applied by a dead-weight, cantilever-beam system. The A.S.T.M. Recommended Practices E 22-41 and E 85-50T were followed for all tests.

In general, the specimens were brought to within 100°F of the test temperature 15 to 20 hours prior to loading, and the final temperature adjustments just prior to loading covered a 3 to 5 hour period. In the few instances where the test temperature was equal to or greater than the tempering temperature the sample was placed in the hot furnace only 4 to 6 hours before the load was applied. Extension measurements were recorded at least once every 24 hours using a modified Martens optical extensometer system capable of detecting an extension of 0.000010 inch.

All specimens were of the standard 0.505-inch or 0.250-inch diameter design with a length to diameter ratio of 4. The 0.505-inch diameter specimens were machined from the center of the bar stock, while the 0.250-inch diameter specimens were machined from the mid-radius of the bar stock. The machining was done after the heat treating.

PART I - EFFECT OF HARDNESS LEVEL ON THE PROPERTIES OF SAE 4340 AND "17-22-A"S STEELS

Previous work on SAE 4340 and "17-22-A"S included an evaluation of their elevated-temperature properties as a function of the type of microstructure. The structures in that study were all tempered to a hardness level of 300 BHN (± 20 BHN). To obtain information on the influence of hardness level, structures were studied which were exactly similar to those in the previous work, except that they were tempered to a hardness of 350 BHN (± 20 BHN).

Procedure

It was found that for 4340, the 350 BHN hardness level could be attained only with three structures; whereas, six "17-22-A"S structures could be successfully prepared at the higher hardness level. They were as follows:

SAE 4340	"17-22-A"S	
1. Oil Quenched	1. Oil Quenched	4. Upper Bainite
2. Normalized	2. Normalized	5. Middle Bainite
3. Lower Bainite	3. Lower Pearlite	6. Lower Bainite

The details of the heat treatments used to produce these structures are presented in Table I.

Survey-type creep and rupture tests were carried out on the higher hardness material under conditions identical with those previously used for the 300 BHN material (see pages 3 and 4). In this way, direct comparisons of the individual test data could be made in order to show the effect of hardness level on the creep-rupture properties. The upper testing temperature was limited to 1000°F due to the very low strength of 4340 steel at higher temperatures.

Results

SAE 4340 Steel

The test data for 4340 steel at both hardness levels are listed in Table II, and the same data are presented graphically in Figure 1.

The martensitic structure obtained by oil quenching was considerably stronger at 700° and 900°F when tested at a hardness level of 350 BHN than at 300 BHN. The softer material, however, was slightly stronger at 1000°F. Part of the superiority at 700°F appeared to be due to the yield strength of the 350 BHN material being above the testing stress of 90,000 psi, whereas the 300 BHN material yielded under this stress.

The trend of the results for the lower bainite structure was less consistent. At 700°F, the 350 BHN condition was subject to extensive primary creep and, therefore, attained 1.0-percent total deformation in much less time than the 300 BHN condition, although the small difference in final minimum creep rate favored the 350 BHN condition. At 900°F, the rapid primary creep again resulted in a lower deformation strength for the 350 BHN condition even though rupture time and minimum creep rate were superior for the higher hardness condition. At 1000°F all measures of strength favored the lower hardness condition. Again the more extensive primary creep resulted in a wide margin of inferiority for the higher hardness condition on a total-deformation basis.

When normalized, the relative properties were similar to those for the quenched martensitic condition, except that the differences were generally less. The only exception was the total deformation strength at 900°F where the test gave an abnormally high deformation on loading. This result was inconsistent and should not be accepted without further proof. The structure of the normalized material was about 35 percent martensite and 65 percent non-isothermal bainite. It seems reasonable that its properties as influenced by hardness level should be an average of the two effects as the data generally indicate.

Hardness level did not change the relative strengths of the three structures considered in most cases. Exceptions included the following:

1. At 700°F the harder tempered martensitic structure became superior to the other two.

2. At 900°F, the loss in superiority of the normalized structure at 300 BHN level seems questionable as previously discussed.

3. The tendency for the lower bainite to be superior at 300 BHN was offset by the rapid primary creep of the 350 BHN condition.

The properties of the three structures were compared with the data in References 1 and 2 to determine if the treatments giving maximum properties were different at the higher hardness. The conclusions derived were:

1. The highest strength properties at 700°F were exhibited by the martensitic structure tempered to 350 BHN. The next best structure was lower

bainite tempered to 300 BHN. The normalized material at 350 BHN was third. It should be emphasized that there was little difference on the basis of minimum creep rate. The advantages of the stronger structures were derived from the yield point being above the test stress of 90,000 psi and the smaller amounts of primary creep.

2. At 900°F optimum properties were obtained with the middle or upper bainite structures tempered to 300 BHN or with the lower bainite or normalized structures tempered to 350 BHN.

3. At 1000°F either the upper bainite or the normalized structures were best at the 300 BHN hardness level; whereas, only the normalized structure would be recommended for use at 350 BHN.

4. Ductility at rupture at 1000°F was generally higher at the higher hardness level, with the possible exception of the lower bainite structure.

"17-22-A"S Steel

A comparison of the test data at both hardness levels is given in Table III and Figure 2.

The tests all showed a large increase in strength for all structures at 700° and 900°F from reducing the tempering to raise the BHN from 300 to 350. The relative strengths of the various structures were in general unchanged. Lower and upper bainite, however, compared more favorably at the higher hardness level.

At 1100°F, there was very little difference between the two hardness levels for the various structures. Lower pearlite compared more favorably at the higher hardness level so that there was surprisingly little difference between the various structures.

Elongation and reduction of area values for the rupture tests were invariably reduced by increasing the hardness.

The large increase in strength at 700°F for the higher hardness condition was apparently due to the higher yield strength. All of the 300 BHN structures yielded on loading under the 115,000 psi stress. At 350 BHN there was no or very little yielding.

There is some question regarding the results arising from many of the comparisons being made with specimens from different heats. Only a few comparisons at 1100°F involved specimens from the same heat. Because there was very little difference in properties at 1100°F in any case, the general agreement in properties for the two heats at this temperature does not necessarily prove that this was not a factor in the larger effects at 700° and 900°F.

Discussion

One of the objectives was to determine if the various types of transformation products causing differences in microstructure responded differently when tempering was reduced and hardness increased from 300 to 350 BHN. The effects are somewhat complicated due to differences in the effects depending on the temperature and type of test as well as the initial structure. The following statements are indicated by the data:

1. In general the strengths were higher for the higher hardness condition at 700° and 900°F. Lower bainite in 4340 seemed to be an exception mainly due to increased primary creep. There was some indication that martensite in 4340 steel had better properties at these temperatures as a result of less tempering than would bainitic type structures.

2. The Cr - Mo - V ("17-22-A"S) steel showed far more strengthening at 700° and 900°F than did the Ni - Cr - Mo (4340) steel from increasing the hardness from 300 to 350 BHN. This suggests that some other factor than the type of microstructure was involved. Vanadium-bearing steels are known to undergo secondary hardening, presumably due to precipitation of vanadium carbides. Possibly the main reason for the higher strength of the vanadium steel at the higher hardness level is the avoidance of overaging during tempering.

3. There was far less difference in strength between types of structure in the vanadium-bearing steel at the higher hardness level than at the lower. The greater amount of tempering would normally be expected to equalize the structures and increase stability, thus reducing differences. If factors involving secondary hardening are involved, as suggested, it may be that there are substantial differences in the rates or forms in which it occurs during tempering in the various types of microstructures. Thus, more drastic tempering may cause "overaging" in some structures and not in others.

4. There was very little difference between the hardness levels for either steel at the higher testing temperatures. There was some evidence that the higher-hardness 4340 steel structures were becoming weaker as a result of more tempering during the tests at 1000°F. Structural instability of this type during testing generally lowers strength. There seemed to be little difference between the two hardness levels for "17-22-A"S at 1100°F. There was also little variation in strength between the different types of structures. This again suggests that some other factor than type of structure was controlling strength.

5. The role of degree of tempering and instability effects during testing are not clear from the results. There is no case where reduced tempering indicated substantial weakening for a given structure. It is, therefore, difficult to rationalize higher strength for one structure over another on the basis of more tempering. The results tend, therefore, to suggest some additional factor related to types of structure but not to structural stability as the controlling factor.

6. It was necessary to use rather high stresses in tests at 700° and 900°F to obtain appreciable creep. These stresses were in many cases above the yield strength. Thus the variation in deformation on loading as controlled by yield strength influenced comparative total deformation values far more than did the creep resistance. This points to the importance of yield strength as a limiting factor for service at these temperatures.

7. The lowered ductility in rupture tests for the Cr - Mo - V steel at 350 BHN again points to some precipitation reaction as a controlling factor. The 4340 steel which is presumably relatively free from secondary hardening did not show the loss in ductility from increased hardness and may in fact have had higher ductility.

PART II - GENERAL SURVEY OF THE RESPONSE OF "17-22-A"V STEEL TO HEAT TREATMENT

A higher vanadium modification of the "17-22-A"S type of low-alloy steel with reportedly considerably improved high-temperature properties was included in the present investigation for two reasons: (1) to increase the general pool of data on the high-temperature properties of low-alloy, ferritic materials; and (2) to check the generality of proposed principles derived from data on other ferritic materials. The steel was a medium carbon 1.25 Cr - 0.5 Mo - 0.8 V steel designated as "17-22-A"V.

The purpose of the general survey of "17-22-A"V steel was to determine its creep and/or rupture resistance at 700°, 900°, and 1100°F as a function of : (1) type of microstructure, (2) tempered hardness level, (3) rate of continuous cooling, and (4) austenitizing temperature.

Procedure

The initial step was the determination of an approximate isothermal transformation (TTT) diagram. Approximately 100 samples were used in the determination. The samples were one sixteenth-inch thick wafers, and they were examined microscopically after transformation at various temperatures and times.

Conditions of temperature and time were selected from the TTT diagram for six isothermal heat treatments: three covering the austenite → ferrite + pearlite transformation and three covering the austenite → bainite transformation. As in the previous work of this type on SAE 4340 and "17-22-A"S, the structures obtained by these six treatments were called upper pearlite, middle pearlite, lower pearlite, upper bainite, middle bainite, and lower bainite, in the order of descending temperature of transformation. These six isothermal produced structures together with the oil-quenched (martensitic) and the normalized (non-isothermal bainite) structures were all tempered to

300 BHN (+ 20 BHN) and constituted the eight basic types of structures planned for the study of the effect of type of microstructure. Actually, only seven structures were tested because the upper pearlite structure was so soft (less than 200 BHN) and weak that it was dropped from the program. The middle pearlite was also soft; hence, it was tested only at the untempered hardness of 250 BHN.

The effect of hardness level was studied by repeating the testing on the lower pearlite, upper bainite, middle bainite, lower bainite, oil-quenched, and normalized structures which had been tempered to a hardness of 350 BHN (± 20 BHN) instead of 300 BHN (± 20 BHN).

The effect of rate of continuous cooling was studied by producing and testing structures corresponding to the structures at the centers of normalized 3-inch and 6-inch diameter rounds. The structures were produced by air cooling 1-inch rounds in firebrick jackets to simulate the cooling at the centers of 3- and 6-inch rounds. The appropriate thicknesses of the firebrick jackets were determined by trial and error, using an actual cooling curve as a standard for the 3-inch round and a calculated cooling curve for the 6-inch round.

The effect of austenitizing temperature was studied by testing material oil-quenched from 1850°F and 2000°F, and material normalized from 1850°, 2000°, and 2200°F.

The details of all the heat treatments are presented in Table IV. The creep-rupture testing conditions and procedures were described on pages 3 and 4.

Results

The approximate isothermal transformation diagram is presented in Figure 3.

Figures 4 through 15 are photomicrographs of the structures of the "17-22-A"V steel before tempering and before and after creep testing. The individual creep- and rupture-test data are given in Tables V and VI. The same data are presented graphically in Figures 16 through 19.

The basic information used to evaluate the structural variations and their relations to properties was the time-temperature-transformation diagram (Figure 3). The lower temperature part of the diagram was difficult to establish with certainty due to the difficulty of distinguishing between low-temperature bainite and martensite. For this reason a definite M_s temperature was not established. There was no question, however, but that transformation occurred at 600°F within the time limits shown that definitely was not martensite. The extensive work required to establish an exact value did not seem warranted.

The "17-22-A"V analysis showed an extensive temperature range between the pearlite and bainite reactions where no transformation could be observed even after prolonged holding. This temperature range was from about 960° to about 1150°F. The lower vanadium "17-22-A"S steel showed some transformation at all temperatures, and the intermediate temperature range of long transformation times was very much narrower (Reference 1) than for "17-22-A"V steel.

Effect of Type of Structure and Hardness Level on Properties at High Temperatures

Based on Figure 3, transformation temperatures of 1350°, 1275°, and 1200°F were selected to produce structures in the upper, middle, and lower part of the pearlite reaction temperature range. Complete transformation was obtained at the two lower temperatures (Figures 11 and 12). Although there was not a large difference in microstructure, the lower pearlite was considerably harder than the middle pearlite (Table IV). The material produced by transformation at 1350°F was so soft, 170 BHN, that it was dropped from the program.

Samples similarly transformed at three temperatures in the bainite region, Table IV and Figures 13, 14, and 15, were produced for testing. The material held at 850°F for 2 hours only partially transformed due to the extremely slow rate at which the bainite reaction proceeds at this temperature and contained 40 percent martensite + 60 percent upper bainite and was, therefore, initially harder than the other samples. The lower pearlite structure was as hard as middle bainite.

The grain structure of all samples was very fine. Thus the austenitizing temperature of 1850°F was definitely below the coarsening temperature.

For comparative purposes, samples were also treated by air cooling and oil quenching. Air cooling produced a non-isothermal bainitic structure (Table IV and Figure 4). Oil quenching produced martensite (Table IV and Figure 9.)

Insofar as was determined, there were only two conditions of treatment which did not produce "pure structures" on transformation. The "upper bainite" was 40 percent martensite. The normalized sample was made up of 100 percent non-isothermal bainite which was quite similar in appearance to middle bainite.

The structures included in the evaluation of properties at high temperatures were tempered to Brinell hardness levels of 300 and 350. In most cases the tempering conditions were established by trial and error. The tempering treatments finally selected are detailed in Table IV. The microstructures after tempering to 350 BHN are shown in Figures 4, 9, 11, 12, 13, 14, and 15. There was no visible difference between structures tempered to 350 BHN and those tempered to 300 BHN. Therefore, photomicrographs for only one hardness level are shown for each type of initial structure. The hardness levels of 300 and 350 BHN were selected to provide data on the alloy at the hardness levels at which the alloy is commonly used. The same hardness levels were used in previous studies on the other alloys. The middle pearlite initially had a hardness of 255 BHN and consequently was tested without tempering.

The results of the tests at high temperatures are given in Table V and the properties are plotted as a function of transformation temperature and type of structure in Figure 16. The properties of the normalized material were plotted at a pseudo transformation temperature of 775°F mainly because they correlated best with the other structures at this temperature. This temperature agreed quite well with the appraisal of the initial microstructure being closest to middle bainite.

Study of the data indicates the following relationships between type of structure and properties at high temperatures:

1. At 700°F and a hardness of 350 BHN, the tempered bainites were considerably stronger than the tempered martensite or pearlitic structures. The normalized condition, however, was strongest.

When tested at 300 BHN, there was considerably more variation between structures, so that the weakest was lower pearlite and lower bainite, except for the middle pearlite which was always very weak. Upper bainite was little better than martensite.

It appeared that a major factor in differences in strength between structures at 700°F was the yield characteristics, particularly at the 300 BHN hardness level. The testing stress was both above and below the yield strength at this hardness level, depending on the structure. This seems likely to be the major reason for the relatively low strength of the middle pearlite with its 250 BHN. At 300 BHN, the middle bainite and normalized structures yielded least. At 350 BHN, there was little yielding by any of the structures on loading for testing. Consequently, the differences in strength were less and presumably due to differences in creep resistance. There is no obvious explanation for the superiority of the normalized structure at 350 BHN.

2. At 900°F, the bainitic structures again had the highest strength with lower pearlite having equivalent strengths. The middle pearlite was distinctly the weakest. Martensite was somewhat inferior to the bainites. Middle bainite was somewhat the strongest and upper bainite the weakest of the bainites. The non-isothermal bainitic structure produced by normalizing had strengths which would be anticipated from the predominantly middle bainite structure.

Altering the tempering to produce 300 and 350 BHN simply changed the strength level at 900°F but not the order of strength of the structures. The higher hardness material was the strongest in every case.

3. When tested at 1100°F, the differences in strength level between structures was reduced. Again the bainites and lower pearlite were the strongest, with the maximum strengths shifted to lower bainite. There was very little difference between the 300 and 350 BHN level conditions. In fact, the middle pearlite at 250 BHN compared quite favorably with the bainites.

4. The elongation and reduction of area in the rupture tests at 1100°F were comparatively high for all structures. The normalized material had the lowest values and the highest values were exhibited by the pearlites and upper bainite. In most cases the ductility values were lower for 350 BHN than for the 300 BHN level material. Upper bainite was an exception.

5. The results from this study indicate that bainitic type structures are generally superior in strength to all others. However, pearlitic structures tend to become equal at 900° to 1100°F. The data suggest that pearlitic type structures probably would be nearly equal to the bainites at all temperatures provided the stress was below the yield strength. Initially martensitic type structures tend to be inferior to the bainites. The mixed bainitic-martensitic structure of upper bainite definitely was inferior to the completely bainitic structures at temperatures of 900° to 1100°F.

When there are variations in the degree of yielding on stressing, relatively minor variations in yield strength can lead to wide variations in total deformation strength. This tends to exaggerate differences between initial structures which seems mainly dependent on yield characteristics. The variations in yield characteristics appear to be dependent on initial structure as well as hardness level.

6. The data on the influence of hardness level show the following important trends:

(a) There is no all-inclusive correlation between hardness and properties at high temperatures, even when there is no yielding on loading.

(b) Where there are relationships between properties and hardness they would only hold for one type of structure.

(c) The increases in strengths associated with increased hardness for a given structure decrease at the higher temperatures. It is probable that it also decreases with time at temperature at the higher temperatures.

The structures all underwent considerable spheroidization of carbides during testing at 1100°F, as is shown by Figures 4, 9, 11, 12, 13, 14, and 15. When tested at 700° and 900°F there was no appricable change in microstructure. All specimens except middle pearlite underwent a significant decrease in hardness during testing at 1100°F. The degree of softening increased from lower pearlite through upper, middle, and lower bainite to martensite. The change in hardness for the normalized structure was about the amount expected for the bainite present. The amount of softening was influenced to some extent by the testing time. It seemed, however, that the type of structure was the predominant factor.

It should be noted that the change in hardness during testing at 1100°F did not correlate with the relative strengths. The lower bainite which was the strongest underwent the most change, except for martensite. Upper bainite which was no stronger than the martensitic structure did not fall off nearly as much in hardness.

Structure	Hardness (BHN) Initial	Hardness (BHN) Final	Decrease in Hardness (BHN)	Testing Time at 1100°F (Hours)
Middle pearlite	255	253	2	743
Lower pearlite	347	393	54	839
Middle bainite	338	281	57	743
Upper bainite	348	276	72	763
Normalized	359	274	85	1103
Lower bainite	348	259	89	861
Martensite	345	160	185	1492

Effect of Rate of Continuous Cooling

Decreasing the rate of continuous cooling by oil quenching a 0.8-inch round, air cooling a 0.8-inch round, and simulating the air cooling of 3- and 6-inch rounds resulted in a wide range of microstructures (Table IV and Figures 4, 5, 6, and 9). Oil quenching produced a martensitic structure and normalizing a 0.8-inch round produced a structure near middle bainite. The transformation products for the simulated 3- and 6-inch rounds did not closely resemble any of the isothermally produced structures. A largely bainitic type structure with a little ferrite resulted from the simulated air cooling of a 3-inch round which probably underwent considerable alteration by tempering due to the slow cooling rate. The structure of the simulated 6-inch round resembled that of the isothermally produced "lower pearlite" (compare Figures 6 and 12) except that small areas of bainite were present instead of pearlite.

The properties of these structures at high temperatures (Table VI and Figure 19) generally showed superiority for the normalized 0.8- and 6-inch rounds. The 3-inch round was inferior to the oil-quenched material at 700° and 900°F, although there was little difference between the three normalized structures at 1100°F.

The ductility at rupture at 1100°F tended to increase as the cooling rate decreased.

Correlation of the properties of the continuously cooled structures with the properties of the isothermal structures shows the following trends:

1. The normalized simulated 6-inch round correlated quite well with the lower pearlite structure with respect to both appearance and properties. The only sizable discrepancy between the properties of the two structures occurred at 700°F where the creep rate of the simulated 6-inch round was significantly lower. At 1100°F, the lower pearlite structure resisted softening during testing better than did the 6-inch round.

2. The normalized simulated 3-inch round at 700°F was much weaker than any of the other structures, probably because of the severe tempering conditions used to bring the specimen down to the 300 BHN level. At 900°F a good correlation was found with the properties of the upper bainite structure; whereas, at 1100°F an excellent correlation was found with the properties of the middle bainite structure. The bainite in the simulated 3-inch round seemed to fall between the middle and upper bainites in appearance.

3. The 0.8-inch normalized structure, as mentioned previously, exhibited properties which fell on or near the line connecting the properties of the middle and upper bainite structures.

Effect of Austenitizing Temperature

Photomicrographs are presented in Figures 4, 7, 8, 9, and 10 showing the effect of austenitizing temperature on the normalized and the oil-quenched structures. The general effect of increasing the austenitizing temperature was to coarsen both the austenite grain size and the structures which formed during cooling or quenching. The creep- and rupture-test data for these structures are given in Table VI. The data for the normalized structure are also shown graphically in Figure 19.

At 700° and 900°F there were only minor changes in creep properties due to the higher austenitizing temperature. At 1100°F, however, both the normalized and the oil-quenched structures experienced significant increases in creep and rupture strengths, but the decrease in ductility more than offset the advantage of the gain in strength for most applications.

The ductility at rupture at 1100°F was very drastically reduced as the austenitizing temperature was raised from 1850°F to 2000° and 2200°F. The brittleness of the material normalized from 2200°F was so great that fracture occurred prematurely and without warning during the low-stress creep tests at 900° and 1100°F.

Discussion

The most general relationship derived from this study is the usual superiority in strength of bainitic-type structures. The pearlites, however, compared very favorably at the higher temperatures provided that the stress did not greatly exceed the yield point. In some cases they were better than the bainites. Within these generalizations there were numerous exceptions in detail because the structures varied in comparative strength depending on the test temperature.

The "17-22-A"V material studied had an extremely fine grain size when heat treated at 1850°F, the usual temperature for the alloy. Increasing the heat-treating temperature was very deleterious to ductility in the rupture tests at 1100°F. It also considerably increased the resistance to tempering, perhaps by increasing the amount of secondary hardening.

Structures produced by continuous cooling generally had properties in accordance with their type of microstructure as estimated from isothermally produced structures. There were, however, exceptions to this generality, particularly at a test temperature of 700°F.

Some of the data suggested that the amount of yielding on loading was a major factor in the evaluation of relative strengths of structures at 700°F. This was not true in all cases. Primary creep especially varied which considerably altered relative strengths based on total deformation.

Increasing the Brinell hardness to 350 by reducing the amount of tempering increased strength at 700° to 900°F for all structures. The amount of increase was usually quite uniform for all structures at 900°F. At 700°F the increases were more erratic due to the reasons discussed in the preceding paragraph. There was relatively little difference in strength between the two hardness levels at 1100°F. Usually ductility in rupture tests was reduced by the higher hardness.

The particular lot of material tested had relatively low strength for the alloy. The reason for this was not clear. Certainly increasing the austenitizing temperature above 1850°F did not develop the strength considered characteristic of the alloy.

When it is considered that the structures could be varied from lower bainite to lower pearlite and even middle pearlite without necessarily sacrificing strength, it becomes difficult to ascribe strength to the type of microstructure. In some cases tempered martensite compared quite well with the other structures. Some of the data suggested that prolonged tempering was harmful to strength. The data strongly suggest that some other factor than the type of microstructure actually controls strength, with the possible exception of the general inferiority of initially martensitic structures. Possibly the reactions which exhibit themselves as secondary hardening during tempering are the important factor. If so, the conditions which form bainite are usually favorable for high strength, although there are exceptions.

One important feature was revealed by the study of the influence of hardness. The relationship between strength and hardness level is dependent on the type of structure. Thus, the effect of hardness on the strength of one type of structure cannot be used to predict what effect hardness changes would have on another type of structure.

The relationship of properties of the "17-22-A"V steel to its microstructure follow most of the trends previously found (Reference 1) for 4340 and "17-22-A"S steels. In general, bainitic structures tend to have a high level of strength. In vanadium-bearing steels, however, there is not a regular progression of maximum strength from lower to middle to upper bainite with increasing test temperature as there was for the Ni - Cr - Mo (4340) steel. The lower and middle pearlite structures tend to compare better in the vanadium-bearing steels. Martensitic structures tend to have low to medium strengths.

Comparisons of the data of this report with that of Reference 1 shows that for "17-22-A"S and "17-22-A"V steels, middle bainite had the highest strength at 700°F at a hardness of 300 BHN. Also, lower bainite and the pearlites had inferior properties in both steels. Normalizing the "17-22-A"V produced higher relative properties than for "17-22-A"S.

At 900°F, the structures had about the same relative strengths for the two vanadium-bearing steels. The same was true at 1100°F, except that possibly the pearlite structures compared better with the bainites for the "17-22-A"V steel.

The outstanding difference was the much higher ductility of the extremely fine grained "17-22-A"V steel.

The experiments on the effect of continuous cooling rate showed some a decrease in strength for 4340 at 700°F (Reference 2) with decrease in cooling rate. On the other hand, "17-22-A"S (Reference 2) showed rather low strength for the 3-inch round as did "17-22-A"V in this report. Otherwise the relative strengths for the structures were similar for the two vanadium steels. At 900°F, the trends were also similar for the two vanadium steels, except that the normalized 0.8-inch round compared better for the "17-22-A"V steel. There was a slight increase in strength for 4340 steel with decreasing cooling rate. At 1100°F, both vanadium steels varied in the same way with cooling rate.

It should be noted that the tendency for the weak and strong structures to be the same for both "17-22-A"S and "17-22-A"V steels lends considerable significance to the effects noted when the variations based on one test seem questionable.

In general, the data for "17-22-A"V showed less influence of normalizing temperature than did the data for "17-22-A"S (Reference 2). It more nearly resembled the behavior of 4340 steel (Reference 2). Part of the difference between "17-22-A"V and "17-22-A"S may have been due to the major comparison being based on "17-22-A"V at 350 BHN and "17-22-A"S at 300 BHN. Other data have shown less variation in properties of the "17-22-A"V with structure at the higher hardness.

PART III - STUDY OF MIXED BAINITIC STRUCTURES

Interest in the development of microstructures containing a mixture of the upper- and lower-temperature forms of bainite grew from the idea that bainitic structures formed during continuous cooling (as in normalizing) are made up of an intimate mixture of bainites formed over a range of temperature. It was believed that one step toward a better understanding of these structures could be achieved through a study of structures containing a controlled mixture of two or more types of bainite. Stepwise, isothermal transformation heat treatments were used as a means of producing the mixed structures.

Procedure

To avoid the introduction of too many variables into the study it was decided that only structures containing two types of bainites would be considered. Structures of approximately 50-50 proportions of upper bainite and lower bainite were selected as being first approximations to the "stepwise isothermal equivalents" of the non-isothermal type of bainitic structures formed during continuous cooling.

The procedure used in producing the mixed bainitic structures was as follows: The steel was austenitized and quenched into an agitated salt bath maintained at a high bainitic temperature where it was held until the transformation to upper bainite was about 50 percent complete. Then it was transferred to a second salt bath maintained at a low bainitic temperature and held until the remaining austenite was completely transformed to lower bainite. The upper and lower bainitic temperatures selected were those used in the previous work on "pure" bainitic structures (Reference 1 for SAE 4340 and "17-22-A"S and Table IV of this report for "17-22-A"V. The holding or transformation time at each temperature was selected for each steel with the aid of a metallographic examination of a series of samples quenched out at various times. The specific heat-treating conditions finally selected for each steel are presented in Table VII.

Results

The structures of mixed bainites produced by the stepwise, isothermal heat treatments are shown in Figures 20, 21, and 22.

The creep and rupture test results are presented in Table VIII together with data for the normalized and the upper, middle, and lower bainite structures of all three steels. Figures 23, 24, and 25 show the same data graphically.

SAE 4340 Steel

The structure produced, Figure 20, was a mixture of upper and lower bainite. Comparison with the normalized structure (Reference 1) indicated that transformation to approximately 50 percent of upper and lower bainite does not produce the same structure as normalizing a 1-inch round.

The strength at high temperatures of the mixed bainitic structures (Table VIII and Figure 23) seemed to be an average for the two structures at 700°F. At 900°F and at 1000°F it was generally higher in creep strength than either one of the "pure" structures. The rupture strength at 1000°F for the conditions of testing were about the same as for lower bainite. Ductility in the rupture tests was low, however.

It appears that controlled mixtures of bainites in 4340 can be significantly stronger than the "pure" components under certain conditions, but in general this may not be true. At 900° and 1000°F the normalized structure was weaker than the mixed bainite structure probably because the normalized material was 35 percent martensite.

"17-22-A"S Steel

The structure produced, Figure 21, was about half upper and half lower bainite. It was considerably different from the structure produced by normalizing 1-inch round stock (Reference 1).

At 700° and 900°F, the mixed bainite structure was substantially stronger than either the upper or lower bainites tested (Table VIII and Figure 24). It was, however, somewhat weaker at 700° and slightly stronger at 900°F than middle bainite. It was substantially stronger than the normalized condition at these temperatures.

At 1100°F, there was not too much difference in strength between any of the bainitic type structures. The mixed bainite appeared to have creep and rupture strengths averaging between those for the pure structures. There was not much difference in ductility in the rupture tests.

As for the 4340 data, the indications are that mixed bainitic structures have varying strengths depending on temperature and stress of testing and the type of structure. At any one test condition one type of mixed structure may have superior properties to the pure structures. The strength of the mixed structures cannot always be estimated by averaging the properties of the "pure" structures.

"17-22-A"V Steel

The structure of the "17-22-A"V material was approximately half lower and half upper bainite as may be seen by comparing Figures 22 with Figures 13 and 15. Furthermore, it closely resembled the normalized structure (Figure 4). It seemed as if the combination of cooling conditions and transformation rates for this very fine-grained alloy resulted by chance in a fairly good reproduction of the normalized structure by attempting to produce the mixed upper and lower bainite structure.

The properties of the mixed bainitic structure (Table VIII and Figure 25) were generally similar to those of the normalized material. It must be admitted that it was equally close to the lower bainite in properties. It was, however, considerably better than upper bainite at 900° and 1100°F and probably inferior at 700°F. Ductility in the rupture tests was not greatly different from the other structures.

In "17-22-A"V steel, the range in strength for all the bainites was not very great. The main exception was upper bainite which actually contained a large amount of martensite as transformed. It almost appears that some factor in composition or transformation characteristics, possibly the fine grain size, other than the type of bainite was governing properties.

Discussion

This study of the properties of mixed bainitic structures mainly demonstrates that the properties cannot be estimated from the percentage of types of bainite present. Possibly there are different optimum combinations for each test condition.

It must, however, be admitted that part of the difficulty of estimating properties from the percentage of type of structure present may be due to the presence of considerable amounts of martensite in the samples tested as upper bainite. A pure upper bainite cannot be produced due to the extremely long time for complete transformation in the upper part of the bainitic region.

PART IV - STUDY OF THE EFFECT OF A PRIOR HOMOGENIZATION NORMALIZE

Differences in the prior thermal histories of two samples of a low-alloy steel could result in appreciable differences in strength even after identical final heat treatments. To moderate the effect of differences in prior history, and to improve chemical homogeneity, it is common practice to use a normalizing treatment at a somewhat higher temperature than the final heat treating temperature prior to the final heat treatment.

The purpose of this study was to determine for the three subject steels whether the prior normalizing treatment appreciably affects the relationships of elevated-temperature creep and rupture strengths to types of microstructures.

Procedure

The procedure followed in this study was simply to repeat the preparation and testing of three typical structures for each steel, with the only difference being the use of a normalizing treatment prior to the final heat treatment. The austenitizing temperature used for the prior normalize was 100°F higher than that used for the final heat treatment. The details of the heat treatments are given in Table VII.

The structures selected for testing were the same for all three steels and included the normalized, oil-quenched, and middle bainite structures. The creep-rupture testing conditions used were the same as for the original studies of these structures. (See pages 3 and 4 of this report.)

Results

The microstructures produced by the heat treatments involving the prior normalize are presented in Figures 26 through 34. The creep- and rupture-test data for these structures are given in Table IX where they are compared directly with the data from exactly similar tests on material which was not given a prior normalizing treatment. The results are also shown in Figures 35, 36, and 37.

SAE 4340 Steel

The prior normalize at 1850°F followed by the final treatment at 1750°F apparently resulted in an increase in the austenitic grain size. The normalized structure (Figure 26) was definitely coarser than the structures shown in Reference 1 for a single normalize. The same was true for the oil-quenched structure (Figure 27), although there were other alterations in the detailed structure of the martensite. The middle bainite structures for the two cases were similar except for a background indication of a larger austenitic grain size in Figure 28.

The prior normalize raised strengths in every case considered, Table IX and Figure 35, except possibly for the martensitic, oil-quenched condition at 900°F. The largest effect was at 900°F. The rupture tests were influenced less at 1000°F than the creep tests. In general, there was not very much difference in the effect between the three structures considered.

The prior normalize lowered ductility in the rupture test in every case.

"17-22-A"S Steel

The prior normalize had no apparent effect on the properties of "17-22-A"S in the oil-quenched and the normalized conditions. In the case of the middle bainite structure there appeared to be some minor strengthening of the long-time properties due to the prior normalize.

The ductility at fracture at 1100°F appeared to be essentially unaffected by the prior normalizing treatment.

"17-22-A"V Steel

The normalize at 1950°prior to final treatment at 1850°F considerably coarsened all three structures. Compare Figures 32, 33, and 34 with Figures 4, 9, and 14, respectively. In addition, the middle bainite became considerably more needle like in form.

The strengths at 1100°F were increased for all three structures by the prior normalize. Ductility in the rupture tests was reduced.

There was little effect of the prior normalize on properties at 900°F. At 700°F, the martensite structures showed some loss in strength. The middle bainite showed a decrease in total deformation strength and an increase in secondary creep resistance. The normalized condition was changed very little.

Discussion

The use of a prior normalizing treatment at 100°F above the final heat-treating temperature gave varying effects. In general, the relative strengths of the structures considered were not changed. The SAE 4340 was strengthened at all three test temperatures. There was little effect on the strength of "17-22-A"S steel at any of the test temperatures. The strength of the "17-22-A"V steel was improved to a minor extent at 1100°F. Ductility in rupture tests was reduced.

The main effect of the prior normalize was to coarsen the structure. It also demonstrated that the appearance of the bainites formed at a given temperature can be changed, at least in an initially extremely fine-grained structure like the "17-22-A"V steel tested.

A prior normalize might be expected to achieve more complete solution of carbides and other possible precipitates. These act as grain growth restrainers. It appeared that they were more soluble after the prior normalize in all three steels because a coarser structure resulted during final treatment. The more complete solution, however, had surprisingly little effect on strength. The results suggest that some other factor than degree of solution or coarseness of structure is a controlling factor in variation in strength.

PART V - EFFECT OF HOT-WORKING CONDITIONS

The purpose of this phase of the investigation was to survey for the three subject steels (1) the effect of hot-working conditions on the response to subsequent heat treatment,and (2) the possibility of using controlled hot rolling as a means of producing new structures with superior strength and ductility.

Procedure

Effect of Hot Working on Response to Subsequent Heat Treatment

It was suggested that the finishing temperature might be the hot-rolling variable which has the greatest effect on the response of a low-alloy steel to subsequent heat treatment. Therefore, a brief study was made of the effect of finishing temperature on the response to a subsequent normalizing heat treatment for the SAE 4340, "17-22-A"S, and "17-22-A"V steels.

Three finishing temperatures, 1800°, 2000°, and 2200°F were chosen as being below, at or near, and above the grain-coarsening temperature for the austenite of the subject steels, respectively. At each of the three temperatures, one bar of each steel was hot rolled 25 percent (± 3 percent) in one pass through the rolls and air cooled. The bars were then normalized and tempered as they were for the original studies of these steels. The details of the treatments are given for each steel in Table X and are designated there as Conditions A, B, and C.

Controlled Hot Working

Past experience has shown that high creep strengths are often associated with high austenitizing temperatures. Unfortunately, low ductility also results from the use of high austenitizing temperatures. It was thought that a good combination of strength and ductility might be obtained if the steel were austenitized at a high temperature and then hot rolled at a lower temperature to refine the austenite grain size just prior to the transformation to bainite during air cooling. It has also been noted in many isolated cases that remarkably high strengths and ductilities are associated with hot-rolled structures. One of the objectives was to determine if the combination of high temperature of heat treatment followed by subsequent grain refinement by working was responsible.

Two variations of this type of treatment were carried out on each steel. In the first, the bars were withdrawn from the austenitizing furnace and allowed to air cool until their surface temperature had fallen 300°F, and then they were hot rolled 25 percent in one pass. The second variation differed from the first only that the 25 percent reduction was accomplished in three steps while the temperature was falling 300°F. In all cases the surface temperature was determined by the use of Tempilstiks (Reference 3). After rolling, the bars were allowed to air cool, and then they were tempered to 300 BHN or 350 BHN, depending on the steel. The details of these two treatments are given for each steel in Table X where they are designated as Conditions D and E.

Creep-rupture testing was carried out on all of the structures of the hot-rolling study in accordance with the procedure described on page 4 and under the following testing conditions:

Steel	Test Temperature (°F)	Stress (psi)	No. of Tests
SAE 4340	1000	31,000	1
	1000	20,000	1
	1000	12,000	1
"17-22-A"S	1100	41,000	1
	1100	30,000	1
	1100	19,000	1
"17-22-A"V	1100	40,000	1
	1100	30,000	1
	1100	19,000	1

The relative strengths of the structures were evaluated on the basis of three types of graphs: (1) log stress vs. log time to rupture, (2) log stress vs. log minimum creep rate, and (3) stress vs. log time to reach 0.5-percent total deformation.

Results

The structures produced for the study on hot-rolling conditions are shown in Figures 38 through 52. The creep- and rupture-test results are given in Table XI and Figures 53, 54, 55, along with comparable data for normalized conditions for the original bar stock.

SAE 4340

Increasing the temperature of a reduction of 25 percent prior to normalizing at 1750°F generally increased the coarseness of the largely bainitic structures for the as-rolled, air-cooled structures (see Figures 38, 39, and 40). When subsequently normalized from 1750°F, the variation in coarseness was greatly reduced with the material rolled at 2000°F possibly being slightly coarser than the others. The material rolled 25 percent at 2200°F may have had more martensite present.

The material reduced 25 percent at 1800°F was weaker than those reduced at 2000° and 2200°F (Figure 53). The only exception to this was the material reduced at 2200°F in the highest stress tests. It was also generally slightly weaker than the bar stock tested without prior working. The increase in strength for longer-time service from the reduction of 25 percent at 2000°F and 2200°F was very substantial. Rupture test ductility was not appreciably altered by the prior hot work.

It must be recognized that at the present state of estimation of properties from microstructures, it would not have been possible to anticipate the observed effects. The study of prior normalizing showed an increase in strength from treatment at 1850°F. In this case rolling at 1800°F reduced strength. The increase in coarseness of structure observed from the prior normalize did not appear in the material rolled prior to final treatment. The increasing coarseness of the as-rolled structures suggests that no substantial refinement in austenitic grain size was achieved by the 25 percent reduction.

The structures developed from heating to 2100° and working at 1800°F and for working down from 2100°F are shown by Figures 41 and 42. The latter material appeared to be somewhat the finer of the two structures. Both showed a greater tendency for a Widmanstatten type structure than did those worked isothermally.

The specimens worked and then tempered generally had strengths at 1000°F on the high side of the range of values of Table XI and Figure 53. This was more nearly true for creep properties than for rupture tests. The material simply heated to 2100°F and air cooled was as strong or stronger by all of the strength criteria except time to reach 0.5-percent total deformation. Those samples which were hot worked and tempered had considerably lower ductility in the rupture tests than those which were subsequently normalized.

This study indicates that conditions of heating and working have a substantial effect on the response to subsequent heat treatment. The attempt to produce superior properties by hot working and tempering without an intermediate normalize was not successful in the limited study made. The degree of refinement of austenitic grain size necessary was not obtained by the working conditions studied.

"17-22-A"S

The reduction of 25 percent at 1800°, 2000°, and 2200°F resulted in some coarsening of the structure in the hot-worked condition. (See Figures 43, 44, and 45.) Working at 1800°F apparently caused predominantly upper bainite to form while the other two were largely middle bainite. When subsequently normalized at 1750°F, there did not appear to be much variation in structure. The structures were similar to that of the original bar stock normalized from 1750°F as shown in Reference 1.

The strength properties, Table XI and Figure 54, were not changed significantly by the conditions of hot working prior to heat treatment. The strengths were generally slightly lower than for the material produced by normalizing the original stock. Ductility in the rupture tests was not appreciably changed, all being low.

When heated to 2100°F and cooled to 1800°F for 25 percent reduction, the structure (Figure 46) was similar to that for specimens reduced 25 percent at 2000° or 2200°F (Figures 44 and 45). There appeared to be little, if any, refinement of grain structure. Reducing 25 percent during cooling from 2100°F to 1800°F produced a very similar structure (Figure 47). The net result of simply tempering these as-rolled structures was the testing of bainitic structures which were considerably coarser than those which were normalized from 1750°F after rolling.

These as-rolled and tempered structures had substantially increased creep resistance as measured by minimum creep rate or total deformation strength at 1000°F (Figures 54). Simply normalizing from 2100°F, however, gave the highest values. The same types of treatment possibly increased the longer time rupture strengths.

Working from 2100° to 1800°F or at 1800°F after heating to 2100°F and then simply tempering developed ductilities in the rupture test about the same or slightly higher than a single normalize from 1750°F. It was, however, better than for a simple normalize from 2100°F.

The absence of any effect on properties from a reduction of 25 percent at 1800°, 2000°, or 2200°F suggests that the stock initially was prepared under conditions which represented reasonably complete solution effects. The subsequent working did not greatly alter the response to heat treatment. The coarser structure and the change in the bainite resulting from testing hot-rolled and tempered structures resulted in higher strengths. The working apparently restored the ductility in the rupture tests lost from simply normalizing from 2100°F. Thus the latter experiment began to approach the objectives of obtaining high strength from high temperature treatments and high ductility in the rupture test by subsequent refinement of the structures by working.

"17-22-A"V Steel

In the samples rolled 25 percent at 1800°, 2000°, and 2200°F, the as-rolled structures were increasingly coarse (Figures 48, 49, and 50). When subsequently normalized from 1850°F the material reduced 25 percent at 1800° or 2200°F showed an increase in grain size. Even the material rolled at 2000°F prior to normalizing was coarser grained than the original stock normalized from 1850°F. Compare Figures 48, 49, and 50 with Figure 4.

The type of bainite formed was similar to that of the plain normalize from 1850°F.

The working at 1800°, 2000°, or 2200°F did not increase rupture strength (Table XI and Figure 55). Creep resistance, particularly at the lower two stresses, was increased with working at 1800° and 2000°F being most effective. Hot working, especially at 2200°F, reduced the rupture ductility from that of a simple normalize from 1850°F. The material reduced 25 percent at 2000°F had the finest grain size and the highest ductility of the three conditions of hot working investigated.

When hot worked and tempered without a normalize, coarser structures were produced (Figures 51 and 52). The bainite changed in appearance from the normalized structures but was still largely middle bainite.

Rupture strengths (Table XI and Figure 55) were less than for a simple normalize from 1850°F but considerably higher than for a simple normalize from 2200°F. Creep resistance was as high or slightly higher than when reduced 25 percent and subsequently normalized from 1850°F. The simple normalize from 2200°F, however, gave higher creep strength.

Both hot-rolled and tempered conditions had very low ductility in the rupture tests. It was, however, higher than for the simple normalize from 2200°F. The low ductility was probably responsible for the comparatively low rupture strength.

The results suggest that control of hot-working conditions could considerably improve creep resistance with still adequate rupture test ductility when normalized from 1850°F. The experiments carried out did not, however, develop a combination of high strength and high ductility. This seemed to be due to the failure to obtain grain refinement during working. The indication of coarsening of the structure obtained by normalizing at 1850°F after a 25 percent reduction at 1800°F was unexpected and is not understood.

Discussion

Only a very limited number of conditions of hot working were studied. It is therefore, difficult to generalize. The evidence presented shows some conditions which should be avoided, particularly from the viewpoint of ductility in the rupture tests. Also there are indications that improvement in strengths can be obtained with adequate ductility. One of the disappointing features was the absence of significant grain refinement in the hot-worked condition. Further experiments should be undertaken where working is started at a high temperature for good solution and continued with decreasing temperatures below the coarsening temperatures of the austenite. By proper working below the coarsening temperature of the austenite, it should be possible to develop a ductile, fine-grained structure with the high strength from the original high temperature treatment.

LIMITATIONS OF RESULTS

There are certain limitations to the generality of the results. A very limited number of tests were used to evaluate properties in most cases. The data were, however, surprisingly consistent in most instances. It was evident in attempting to correlate results, that considerably more experience in interpreting the structures would be desirable. This was particularly true when heat-treating temperature and prior history were varied. The structures then were often considerably different in appearance from those developed for the base stock. The ability to better interpret structures resulting from continuous cooling would also be helpful.

It was necessary to change heats of 4340 and "17-22-A"S steels for experimental stock. Although no definite difference in response between heats was identified, it could be a factor in the results. The "17-22-A"V stock tested had considerably lower strength than is considered typical for the alloy. It was extremely fine grained when treated at the usual heat-treating temperature of 1850°F. Surprisingly, increasing solution-treating temperature did not appreciably increase strength, and no treatments were found which brought the strength up to expected levels. When the relatively low strength was initially found it was thought that prior history was probably responsible for the low strength. However, the absence of a drastic improvement in strength suggests that some unidentified factor characteristic of the heat was responsible.

Attempts were made to correlate results in terms of structural stability during testing. However, no consistent trends could be developed. A high-strength structure in one case might show little change while in another pronounced changes would occur. The same was true for low-strength structures. Consequently, little was done beyond showing microstructures and hardness after testing. Likewise, little could be gleaned from the degree of tempering before testing. The only trend noted was abnormally low strengths for a structure when longer than or higher tempering temperatures than usual were required to obtain the desired hardness. It should also be noted that no systematic data were obtained on the influence of tempering conditions for a given hardness level.

CONCLUSIONS

The studies carried out on the various aspects of the relationships between microstructure and high temperature properties at 700° to 1100°F of a Ni - Cr - Mo (SAE 4340) steel and two Cr - Mo - V ("17-22-A"S and "17-22-A"V) steels for this report and as previously reported in References 1 and 2 lead to certain generalities and conclusions:

1. In most cases bainitic structures provide the best properties. At the higher temperature end of the range, the pearlitic structures tend to have equal and sometimes better properties, especially for Cr - Mo - V steels.

2. In 4340 steel, the trend for maximum strength varied from lower bainite to upper bainite as the test temperature was increased from 700° to 1100°F. In the Cr - Mo - V steels, however, this regular trend did not exist. Furthermore, under most testing conditions one bainitic structure would prove to be abnormally weak. The agreement obtained between the two vanadium-bearing steels in those cases indicates that the effects were real and not due to experimental errors.

3. In most cases, increasing the hardness level by reducing the tempering improved strength but was detrimental to ductility in the rupture tests. The effect, however, became quite small at 1000°F for 4340 steel and at 1100°F for the Cr - Mo - V steels. There were exceptions to this, particularly at the lower test temperatures where apparently, the increase in yield strength reduced the effect of yielding during loading for tests at the lower hardness level. Differences in properties between structures tended to be reduced at the higher hardness level, particularly for the "17-22-A"V steel.

4. The data indicate that different initial transformation structures can have very different strength properties at the same hardness level. At best, hardness can be used to predict strength only when it is applied to a specific structure.

5. A considerable amount of the data indicated that yielding during application of the stress was harmful to properties. This was most evident in testing at 700° and 900°F. There were a sufficient number of exceptions, however, to indicate that this was not the only factor. It was evident, however, that variations in yield characteristics as influenced by the type of microstructure at a given hardness level was important to properties in most cases.

6. A very limited study of controlled, mixed bainite structures showed that generally the properties cannot reliably be estimated from the proportions of the isothermally formed structures present. This may have been due, however, to the use of upper bainite as one of the structures. The so called "pure" upper bainite structures produced isothermally contained large proportions of martensite due to the impossibility of obtaining complete transformation to upper bainite in reasonable time periods.

7. Certain mixed structures have superior or inferior properties. These vary with the test conditions. The investigation was too limited to define the exact relationship. Apparently it might, however, be possible to attain superior properties for each steel through a particular mixed structure.

8. Continuous cooling produces mixed structures except when the rate is fast enough to form martensite. The studies of the effect of continuous cooling rate did not, therefore, give very uniform results between steels. The structure formed by continuous cooling of the Cr-Mo-V steels as simulated 3-inch rounds was suprisingly weak for both steels, particularly at 700° and 900°F.

A largely ferritic structure containing lower pearlite developed in the "17-22-A"V analysis on cooling as a 6-inch round with remarkably high properties in spite of the apparent large amount of ferrite in the structure.

9. The use of a prior normalize 100°F above the final heat-treating temperature increased strengths for 4340 and "17-22-A"V steels but had relatively little effect on "17-22-A"S. The ductility of 4340 and "17-22-A"V in rupture tests was reduced. Such treatments coarsened the microstructure.

10. Increasing the normalizing temperature above the usual heat-treating temperature increased creep resistance in most cases. It was not effective in increasing rupture strengths, probably because the ductility became so low.

11. A very limited survey of the influence of conditions of hot working on properties was carried out. Data were obtained indicating considerable influence on response to subsequent heat treatment for 4340 and "17-22-A"V steels. Attempts to take advantage of the strengthing from a high-temperature treatment followed by refining the grain size by hot working and then testing with only a temper were not too successful. Partial success was attained for "17-22-A"S. So little work was done, however, that no conclusions should be drawn from the data.

12. The results seem to raise serious question as to the real significance of the type of microstructure formed. This is particularly true for the vanadium-bearing steels where maximum strength can vary between lower bainite and middle pearlite. Also certain treatments developing mixed structures gave even better properties. It may be that other precipitation-type reactions such as the secondary hardening reactions in the vanadium-bearing steels are the real controlling factor. The usual superiority of the bainite-type structures may largely be due to accompanying unidentified reactions.

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TABLE I

Structures and Heat Treatments Used in the Study of the Effect of Hardness on Properties of SAE 4340 and "17-22-A"S Steels

Structure	Initial Heat Treatment	Average Hardness Before Tempering (BHN)	Tempering Conditions	
			300 BHN	350 BHN
	SAE 4340 Steel			
Oil Quenched (100% Martensite)	1 Hour at 1750°F, Oil Quenched (0.8-in. round)	585	10 hrs. at 1100°F	1.5 hrs. at 1000°F
Normalized (65% Bainite + 35% Martensite)	1 Hour at 1750°F, Air Cooled (0.8-in. round)	385	1 hr. at 1100°F	0.5 hr. at 900°F
Lower Bainite (100% Fine Bainite)	1 Hour at 1750°F, Isothermally Transformed 1.5 hrs. at 650°F, Water Quenched (0.4-in. round)	430	1.25 hrs. at 1100°F	0.5 hr. at 900°F
	"17-22-A"S Steel*			
Oil Quenched (100% Martensite)	1 Hour at 1750°F, Oil Quenched (0.8-in. round)	525	1 hr. at 1300°F	3 hrs. at 1200°F
Normalized (85% Bainite + 15% Martensite)	1 Hour at 1750°F, Air Cooled (0.8-in. round)	355	10 hrs. at 1200°F	15 hrs. at 1100°F
Lower Pearlite (40% Pearlite + 60% Ferrite)	1 Hour at 1750°F, Isothermally Transformed 10 hours at 1150°F, Water Quenched (0.4-in. round)	375	12 hrs. at 1200°F	3 hrs. at 1100°F
Upper Bainite (60% Bainite + 40% Martensite)	1 Hour at 1750°F, Isothermally Transformed 2 hrs. at 900°F, Water Quenched (0.4-in. round)	465	16 hrs. at 1200°F	12 hrs. at 1100°F
Middle Bainite (97% Bainite + 3% Martensite)	1 Hour at 1750°F, Isothermally Transformed 0.5 hr. at 800°F, Water Quenched (0.4-in. round)	360	4 hrs. at 1200°F	8 hrs. at 1100°F
Lower Bainite (100% Fine Bainite)	1 Hour at 1750°F, Isothermally Transformed 0.2 hr. at 700°F, Water Quenched (0.4-in. round)	365	12 hrs. at 1200°F	12 hrs. at 1100°F

* All values given are for Heat No. 10420.

TABLE II.

Comparison of Rupture, Creep, and Total Deformation Data at the 300 and 350 BHN Hardness Levels for SAE 4340 Steel Tested in the Range of 700° to 1000°F

Structure	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)		Elongation (% in 4D)		Reduction of Area (%)		Def. on Loading (%)		Min. Creep Rate (%/hr)		Time to Reach Specified Total Deformation (hours)					
													0.2 Percent		0.5 Percent		1.0 Percent	
			300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN
Oil Quenched (Tempered)	700	90,000	>1350.0	>1222.9	-	-	-	-	0.430	0.342	0.00027	0.000138	b	b	2.0	350.0	675.0	~3000 e
	900	55,000	381.0	887.4	19.5	11.0	39.5	12.3	0.269	0.292	0.01480	0.00546	b	b	2.0	~ 2.0	13.0	20.0
	1000	31,000	160.0 e	143.1	11.0	12.5	15.0	17.0	0.149	0.376	0.02500	c	~1.0	-	3.5	-	16.0	-
	1000	20,000	780.0 e	693.9	12.0	21.5	15.0	23.0	0.099	0.113	0.00380	0.0060	7.0	~ 2.0	47.0	15.0	190.0	72.0
Normalized (Tempered)	700	90,000	>1294.0	>1224.9	-	-	-	-	0.467	0.408	0.00016	0.00015	b	b	1.0	25.0	1000.0	~1700 e
	900	55,000	842.0	>1177.7	12.0	-	22.3	-	0.260	0.381	0.00414	0.0016	b	b	8.0	<1.0	64.0	~ 5.0
	1000	31,000	371.0	268.1	5.5	12.5	7.4	13.5	0.126	0.164	0.00505	0.01260	~ 5.0	<1.0	50.0	10.0	145.0	40.0
	1000	20,000	1392.0	1090.1	5.0	7.0	4.0	7.0	0.090	0.106	0.00114	0.00213	20.0	~5.0	228.0	55.0	650.0	275.0
Lower Bainite (Tempered)	700	90,000	>1485.0	>1223.6	-	-	-	-	0.502	0.482	0.00016	0.00022	b	b	~1.0	b	2000 e	575.0
	900	55,000	897.0	1410.3	18.5	5.0	15.4	6.3	0.250	0.298	0.00530	0.0020	b	b	8.0	~ 5.0	51.0	35.0
	1000	55,000	f	13.5	-	19.0	-	34.8	-	0.350	-	c	-	b	-	c	-	c
	1000	31,000	210.0	263.7	9.4	10.0	17.0	10.1	0.161	0.220	0.01790	0.00188	~ 1.0	~ 1.0	~ 6.0	~ 6.0	26.0	20.0
	1000	20,000	f	1074.6	-	8.0	-	7.4	-	0.161	-	0.00244	-	~ 2.0	-	18.0	-	123.0
	1000	13,000	>1035.0	f	-	-	-	-	0.055	-	0.00053	-	32.0	-	300.0	-	1100 e	-

b	Value exceeded on loading
c	Unavailable because of insufficient data
d	Ruptured on loading
e	Extrapolated or interpolated value
f	No test run under these conditions
>	Greater than (test was discontinued at this time)
>>	Much greater than
<	Less than
~	Approximately

TABLE III

Comparison of Rupture, Creep, and Total Deformation Data at the 300 and 350 BHN Hardness Levels for "17-22-A"S Steel Tested in the Range of 700° to 1100°F

Structure	Test Temp. (°F)	Stress (psi)	Rupture Time (hrs)		Elongation (% in 4D)		Reduction of Area (%)		Def. on Loading (%)		Min. Creep Rate (%/Hr)		Time to Reach Specified Total Deformation (Hours)					
													0.2 Percent		0.5 Percent		1.0 Percent	
			300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN
Oil Quenched (Tempered)	700	115,000	289.0 a	>1125.7	19.8	-	63.3	-	0.6700	0.538	0.00950	0.00016	b	b	b	b	1.0	~1500
	900	70,000	756.0 a	> 888.0*	30.3	-	64.0	-	0.3780	0.365	0.00384	0.00028	b	b	3.0	30.0	50.0	~1500
	1100	41,000	23.4 a	52.7	28.0	5.5	27.5	10.0	0.1730	0.224	0.00650	c	c	b	b	~4.0	c	24.0
	1100	19,000	850.0 a e	712.7	4.0	2.0	-	5.5	0.1050	0.102	0.00152	0.00150	17.0	30.0	170.0	220.0	420.0	492.0
Normalized (Tempered)	700	115,000	132.0 a	>1205.0	21.0	-	61.9	-	0.6600	0.623	0.0220	0.000047	b	b	b	b	1.0	>>1205.0
	900	70,000	>1482.0 a	>1205.0	-	-	-	-	0.3350	0.352	0.0003	0.000079	b	b	24.0	175.0	1400.0	>>1205.0
	1100	41,000	112.0 a	92.8	2.5	2.0	3.1	2.4	0.2120	0.1980	0.00614	0.00420	b	~0.1	26.0	~10.0	-	60.0
	1100	19,000	900.0 a e	1211.4	2.0	1.0	-	0.8	0.0850	0.096	0.00063	0.00050	80.0	55.0	580.0	500.0	800.0	1050.0
Lower Pearlite (Tempered)	700	115,000	a d	>1296.0	19.0	-	61.0	-	-	0.843	-	0.000540	b	b	b	b	b	<0.5
	900	70,000	>1205.0 a	>1176.0	-	-	-	-	0.4060	0.279	0.00223	0.000385	b	b	2.0	60.0	53.0	1180.0
	1100	41,000	42.0	49.1	8.5	5.5	8.7	5.1	0.2260	0.231	c	c	b	b	4.0	c	12.0	c
	1100	19,000	f	677.2	-	4.5	-	3.5	-	0.0780	-	0.00178	-	22.0	-	185.0	-	385.0
	1100	15,000	652.0 a	>1148.7	15.5	-	17.1	-	0.0650	0.0630	0.00340	0.00068	54.0	72.0	107.0	500.0	218.0	1025.0
Upper Bainite (Tempered)	700	115,000	147.0 a	>1176.8	20.2	-	62.0	-	0.7100	0.424	0.0180	0.00011	b	b	b	~10.0	<1.0	2000
	900	70,000	686.0 a	>2376.7	30.0	-	59.5	-	0.3550	0.3900	0.00504	0.000064	b	b	1.0	70.0	50.0	>>2376.0
	1100	41,000	51.5	58.9	7.2	5.0	8.6	7.1	0.2690	0.2700	c	0.0224	b	b	4.0	5.0	13.0	24.0
	1100	19,000	796.0 a	851.2	5.8	3.0	6.6	4.1	0.1100	0.087	0.00140	0.00155	8.0	65.0	177.0	230.0	447.0	490.0
Middle Bainite (Tempered)	700	115,000	>1827.0 a	>2544.2	-	-	-	-	0.6100	0.513	0.00029	<0.00001	b	b	b	b	45.0	>>2544.0
	900	70,000	>1648.0 a	>2448.6	-	-	-	-	0.3230	0.309	0.00014	0.000052	b	b	65.0	510.0	2500 e	>>2448.0
	1100	41,000	88.2 a	83.6	5.1	2.5	4.9	3.3	0.2170	0.232	c	c	b	b	6.0	9.0	19.0	40.0
	1100	19,000	815.0 a	938.1	4.0	~1.0	3.0	~1.0	0.0960	0.105	0.0015	0.00081	30.0	35.0	222.0	360.0	575.0	735.0
Lower Bainite (Tempered)	700	115,000	59.4 a	>1298.0	18.8	-	66.7	-	0.8150	0.5110	0.0452	0.000047	b	b	b	b	<1.0	>>1298.0
	900	70,000	1456.0 a	>1200.0	24.0	-	56.2	-	0.3500	0.3480	0.00115	0.000072	b	b	12.0	550.0	362.0	>>1200.0
	1100	41,000	92.8	119.1	5.0	2.0	4.0	2.5	0.2520	0.2400	0.0165	0.0090	b	b	9.0	22.0	32.0	64.0
	1100	21,000	889.0 a	f	2.0	-	5.6	-	0.1740	-	0.00113	-	6.0	-	198.0	-	604.0	-
	1100	19,000	f	1278.9	-	4.0	-	4.7	-	0.0940	-	0.00085	-	60.0	-	375.0	-	855.0

a	Heat No. 24797: all others from Heat No. 10420
b	Value exceeded on loading
c	Unavailable because of insufficient data
d	Ruptured on loading
e	Extrapolated or interpolated value
f	No test run under these conditions
>	Greater than (Test was discontinued at this time)
>>	Much greater than
<	Less than
~	Approximately
*	Test discontinued because of accidental overheat

TABLE IV

Structures and Heat Treatments Used in the General Survey of the Response of "17-22-A"V Steel to Heat Treatment

Structure	Initial Treatment	Average Hardness Before Tempering (BHN)	Tempering Treatment		Average Final Hardness (BHN)	
			300 BHN	350 BHN		
Normalized (100% Bainite)	1 Hour at 1850°F, Air Cooled (0.8-in. Round)	374	1.3 hrs at 1300°F	2 hrs at 1250°F	308	359
Normalized (10% Ferrite + 90% Bainite)	1 Hour at 1850°F, Air Cooled (Simulated 3-in. Round)	365	23 hrs at 1200°F		300	
Normalized (95% Ferrite + 5% Bainite)	1 Hour at 1850°F, Air Cooled (Simulated 6-in. Round)	303	None		303	
Normalized (100% Bainite)	1 Hour at 2000°F, Air Cooled (0.8-in. Round)	384	4 hrs at 1250°F		349	
Normalized (100% Bainite)	1 Hour at 2200°F, Air Cooled (1.0-in. Round)	377	7 hrs at 1250°F		362	
Oil Quenched (100% Martensite)	1 Hour at 1850°F, Oil Quenched (0.8-in. Round)	476	1 hr at 1300°F	2 hrs at 1250°F	304	345
Oil Quenched (100% Martensite)	1 Hour at 2000°F, Oil Quenched (0.8-in. Round)	487	4 hrs at 1250°F		348	
Middle Pearlite (5% Pearlite + 95% Ferrite)	1 Hour at 1850°F, Isothermally Transformed at 1275°F for 3.5 Hours, Water Quenched (0.4-in. Round)	255	None	-	255	
Lower Pearlite (5% Pearlite + 95% Ferrite)	1 Hour at 1850°F, Isothermally Transformed at 1200°F for 5 Hours, Water Quenched (0.4-in. Round)	360	1 hr at 1300°F	1 hr at 1200°F	289	347
Upper Bainite (60% Bainite + 40% Martensite)	1 Hour at 1850°F, Isothermally Transformed at 850°F for 2 Hours, Water Quenched (0.4-in. Round)	447	1.3 hrs at 1300°F	4.5 hrs at 1200°F	290	348
Middle Bainite (100% Bainite)	1 Hour at 1850°F, Isothermally Transformed at 750°F for 0.3 Hour, Water Quenched (0.4-in. Round)	364	1 hr at 1300°F	5 hrs at 1200°F	298	338
Lower Bainite (100% Bainite)	1 Hour at 1850°F, Isothermally Transformed at 650°F for 0.2 Hour, Water Quenched (0.4-in. Round)	405	1.5 hrs at 1300°F	6 hrs at 1200°F	294	348

TABLE V

Comparison of Rupture, Creep, and Total Deformation Data for "17-22-A"V Steel at 700° to 1100°F Showing the Effects of Microstructure and Hardness Level

Structure	Test Temp (°F)	Stress (psi)	Rupture Time (hours)		Elongation (% in 4 D)		Reduction of Area (%)		Deformation on Loading (%)		Minimum Creep Rate (%/hr)		Time to Reach Specified Total Deformation (hours)					
													0.2 Percent		0.5 Percent		1.0 Percent	
			300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN
Oil Quenched (Tempered Martensite)	700	115,000	745.4	>1200.9	18.0	--	61.2	--	1.310	0.612	0.00162	0.00138	b	b	b	b	b	150.0
	900	70,000	257.9	>1200.3	29.0	--	71.1	--	0.353	0.348	0.0134	0.00262	b	b	11.0	20.0	49.0	120.0
	1100	40,000	23.2	43.4	41.0	17.0	76.7	48.8	0.283	0.265	0.470	c	b	b	<0.1	<0.1	0.8	c
	1100	30,000	83.7	177.5	27.5	23.5	64.1	47.8	0.190	0.210	0.0430	0.00800	<1.0	b	2.5	13.0	11.5	36.0
	1100	19,000	1122.5	1491.6	28.5	20.5	38.3	24.4	0.118	0.115	0.00275	0.00190	~5.0	10.0	80.0	150.0	265.0	400.0
Normalized (Tempered Bainite)	700	115,000	>1007.3	>1009.2	--	--	--	--	0.702	0.475	0.000378	0.000120 d	b	b	b	5.0	220.0	>>1000.0
	900	70,000	> 483.7	>1008.9	--	--	--	--	0.347	0.359	0.00292	0.000345	b	b	~5.0	20.0	160.0	870.0
	1100	40,000	63.7	123.3	21.0	12.0	44.6	23.5	0.257	0.195	0.0544	0.0160	b	<1.0	~1.0	9.5	7.5	33.0
	1100	30,000	231.0	514.8	11.5	19.5	31.8	19.9	0.150	0.187	0.00800	0.00836	~3.0	<1.0	28.0	22.0	83.0	60.0
	1100	19,000	1414.2	>1103.3	13.5	--	23.1	--	0.111	0.128	0.00194	0.000660	10.0	30.0	130.0	330.0	355.0	995.0
Middle Pearlite (Not Tempered)	700	115,000	0.1 a		21.0		59.8		0.840		c		b		b		c	
	900	70,000	201.2 a		29.0		71.1		0.341		0.0210		b		2.0		10.0	
	1100	40,000	93.3 a		34.0		51.3		0.208		0.0530		b		1.5		7.0	
	1100	19,000	>743.0 a		--		--		0.090		0.00121		20.0		230.0		625.0	
Lower Pearlite (Tempered)	700	115,000	101.7	>1003.1	17.0	--	59.0	--	2.121	0.433	0.0108	0.00122	b	b	b	~5.0	b	110.0
	900	70,000	>1079.0	>1005.8	--	--	--	--	0.336	0.343	0.00320	0.000380	b	b	~4.0	~15.0	130.0	650.0
	1100	40,000	89.2	138.8	35.0	18.0	39.6	21.8	0.255	0.198	0.0750	0.0353	b	<1.0	3.0	~2.0	9.0	8.0
	1100	19,000	> 838.0	> 839.0	--	--	--	--	0.080	0.105	0.000590	0.000620	255.0	15.0	515.0	290.0	860.0	~1030.0e
Upper Bainite (Tempered)	700	115,000	>1100.4	> 979.8	--	--	--	--	0.746	0.514	0.00132	0.0000850 d	b	b	b	b	15.0	770.0
	900	70,000	230.3	>1138.7	27.0	--	69.7	--	0.350	0.367	0.00950	0.00103	b	b	5.0	~5.0	43.0	200.0
	1100	40,000	29.8	59.6	40.0	25.0	69.3	39.7	0.330	0.290	0.205	c	b	b	<1.0	c	~2.0	c
	1100	19,000	> 336.0	> 763.0	--	--	--	--	0.140	0.136	0.00400	0.00124	~2.0	5.0	50.0	150.0	180.0	500.0
Middle Bainite (Tempered)	700	115,000	>1100.4	>1005.7	--	--	--	--	0.612	0.547	0.000220	0.000282	b	b	b	b	620.0	660.0
	900	70,000	>1053.4	> 934.0	--	--	--	--	0.359	0.340	0.00163	0.000250	b	b	~15.0	20.0	240.0	~1050.0e
	1100	40,000	75.6	89.0	22.0	35.0	35.9	42.1	0.280	0.232	0.0420	0.0282	b	b	1.0	6.0	8.0	24.0
	1100	19,000	> 838.0	> 743.0	--	--	--	--	0.148	0.190	0.000960	0.000550	~5.0	<1.0	270.0	320.0	780.0	~1200.0e
Lower Bainite (Tempered)	700	115,000	239.5	> 979.7	16.0	--	60.5	--	1.050	0.485	0.00630	0.000205 d	b	b	b	~1.0	b	650.0
	900	70,000	> 431.0	> 933.6	--	--	--	--	0.330	0.364	0.00254	0.000300 d	b	b	12.0	~5.0	170.0	900.0
	1100	40,000	102.7	201.8	24.0	19.6	43.5	23.8	0.272	0.263	0.0390	0.0164	b	b	~1.0	10.0	11.0	36.0
	1100	19,000	> 934.0	> 861.0	--	--	--	--	0.073	0.149	0.000402	0.00071	35.0	7.0	610.0	295.0	~2000.0 e	985.0e

a This structure tested only at the single, untempered hardness level of 250 BHN.
b Deformation exceeded on loading.
c Unknown because of insufficient elongation vs. time data.
d Creep rate at 1000 hours; test still in primary stage of decelerating creep.
e Interpolated or extrapolated value.
> "Greater than"; test was discontinued at this time.
>> "Much greater than."
< "Less than."
~ "Approximately."

TABLE VI

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

Austenitizing Temperature (°F)	Quenching Medium	Bar Dia. (in.)	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 4 D)	Reduction of Area (%)	Deformation on Loading (%)	Minimum Creep Rate (%/hr)	Time to Reach Specified Total Deformation (hours			
										0.2%	0.5%	1.0%	2.0%
							700°F						
1850	Oil	0.8	302	115,000	745.7	18.0	61.2	1.310	0.00162	b	b	b	380.0
	Air	0.8	305	115,000	>1007.3	--	--	0.702	0.000378	b	b	220.0	>>1000.0
	Air	3.0 a	309	115,000	0.2	18.0	61.4	0.333	1.11	b	0.1	--	--
	Air	6.0 a	303	115,000	>1002.8	--	--	2.00	0.00045	b	b	b	b
	Oil	0.8	350	115,000	>1200.9	--	--	0.612	0.00138	b	b	150.0	730.0
	Air	0.8	365	115,000	>1009.2	--	--	0.475	0.00012 c	b	5.0	>>1000.0	--
2000	Oil	0.8	354	115,000	>1197.6	--	--	0.596	0.00136	b	b	65.0	750.0
	Air	0.8	350	115,000	>1000.0	--	--	0.580	0.000330	b	b	350.0	>>1000.0
2200	Air	1.0	362	115,000	> 862.8	--	--	0.576	0.000224	b	b	b	530.0
							900°F						
1850	Oil	0.8	302	70,000	257.9	29.0	71.1	0.353	0.0134	b	11.0	49.0	117.0
	Air	0.8	305	70,000	> 483.7	--	--	0.347	0.00292	b	~5.0	160.0	380.0
	Air	3.0 a	309	70,000	131.7	24.0	68.1	0.302	0.0263	b	2.0	19.0	52.0
	Air	6.0 a	303	70,000	> 961.2	--	--	0.485	0.00285	b	<1.0	80.0	365.0
	Oil	0.8	350	70,000	>1200.3	--	--	0.348	0.00262	b	20.0	120.0	485.0
	Air	0.8	365	70,000	>1008.9	--	--	0.359	0.000345	b	20.0	870.0	--
2000	Oil	0.8	350	70,000	984.0	5.0	9.1	0.395	0.00235	b	~1.0	80.0	420.0
	Air	0.8	354	70,000	>1001.0	--	--	0.370	0.000190	b	15.0	~2000.0 e	--
2200	Air	1.0	362	70,000	646.0	1.0	0.5	0.323	0.000190	b	160.0	>>1000.0	--

TABLE VI (con'd.)

Austenitizing Temperature (°F)	Quenching Medium	Bar Dia. (in.)	BHN	Stress (psi)	Rupture Time (hours)	Elongation (% in 4 D)	Reduction of Area (%)	Deformation on Loading (%)	Minimum Creep Rate (%/hr)	Time to Reach Specified Total Deformation (hours) 0.2%	0.5%	1.0%	2.0%
							1100°F						
1850	Oil	0.8	305	40,000	23.2	41.0	76.7	0.283	0.470	b	<0.1	0.8	1.5
	Air	0.8	307	40,000	63.7	21.0	44.6	0.257	0.0544	b	~1.0	7.5	24.0
	Air	3.0 a	309	40,000	69.8	24.0	50.5	0.360	0.0630	b	<1.0	~3.0	14.0
	Air	6.0 a	306	40,000	63.8 ± 4.0	34.5	53.2	0.249	0.0383	b	2.0	12.0	--
	Oil	0.8	344	40,000	43.4	17.0	48.8	0.265	d	b	<1.0	d	d
	Air	0.8	352	40,000	123.3	12.0	23.5	0.195	0.0160	<1.0	9.5	33.0	--
2000	Oil	0.8	350	40,000	106.6	4.0	7.5	0.294	0.0160	b	3.0	30.0	85.0
	Air	0.8	354	40,000	196.0	2.0	4.1	0.246	0.00615	b	~ 2.0	77.0	179.0
2200	Air	1.0	362	40,000	86.0	1.0	1.9						
1850	Oil	0.8	310	19,000	1122.5	28.5	38.3	0.118	0.00275	~5.0	80.0	265.0	490.0
	Air	0.8	311	19,000	1414.2	13.5	23.1	0.111	0.00194	10.0	130.0	355.0	680.0
	Air	3.0 a	309	19,000	>1038.5	--	--	0.105	0.00104	15.0	240.0	650.0	~1200.0 e
	Air	6.0 a	300	19,000	>1053.9	--	--	0.113	0.00182	15.0	180.0	455.0	910.0 e
	Oil	0.8	338	19,000	1491.6	20.5	24.4	0.115	0.00190	10.0	150.0	400.0	770.0
	Air	0.8	359	19,000	>1103.3	--	--	0.128	0.000660	30.0	330.0	995.0	--
2000	Oil	0.8	350	19,000	>1002.0	--	--	0.024	0.000500	260.0	850.0	~1500.0 e	--
	Air	0.8	354	19,000	>1002.0	--	--	0.079	0.000070	235.0	>>1000.0	--	--
2200	Air	1.0	362	19,000	351.0 ± 3.0	1.0	2.0	0.073	0.000106	~500.0 e	--	--	--

a One-inch diameter bars were air cooled in insulating firebrick cylinders to simulate cooling cycles of normalized 3- and 6-inch diameter bars.
b Indicated deformation was exceeded on loading.
c Creep rate at 1000 hours; test still in primary stage of decelerating creep.
d Unknown because of insufficient elongation vs. time data.
e Extrapolated or interpolated value.
> "Greater than"; test was discontinued at this time.
>> "Much greater than."
< "Less than."
~ "Approximately."

TABLE VII

Structures and Heat Treatments Used in the Study of Mixed Bainites and the Study of the Effect of a Prior Homogenization Normalize for the "17-22-A"V, "17-22-A"S, and SAE 4340 Steels

Structure	Initial Heat Treatment	Average Hardness Before Tempering (BHN)	Tempering Treatment	Average Final Hardness (BHN)
	"17-22-A"V (Heat No. 11833)			
Mixed Bainite (60% Upper Bainite + 40% Lower Bainite)	1 Hour at 1850°F, Isothermally Transformed Stepwise at 850°F for 5 Min. and at 650°F for 45 Min., Water Quenched	397	4.5 hrs at 1200°F	360
Double Normalize (100% Bainite)	1 Hour at 1950°F, Air Cooled + 1 Hour at 1850°F, Air Cooled	360	2 hrs at 1250°F	348
Normalize + Oil Quench (100% Martensite)	1 Hour at 1950°F, Air Cooled + 1 Hour at 1850°F, Oil Quenched	471	2 hrs at 1250°F	348
Normalize + Isothermal Transformation (100% Middle Bainite)	1 Hour at 1950°F, Air Cooled + 1 Hour at 1850°F, Isothermally Transformed at 750°F for 0.3 Hour, Water Quenched	355	6 hrs at 1200°F	360
	"17-22-A"S (Heat No. 10420)			
Mixed Bainite (50% Upper Bainite 50% Lower Bainite)	1 Hour at 1750°F, Isothermally Transformed Stepwise at 900°F for 0.5 Hour and at 700°F for 1.5 Hours, Water Quenched	353	8 hrs at 1200°F	298
Double Normalize (90% Bainite + 10% Martensite)	1 Hour at 1850°F, Air Cooled + 1 Hour at 1750°F, Air Cooled	335	2.25 hrs at 1200°F	351
Normalize + Oil Quench (100% Martensite)	1 Hour at 1850°F, Air Cooled + 1 Hour at 1750°F, Oil Quenched	471	2.25 hrs at 1200°F	356
Normalize + Isothermal Transformation (95% Middle Bainite + 5% Martensite)	1 Hour at 1850°F, Air Cooled + 1 Hour at 1750°F, Isothermally Transformed at 800°F for 0.5 Hour, Water Quenched	382	4 hrs at 1200°F	314
	SAE 4340 (Heat No. D-14064)			
Mixed Bainite (60% Upper Bainite 40% Lower Bainite)	1 Hour at 1750°F, Isothermally Transformed Stepwise at 850°F for 1 Hour and at 650°F for 1 Hour, Water Quenched	316	None	316
Normalize + Oil Quench (100% Martensite)	1 Hour at 1850°F, Air Cooled + 1 Hour at 1750°F, Oil Quenched	506	1.75 hrs at 1200°F	307
Double Normalize (90% Bainite + 10% Martensite)	1 Hour at 1850°F, Air Cooled + 1 Hour at 1750°F, Air Cooled	408	1.5 hrs at 1200°F	307
Normalize + Isothermal Transformation (95% Middle Bainite + 5% Martensite)	1 Hour at 1850°F, Air Cooled + 1 Hour at 1750°F, Isothermally Transformed at 750°F for 24 Hours	321	None	320

Note! All bars which were normalized or oil quenched were 0.8-inch rounds; all bars which were isothermally transformed were 0.4-inch rounds.

TABLE VIII

Rupture, Creep, and Total Deformation Data at 700° to 1100°F for SAE 4340, "17-22-A"S, and "17-22-A"V,

Comparing the Properties of Mixed Bainitic Structures with the Properties of Other Bainitic Structures

Structure	BHN	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 4D)	Reduction of Area (%)	Deformation on Loading (%)	Minimum Creep Rate (%/hr)	Time to Reach Specified Total Deformation (hours)			
									0.1%	0.2%	0.5%	1.0%
						SAE 4340 Steel						
Upper Bainite (70% Upper Bainite + 30% Martensite)	**324**	**700**	90,000	**>1316.0**	--	--	0.465	**0.00032**	b	b	1.0	198.0
	325	**900**	55,000	**1215.0**	6.0	6.4	0.265	**0.00163**	b	b	6.0	48.0
	327	**1000**	31,000	**389.0**	10.0	10.1	0.185	**0.00720**	b	<1.0	10.0	75.0
	322	**1000**	13,000	>1075.0	--	--	0.057	**0.00023**	5.0	91.0	1130.0 e	--
Mixed Bainite (60% Upper Bainite + 40% Lower Bainite)	315	700	90,000	>1123.6 d	--	--	0.539	0.000175	b	b	b	950.0
	315	900	55,000	>1098.1 d	--	--	0.371	0.0000780	b	b	∼10.0	∼2000.0 e
	310	1000	31,000	374.3 d	0.5	1.0	0.168	0.00120	b	<1.0	138.0	370.0
	318	1000	13,000	>1532.3 d	--	--	0.101	0.000125	b	310.0	>>1000.0	--
Normalized (65% Non-Isothermal Bainite + 35% Martensite)	300	700	90,000	>1294.0	--	--	0.467	0.00016	b	b	1.0	1000.0
	300	900	55,000	842.0	12.0	22.4	0.260	0.00414	b	b	8.0	64.0
	290	1000	31,000	371.0	5.5	7.4	0.126	0.00505	b	5.0	50.0	145.0
	301	1000	13,000	>1000.0	--	--	0.053 e	0.00040 e	10.0 e	90.0 e	650.0 e	∼1700.0 e
Middle Bainite (100% Middle Bainite)	309	700	90,000	>1315.0	--	--	0.472	0.000190	b	b	∼1.0	1291.0
	313	900	55,000	1417.0	4.1	4.7	0.380	0.000640	b	b	1.0	51.0
	295	1000	31,000	261.0	5.9	5.6	0.190	0.00700	b	<1.0	18.0	85.0
	307	1000	13,000	>1706.0	--	--	0.068	0.00030	4.0	42.0	472.0	1920.0 e
Lower Bainite (100% Lower Bainite)	277	700	90,000	>1485.0	--	--	0.440	0.000160	b	b	1.0	∼2000.0 e
	277	900	55,000	897.0	18.5	15.4	0.250	0.00530	b	b	8.0	51.0
	291	1000	31,000	210.0	9.4	17.0	0.161	0.0179	b	<1.0	6.0	26.0
	294	1000	13,000	>1035.0	--	--	0.055	0.00053	2.0	32.0	300.0	1104.0 e
						"17-22-A"S Steel						
Upper Bainite (60% Upper Bainite + 40% Martensite)	285	700	115,000	147.0 f	20.2	62.0	0.710	0.0180	b	b	b	<1.0
	289	900	70,000	686.0 f	30.0	59.5	0.355	0.00504	b	b	1.0	50.0
	310	1100	41,000	51.5	7.2	8.6	0.269	c	b	b	4.0	13.0
	327	1100	19,000	796.0 f	5.8	6.6	0.110	0.00140	b	8.0	177.0	447.0
Middle Bainite (97% Middle Bainite + 3% Martensite)	309	700	115,000	>1827.0 f	--	--	0.610	0.00029	b	b	b	45.0
	307	900	70,000	>1648.0 f	--	--	0.323	0.00014	b	b	65.0	2500.0 e
	309	1100	41,000	88.2 f	5.1	4.9	0.217	--	b	b	6.0	19.0
	310	1100	19,000	815.0 f	4.0	3.0	0.096	0.00150	b	30.0	222.0	575.0
Mixed Bainite (50% Upper Bainite + 50% Lower Bainite)	302	700	115,000	1036.0	16.0	61.6	1.040	0.00156	b	b	b	b
	313	900	70,000	>1028.1	--	--	0.336	0.000058	b	b	200.0	>>1000.0
	294	1100	41,000	99.2	5.0	5.5	0.156	0.0102	b	<1.0	6.0	46.0
	294	1100	19,000	763.0	4.0	2.4	0.125	0.000750	b	25.0	350.0	660.0
Normalized (85% Non-Isothermal Bainite + 15% Martensite)	302	700	115,000	132.0	21.0	61.9	0.660	0.0220	b	b	b	1.0
	303	900	70,000	>1482.0	--	--	0.335	0.00030	b	b	24.0	1400.0
	309	1100	41,000	111.5	2.5	3.1	0.212	0.00614	b	b	26.0	--
	311	1100	19,000	900.0 e	2.0 e	--	0.087 e	0.00060 e	1.0 e	55.0 e	450.0 e	750.0 e
Lower Bainite (100% Lower Bainite)	275	700	115,000	59.4 f	18.8	66.7	0.815	0.0452	b	b	b	<1.0
	283	900	70,000	1456.0 f	24.0	56.2	0.350	0.00115	b	b	12.0	362.0
	290	1100	41,000	92.8	5.0	4.0	0.252	0.0165	b	b	9.0	32.0
	300	1100	19,000	1100.0 e f	1.9 e	5.5 e	0.170 e	0.00080 e	b	7.5 e	250.0 e	750.0 e

TABLE VIII (continued)

Structure	BHN	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 4 D)	Reduction of Area (%)	Deformation on Loading (%)	Minimum Creep Rate (%/hr)	Time to Reach Specified Total Deformation (hours) 0.1%	0.2%	0.5%	1.0%
						"17-22-A"V Steel*						
Upper Bainite	350	700	115,000	> 979.8	--	--	0.514	0.000085 a	b	b	b	770.0
(60% Upper Bainite +	350	900	70,000	>1138.7	--	--	0.367	0.00103	b	b	~5.0	200.0
40% Martensite)	345	1100	40,000	59.6	25.0	39.7	0.282	c	b	b	c	c
	348	1100	19,000	> 763.0	--	--	0.136	0.00124	b	5.0	150.0	500.0
Middle Bainite	333	700	115,000	>1005.7	--	--	0.547	0.000282	b	b	b	660.0
(100% Middle Bainite)	338	900	70,000	> 934.0	--	--	0.360	0.000250	b	b	20.0	~1050.0 e
	333	1100	40,000	89.0	35.0	42.1	0.232	0.0282	b	b	6.0	24.0
	336	1100	19,000	> 743.0	--	--	0.190	0.000550	b	<1.0	320.0	~1200.0 e
Normalized	365	700	115,000	>1009.2	--	--	0.475	0.00012 a	b	b	5.0	>>1000.0
(100% Non-Isothermal	365	900	70,000	>1008.9	--	--	0.359	0.000345	b	b	20.0	870.0
Bainite)	352	1100	40,000	123.3	12.0	23.5	0.195	0.0160	b	<1.0	9.5	33.0
	359	1100	19,000	>1103.3	--	--	0.128	0.00066	b	30.0	330.0	995.0
Mixed Bainite	361	700	115,000	>1102.3	--	--	0.458	0.000162	b	b	~7.0	>>1000.0
(60% Upper Bainite +	359	900	70,000	>1123.3	--	--	0.353	0.000245	b	b	30.0	~1200.0 e
40% Lower Bainite)	363	1100	40,000	153.7	13.0	16.4	0.233	0.0170	b	b	8.0	33.0
	354	1100	19,000	>1032.1	--	--	0.145	0.000615	b	23.0	400.0	~1300.0 e
Lower Bainite	346	700	115,000	> 979.7	--	--	0.485	0.000205 a	b	b	~1.0	650.0
(100% Lower Bainite)	346	900	70,000	> 933.6	--	--	0.364	0.000300 a	b	b	~5.0	900.0
	354	1100	40,000	201.8	19.6	23.8	0.263	0.0164	b	b	10.0	36.0
	344	1100	19,000	> 861.0	--	--	0.149	0.000710	b	7.0	295.0	985.0 e

Note: Data for the "other" bainitic structures of 4340 and "17-22-A"S were previously reported in WADC TR 53-277 (Part II).

* Timken Heat No. 11833.
a Creep rate at 1000 hours; test still in primary stage of decelerating creep.
b Indicated deformation exceeded on loading.
c Unknown because of insufficient elongation vs. time data.
d Data from Heat No. D-14062; all other 4340 data from Heat No. 19053.
e Value obtained by extrapolation or interpolation.
f Data from Heat No. 10420; all other "17-22-A"S data from Heat No. 24797.
\> "Greater Than"; test was discontinued at this time.
\>> "Much greater than."
~ "Approximately."
< "Less than."

TABLE IX

Rupture, Creep, and Total Deformation Data at 700° to 1100°F for SAE 4340, "17-22-A"S, and "17-22-A"V

Showing the Influence of an Homogenization Normalize Prior to the Final Heat Treatment

											Time to Reach Specified Total Deformation (hours)					
			Rupture Time (hrs)		Elongation (% in 4D)		Reduction of Area (%)		Minimum Creep Rate (%/hr)		0.2 Percent		0.5 Percent		1.0 Percent	
Structure	Test Temp (°F)	Stress (psi)	No Prior Normalize	Prior Normalize	No Prior Normalize	Prior Normalize	No Prior Normalize	Prior Normalize	No Prior Normalize	Prior Normalize	No Prior Normalize	Prior Normalize	No Prior Normalize	Prior Normalize	No Prior Normalize	Prior Normalize
				(Prior Normalize from 1850°F)			SAE 4340 Steel (300 BHN)			(Final Treatment from 1750°F)						
Oil Quenched	700	90,000	>1350.0 a	>1147.8	--	--	--	--	0.000270	0.0000890	b	b	2.0	10.0	675.0	>>1000.0
	900	55,000	381.0	>1033.8	19.5	--	39.5	--	0.0148	0.00205	b	b	2.0	~5.0	13.0	105.0
	1000	31,000	~150.0 e	196.6	10.9	6.0	14.1	10.4	0.0250 e	0.0113	<1.0	<1.0	3.0 e	7.0	18.0 e	26.0
	1000	13,000	>1025.0	>1074.3	--	--	--	--	0.00115	0.000420	27.0	170.0	248.0	755.0	628.0	>>1000.0
Normalized	700	90,000	>1294.0	>1027.2	--	--	--	--	0.000160	0.000070	b	b	1.0	~5.0	1000.0	>>1000.0
	900	55,000	842.0	>1034.1	12.0	--	22.4	--	0.00414	0.000370	b	b	8.0	35.0	64.0	930.0
	1000	31,000	371.0	352.8	5.5	4.5	7.4	3.5	0.00505	0.00367	5.0	<1.0	50.0	31.0	145.0	144.0
	1000	13,000	>1000.0	> 982.3	--	--	--	--	0.00040 e	0.000228	90.0 e	260.0	650.0 e	~1800.0 e	~1700.0 e	--
Middle Bainite	700	90,000	>1315.0	>1005.5	--	--	--	--	0.000190	0.000105	b	b	~1.0	b	1291.0	2000.0 e
	900	55,000	1417.0	>1100.5	4.1	--	4.7	--	0.000640	0.000134	b	b	1.0	20.0	51.0	>>1000.0
	1000	31,000	261.0	299.2	5.9	1.0	5.6	0.6	0.00700	0.00180	<1.0	~2.0	18.0	105.0	85.0	290.0
	1000	13,000	>1706.0	> 839.0	--	--	--	--	0.00030	0.000141	42.0	450.0	472.0	>>1000.0	1920.0 e	--
				(Prior Normalize from 1850°F)			"17-22-A"S Steel (350 BHN)			(Final Treatment from 1750°F)						
Oil Quenched	700	115,000	>1125.0	>1128.9	--	--	--	--	0.000160	0.000161	b	b	b	b	~1500.0 e	610.0
	900	70,000	> 888.0	>1004.1	--	--	--	--	0.000280	0.000190	b	b	30.0	70.0	~1500.0 e	>>1000.0
	1100	41,000	52.7	42.8	5.5	9.2	10.0	8.6	c	0.0552	b	b	~4.0	3.0	24.0	12.0
	1100	19,000	712.7	693.3	2.0	3.1	5.5	5.9	0.00150	0.00200	30.0	15.0	220.0	130.0	492.0	340.0
Normalized	700	115,000	>1205.0	> 814.9	--	--	--	--	0.000047	0.000057	b	b	b	b	>>1205.0	>>1000.0
	900	70,000	>1205.0	> 994.0	--	--	--	--	0.000079	0.000040	b	b	175.0	70.0	>>1205.0	>>1000.0
	1100	41,000	92.8	106.2	2.0	1.0	2.4	1.6	0.00420	0.0101	~0.1	b	10.0	16.0	60.0	65.0
	1100	19,000	1211.4	>1004.1	1.0	--	0.8	--	0.00050	0.00051	55.0	30.0	500.0	540.0	1050.0	1040.0 e
Middle Bainite (g)	700	115,000	>1827.0 d	>1005.3	--	--	--	--	0.000290	0.000177 f	b	b	b	b	45.0	285.0
	900	70,000	>1648.0 d	>1053.7	--	--	--	--	0.000140	0.000045	b	b	65.0	330.0	~2500.0 e	>>1000.0
	1100	41,000	88.2 d	112.8	5.1	5.0	4.9	2.4	--	0.0120	b	b	6.0	9.0	19.0	50.0
	1100	19,000	815.0 d	>1053.8	4.0	--	3.0	--	0.00150	0.000555	30.0	80.0	222.0	540.0	575.0	950.0
				(Prior Normalize from 1950°F)			"17-22-A"V Steel (350 BHN)			(Final Treatment from 1850°F)						
Oil Quenched	700	115,000	>1200.9	>1004.9	--	--	--	--	0.00138	0.0050	b	b	b	b	150.0	60.0
	900	70,000	>1200.3	>1032.1	--	--	--	--	0.00262	0.00265	b	b	20.0	10.0	120.0	110.0
	1100	40,000	43.4	102.9	17.0	11.0	48.8	20.9	c	0.0251	b	b	<1.0	2.5	c	15.0
	1100	19,000	1491.6	>1054.4	20.5	--	24.4	--	0.00190	0.000788	10.0	20.0	150.0	320.0	400.0	900.0
Normalized	700	115,000	>1009.2	>1005.0	--	--	--	--	0.00012 f	0.000108	b	b	5.0	b	>>1000.0	~1400.0 e
	900	70,000	>1008.9	>1009.8	--	--	--	--	0.000345	0.000174	b	b	20.0	30.0	870.0	>>1000.0
	1100	40,000	123.3	185.5	12.0	2.0	23.5	3.8	0.0160	0.00500	<1.0	b	9.5	16.0	33.0	93.0
	1100	19,000	>1103.3	>1054.3	--	--	--	--	0.000660	0.000206	30.0	150.0	330.0	~1500.0 e	995.0	--
Middle Bainite	700	115,000	>1005.7	>1005.0	--	--	--	--	0.000282	0.000116	b	b	b	b	660.0	25.0
	900	70,000	> 934.0	>1005.0	--	--	--	--	0.000250	0.000132	b	b	20.0	50.0	~1050.0 e	>>1000.0
	1100	40,000	89.0	234.5	35.0	5.0	42.1	10.6	0.0282	0.00630	b	b	6.0	20.0	24.0	98.0
	1100	19,000	> 743.0	> 995.0	--	--	--	--	0.000550	0.000237	<1.0	210.0	320.0	~1400.0 e	~1200.0 e	--

Note! The 4340 data under "No Prior Normalize" are from Heat No. 19053, and the 4340 data under "Prior Normalize" are from Heat No. D-14062. All "17-22-A"V data are from Timken Heat No. 11833.

a All data under "No Prior Normalize" for 4340 and "17-22-A"S were previously reported in WADC TR 53-277 Part II.
b Specified deformation exceeded on loading.
c Unknown because of insufficient elongation vs. time data.
d Timken Heat No. 24797; all other "17-22-A"S data are for Timken Heat No. 10420.
e Value obtained by extrapolation or interpolation.

f Creep rate at 1000 hours; test still in primary stage of decelerating creep.
g These tests were run at 300 BHN.
> "Greater Than"; test was discontinued at this time.
>> "Much greater than"
~ "Approximately"
< "Less than"

TABLE X

Conditions of Hot Rolling and Heat Treatment Used in the Study of the Effect of Hot-Rolling Conditions for SAE 4340, "17-22-A"S, and "17-22-A"V

Condition	Initial Treatment	Avg. BHN before Tempering	Tempering Conditions	Avg. BHN after Tempering
	SAE 4340			
A	0.5 Hour at 1800°F, 1-Inch Round Hot Rolled 25%* in One Pass, Air Cooled + 1 Hour at 1750°F, Air Cooled	428	2.75 Hours at 1200°F	285
B	0.5 Hour at 2000°F, 1-Inch Round Hot Rolled 25% in One Pass, Air Cooled + 1 Hour at 1750°F, Air Cooled	387	2.0 Hours at 1200°F	293
C	0.5 Hour at 2200°F, 1-Inch Round Hot Rolled 25% in One Pass, Air Cooled + 1 Hour at 1750°F, Air Cooled	408	2.5 Hours at 1200°F	293
D	0.5 Hour at 2100°F, 1-Inch Round Air Cooled to 1800°F and then Hot Rolled 25% in One Pass, Air Cooled	366	2.25 Hours at 1200°F	297
E	0.5 Hour at 2100°F, 1-Inch Round Hot Rolled 25% in Three Passes During Cooling to 1800°F, Air Cooled	386	2.25 Hours at 1200°F	297
	"17-22-A"S			
A	0.5 Hour at 1800°F, 0.8-Inch Round Hot Rolled 25%* in One Pass, Air Cooled + 1 Hour at 1750°F, Air Cooled	331	2 Hours at 1200°F	342
B	0.5 Hour at 2000°F, 0.8-Inch Round Hot Rolled 25% in One Pass, Air Cooled + 1 Hour at 1750°F, Air Cooled	329	2 Hours at 1200°F	350
C	0.5 Hour at 2200°F, 0.8-Inch Round Hot Rolled 25% in One Pass, Air Cooled + 1 Hour at 1750°F, Air Cooled	332	2 Hours at 1200°F	344
D	0.5 Hour at 2100°F, 0.8-Inch Round Air Cooled to 1800°F and then Hot Rolled 25% in One Pass, Air Cooled	334	2 Hours at 1200°F	347
E	0.5 Hour at 2100°F, 1-Inch Round Hot Rolled 25% in Three Passes During Cooling to 1800°F, Air Cooled	330	2 Hours at 1200°F	352
	"17-22-A"V			
A	0.5 Hour at 1800°F, 1-Inch Round Hot Rolled 25%* in One Pass, Air Cooled + 1 Hour at 1850°F, Air Cooled	360	1.75 Hours at 1250°F	350
B	0.5 Hour at 2000°F, 1-Inch Round Hot Rolled 25% in One Pass, Air Cooled + 1 Hour at 1850°F, Air Cooled	376	1.5 Hours at 1250°F	355
C	0.5 Hour at 2200°F, 1-Inch Round Hot Rolled 25% in One Pass, Air Cooled + 1 Hour at 1850°F, Air Cooled	365	1.25 Hours at 1250°F	350
D	0.5 Hour at 2200°F, 1-Inch Round Air Cooled to 1900°F and then Hot Rolled 25% in One Pass, Air Cooled	381	2.5 Hours at 1250°F	358
E	0.5 Hour at 2200°F, 1-Inch Round Hot Rolled 25% in Three Passes During Cooling to 1900°F, Air Cooled	386	2.75 Hours at 1250°F	342

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* Nominal percent reduction in cross-sectional area; actual reductions varied from 22 to 29 percent.

TABLE XI

Rupture, Creep, and Total Deformation Data at 1000°F for SAE 4340 and at 1100°F for "17-22-A"S and "17-22-A"V, Showing Some Effects of Hot-Rolling Conditions

Condition	BHN	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 4 D)	Reduction of Area (%)	Deformation on Loading (%)	Minimum Creep Rate (%/hr)	Time to Reach Specified Total Deformation (hrs)			
									0.1%	0.2%	0.5%	1.0%
					SAE 4340 Steel							
Normalized from 1750°F	290	1000	31,000	371.0 a g	5.5	7.4	0.126	0.00505	b	5.0	50.0	145.0
	300	1000	20,000	1392.0 a g	5.0	4.0	0.090	0.00116	~1.0	20.0	228.0	650.0
	301	1000	12,000	>1000.0 a g	--	--	0.050	0.00037	12.0	114.0	802.0	2150.0 e
Hot Rolled 25%* at 1800°F, Air Cooled + Normalized from 1750°F	285	1000	31,000	253.8	3.0	4.7	0.155	0.0060	b	~1.0	30.0	105.0
	285	1000	20,000	1341.9	5.0	4.7	0.118	0.0012	b	~10.0	180.0	520.0
	285	1000	12,000	> 931.0	--	--	0.077	0.000474	<1.0	40.0	600.0	1500.0 e
Hot Rolled 25% at 2000°F, Air Cooled + Normalized from 1750°F	293	1000	31,000	375.1	4.0	3.2	0.135	0.00318	b	~2.0	70.0	225.0
	293	1000	20,000	>1654.6	--	--	0.122	0.00067	b	10.0	290.0	1025.0
	293	1000	12,000	> 932.0	--	--	0.082	0.000171	~5.0	290.0	~2000.0 e	--
Hot Rolled 25% at 2200°F, Air Cooled + Normalized from 1750°F	293	1000	31,000	327.6	6.0	8.5	0.165	0.0055	b	~1.0	20.0	104.0
	293	1000	20,000	>1803.5	--	--	0.111	0.000715	b	50.0	430.0	1000.0
	293	1000	12,000	>1003.5	--	--	0.059	0.000147	20.0	225.0	>>1000.0	--
Normalized from 2100°F	328	1000	31,000	490.0 a g	4.5	4.0	0.148	0.00280	b	~2.0	50.0	220.0
	328	1000	20,000	>2257.0 a g	--	--	0.116	0.00043	b	18.0	285.0	1300.0
Air Cooled from 2100°F to 1800°F and then Hot Rolled 25%	297	1000	31,000	271.0	2.0	1.6	0.192	0.00223	b	<1.0	75.0	260.0
	297	1000	20,000	>1654.8	--	--	0.142	0.000435	b	~5.0	500.0	1610.0
	297	1000	12,000	> 932.0	--	--	0.134	0.000202	b	25.0	~1300.0 e	--
Hot Rolled 25% in Three Passes During Air Cooling from 2100°F to 1800°F	297	1000	31,000	299.6	2.0	1.6	0.203	0.00233	b	b	45.0	242.0
	297	1000	20,000	1329.1	1.0	0.8	0.120	0.000368	b	40.0	750.0	--
	297	1000	12,000	> 932.0	--	--	0.082	0.000134	<1.0	285.0	~2000.0 e	--
					"17-22-A"S Steel (c)							
Normalized from 1750°F	354	1100	41,000	92.8 g	2.0	2.4	0.198	0.00420	b	~0.1	~10.0	60.0
	356	1100	19,000	1211.4 g	1.0	0.8	0.096	0.00050	~1.0	55.0	500.0	1050.0
Hot Rolled 25%* at 1800°F, Air Cooled + Normalized from 1750°F	348	1100	41,000	98.5	2.7	3.1	0.306	0.0110	b	b	8.0	47.0
	348	1100	30,000	344.1	4.0	4.0	0.242	0.00263	b	b	46.0	212.0
	348	1100	19,000	> 980.3	--	--	0.108	0.00065	b	25.0	410.0	920.0 e
Hot Rolled 25% at 2000°F, Air Cooled + Normalized from 1750°F	350	1100	41,000	103.1	2.3	3.7	0.406	0.0077	b	b	~1.0	28.0
	350	1100	30,000	328.0	2.0	0.8	0.193	0.0027	b	<1.0	60.0	230.0
	350	1100	19,000	> 861.0	--	--	0.204	0.000644	b	b	170.0	750.0
Hot Rolled 25% at 2200°F, Air Cooled + Normalized from 1750°F	346	1100	41,000	74.3	4.0	2.9	0.211	0.0070	b	b	9.0	60.0
	346	1100	30,000	267.1	1.3	2.4	0.195	0.0026	b	<1.0	68.0	217.0
	346	1100	19,000	> 861.0	--	--	0.114	0.00052	b	20.0	450.0	~1400.0 e
Normalized from 2100°F	317	1100	41,000	79.0 g	1.0	1.0	0.205	--	b	b	54.0	--
	317	1100	19,000	1653.0 g	0.5	f	0.090	0.00012	~1.0	425.0	~1650.0 e	--
Air Cooled from 2100°F to 1800°F and then Hot Rolled 25%	343	1100	41,000	116.2	2.0	2.4	0.220	0.00317	b	b	29.0	~130.0 e
	343	1100	30,000	401.0 ± 3.0	3.0	3.3	0.162	0.000725	b	~3.0	250.0 e	--
	343	1100	19,000	>1077.0	--	--	0.108	0.000225	b	35.0	1000.0	--
Hot Rolled 25% in Three Passes During Air Cooling from 2100°F to 1800°F	352	1100	41,000	83.2	2.0	3.2	0.203	0.00530	b	b	19.0	--
	352	1100	30,000	405.9	2.0	1.6	0.165	0.00140	b	~2.0	124.0	~450.0 e
	352	1100	19,000	> 931.0	--	--	0.113	0.000214	b	25.0	920.0	--

TABLE XI (con'd.)

Condition	BHN	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 4 D)	Reduction of Area (%)	Deformation on Loading (%)	Minimum Creep Rate (%/hr)	Time to Reach Specified Total Deformation (hrs) 0.1%	0.2%	0.5%	1.0%
"17-22-A"V Steel (d)												
Normalized from 1850°F	352	1100	40,000	123.3	12.0	23.5	0.195	0.0160	b	<1.0	9.5	33.0
	359	1100	30,000	514.8	19.5	19.9	0.187	0.00836	b	<1.0	22.0	60.0
	359	1100	19,000	>1103.3	--	--	0.128	0.00066	b	30.0	330.0	995.0
Hot Rolled 25%* at 1800°F, Air Cooled + Normalized from 1850°F	350	1100	40,000	188.2	8.8	4.8	0.265	0.00438	b	b	25.0	123.0
	350	1100	30,000	495.7	3.0	6.3	0.179	0.00194	b	~2.0	113.0	370.0
	350	1100	19,000	> 934.4	--	--	0.056	0.000390	~5.0	110.0	800.0	>>1000.0
Hot Rolled 25% at 2000°F, Air Cooled + Normalized from 1850°F	358	1100	40,000	170.5	10.0	18.3	0.266	0.0107	b	b	~5.0	48.0
	358	1100	30,000	558.7	6.0	9.4	0.182	0.00332	b	<1.0	60.0	210.0
	358	1100	19,000	> 962.0	--	--	0.097	0.000543	<1.0	40.0	530.0	~1500.0 e
Hot Rolled 25% at 2200°F, Air Cooled + Normalized from 1850°F	350	1100	40,000	227.6	2.9	5.9	0.250	0.00480	b	b	13.0	97.0
	350	1100	30,000	556.4	4.0	4.3	0.167	0.00166	b	~3.0	110.0	325.0
	350	1100	19,000	> 963.5	--	--	0.101	0.00040	b	85.0	625.0	~1800.0 e
Normalized from 2200°F	362	1100	40,000	86.0	1.0	1.9	0.299	0.00121	b	b	85.0 e	--
	362	1100	19,000	351.0 ± 3.0	1.0	2.0	0.073	0.000106	~1.0	~500.0 e	--	--
Air Cooled from 2200°F to 1900°F and then Hot Rolled 25%	358	1100	40,000	136.0	1.0	1.6	0.247	0.00380	b	b	33.0	~140.0 e
	358	1100	30,000	397.9	2.0	2.4	0.206	0.000995	b	b	177.0	--
	358	1100	19,000	>1414.0	--	--	0.146	0.00012	b	~5.0	825.0	>>1000.0
Hot Rolled 25% in Three Passes During Air Cooling from 2200°F to 1900°F	342	1100	40,000	117.1	2.0	0.8	0.243	0.00474	b	b	26.0	~115.0 e
	342	1100	30,000	338.1	2.0	1.6	0.222	0.00119	b	b	98.0	330.0
	342	1100	19,000	>1846.0	--	--	0.107	0.000195	b	180.0	~1500.0 e	--

* Nominal percent reduction in cross-sectional area; actual reductions varied from 22 to 29 percent.
a These data are from Heat No. 19053; all other 4340 data are from Heat No. D-14062.
b Indicated deformation was exceeded on loading.
c All "17-22-A"S data are from Timken Heat No. 10420.
d All "17-22-A"V data are from Timken Heat No. 11833.
e Value was obtained by interpolation or extrapolation.
f Fractured in shoulder radius.
g Previously reported in WADC TR 55-388.
\> "Greater than"; test was discontinued at this time.
\>> "Much greater than."
< "Less than."
~ "Approximately."

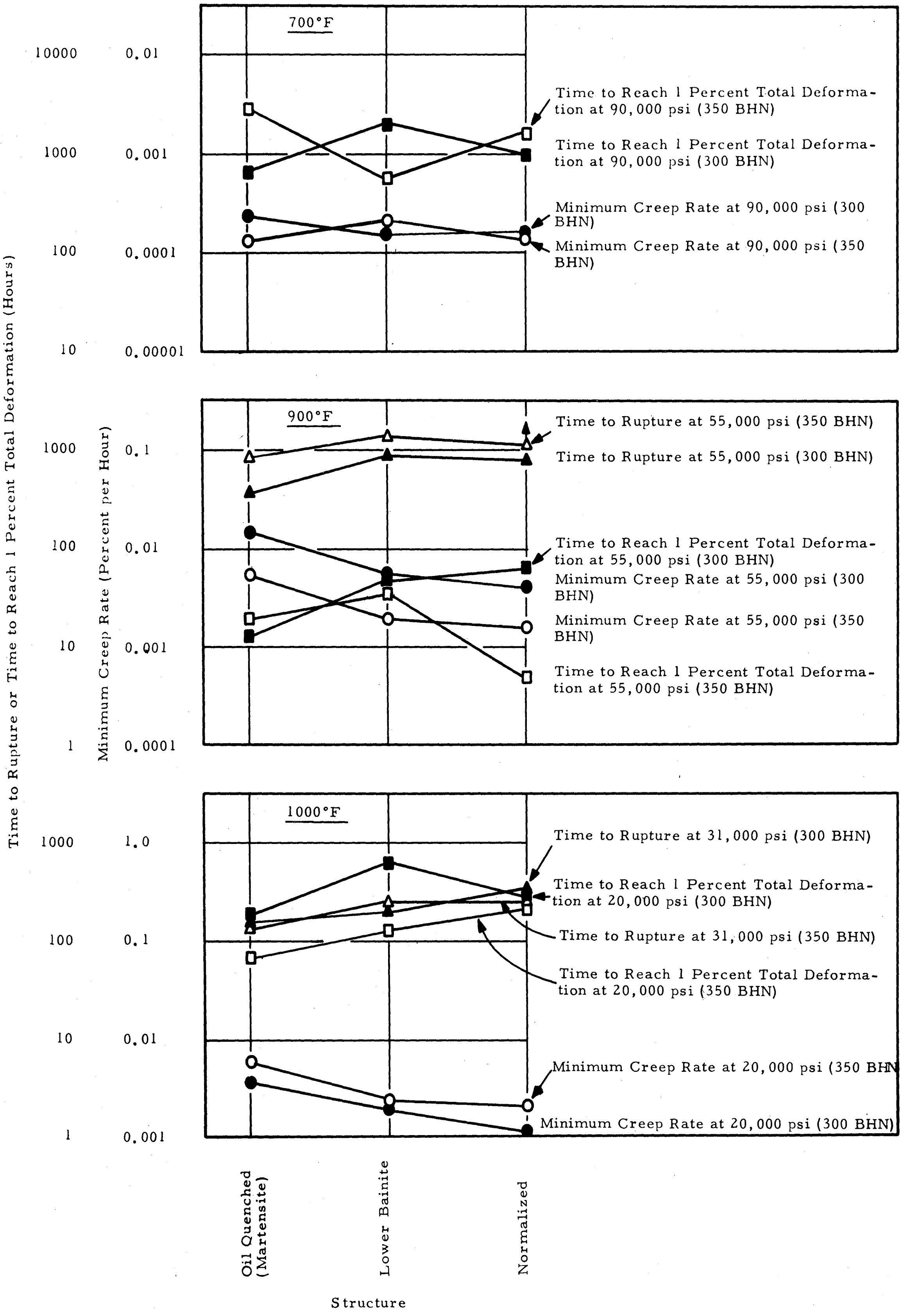


Figure 1. - Influence of Hardness Level on the Properties of Three SAE 4340 Structures at 700°, 900°, and 1000°F.

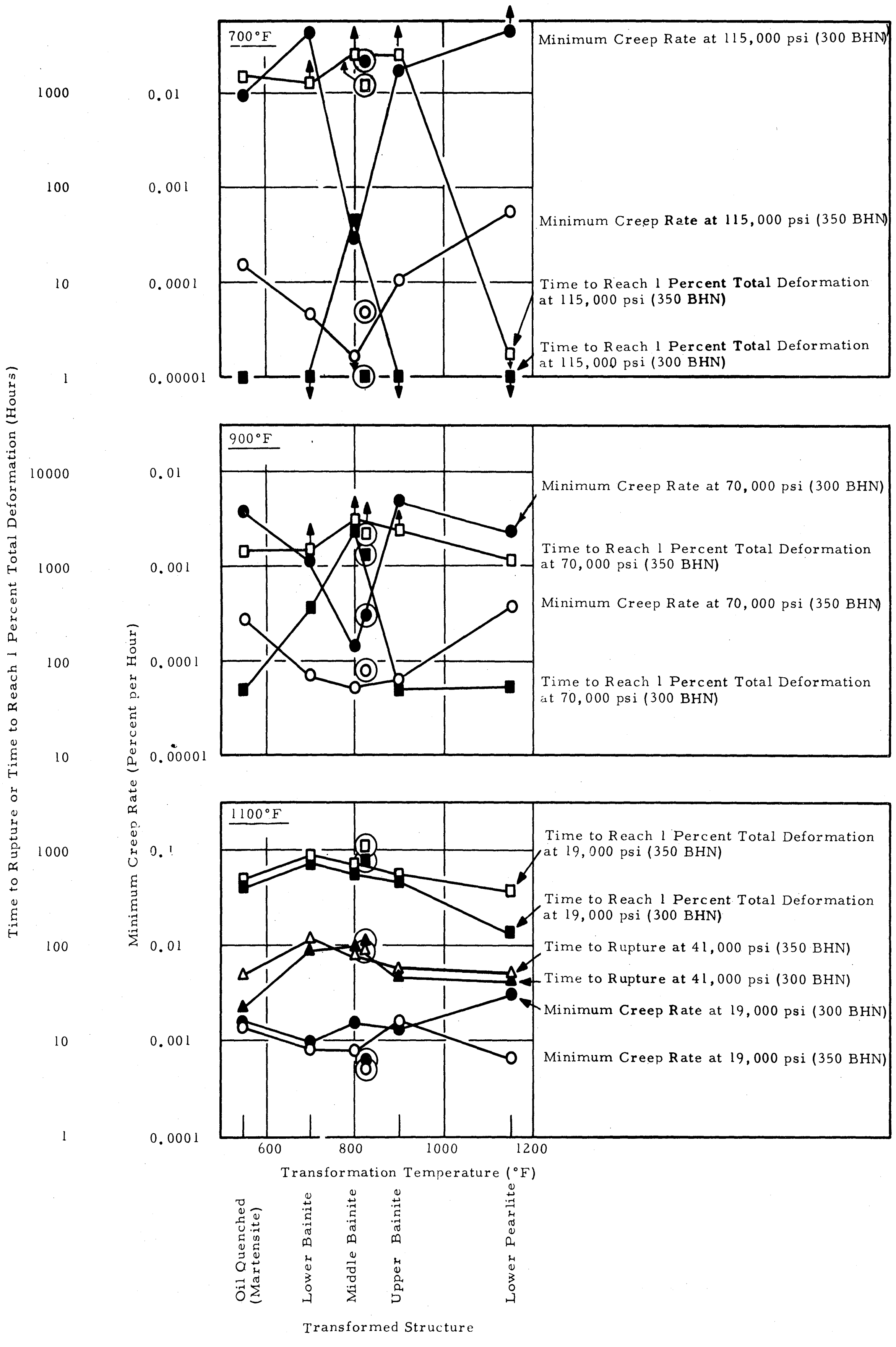


Figure 2. - Influence of Hardness Level on the Properties of Six "17-22-A"S Structures at 700°, 900°, and 1100°F. (The encircled points are for the normalized structure.)

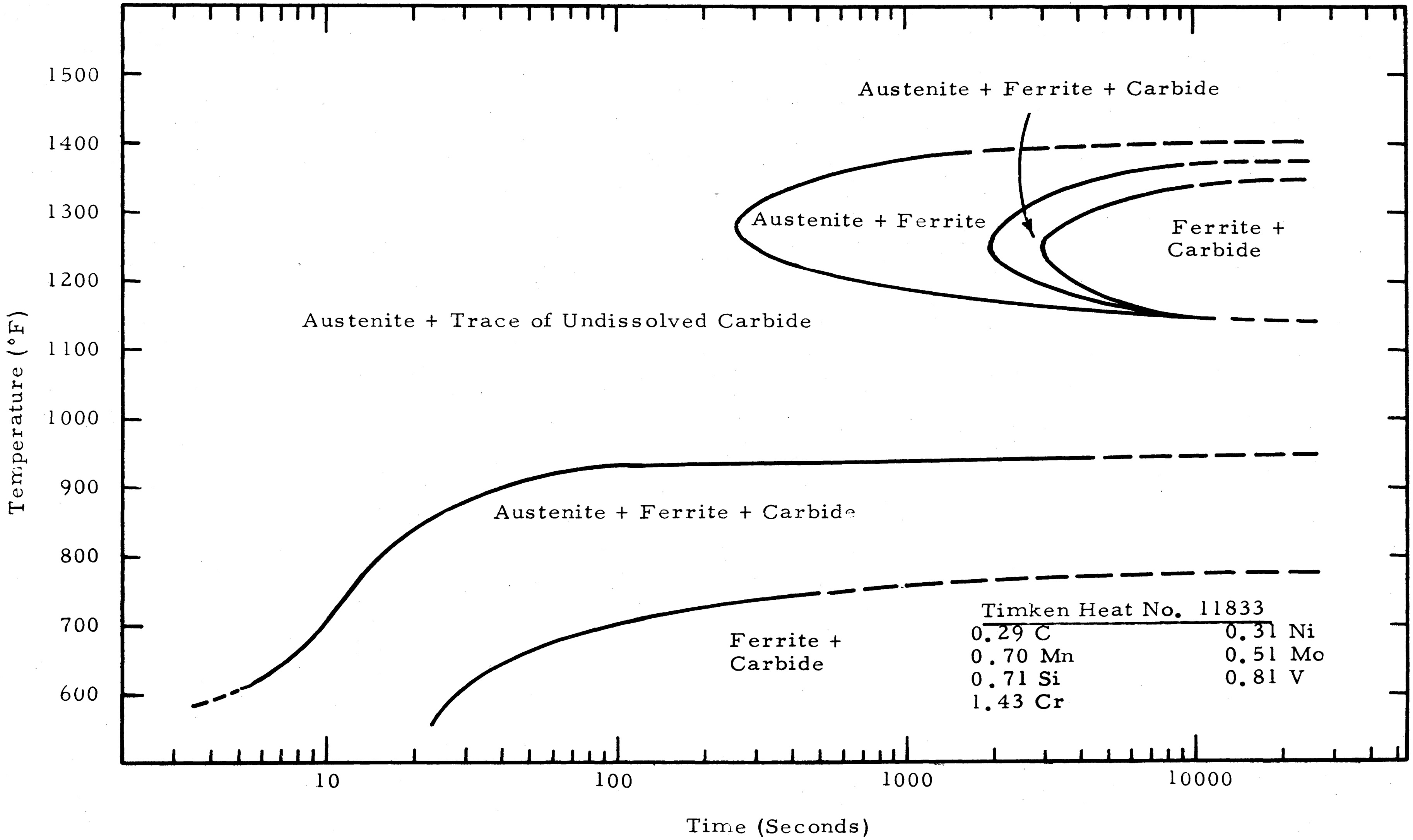
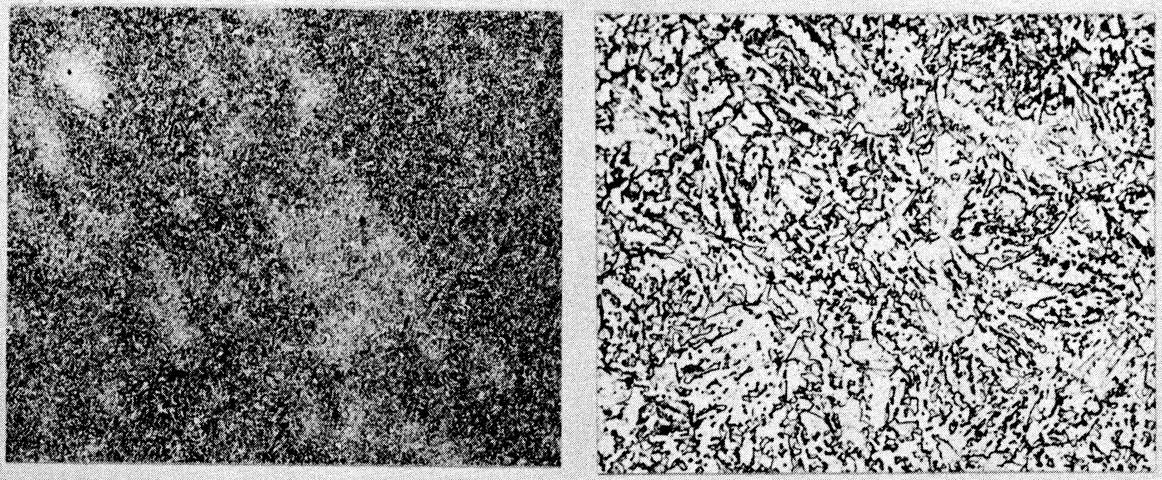
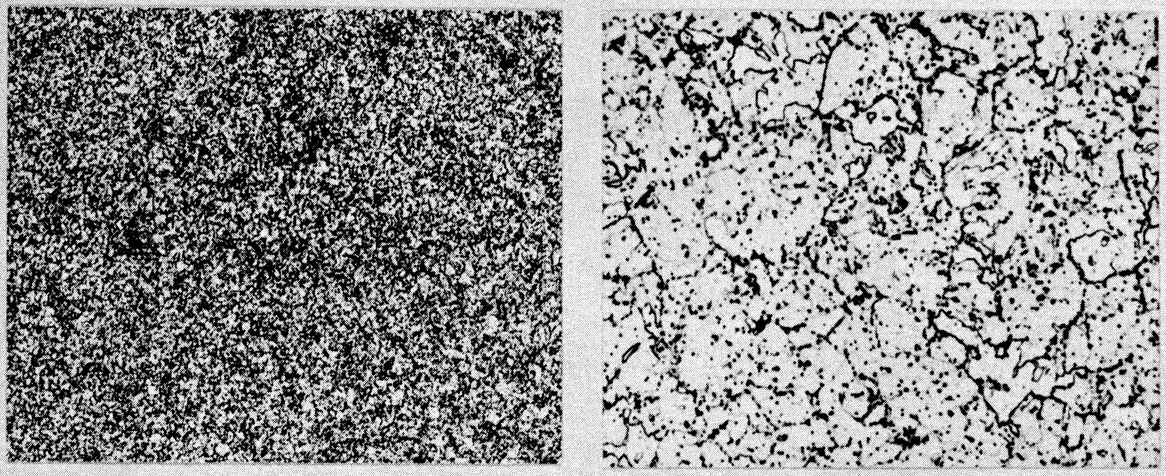


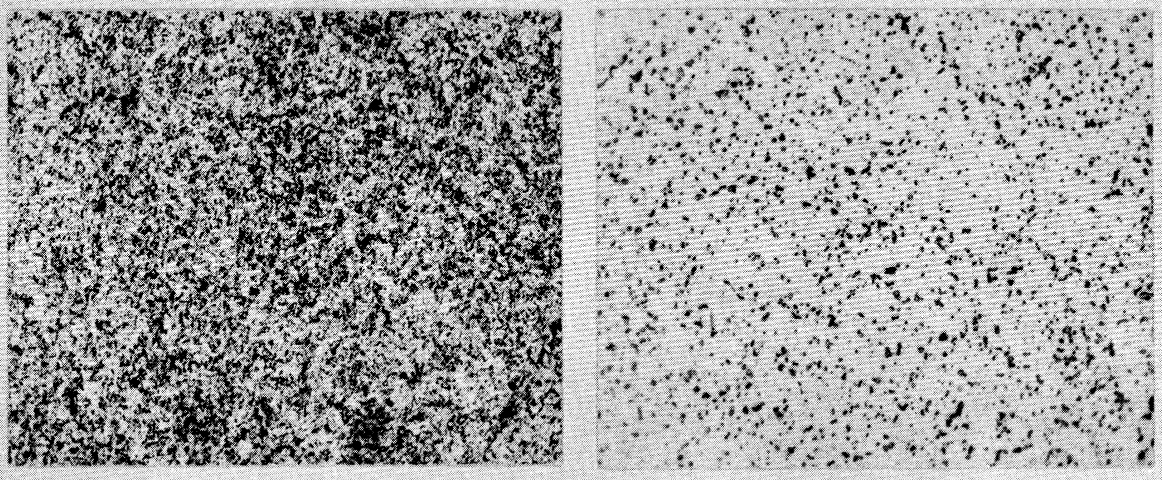
Figure 3. - Isothermal Transformation Diagram for "17-22-A"V Steel Austenitized at 1850°F (A.S.T.M. Grain Size 9 - 10.)



(a) Air Cooled from 1850°F (0.8-Inch Round). Avg. BHN - 374

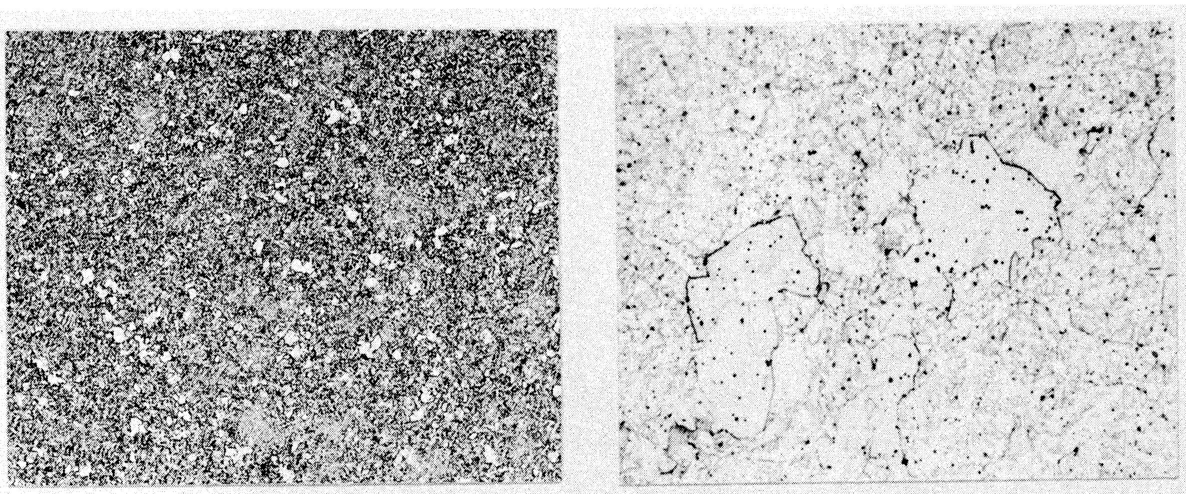


(b) Air Cooled from 1850°F + Tempered 2 Hours at 1250°F. Avg. BHN - 359

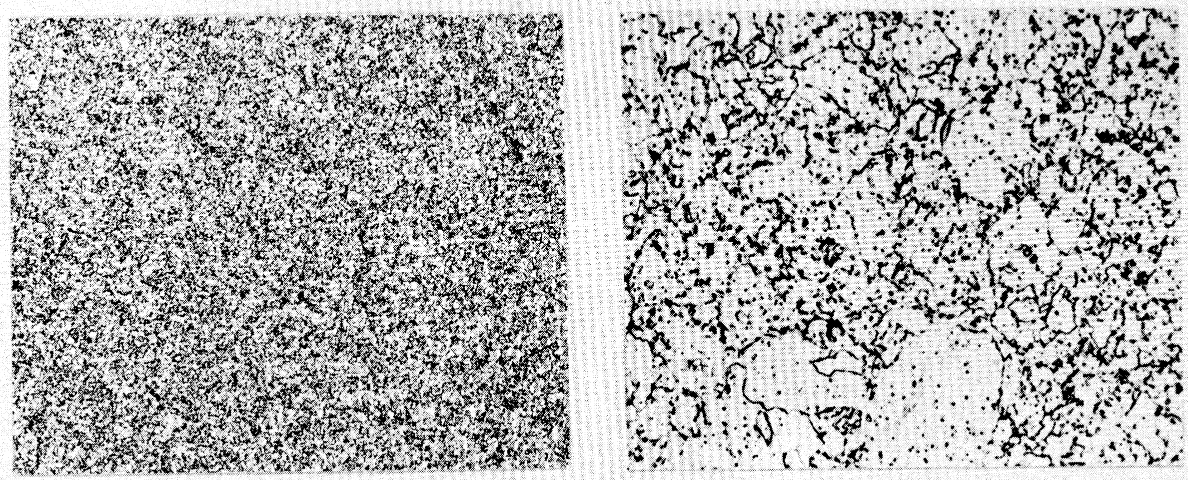


(c) Same As in (b) + Creep Tested 1103 Hours at 1100°F and 19,000 psi
BHN - 274

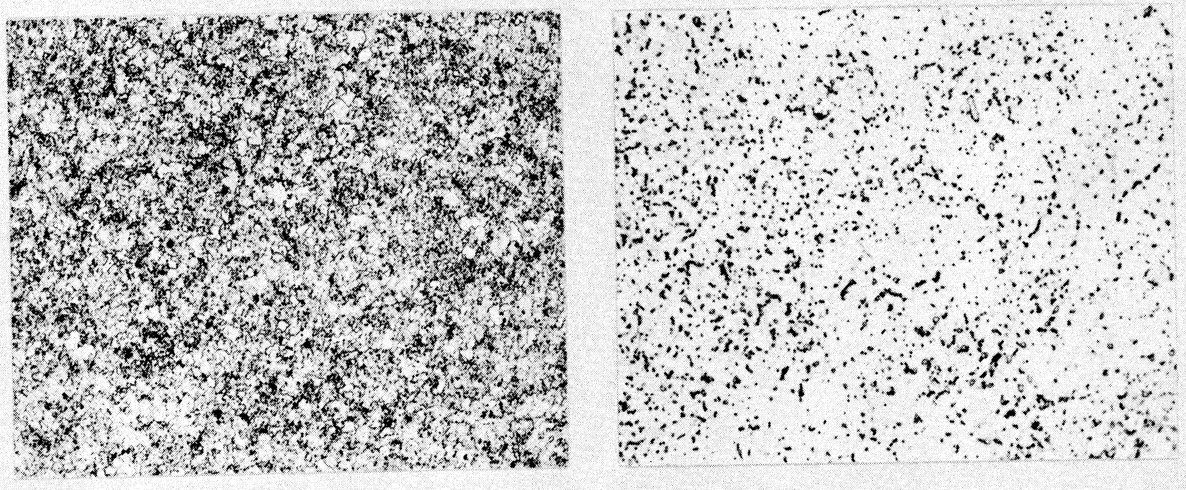
Figure 4. - "17-22-A"V Bar Stock (a) As Normalized from 1850°F, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Air Cooled from 1850°F in Firebrick Jacket to Simulate Cooling Cycle at Center of a 3-Inch Round. Avg. BHN - 365

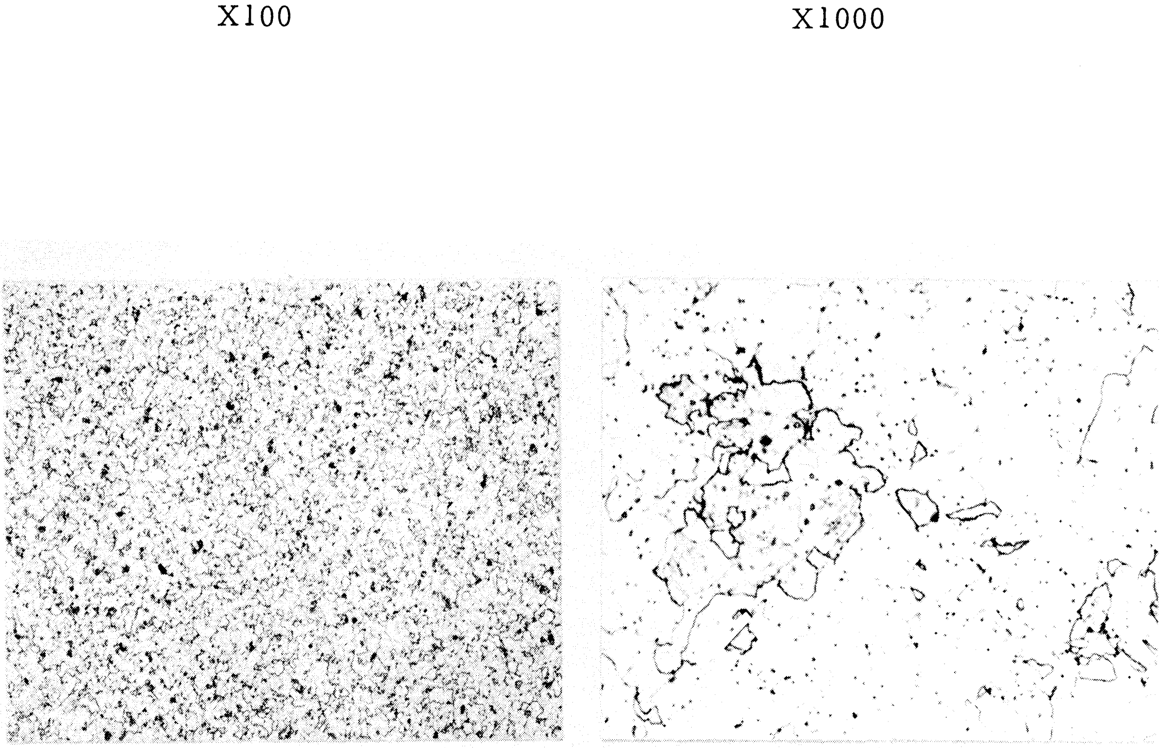


(b) Same As in (a) + Tempered 23 Hours at 1200°F. Avg. BHN - 300

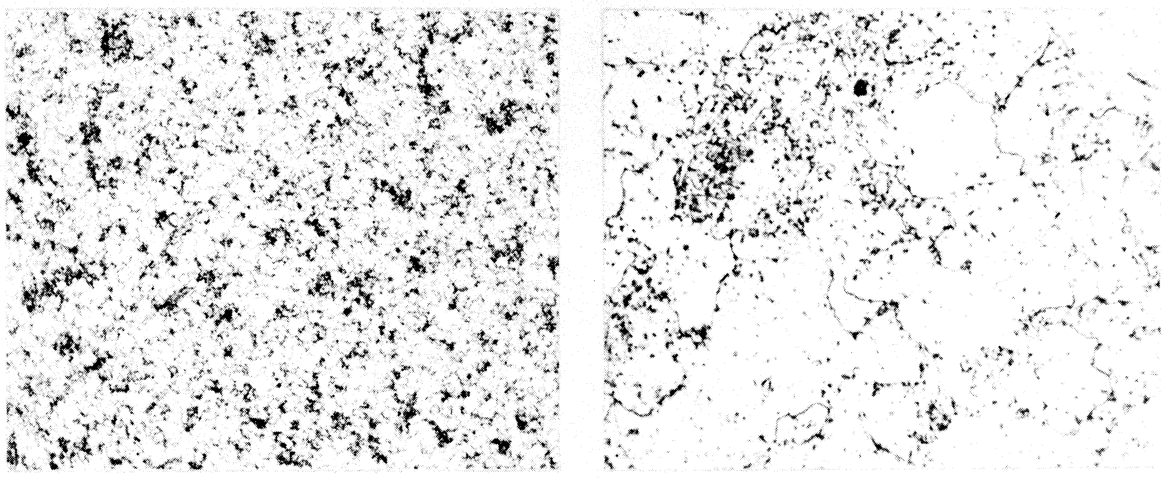


(c) Same As in (b) + Creep Tested 1039 Hours at 1100°F and 19,000 psi. BHN - 243

Figure 5. - "17-22-A"V Bar Stock (a) As Normalized in Simulated 3-Inch Round, (b) As Tempered to 300 BHN, and (c) After Creep Tested at 1100°F.

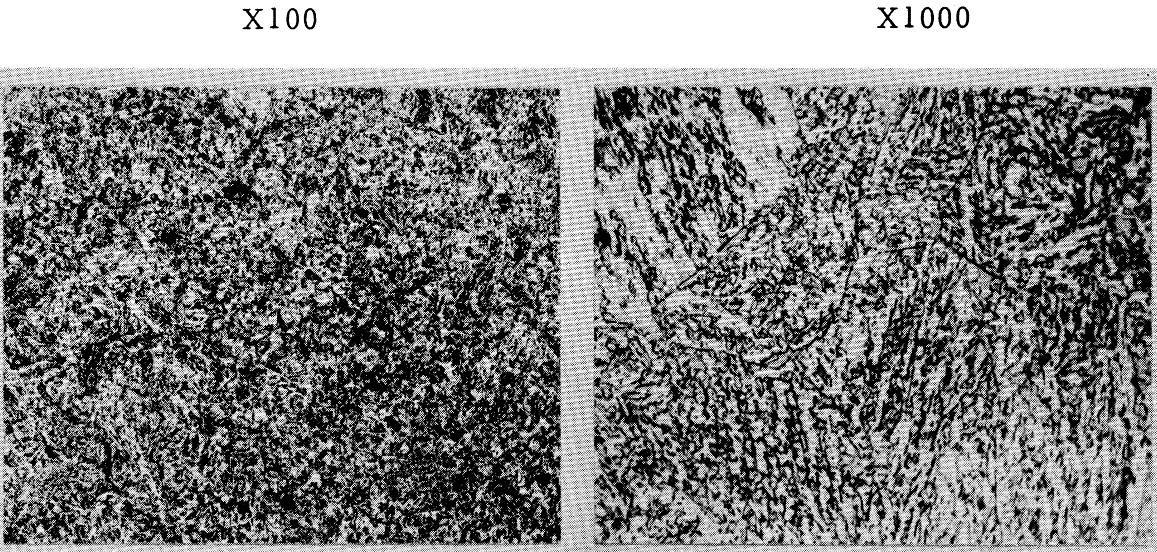


(a) Air Cooled from 1850°F in Firebrick Jacket to Simulate Cooling Cycle at Center of a 6-Inch Round. Avg. BHN - 303

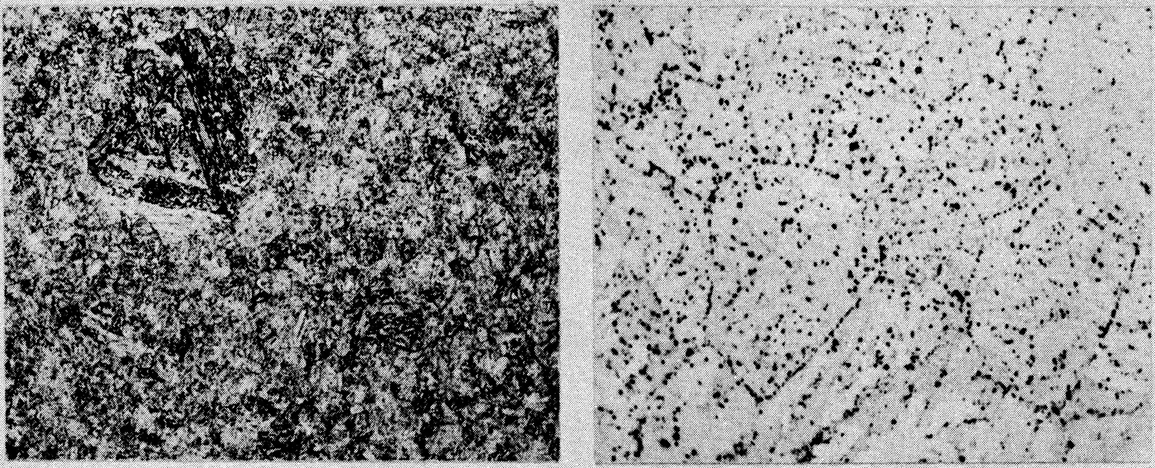


(b) Same As in (a) + Creep Tested 1054 Hours at 1100°F and 19,000 psi. BHN - 222

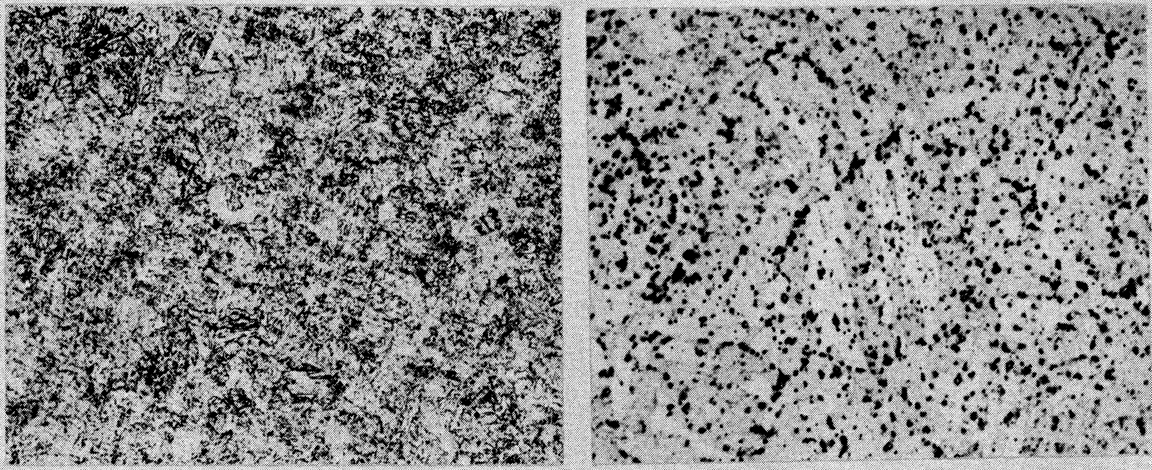
Figure 6. - "17-22-A"V Bar Stock (a) As Normalized in Simulated 6-Inch Round and (b) After Creep Tested at 1100°F.



(a) Air Cooled from 2000°F (0.8-Inch Round). Avg. BHN - 384

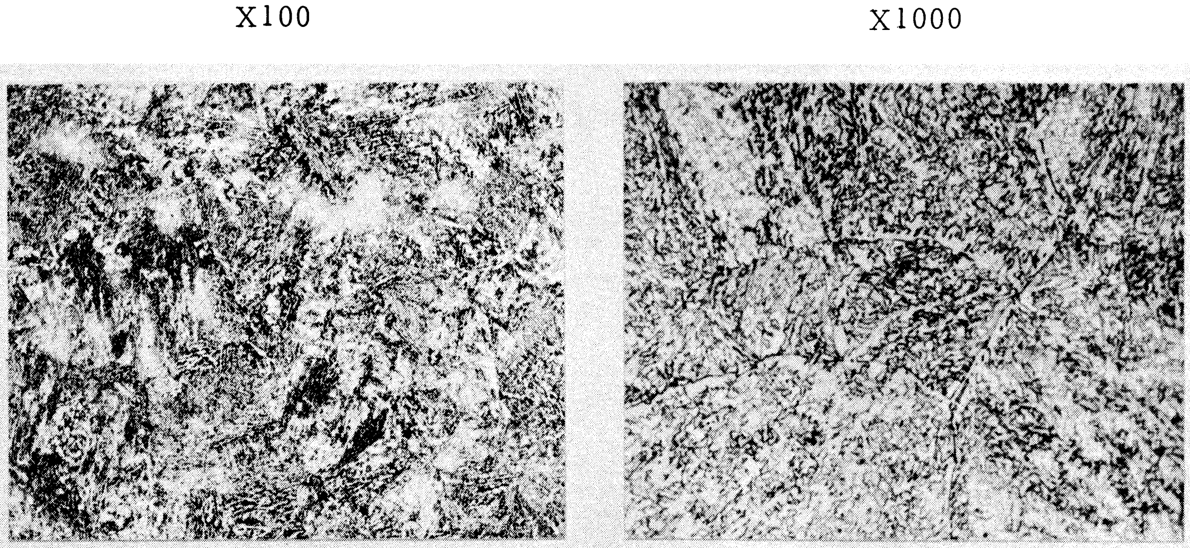


(b) Air Cooled from 2000°F + Tempered 4 Hours at 1250°F. Avg. BHN - 349

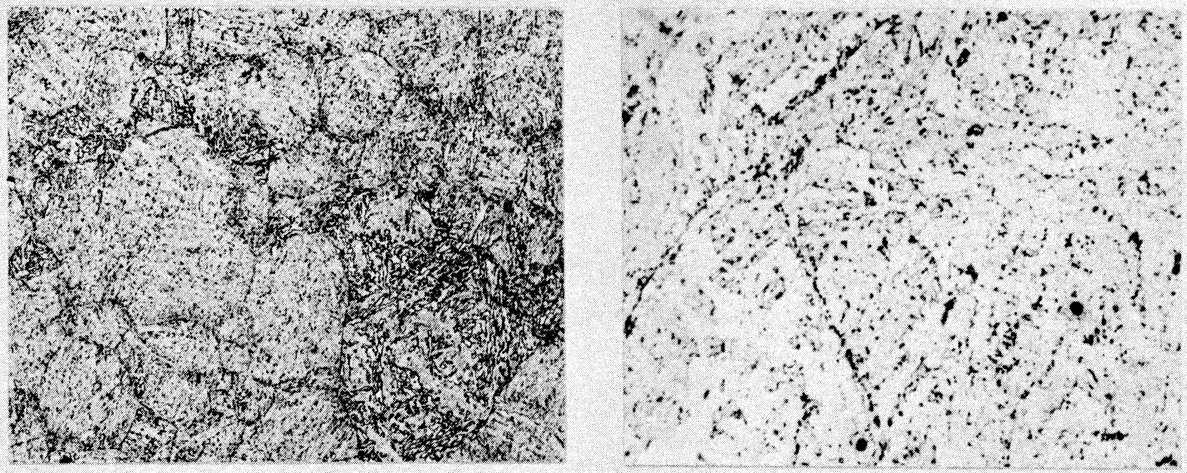


(c) Same As in (b) + Creep Tested 1002 Hours at 1100°F and 19,000 psi. BHN - 302

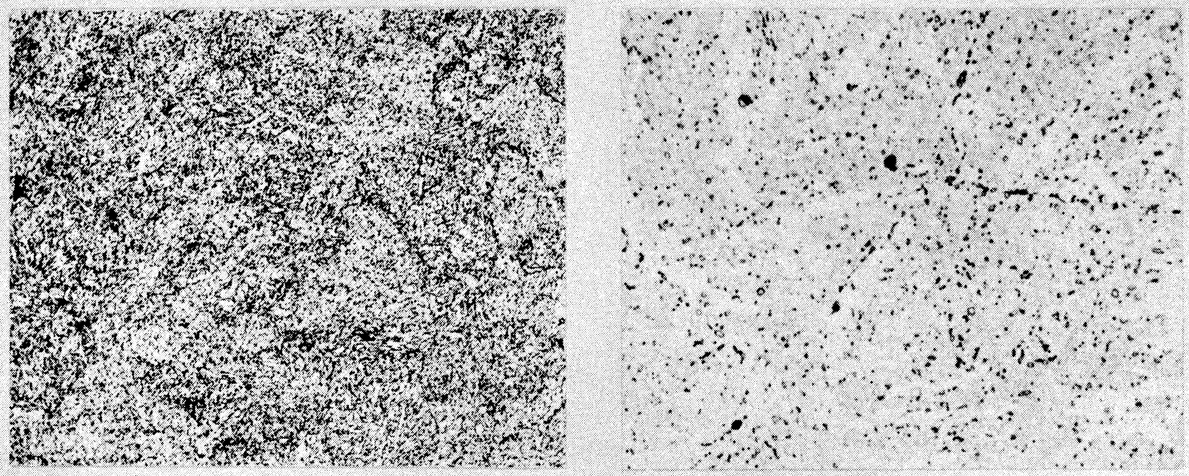
Figure 7. - "17-22-A"V Bar Stock (a) As Normalized from 2000°F, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100° F.



(a) Air Cooled from 2200°F (1-Inch Round). Avg. BHN - 377

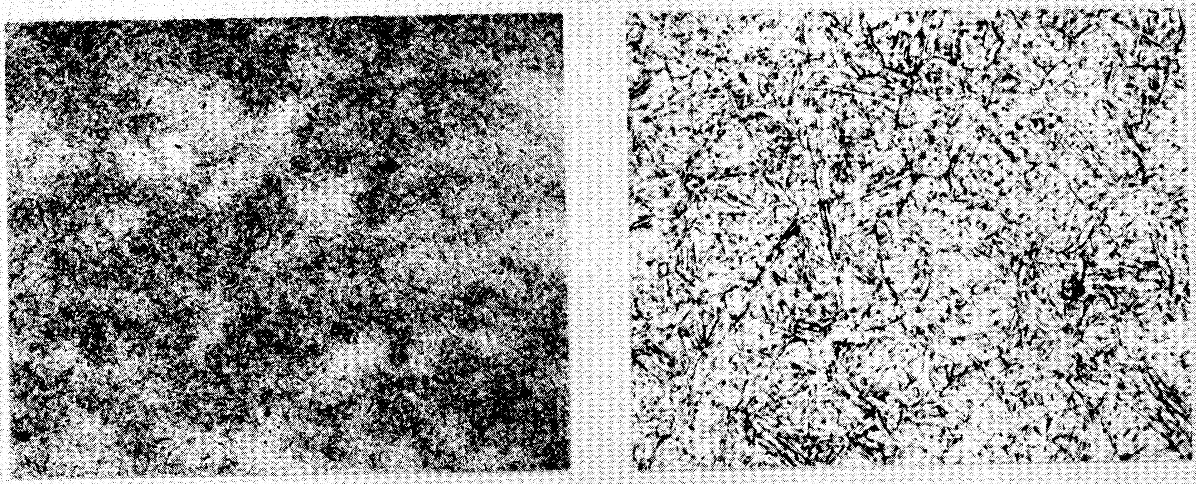


(b) Air Cooled from 2200°F + Tempered 7 Hours at 1250°F. Avg. BHN - 362

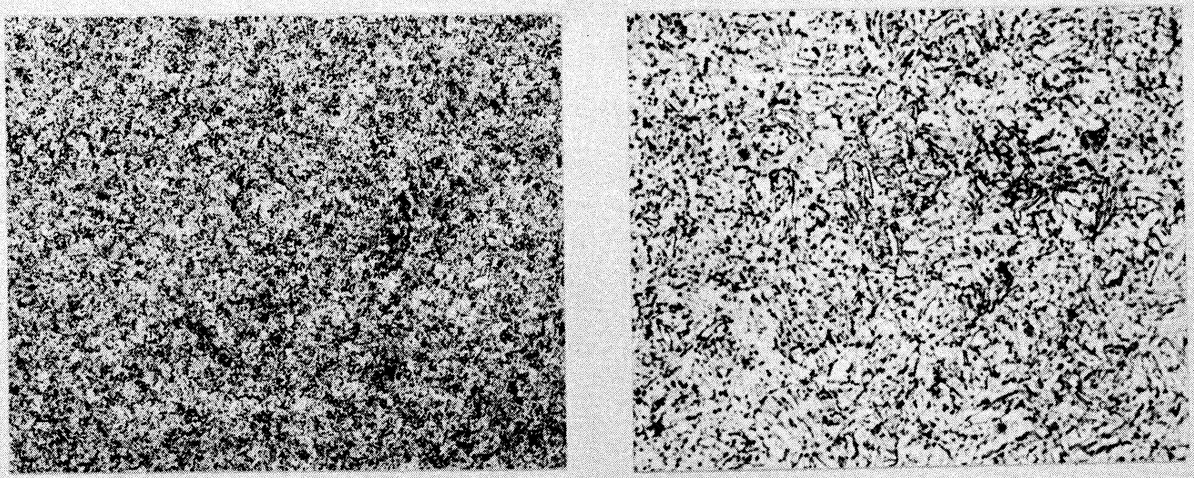


(c) Same As in (b) + Creep-Rupture Tested 351 Hours at 1100°F and 19,000 psi. BHN - 296

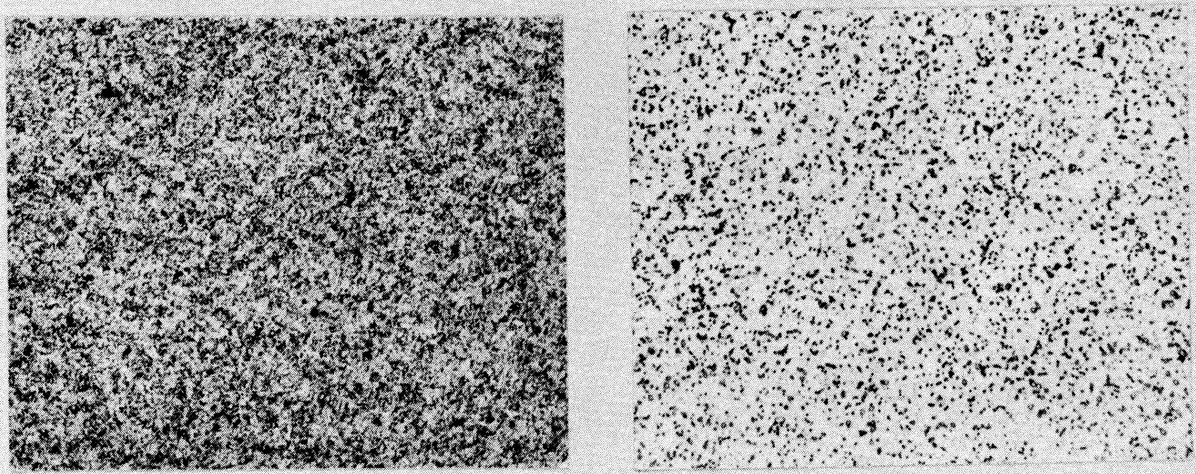
Figure 8. - "17-22-A"V Bar Stock (a) As Normalized from 2200°F, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Oil Quenched from 1850°F (0.8-Inch Round). Avg. BHN - 476

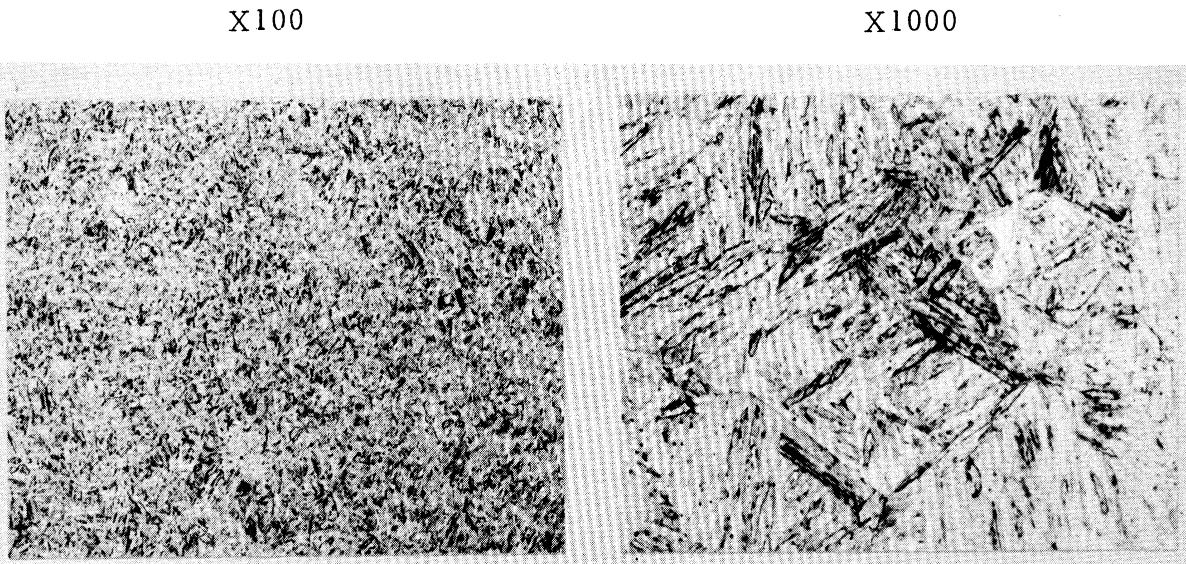


(b) Oil Quenched from 1850°F + Tempered 2 Hours at 1250°F. Avg. BHN - 345

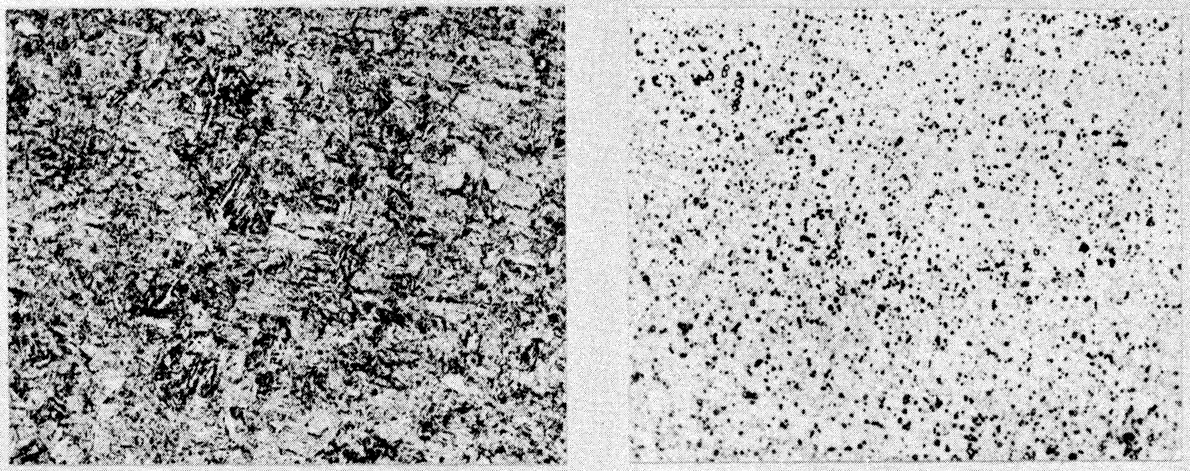


(c) Same As in (b) + Creep-Rupture Tested 1492 Hours at 1100°F and 19,000 psi. BHN - 160

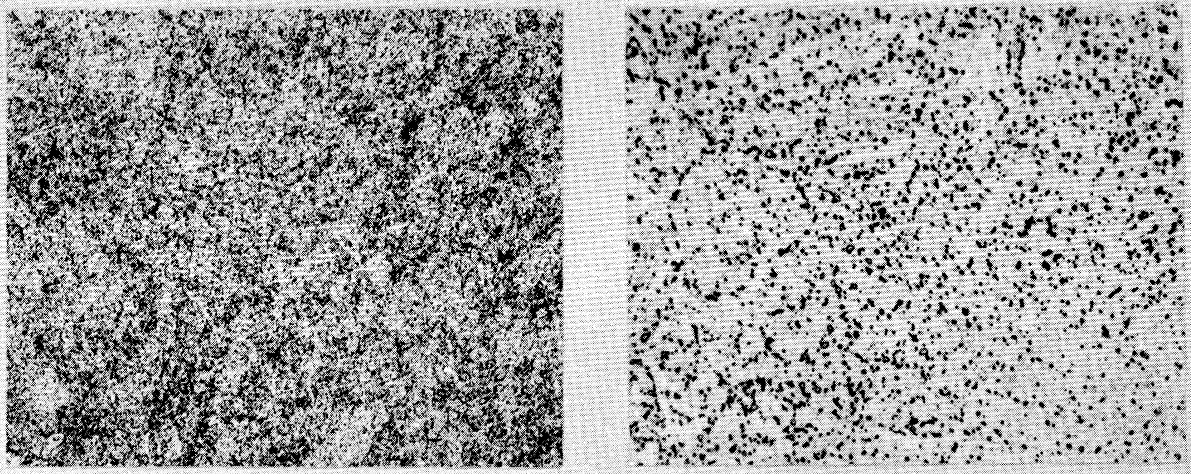
Figure 9. - "17-22-A"V Bar Stock (a) As Oil Quenched from 1850°F, (b) As Tempered to 350 BHN, and (c) After Creep-Rupture Tested at 1100°F.



(a) Oil Quenched from 2000°F (0.8-Inch Round). Avg. BHN - 487

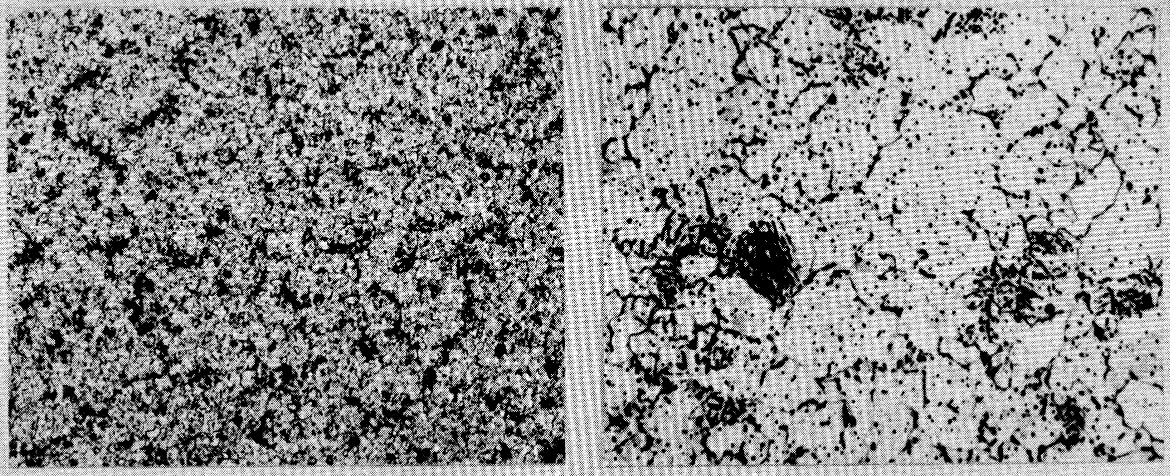


(b) Oil Quenched from 2000°F + Tempered 4 Hours at 1250°F. Avg. BHN - 348

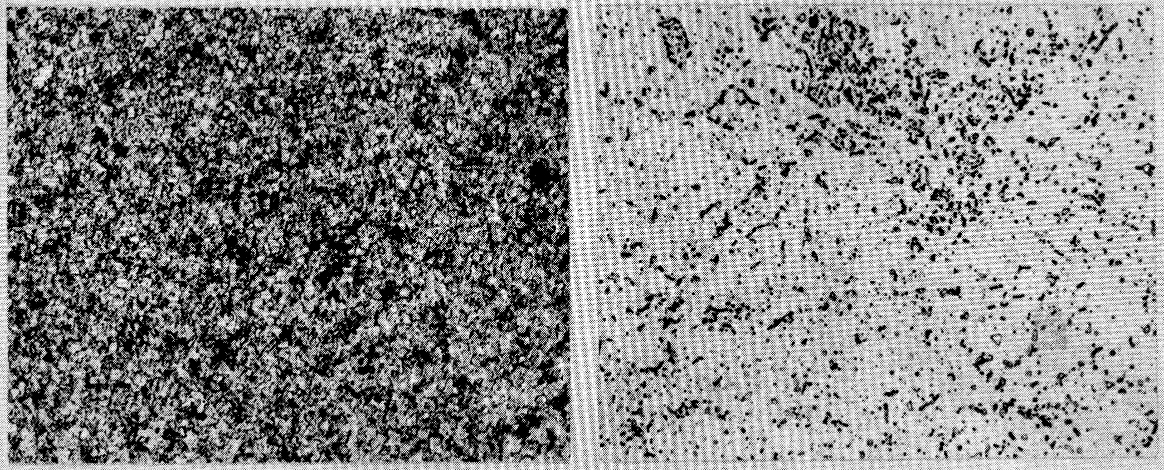


(c) Same As in (b) + Creep Tested 1002 Hours at 1100°F and 19,000 psi. BHN - 286

Figure 10. - "17-22-A"V Bar Stock (a) As Oil Quenched from 2000°F, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.

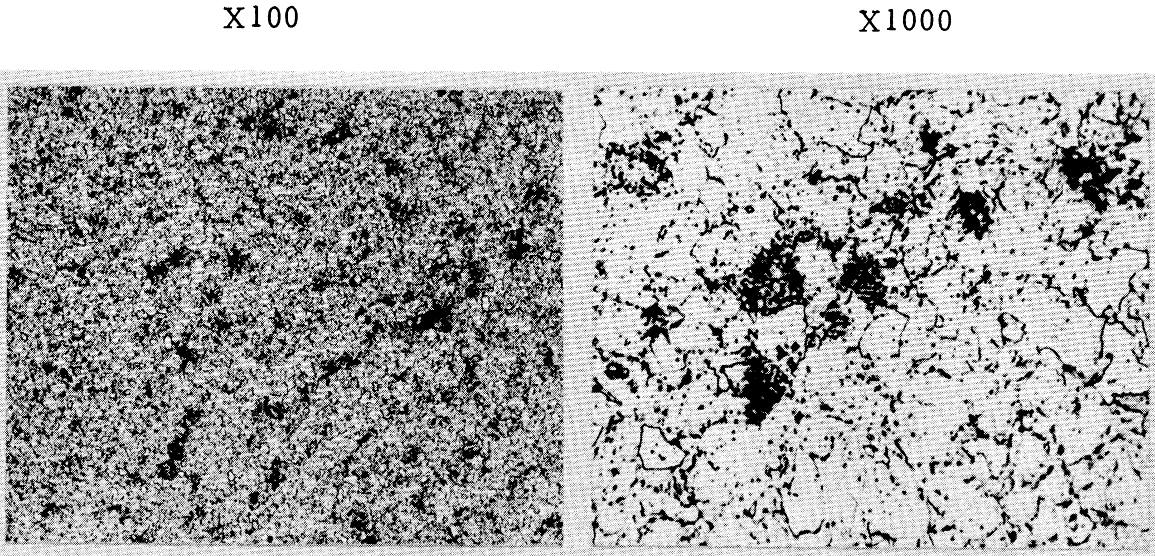


(a) Austenitized at 1850°F and Isothermally Transformed 3.5 Hours at 1275°F to Middle Pearlite (0.4-Inch Round). Avg. BHN - 255

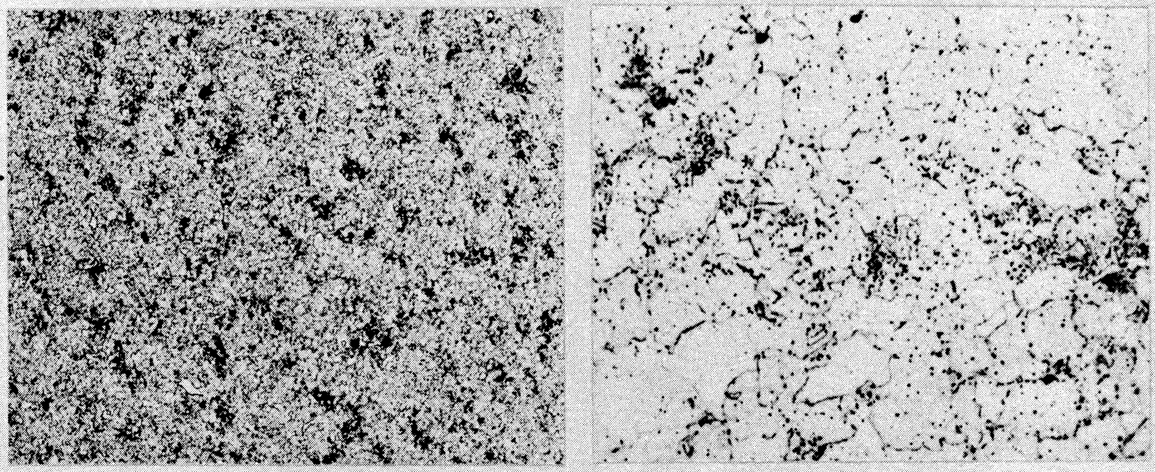


(b) Same As in (a) + Creep Tested 743 Hours at 1100°F and 19,000 psi. BHN - 253

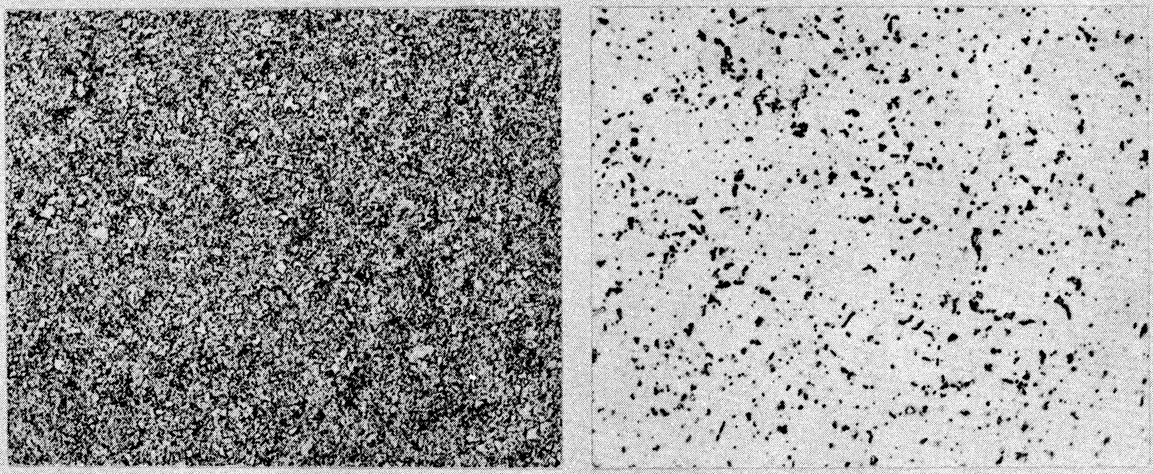
Figure 11. - "17-22-A"V Bar Stock (a) As Transformed to Middle Pearlite and (b) After Creep Tested at 1100°F.



(a) Austenitized at 1850°F and Isothermally Transformed 5 Hours at 1200°F to Lower Pearlite (0.4-Inch Round). Avg. BHN - 360

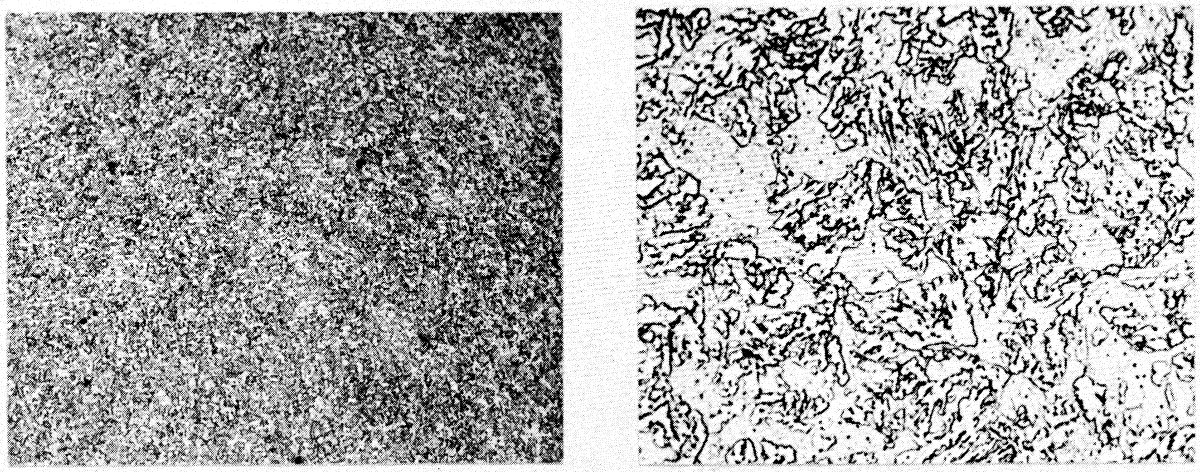


(b) Same As in (a) + Tempered 1 Hour at 1200°F. Avg. BHN - 347

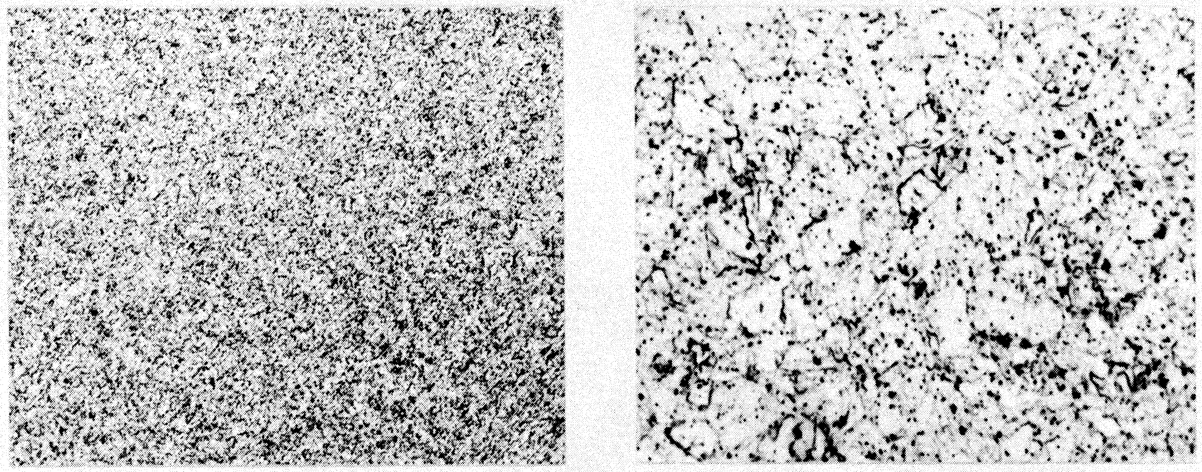


(c) Same As in (b) + Creep Tested 839 Hours at 1100°F and 19,000 psi. BHN - 293

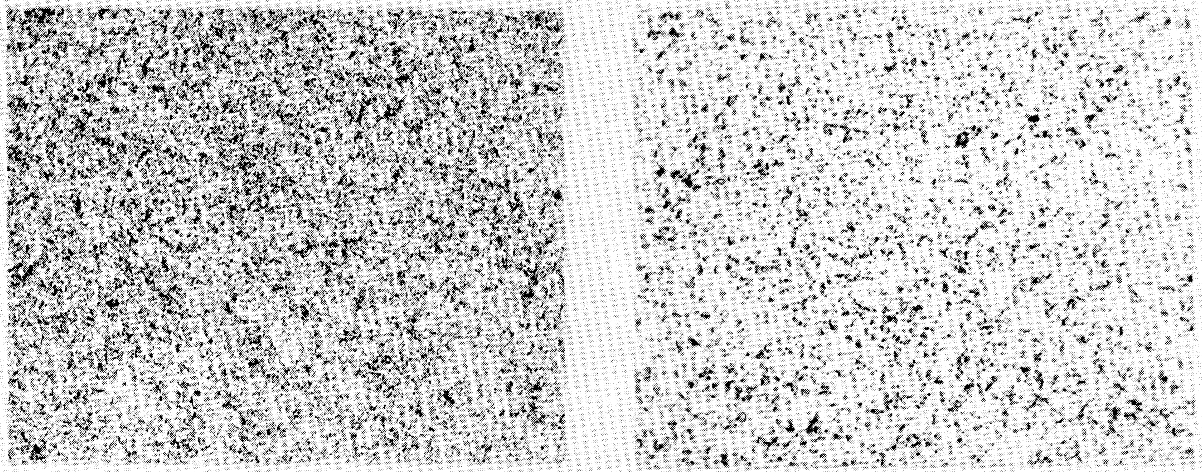
Figure 12. - "17-22-A"V Bar Stock (a) As Transformed to Lower Pearlite, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Austenitized at 1850°F and Isothermally Transformed 2 Hours at 850°F to Upper Bainite (0.4-Inch Round). Avg. BHN - 447

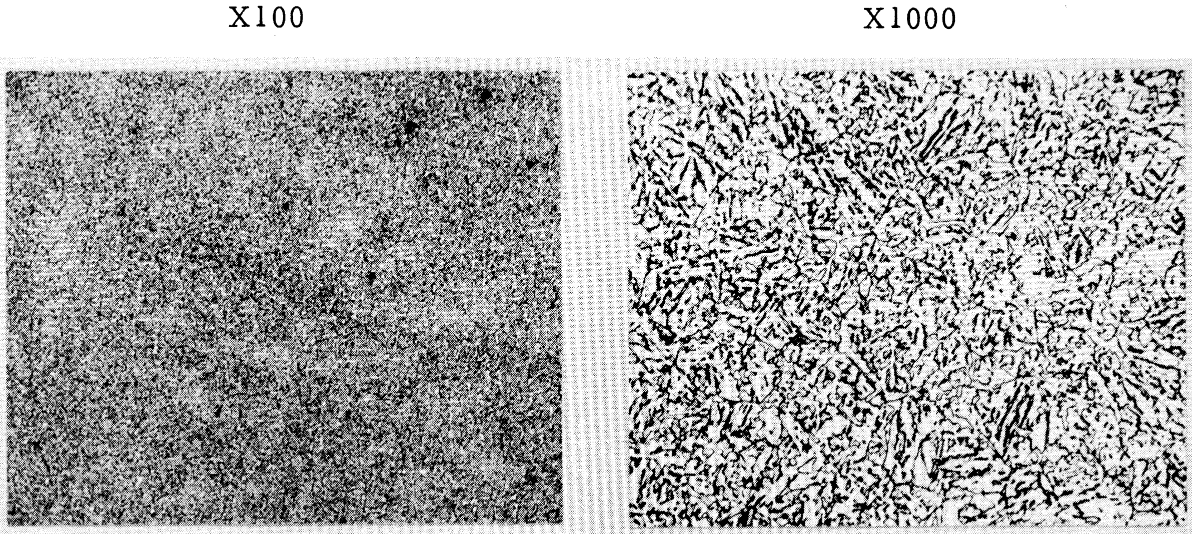


(b) Same As in (a) + Tempered 4.5 Hours at 1200°F. Avg. BHN - 348

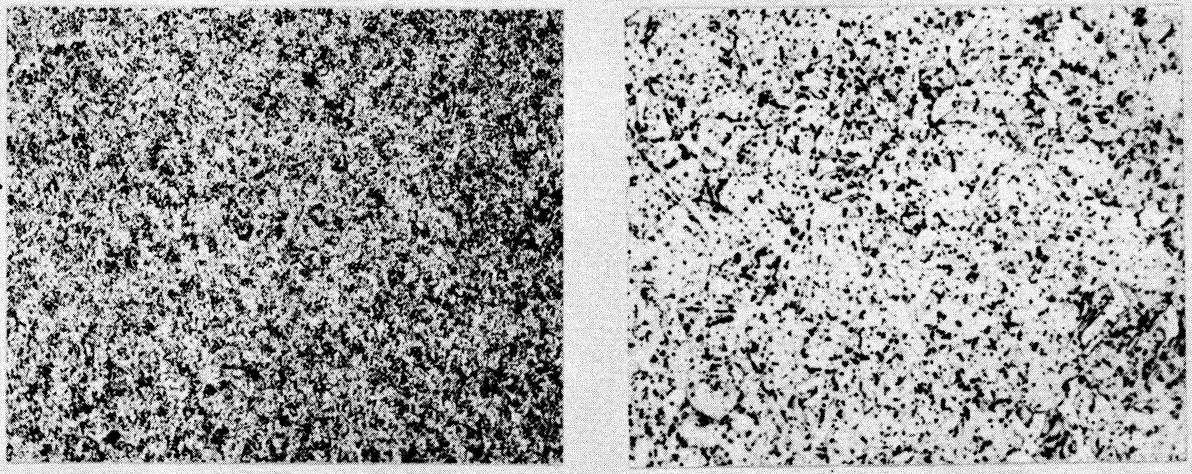


(c) Same As in (b) + Creep Tested 763 Hours at 1100°F and 19,000 psi. BHN - 276

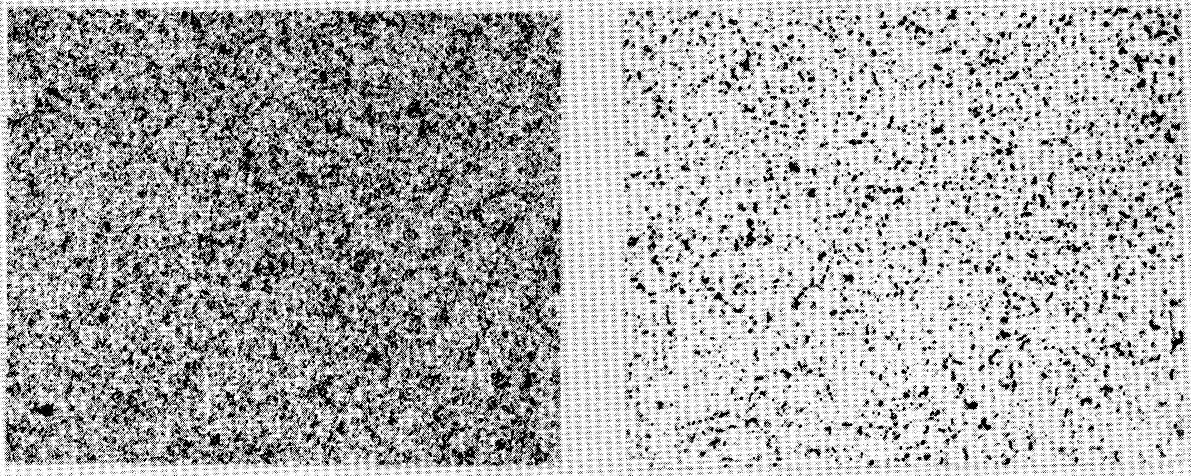
Figure 13. - "17-22-A"V Bar Stock (a) As Transformed to Upper Bainite, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Austenitized at 1850°F and Isothermally Transformed 0.3 Hours at 750°F to Middle Bainite (0.4-Inch Round). Avg. BHN - 364



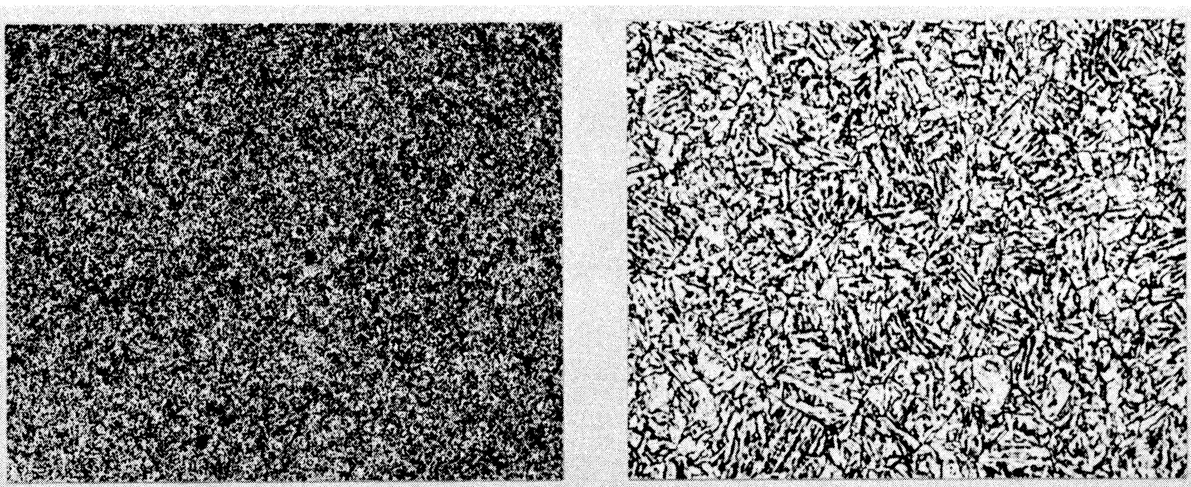
(b) Same As in (a) + Tempered 5 Hours at 1200°F. Avg. BHN - 338



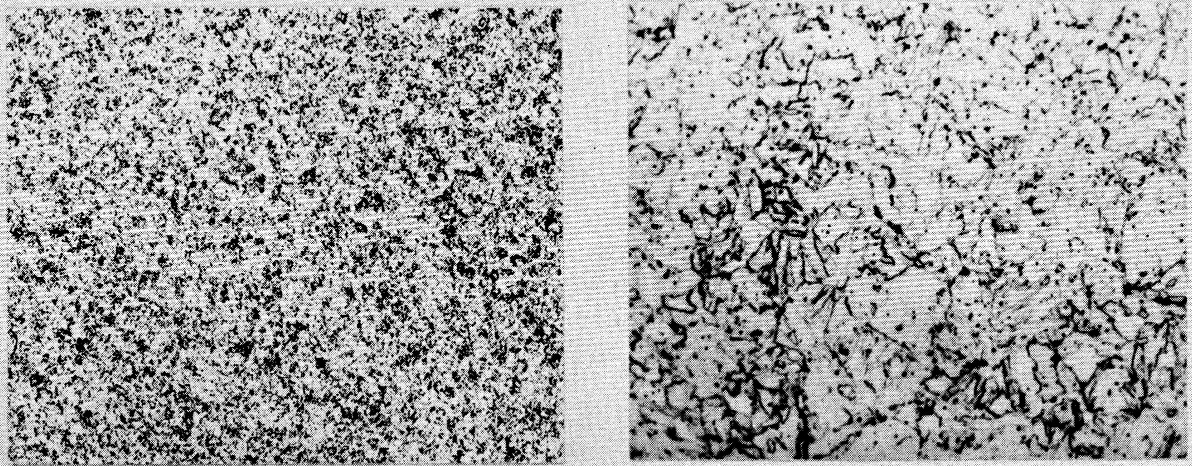
(c) Same As in (b) + Creep Tested 743 Hours at 1100°F and 19,000 psi. BHN - 281

Figure 14. - "17-22-A"V Bar Stock (a) As Transformed to Middle Bainite, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.

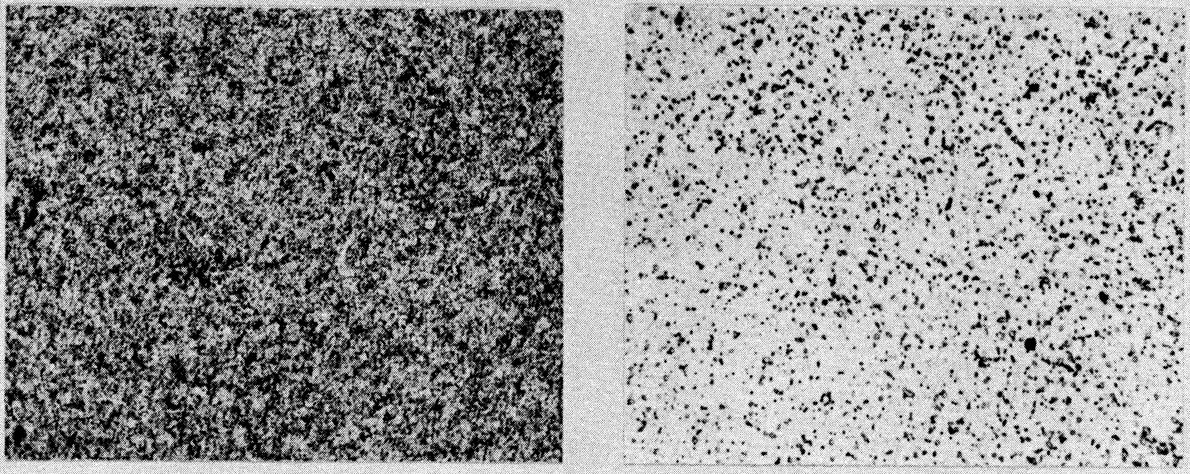
X100 X1000



(a) Austenitized at 1850°F and Isothermally Transformed 0.2 Hour at 650°F to Lower Bainite (0.4-Inch Round). Avg. BHN - 405



(b) Same As in (a) + Termpered 6 Hours at 1200°F. Avg. BHN - 348



(c) Same As in (b) + Creep Tested 861 Hours at 1100°F and 19,000 psi. BHN - 259

Figure 15. - "17-22-A"V Bar Stock (a) As Transformed to Lower Bainite, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.

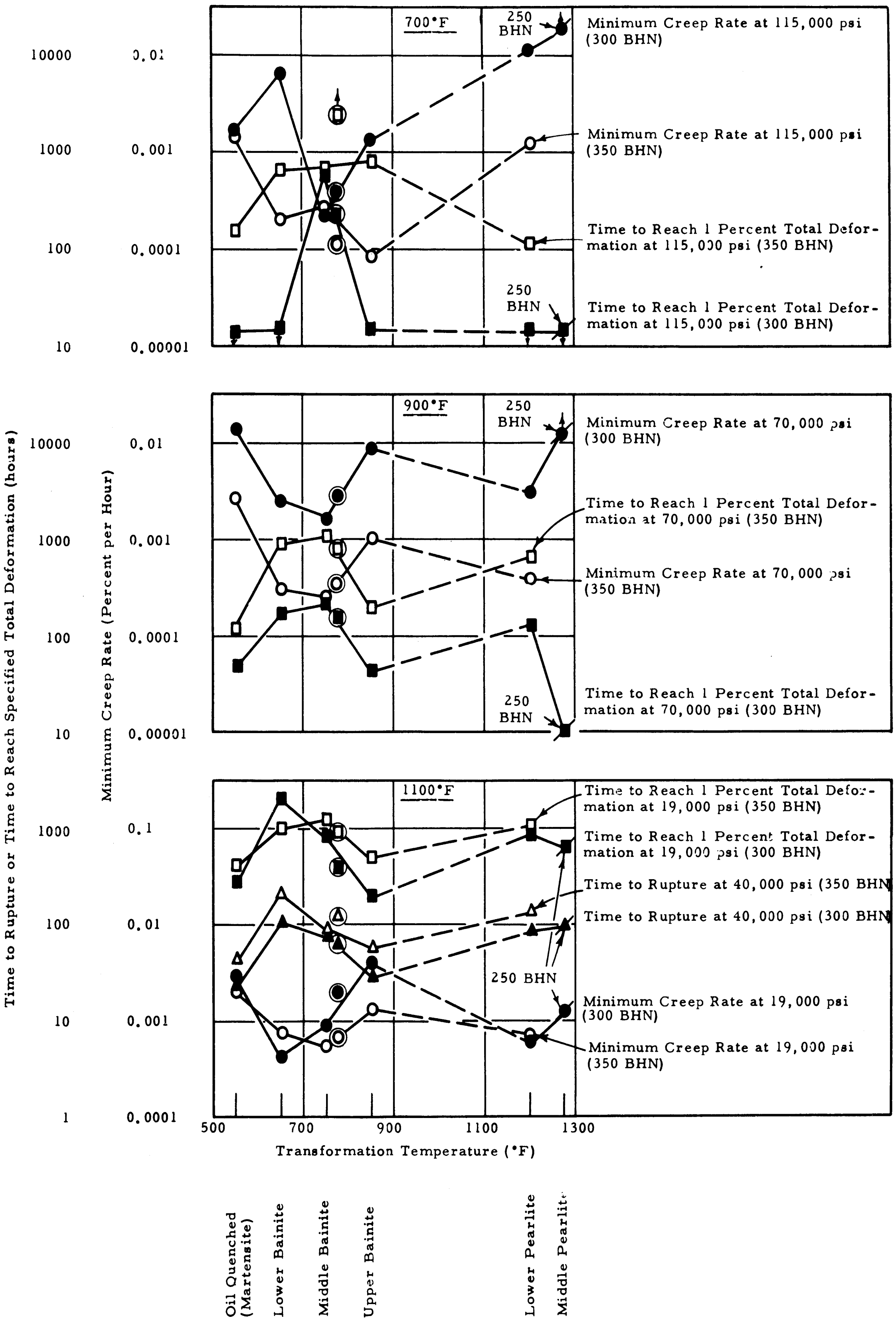


Figure 16. - Relationship between Properties at 700°, 900°, and 1100°F of Typical Transformation Structures of "17-22-A"V and Temperature of Transformation.
(NOTE: Properties of Normalized Bar Stock have been encircled and inserted at transformation temperature yielding the nearest correspondence to an isothermal structure.)

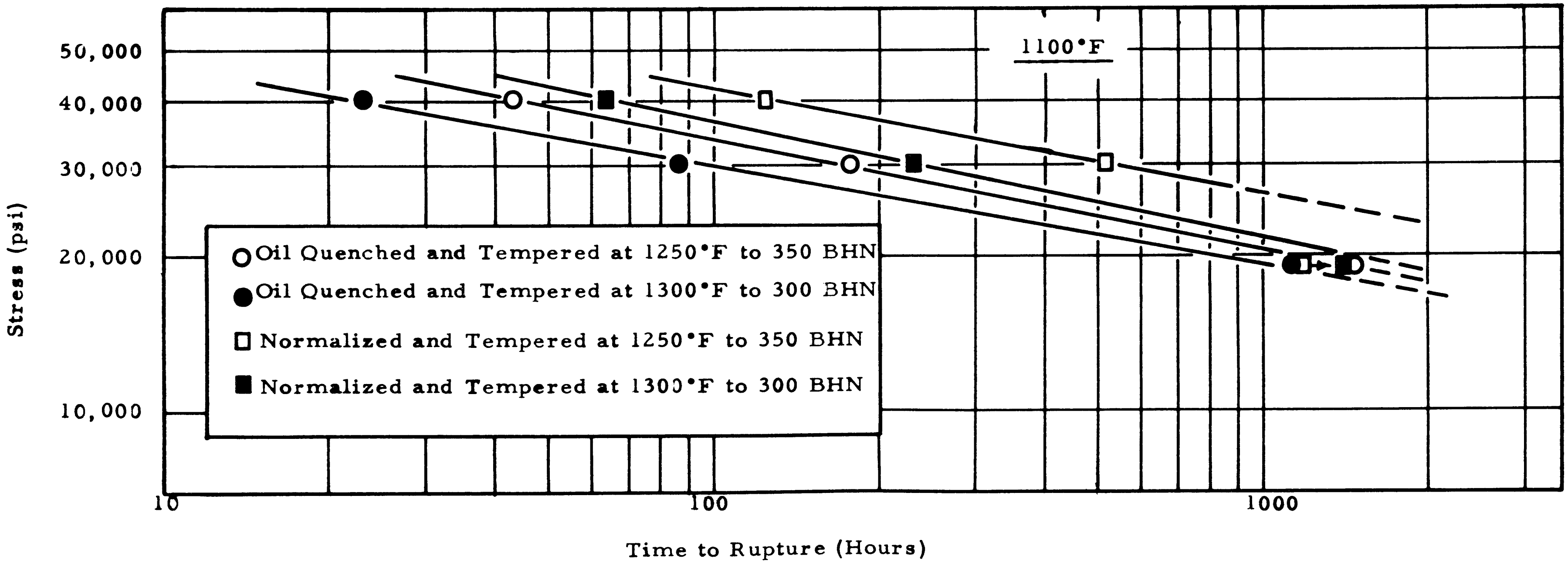


Figure 17. - Influence of Tempered Hardness on the Stress-Rupture Properties of "17-22-A"V Steel at 1100°F in the Oil-Quenched and the Normalized Conditions.

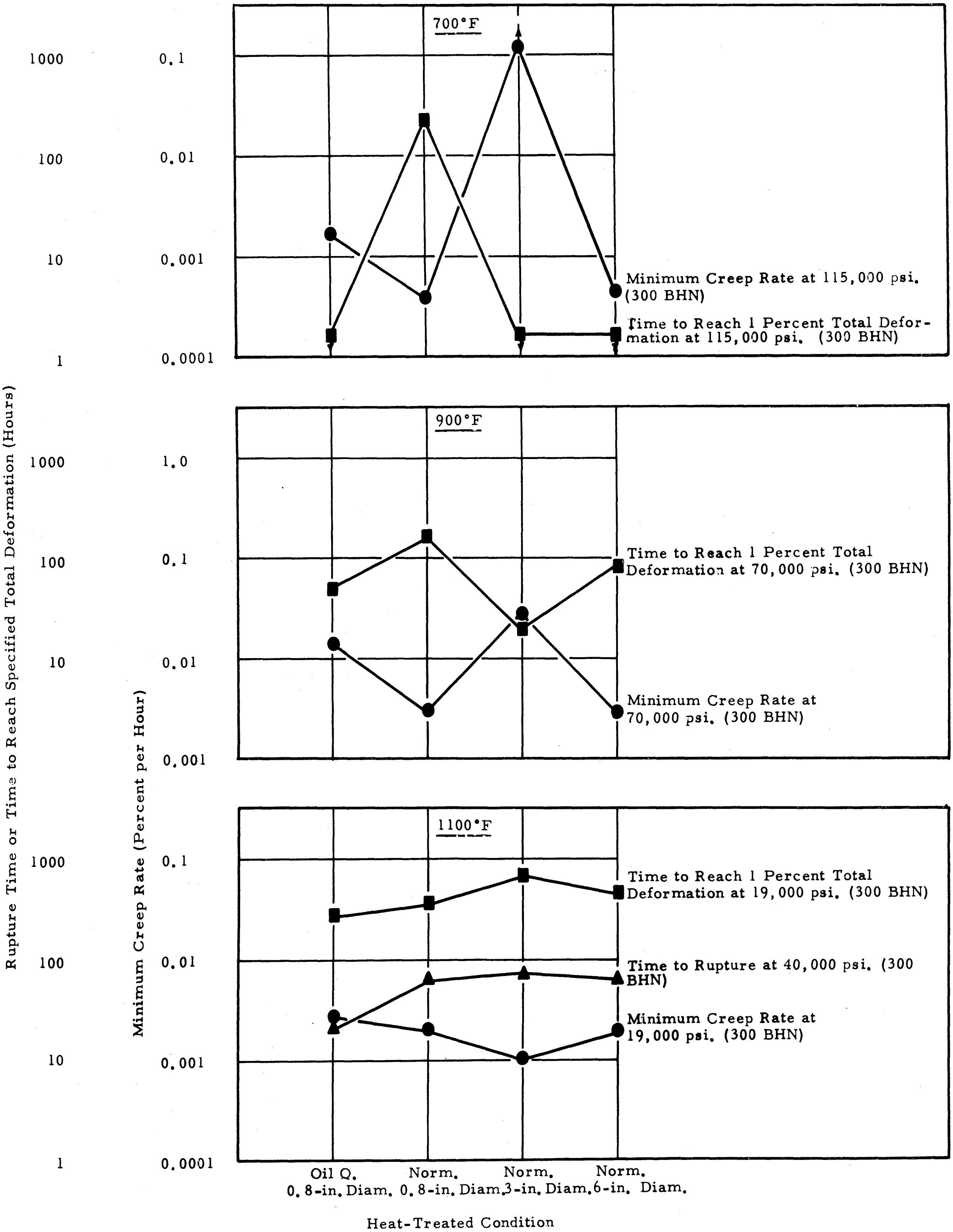
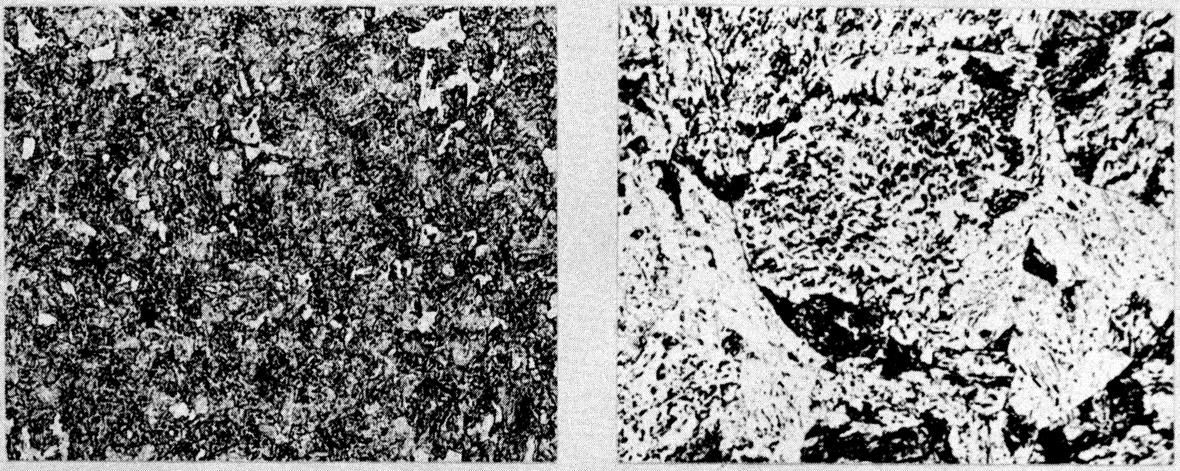
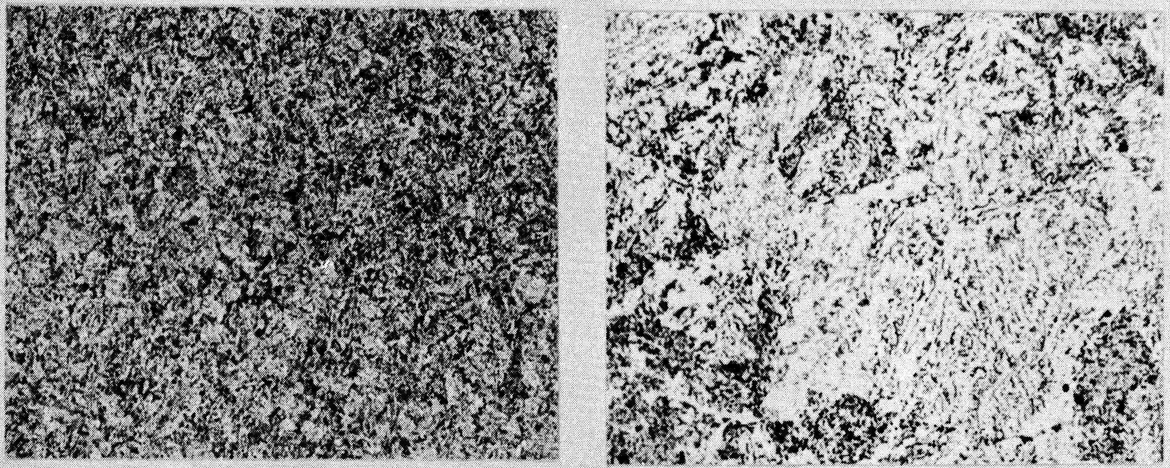


Figure 18. - Influence of Cooling Rate as Controlled by Section Size and Quenching Medium on the High-Temperature Properties of "17-22-A"V Steel at 700°, 900°, and 1100°F.

X100 X1000

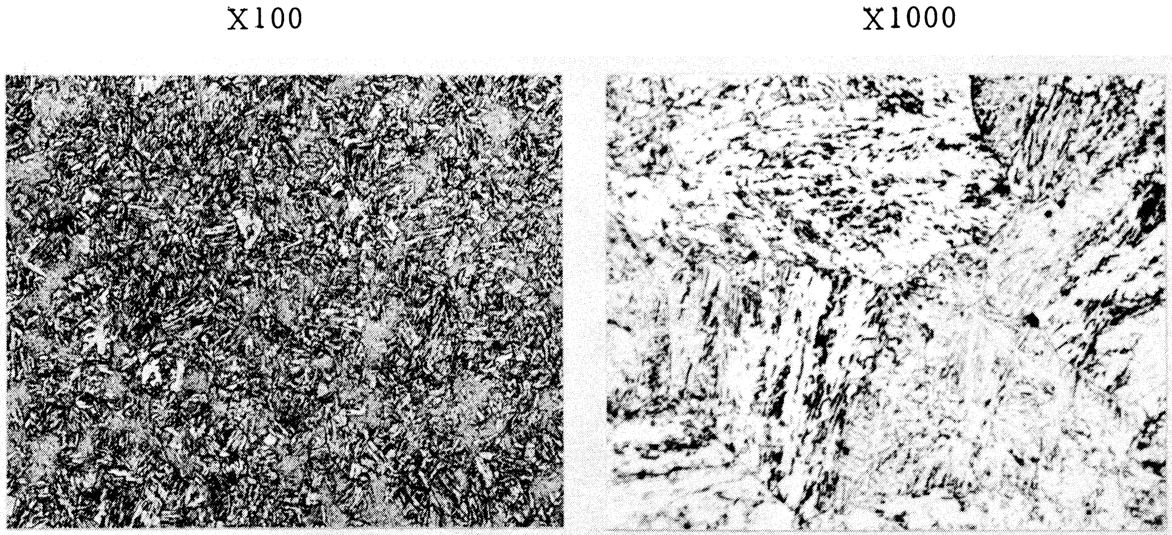


(a) Isothermally Transformed Stepwise at 850° and 650°F to 60 Percent Upper Bainite + 40 Percent Lower Bainite, Avg. BHN - 316

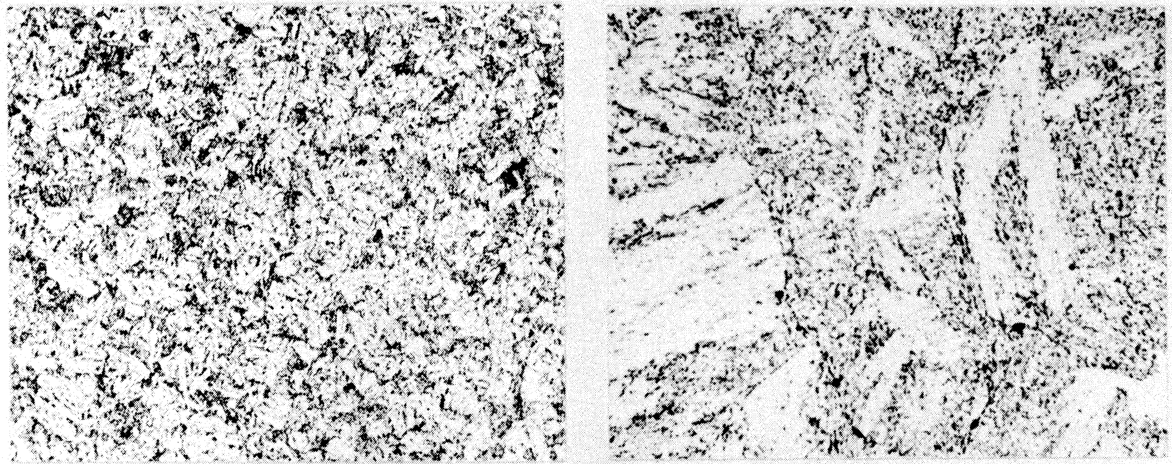


(b) Same As in (a) + Creep Tested 1532 Hours at 1000°F and 13,000 psi. BHN - 268

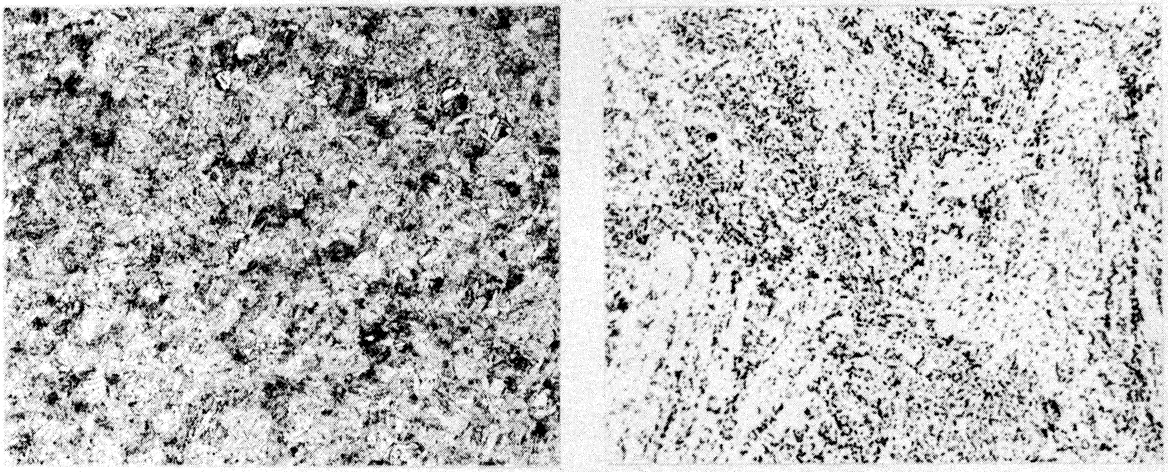
Figure 20. - SAE 4340 Bar Stock (a) As Transformed to a Mixed Bainitic Structure and (b) After Creep Tested at 1000°F.



(a) Isothermally Transformed Stepwise at 900° and 700°F to 50 Percent Upper Bainite + 50 Percent Lower Bainite. Avg. BHN - 353

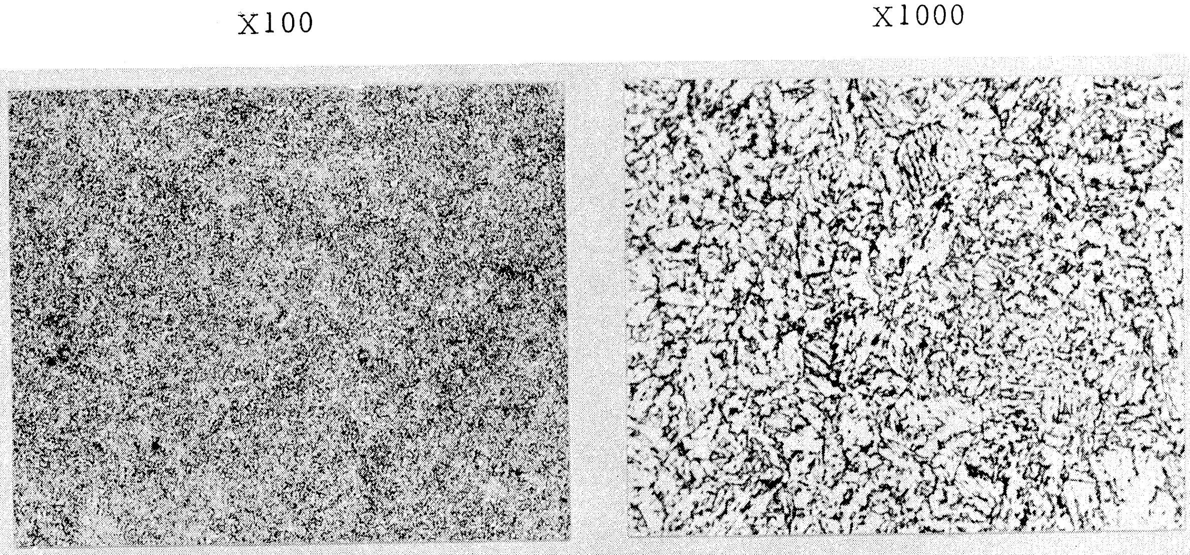


(b) Same As in (a) + Tempered 8 Hours at 1200°F. Avg. BHN - 298

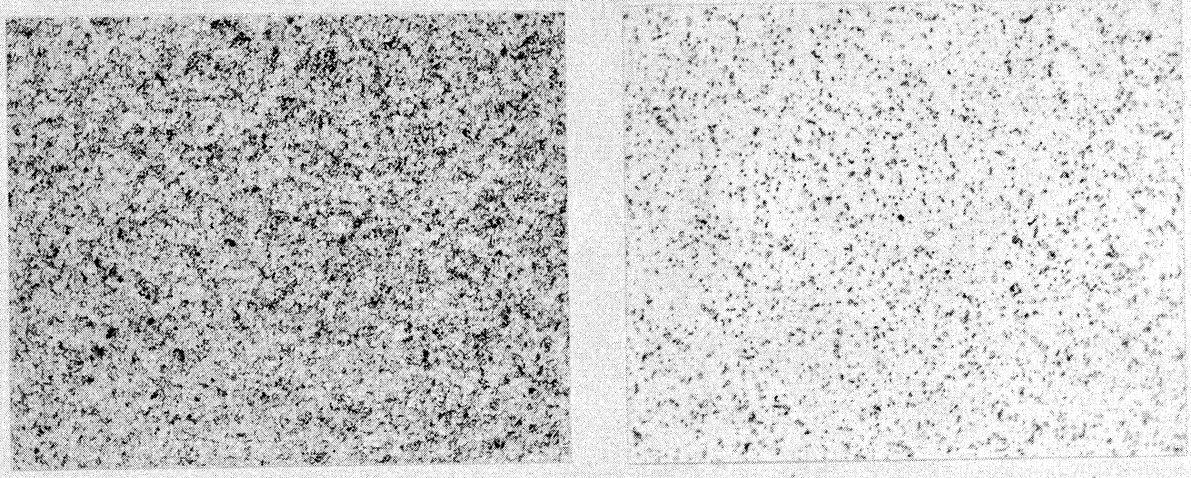


(c) Same As in (b) + Creep-Rupture Tested 763 Hours at 1100°F and 19,000 psi. BHN - 247

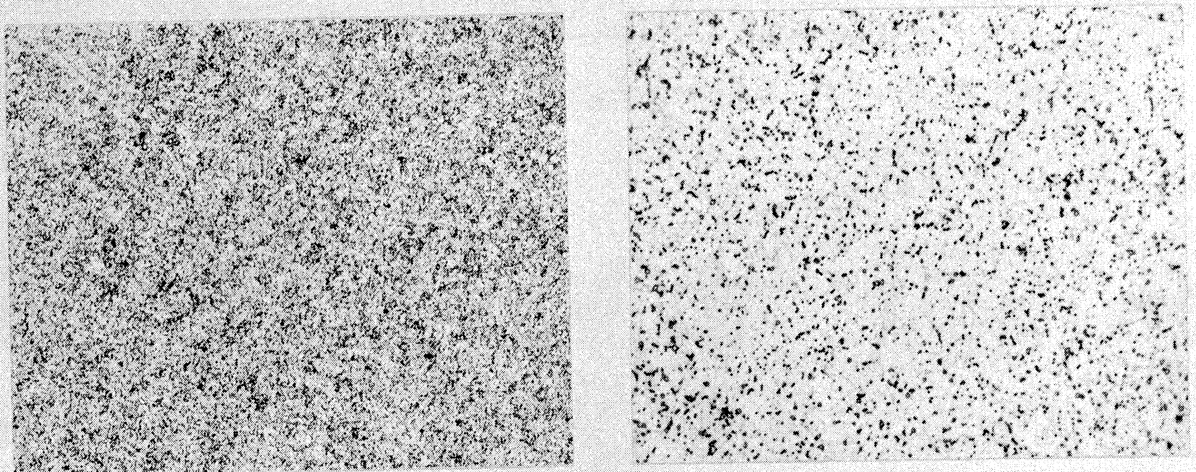
Figure 21. - "17-22-A"S Bar Stock (a) As Transformed to a Mixed Bainitic Structure, (b) As Tempered to 300 BHN, and (c) After Creep-Rupture Tested at 1100°F.



(a) Isothermally Transformed Stepwise at 850° and 650°F to 60 Percent Upper Bainite + 40 Percent Lower Bainite. Avg. BHN - 397



(b) Same As in (a) + Tempered 4.5 Hours at 1200°F. Avg. BHN - 360



(c) Same As in (b) + Creep Tested 1032 Hours at 1100°F and 19,000 psi. BHN - 267

Figure 22. - "17-22-A"V Bar Stock (a) As Transformed to a Mixed Bainitic Structure, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.

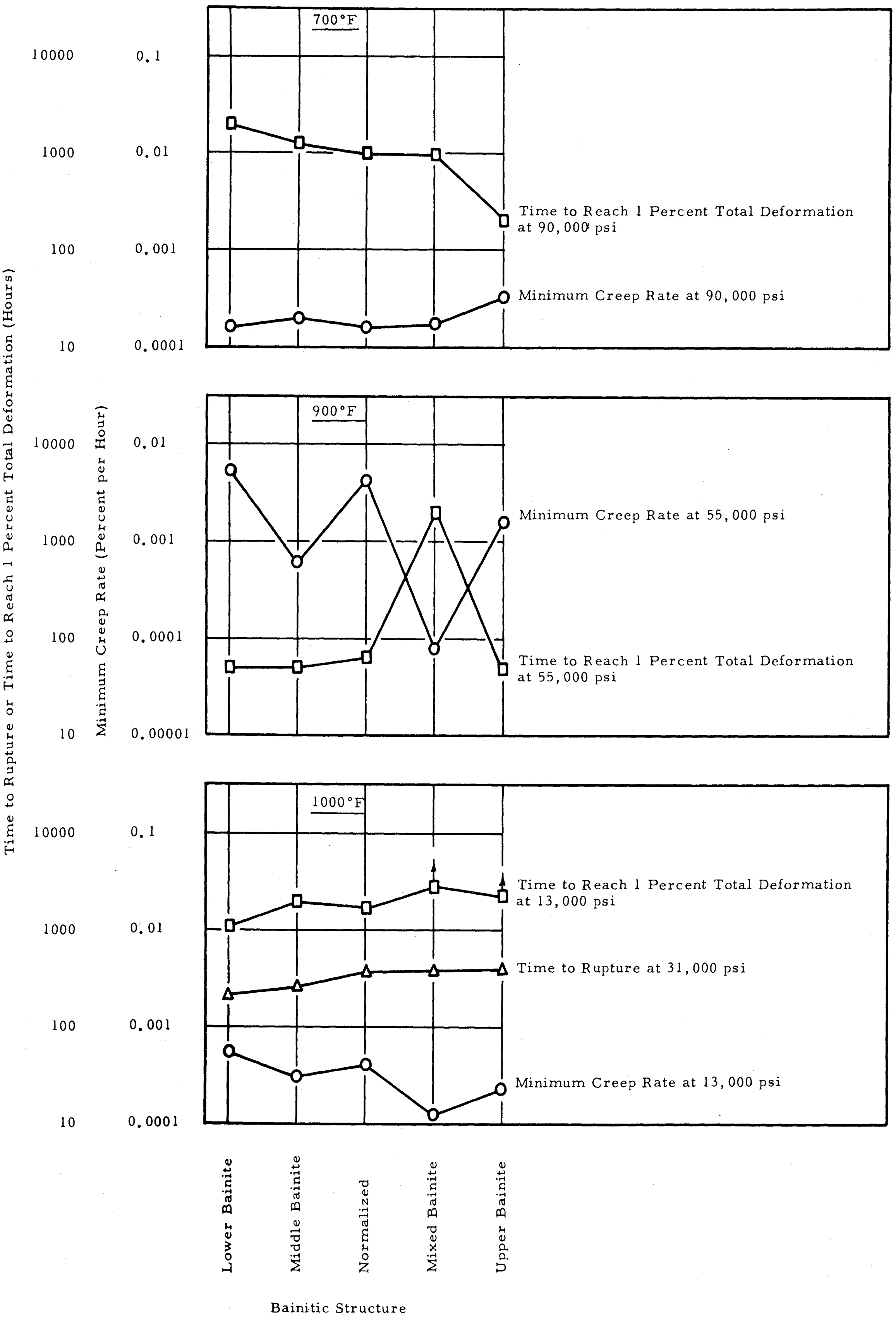


Figure 23. - Comparison of Properties of Mixed Bainite with Properties of Other Bainitic Structures for SAE 4340 Steel at 700°, 900°, and 1000°F.

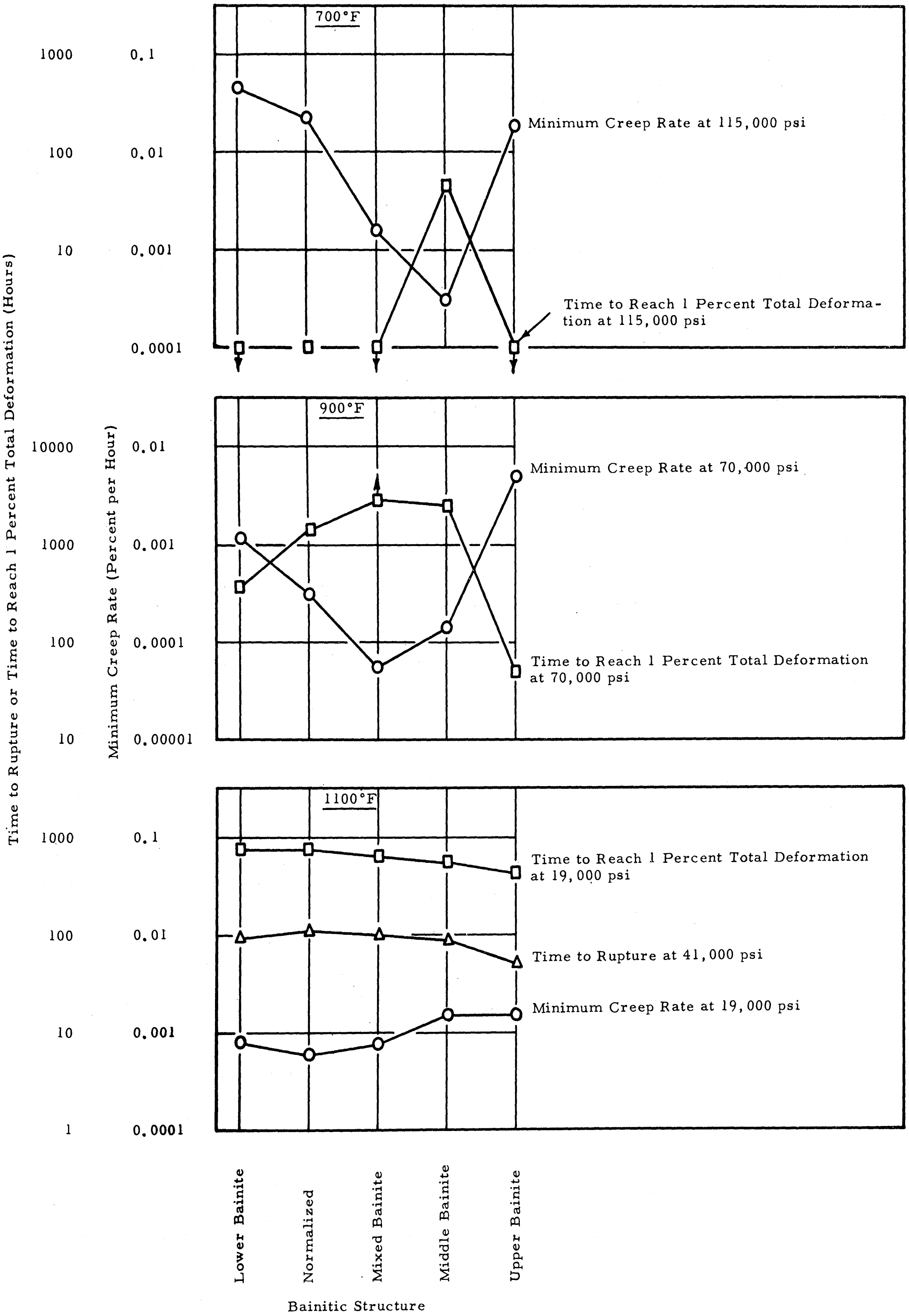


Figure 24. - Comparison of Properties of Mixed Bainite with Properties of Other Bainitic Structures for "17-22-A"S Steel at 700°, 900°, and 1100°F.

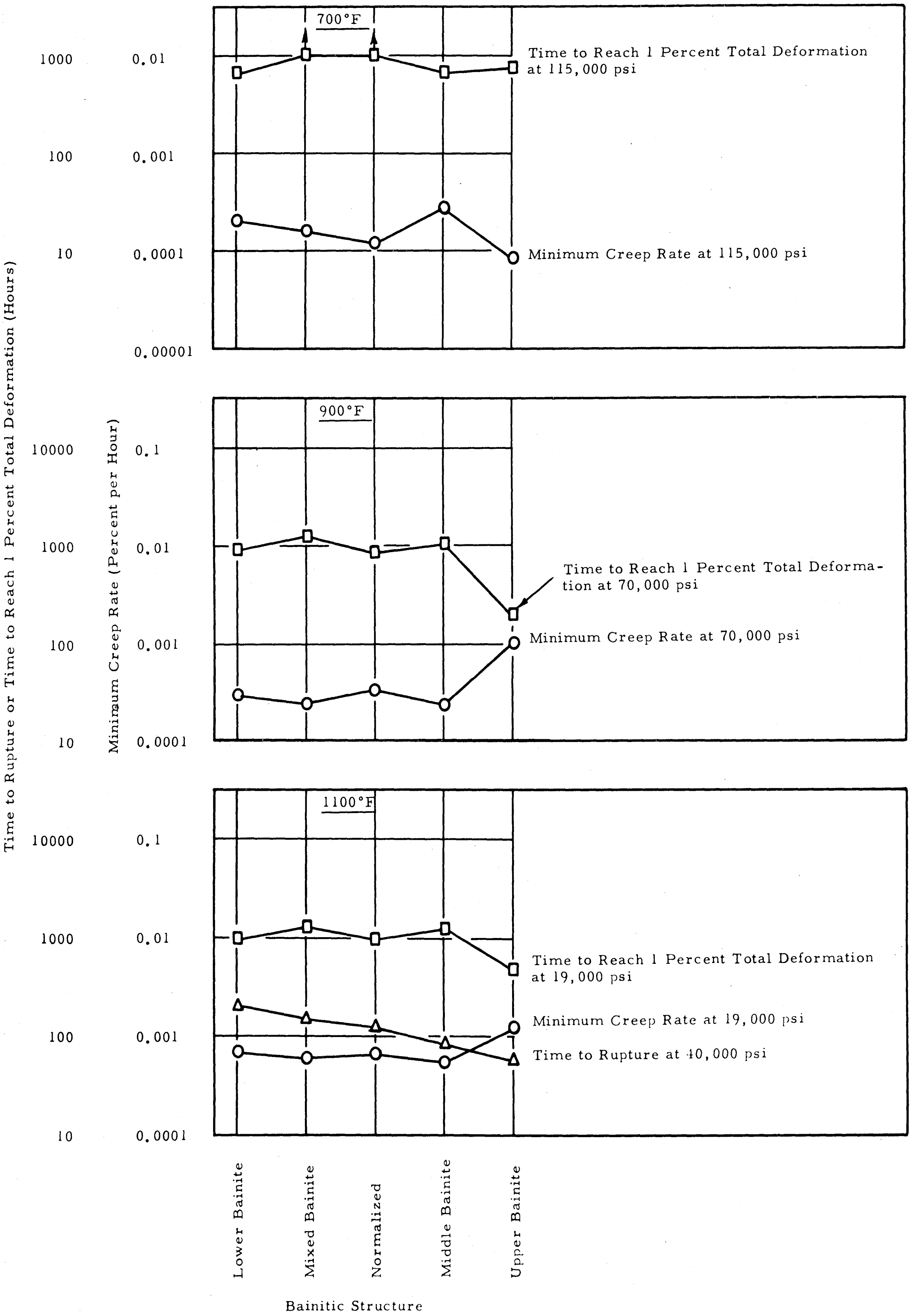
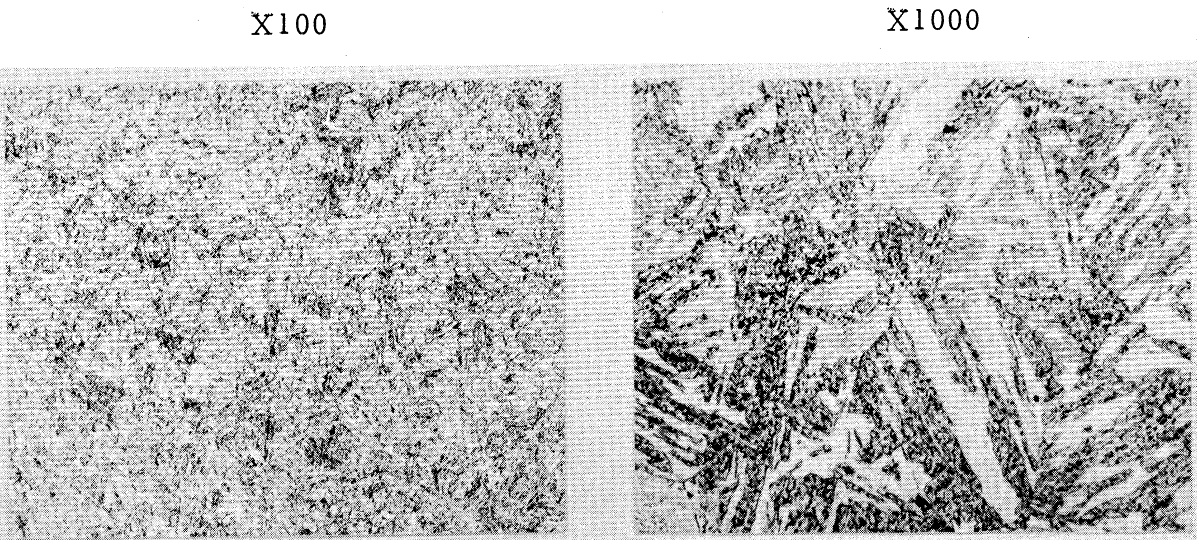
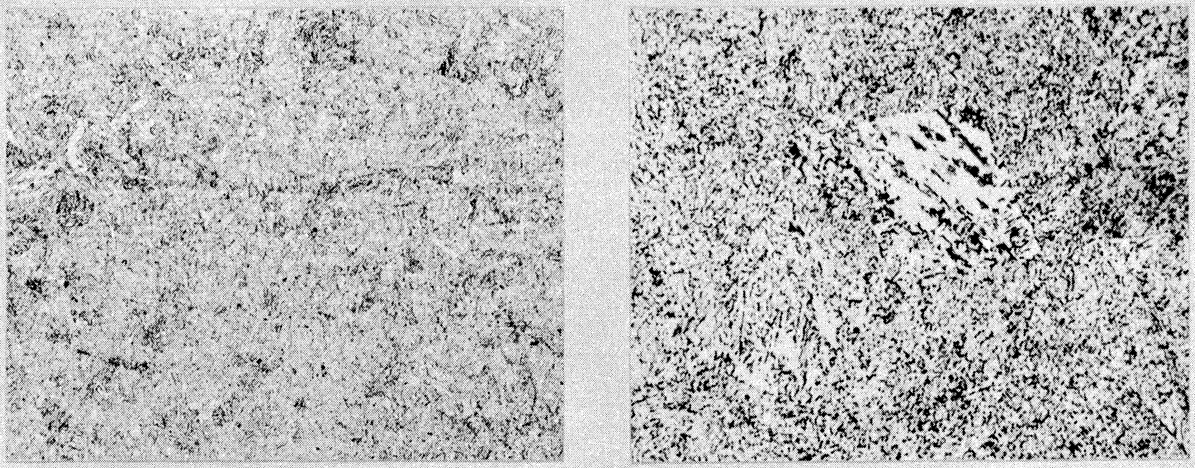


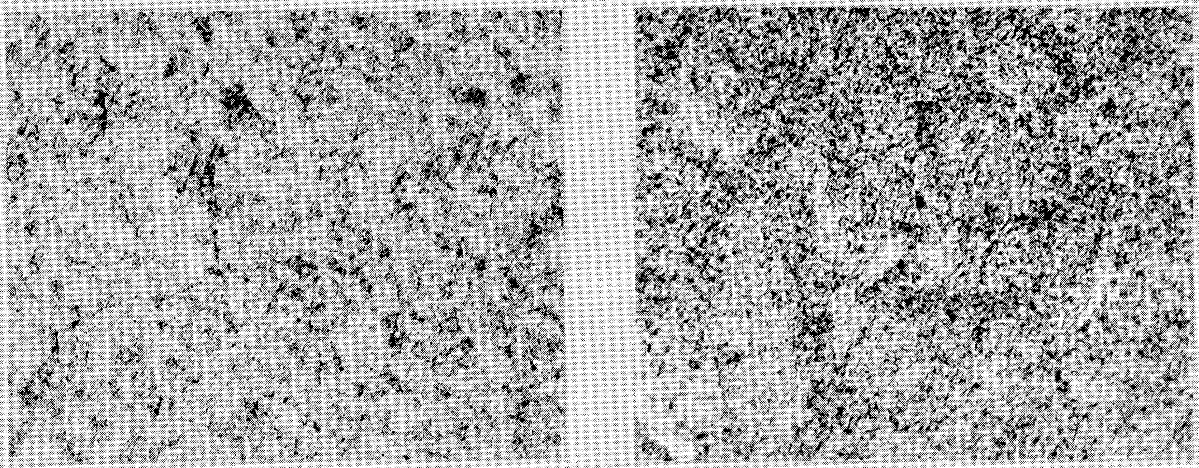
Figure 25. - Comparison of Properties of Mixed Bainite with Properties of Other Bainitic Structures for "17-22-A"V Steel at 700°, 900°, and 1100°F.



(a) Air Cooled from 1850°F + Air Cooled from 1750°F (0.8-Inch Round). Avg. BHN - 408

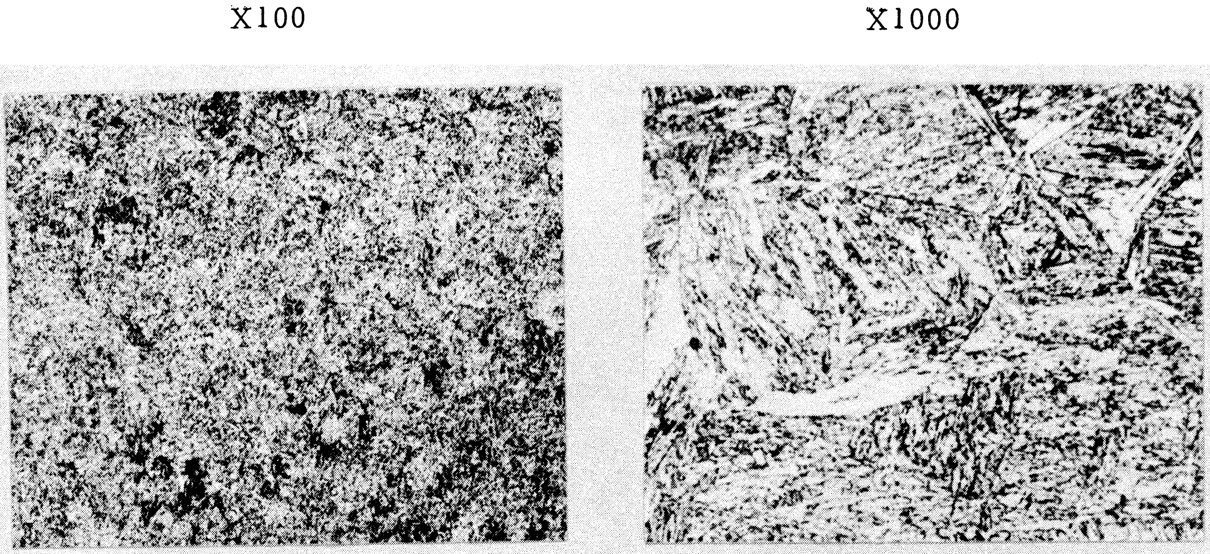


(b) Same As in (a) + Tempered 1.5 Hours at 1200°F. Avg. BHN - 307

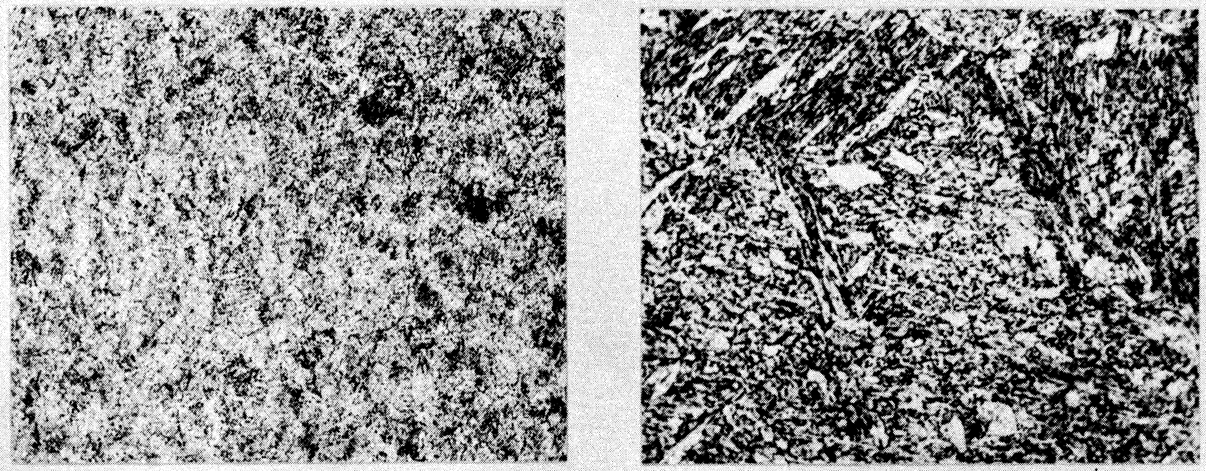


(c) Same As in (b) + Creep Tested 982 Hours at 1000°F and 13,000 psi. BHN - 284

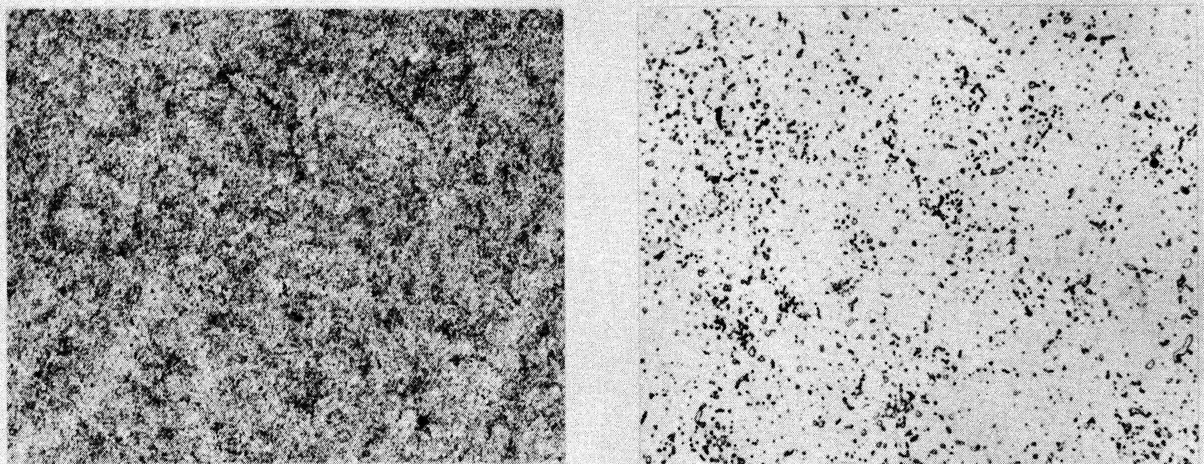
Figure 26. - SAE 4340 Bar Stock (a) As Normalized after Prior Normalize, (b) As Tempered to 300 BHN, and (c) After Creep Tested at 1000°F.



(a) Air Cooled from 1850°F + Oil Quenched from 1750°F (0.8-Inch Round). Avg. BHN - 506

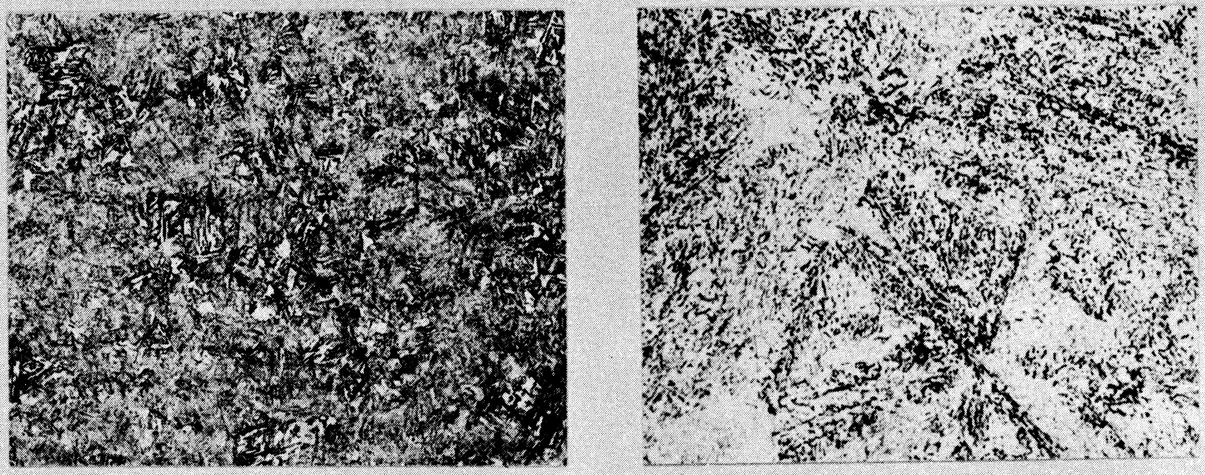


(b) Same As in (a) + Tempered 1.75 Hours at 1200°F. Avg. BHN - 307

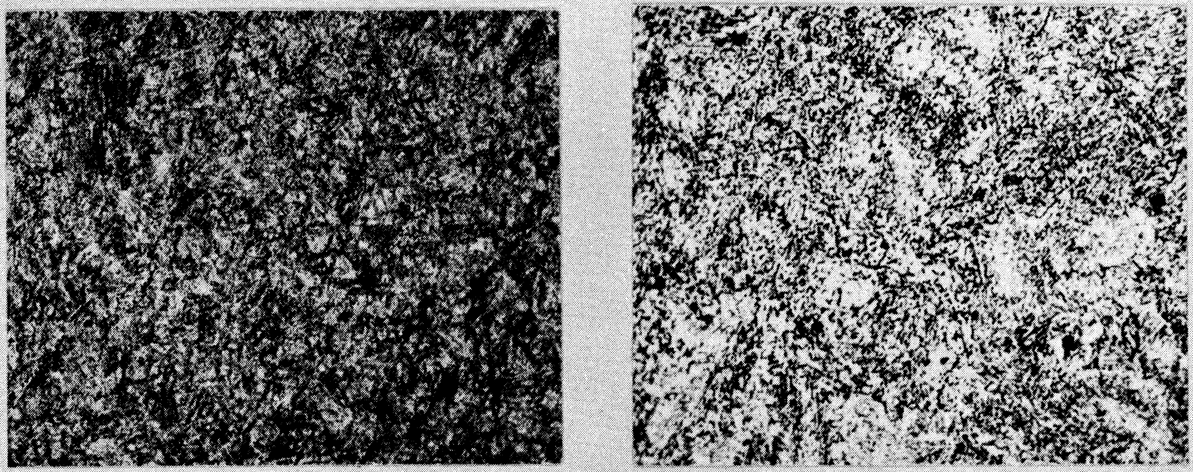


(c) Same As in (b) + Creep Tested 1074 Hours at 1000°F and 13,000 psi. BHN - 289

Figure 27. - SAE 4340 Bar Stock (a) As Oil Quenched after Prior Normalize, (b) As Tempered to 300 BHN, and (c) After Creep Tested at 1000°F.

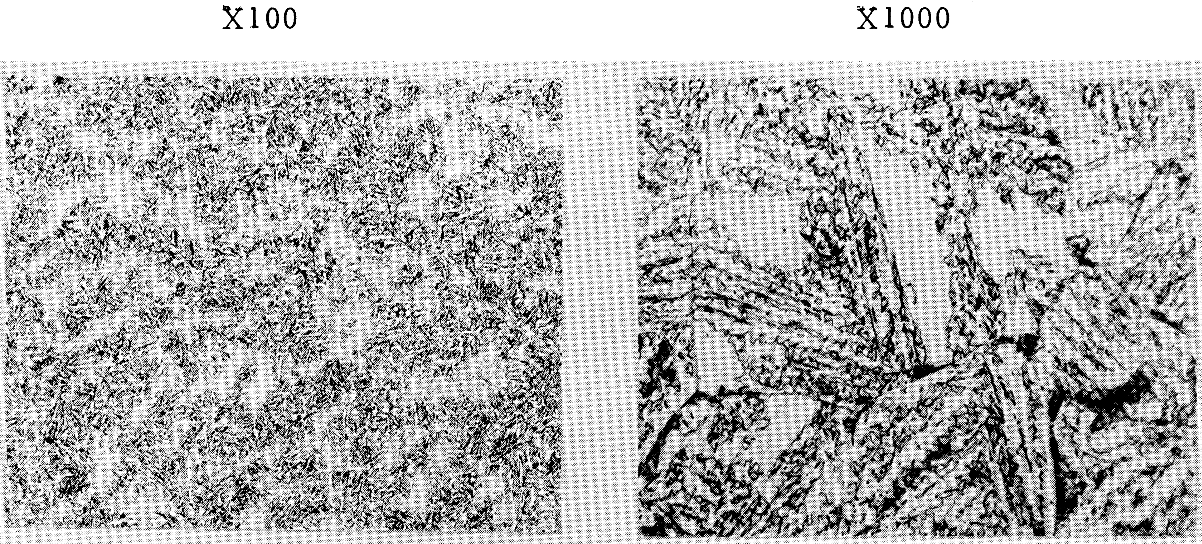


(a) Air Cooled from 1850°F (0.8-Inch Round) + Isothermally Transformed at 750°F to Middle Bainite (0.4-Inch Round). Avg. BHN - 320

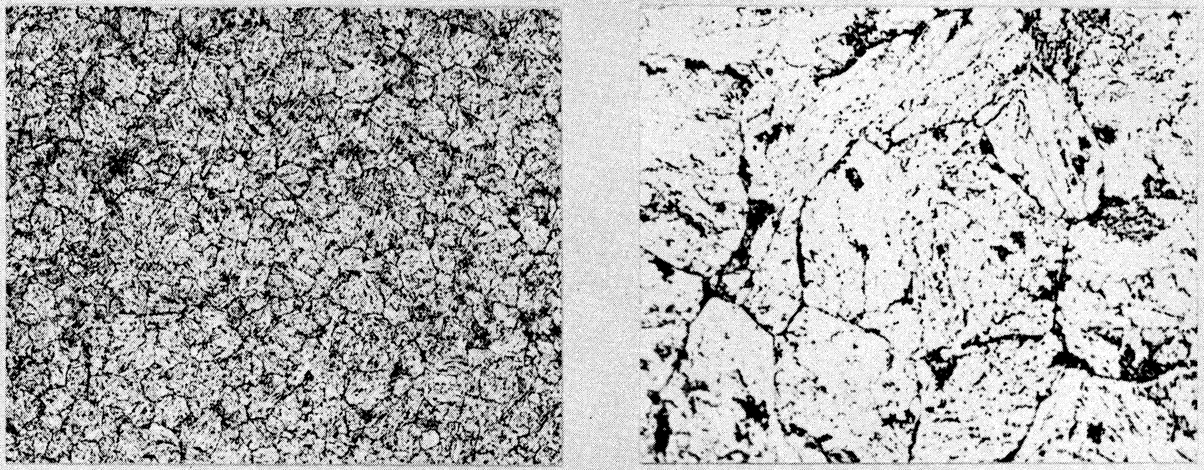


(b) Same As in (a) + Creep Tested 839 Hours at 1000°F and 13,000 psi. BHN - 301

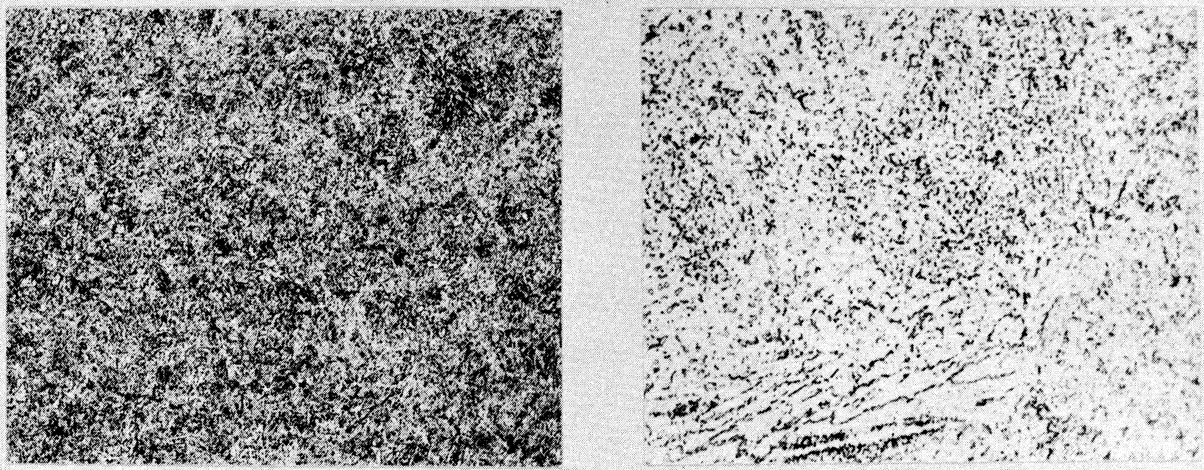
Figure 28. - SAE 4340 Bar Stock (a) As Transformed to Middle Bainite after Prior Normalize and (b) After Creep Tested at 1000°F.



(a) Air Cooled from 1850°F + Air Cooled from 1750°F (0.8-Inch Rounds). Avg. BHN - 335

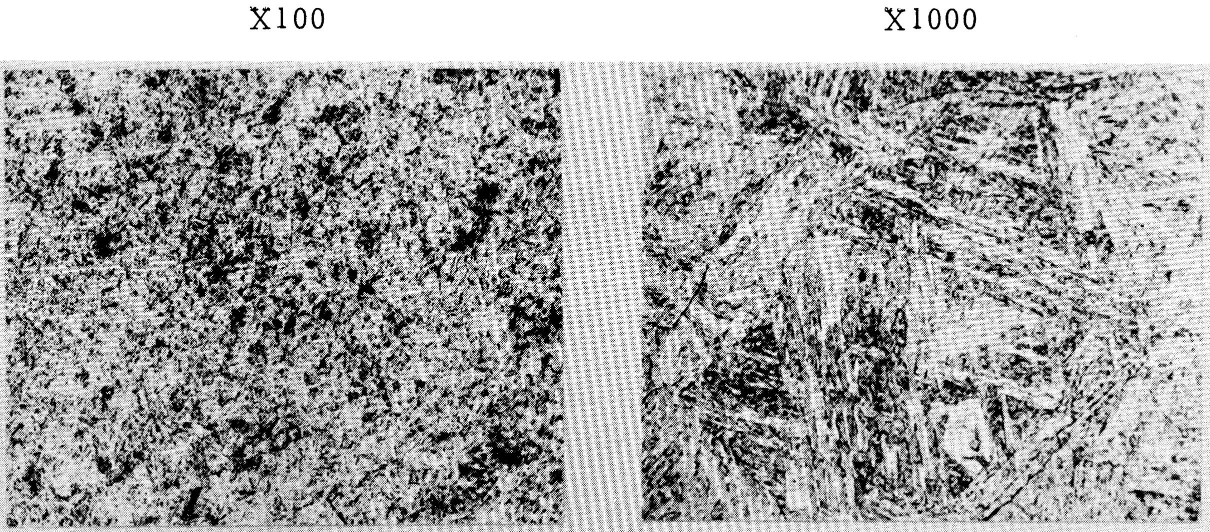


(b) Same As in (a) + Tempered 2.25 Hours at 1200°F. Avg. BHN - 351

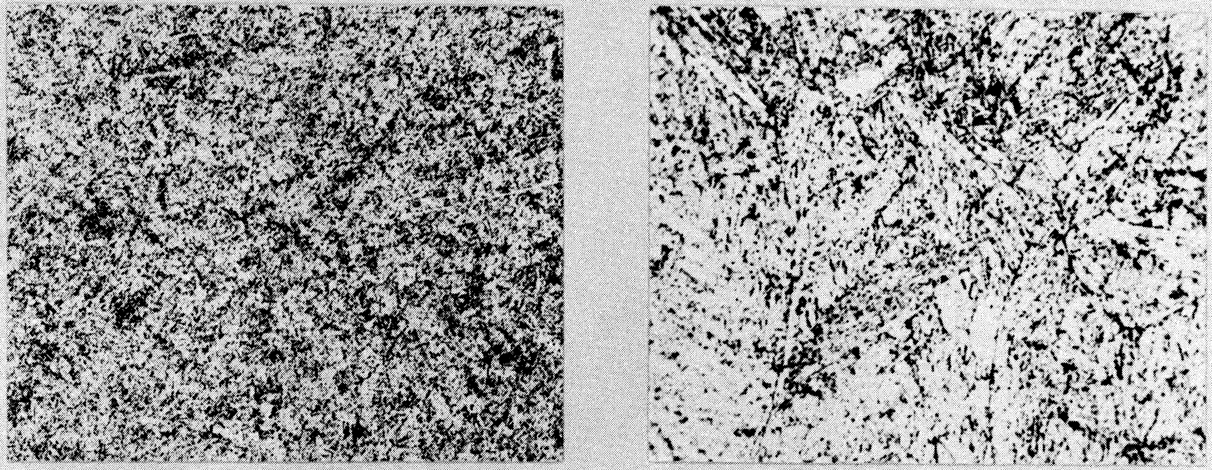


(c) Same As in (b) + Creep Tested 1004 Hours at 1100°F and 19,000 psi. BHN - 251

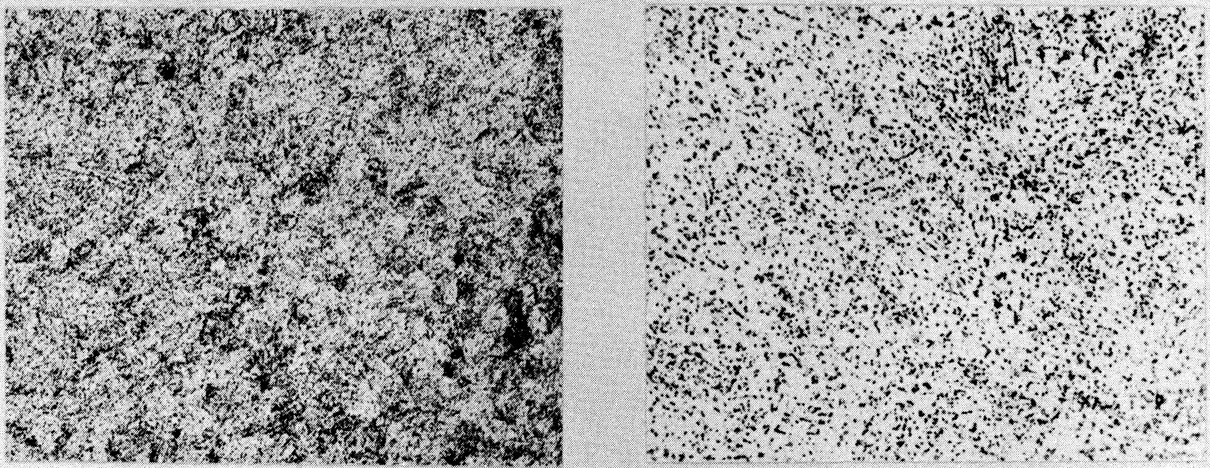
Figure 29. - "17-22-A"S Bar Stock (a) As Normalized after Prior Normalize (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Air Cooled from 1850°F + Oil Quenched from 1750°F (0.8-Inch Round). Avg. BHN - 471

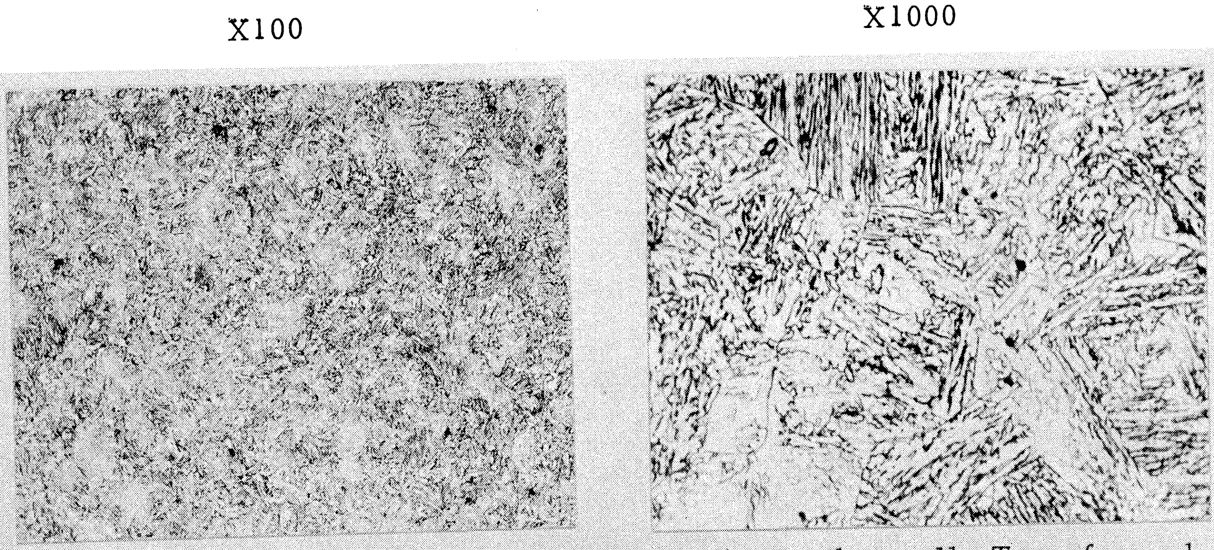


(b) Same As in (a) + Tempered 2.25 Hours at 1200°F. Avg. BHN - 356

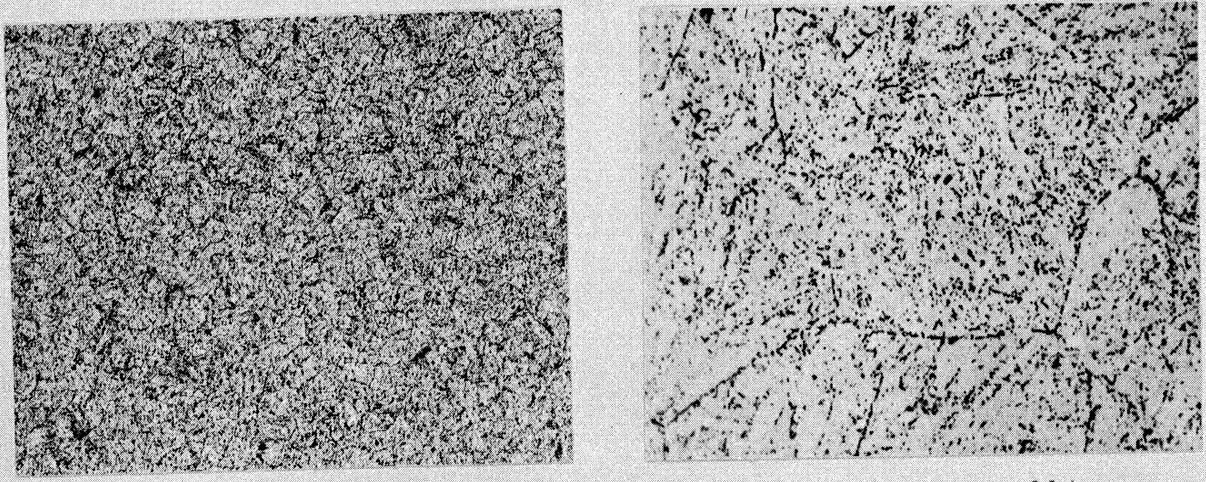


(c) Same As in (b) + Creep-Rupture Tested 693 Hours at 1100°F and 19,000 psi. BHN - 230

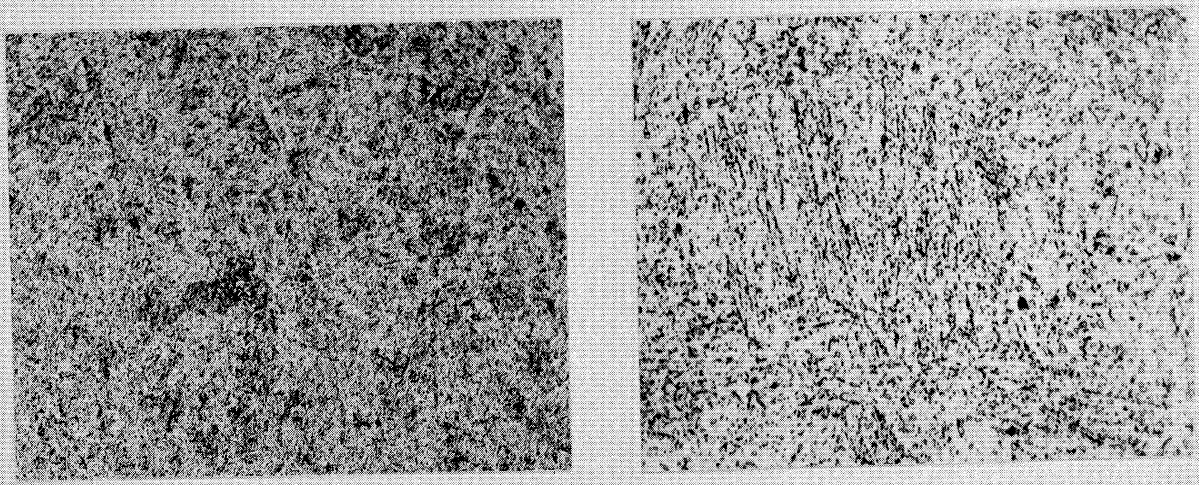
Figure 30. - "17-22-A"S Bar Stock (a) As Oil Quenched after Prior Normalize, (b) As Tempered to 350 BHN, and (c) After Creep-Rupture Tested at 1100°F.



(a) Air Cooled from 1850°F (0.8-Inch Round) + Isothermally Transformed at 800°F to Middle Bainite (0.4-Inch Round). Avg. BHN - 382

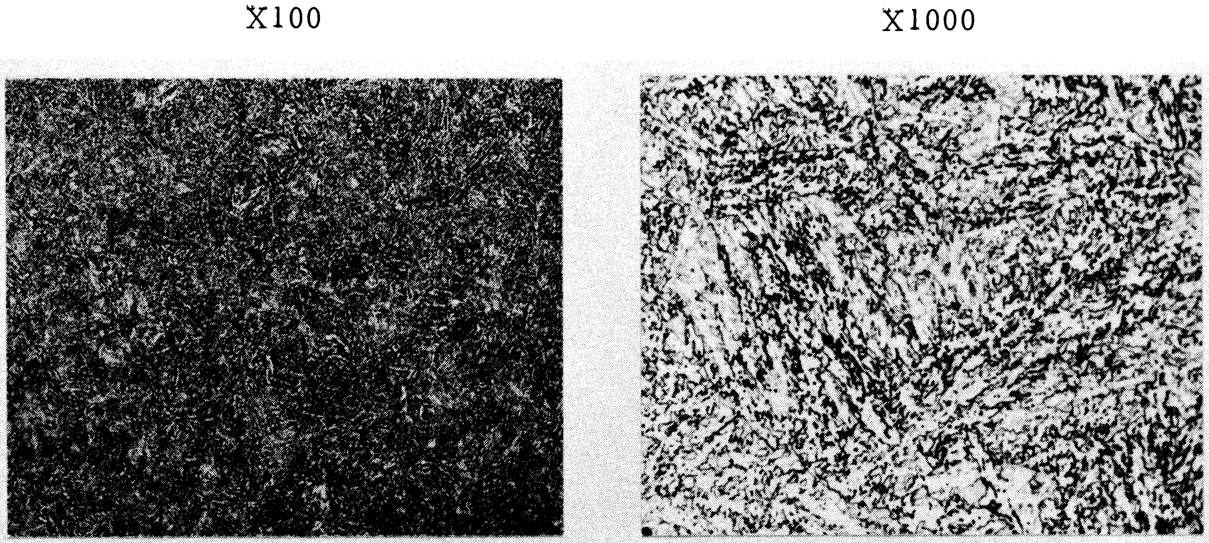


(b) Same As in (a) + Tempered 4 Hours at 1200°F, Avg. BHN - 314

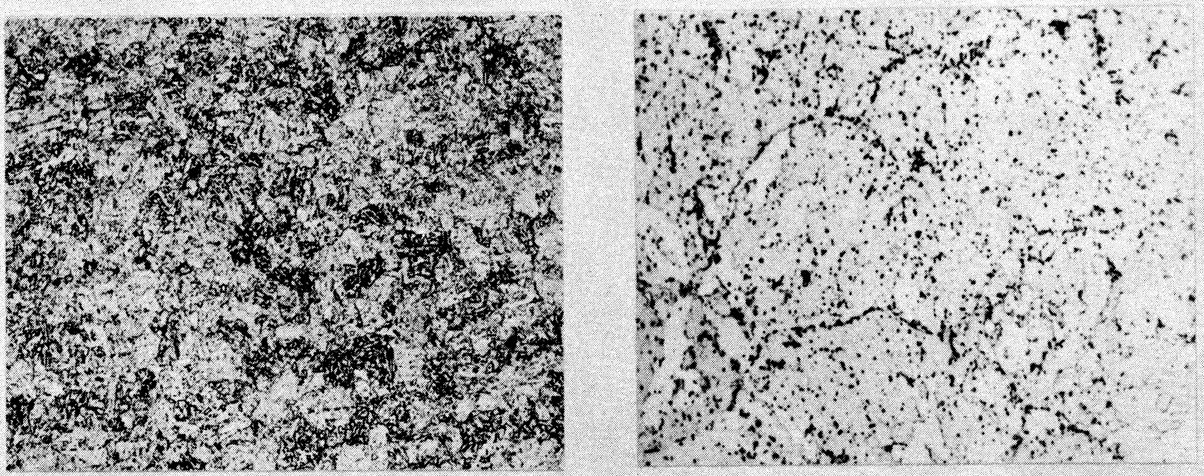


(c) Same As in (b) + Creep Tested 1054 Hours at 1100°F and 19,000 psi. BHN - 233

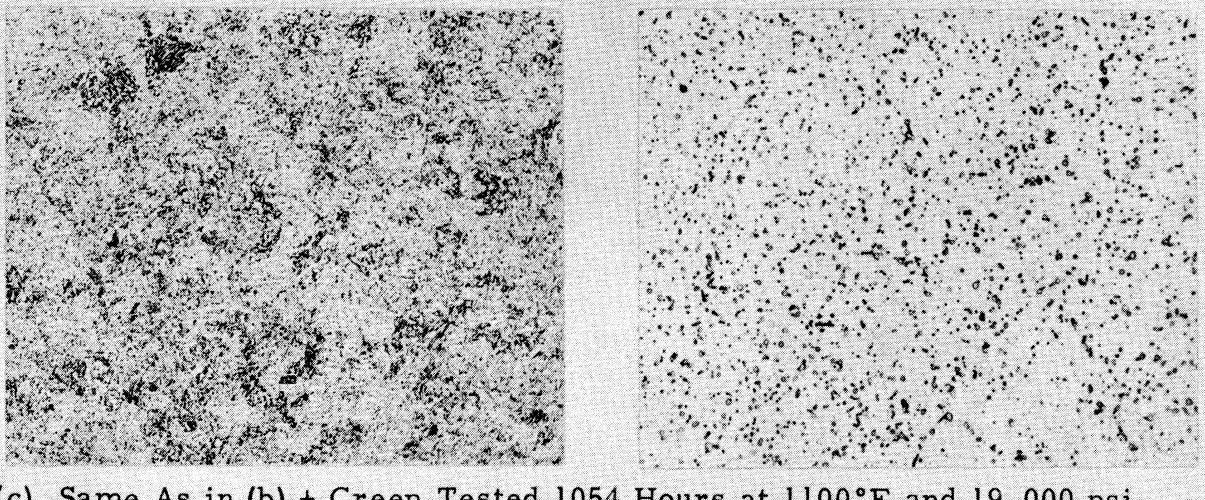
Figure 31. - "17-22-A"S Bar Stock (a) As Transformed to Middle Bainite after Prior Normalize, (b) As Tempered to 300 BHN, and (c) After Creep Tested at 1100°F.



(a) Air Cooled from 1950°F + Air Cooled from 1850°F (0.8-Inch Round). Avg. BHN - 360

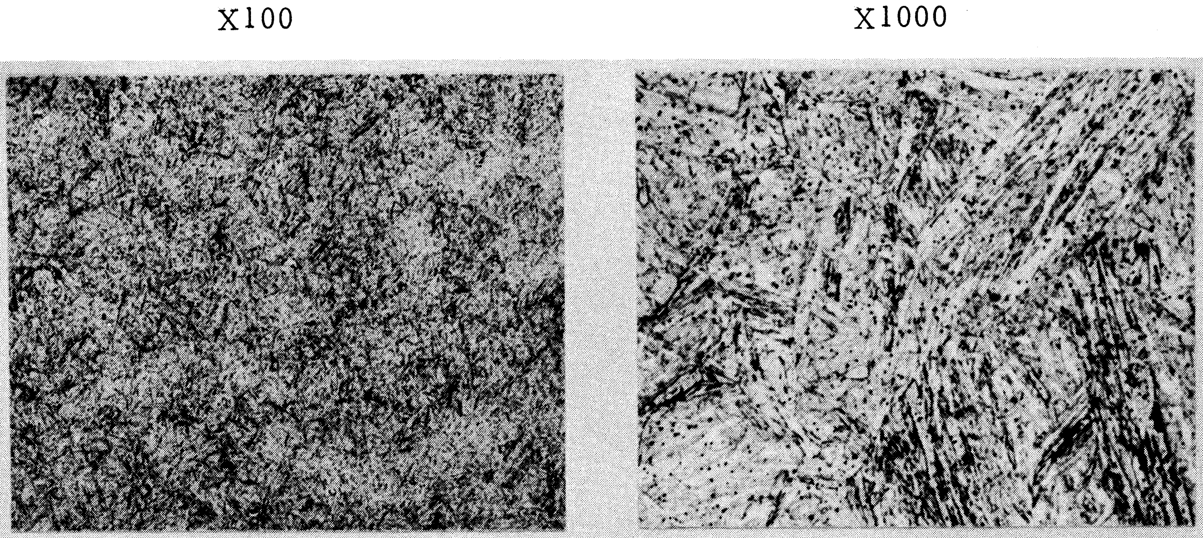


(b) Same As in (a) + Tempered 2 Hours at 1250°F. Avg. BHN - 348

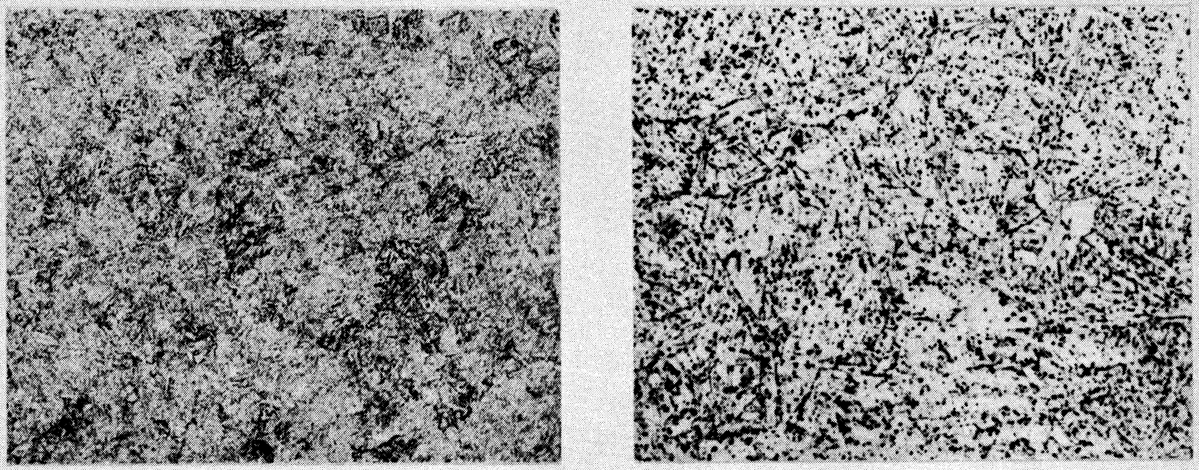


(c) Same As in (b) + Creep Tested 1054 Hours at 1100°F and 19,000 psi. BHN - 282

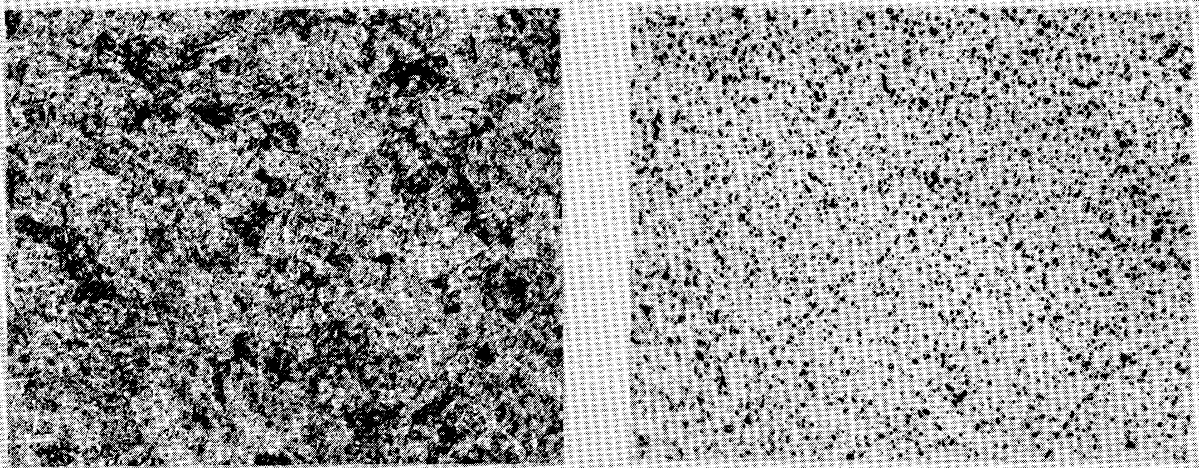
Figure 32. - "17-22-A"V Bar Stock (a) As Normalized after Prior Normalize, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Air Cooled from 1950°F + Oil Quenched from 1850°F (0.8-Inch Round). Avg. BHN - 471

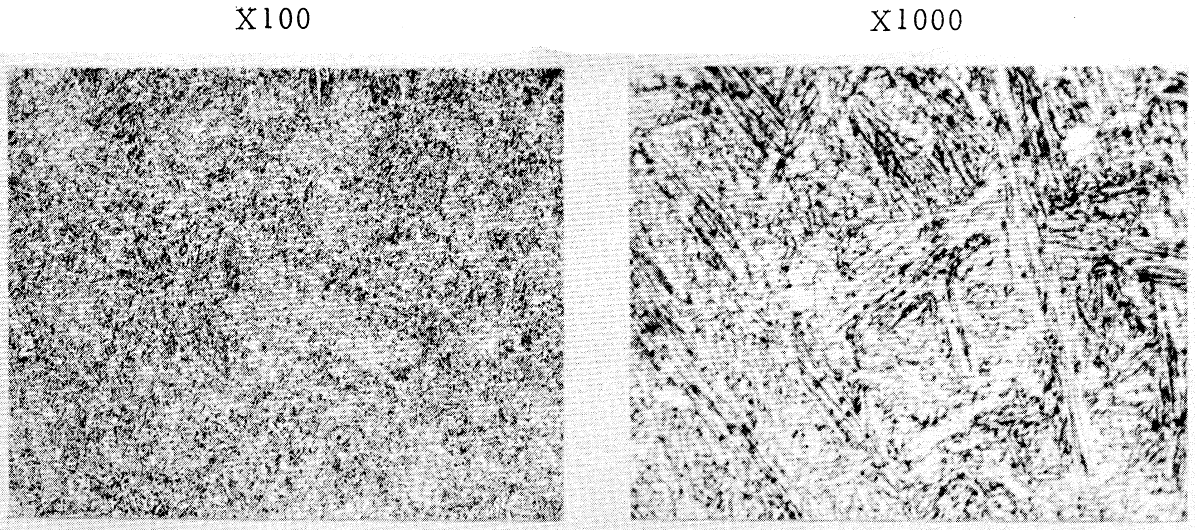


(b) Same As in (a) + Tempered 2 Hours at 1250°F. Avg. BHN - 348

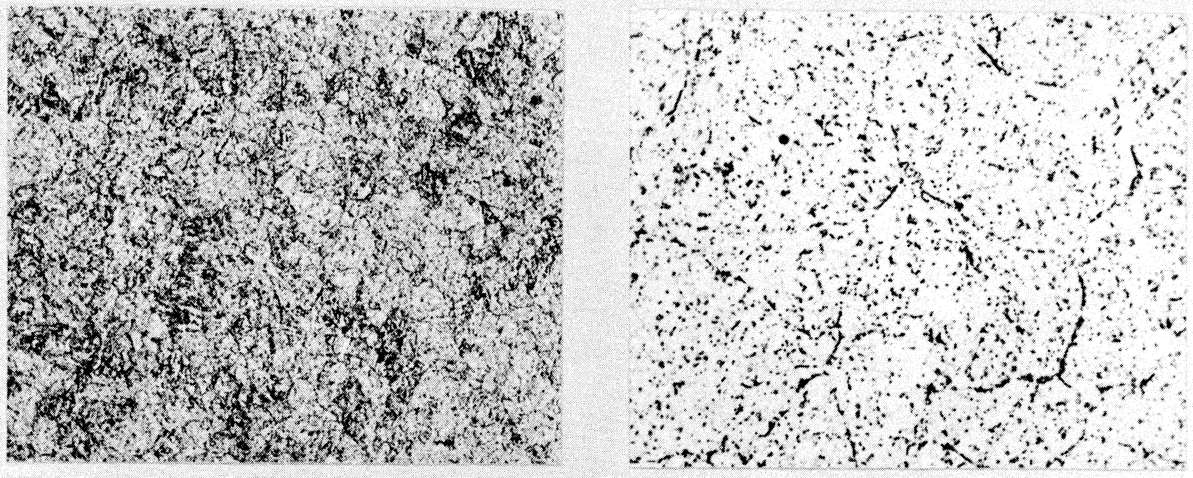


(c) Same As in (b) + Creep Tested 1054 Hours at 1100°F and 19,000 psi. BHN - 262

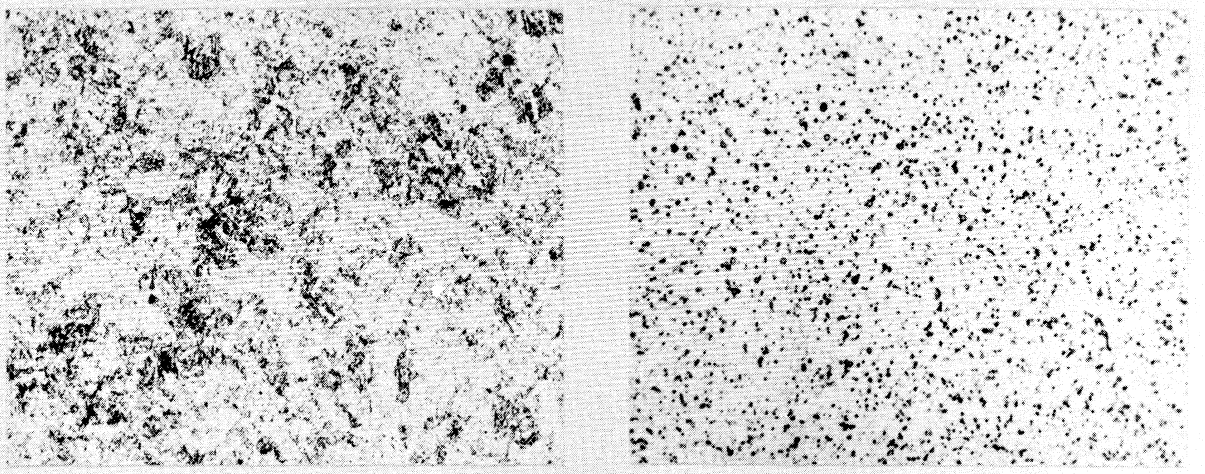
Figure 33. - "17-22-A"V Bar Stock (a) As Oil Quenched after Prior Normalize, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Air Cooled from 1950°F (0.8-Inch Round) + Isothermally Transformed at 750°F to Middle Bainite (0.4-Inch Round). Avg. BHN - 355



(b) Same As in (a) + Tempered 6 Hours at 1200°F. Avg. BHN - 360



(c) Same As in (b) + Creep Tested 995 Hours at 1100°F and 19,000 psi. BHN - 259

Figure 34. - "17-22-A"V Bar Stock (a) As Transformed to Middle Bainite after Prior Normalize, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.

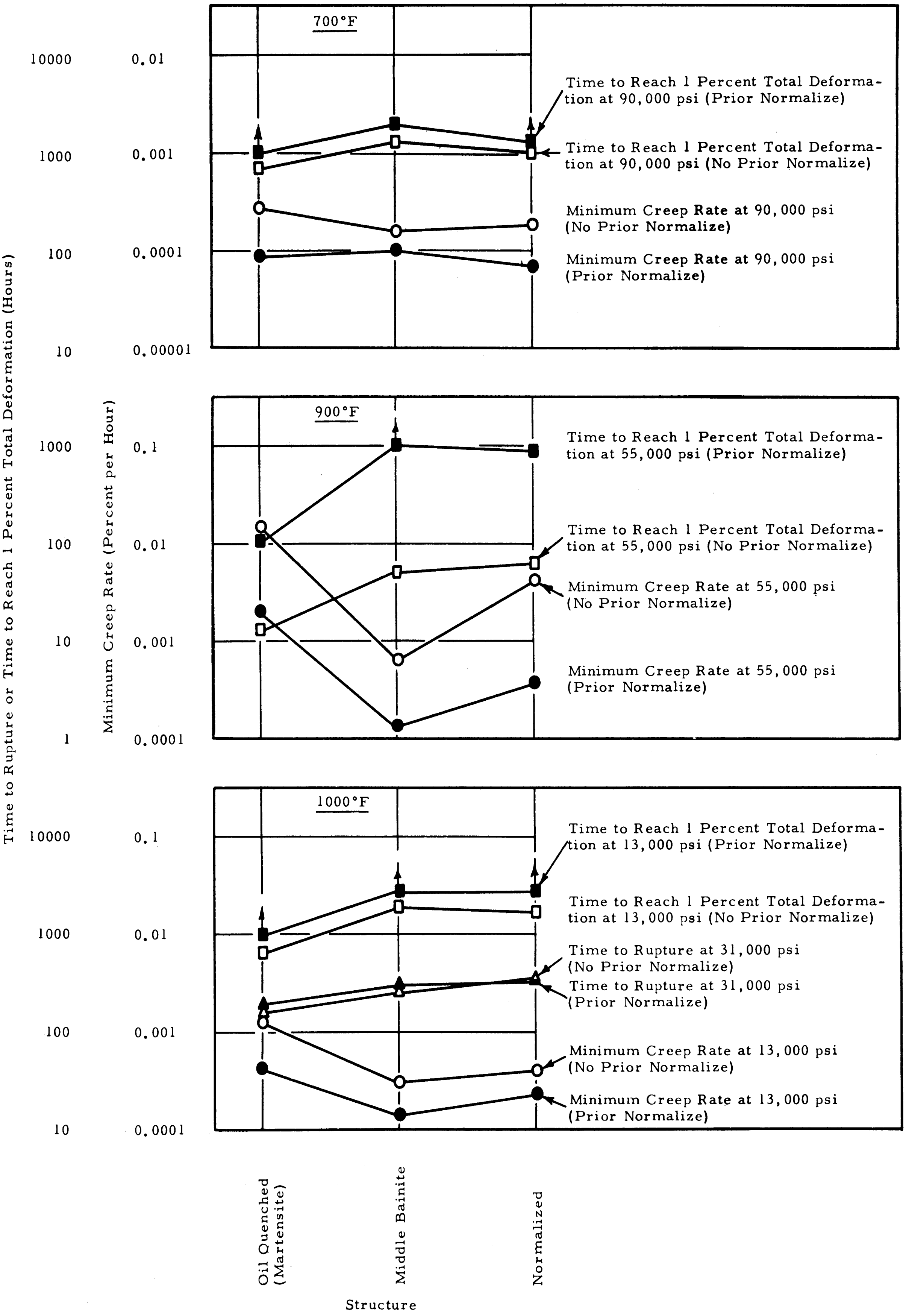


Figure 35. - Influence of a Prior Homogenization Normalize on the Properties of Three SAE 4340 Structures at 700°, 900°, and 1000°F. (The prior normalize was from 1850°F; whereas, the austenitizing temperature for the final heat treatment was 1750°F.)

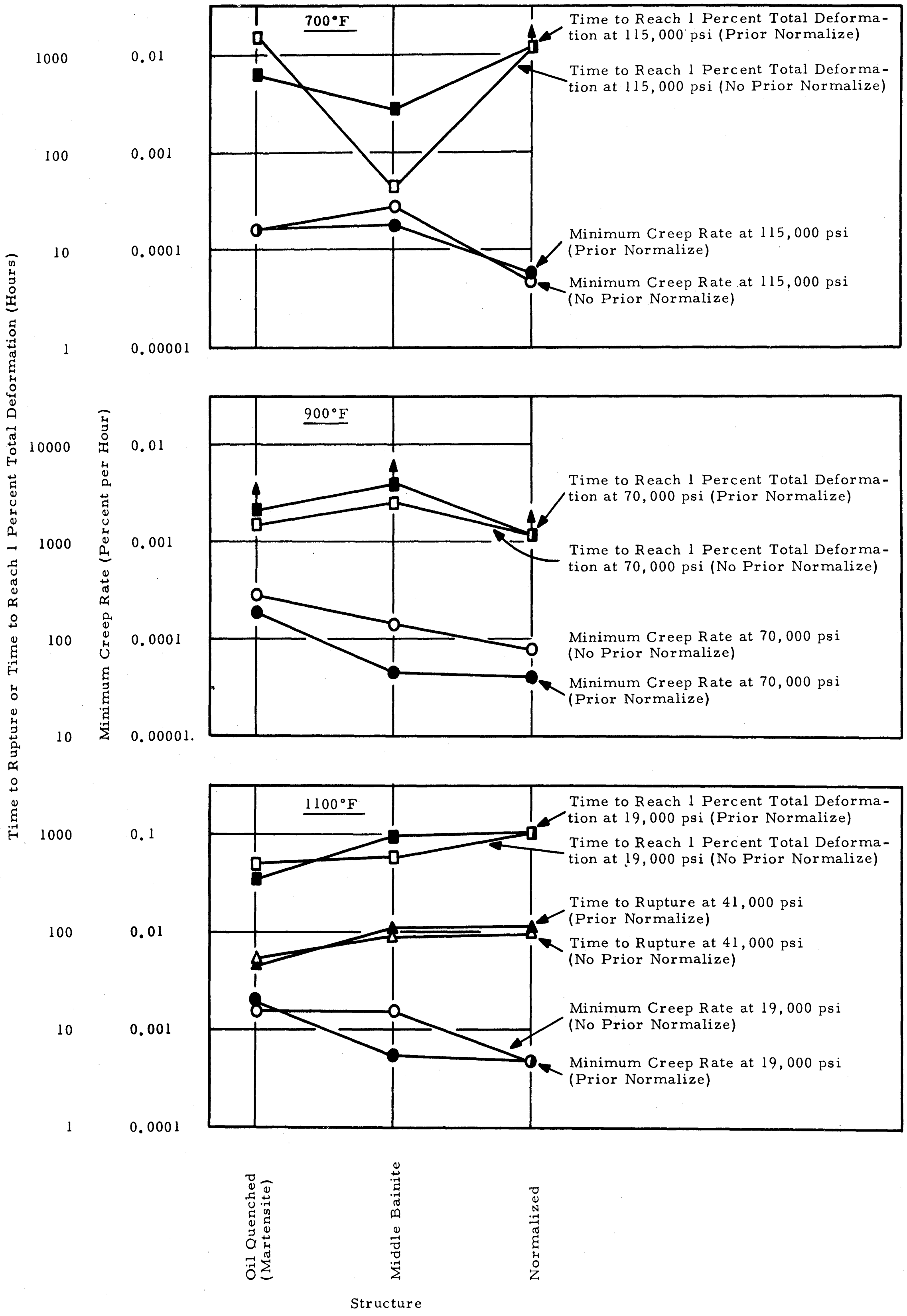


Figure 36. - Influence of a Prior Homogenization Normalize on the Properties of Three "17-22-A"S Structures at 700°, 900°, and 1100°F. (The prior normalize was from 1850°F; whereas, the austenitizing temperature for the final heat treatment was 1750°F.)

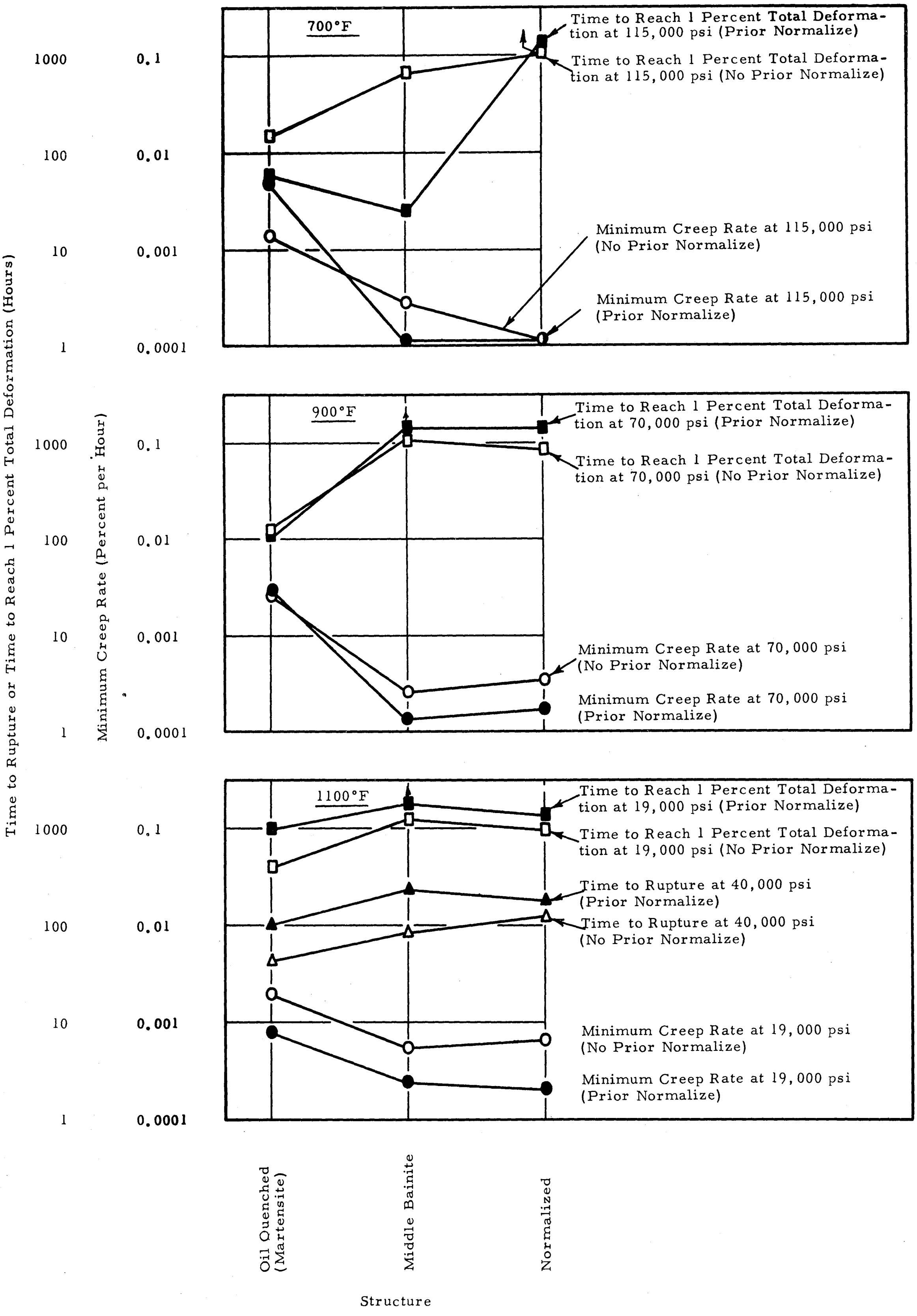
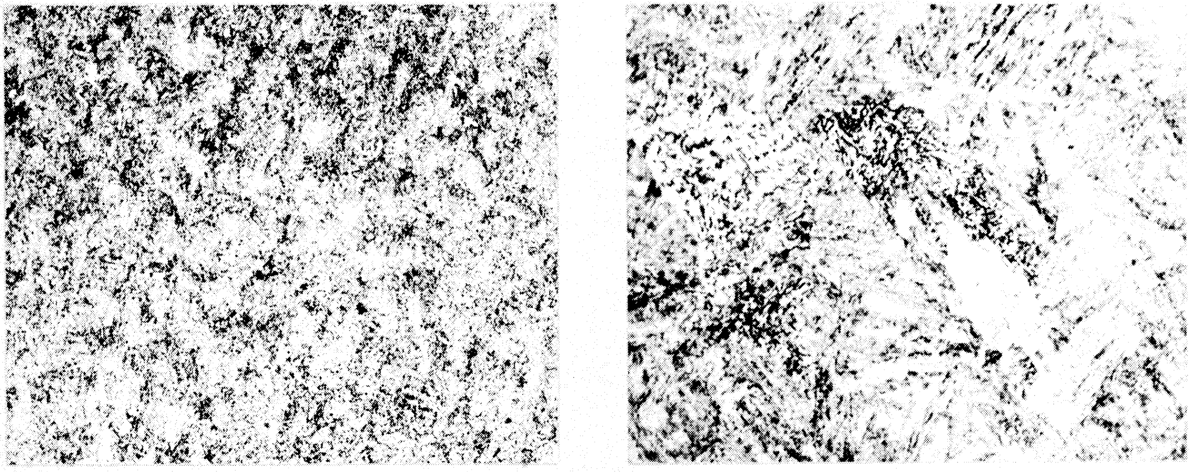
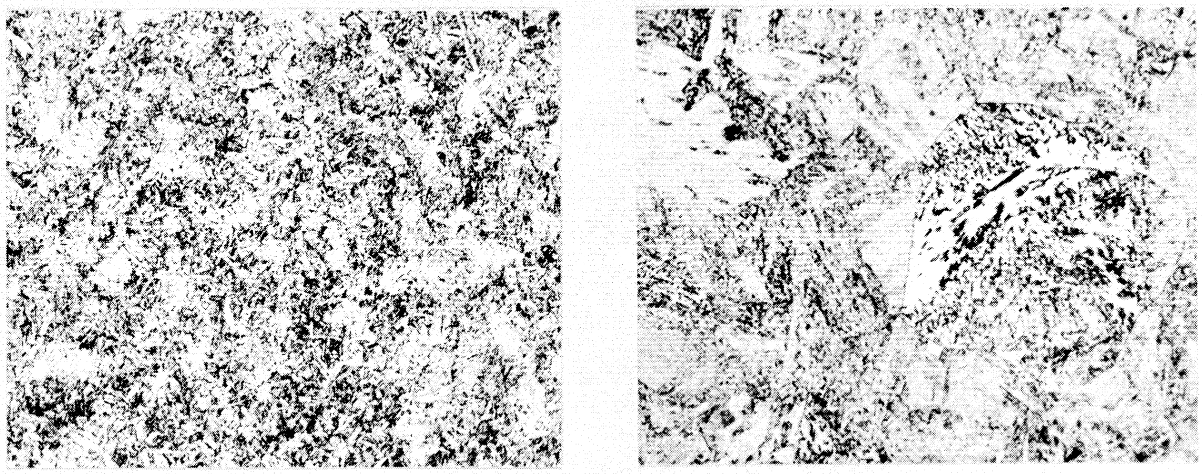


Figure 37. - Influence of a Prior Homogenization Normalize on the Properties of Three "17-22-A"V Structures at 700°, 900°, and 1100°F. (The prior normalize was from 1950°F; whereas, the austenitizing temperature for the final heat treatment was 1850°F.)

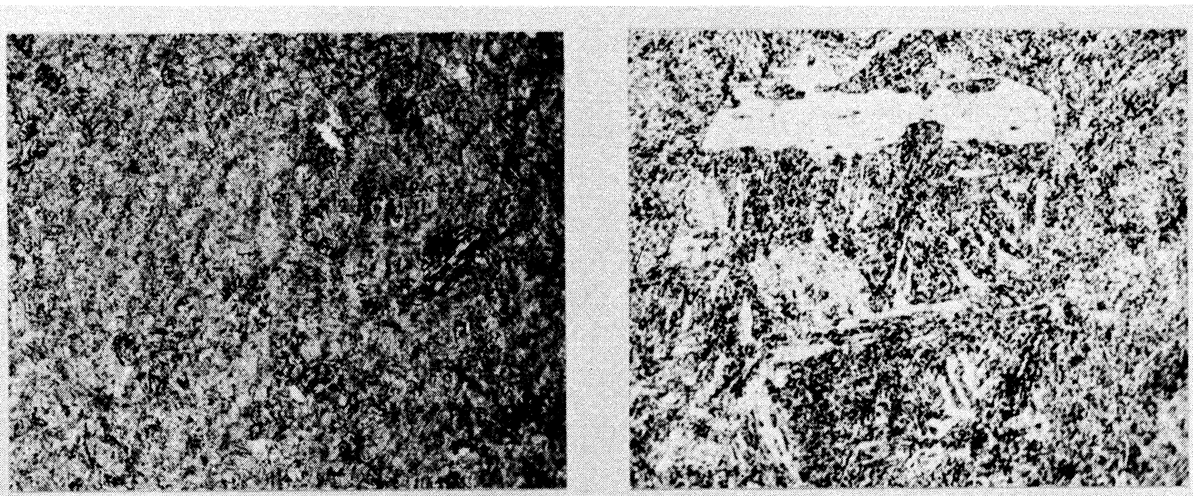


(a) Hot Rolled 25 Percent in One Pass at 1800°F.

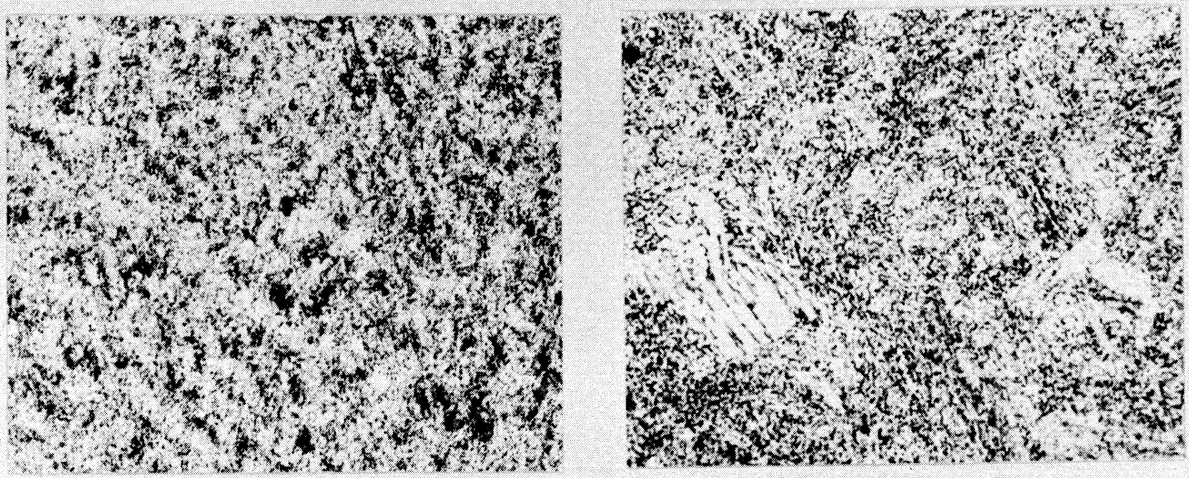


(b) Same As in (a) + Air Cooled from 1750°F. Avg. BHN - 428

Figure 38. - SAE 4340 Bar Stock (a) As Hot Rolled at 1800°F, (b) As Normalized from 1750°F, (c) As Tempered to 300 BHN, and (d) After Creep Tested at 1000°F.



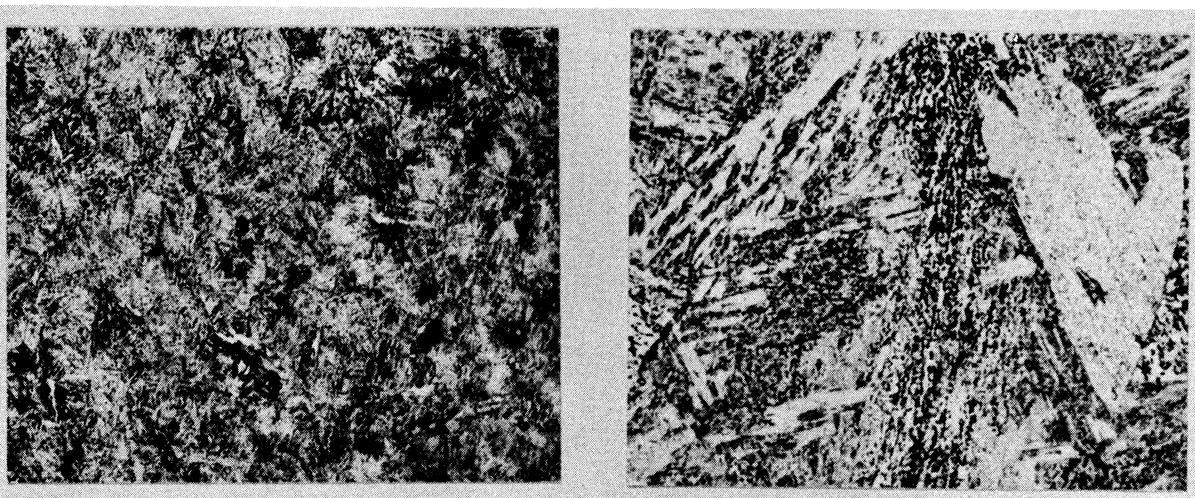
(c) Same As in (b) + Tempered 2.75 Hours at 1200°F. Avg. BHN - 285



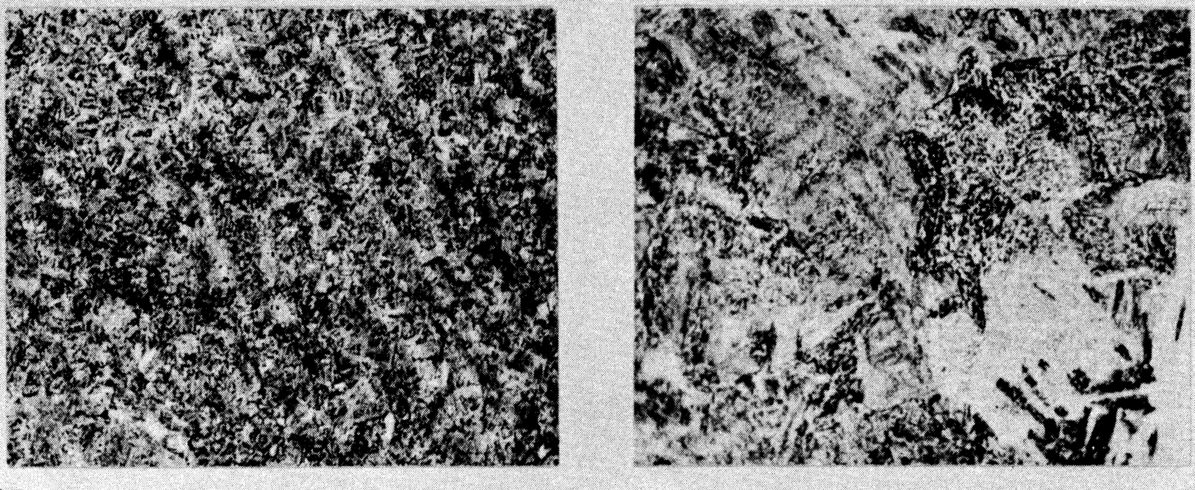
(d) Same As in (c) + Creep Tested 931 Hours at 1000°F and 12,000 psi.
BHN - 263

Figure 38. - Concluded.

X100 X1000



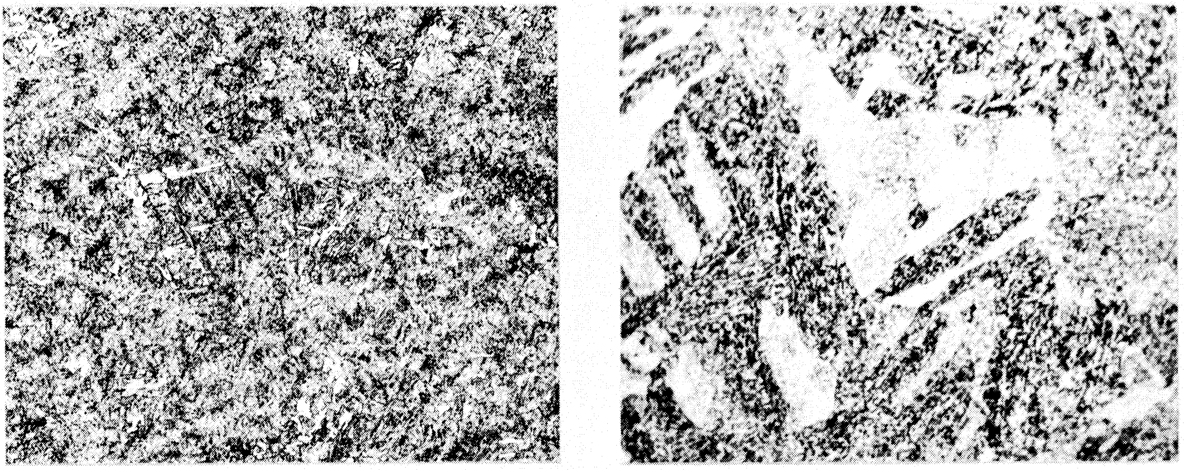
(a) Hot Rolled 25 Percent in One Pass at 2000°F.



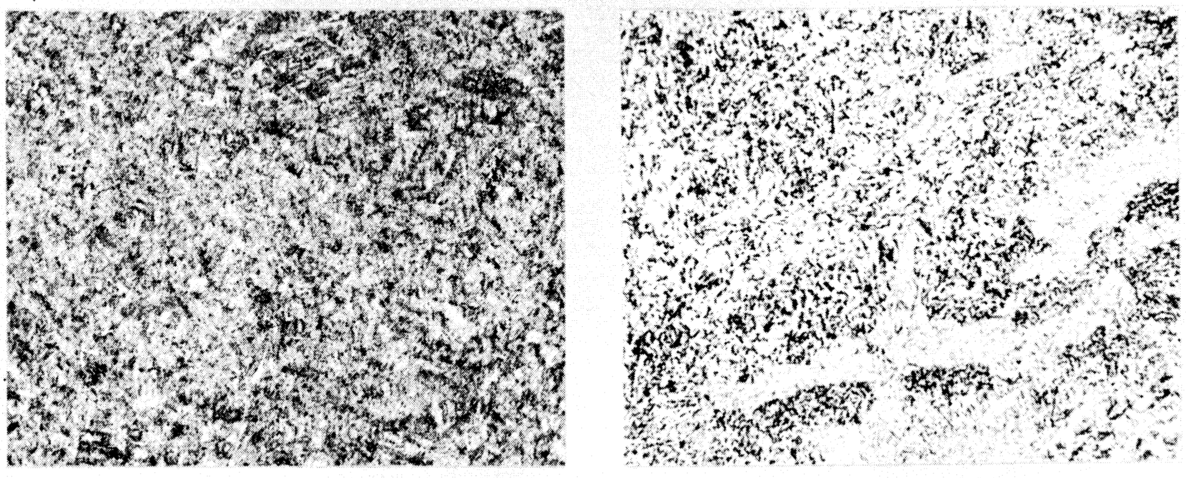
(b) Same As in (a) + Air Cooled from 1750°F. Avg. BHN - 387

Figure 39. - SAE 4340 Bar Stock (a) As Hot Rolled at 2000°F, (b) As Normalized from 1750°F, (c) As Tempered to 300 BHN, and (c) After Creep Tested at 1000°F.

X100 X1000



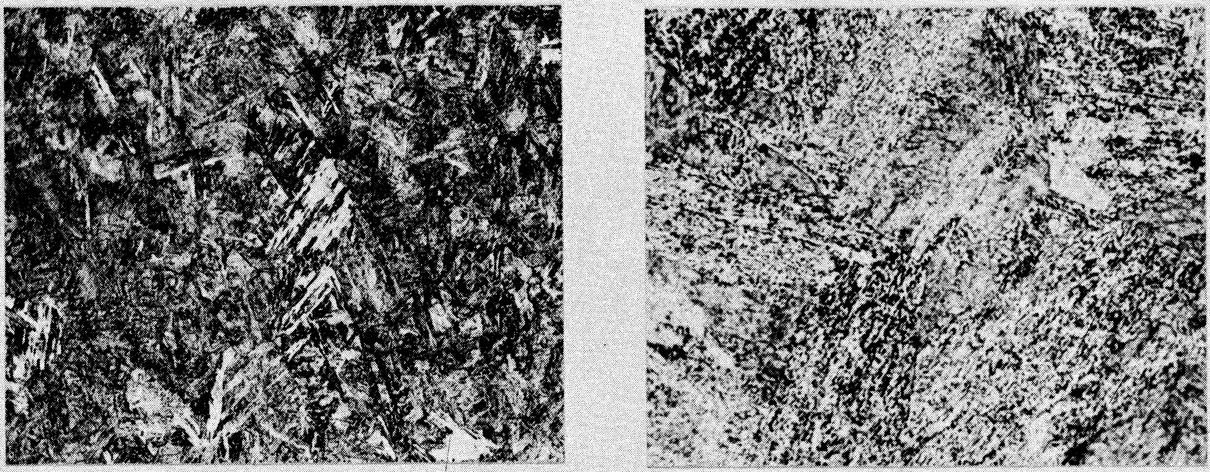
(c) Same As in (b) + Tempered 2 Hours at 1200°F. Avg. BHN - 293



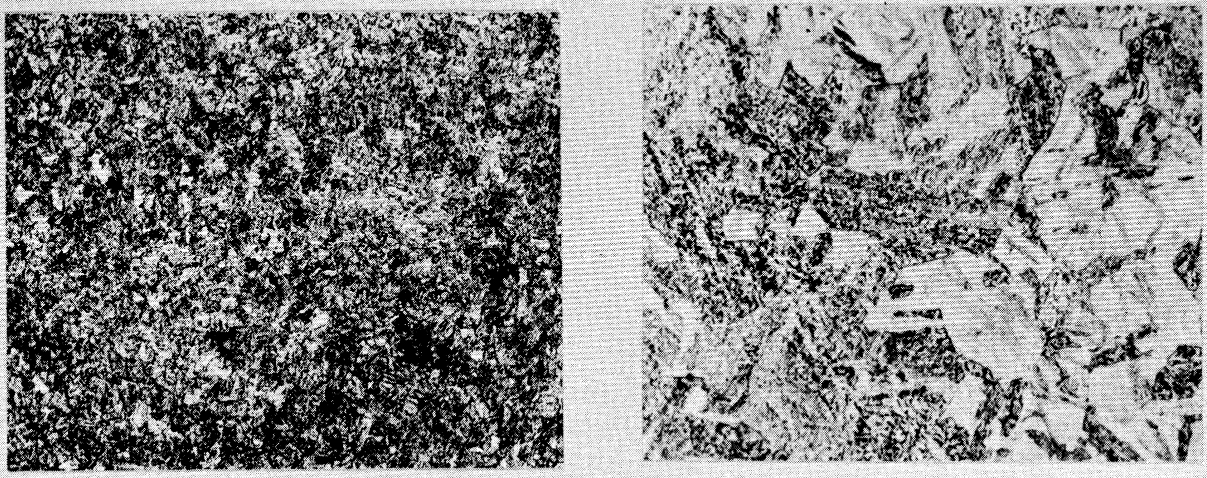
(d) Same As in (c) + Creep Tested 932 Hours at 1000°F and 12,000 psi. BHN - 269

Figure 39. - Concluded.

X100 X1000



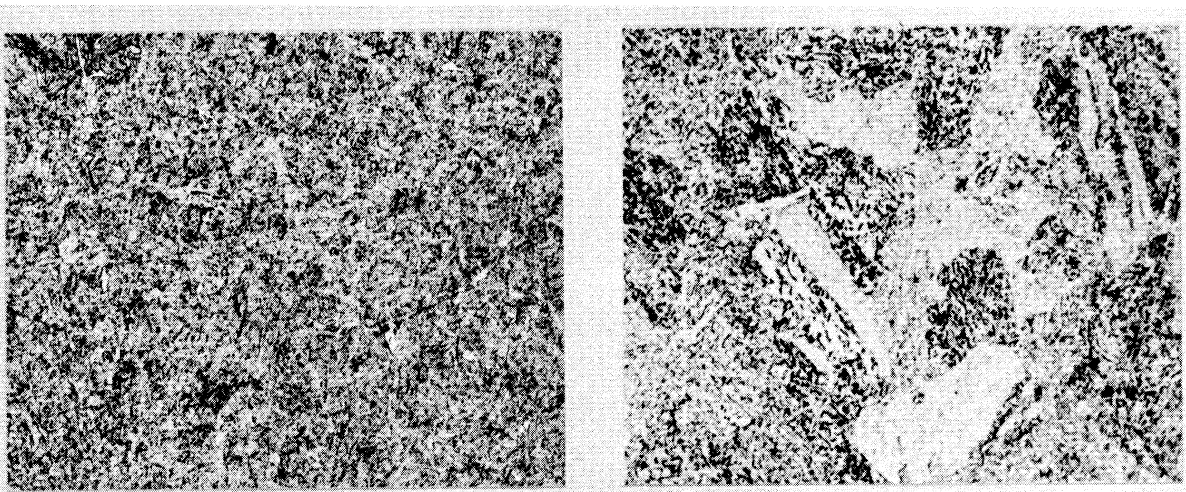
(a) Hot Rolled 25 Percent in One Pass at 2200°F.



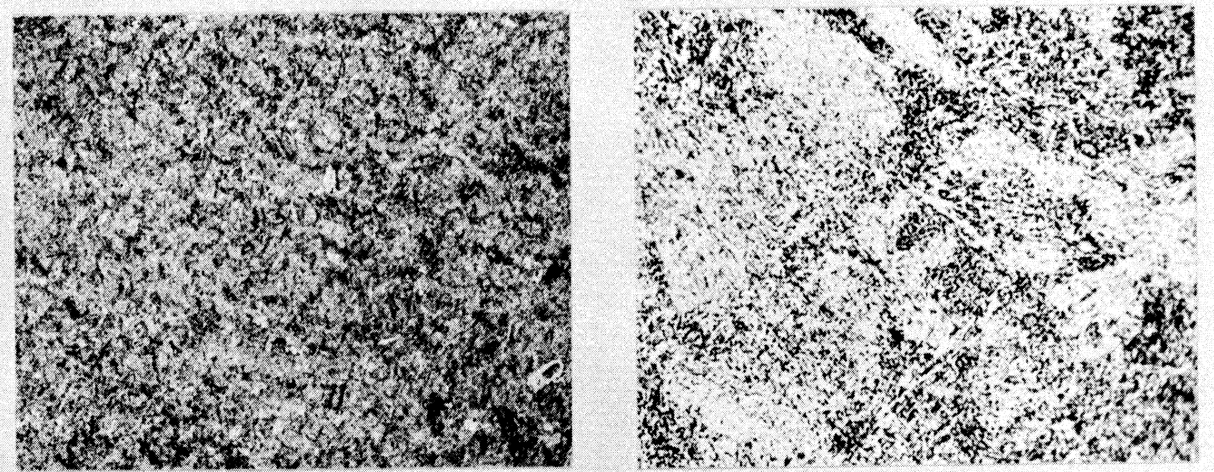
(b) Same As in (a) + Air Cooled from 1750°F. Avg. BHN - 408

Figure 40. - SAE 4340 Bar Stock (a) As Hot Rolled at 2200°F, (b) As Normalized from 1750°F, (c) As Tempered to 300 BHN, and (d) After Creep Tested at 1000°F.

X100 X1000

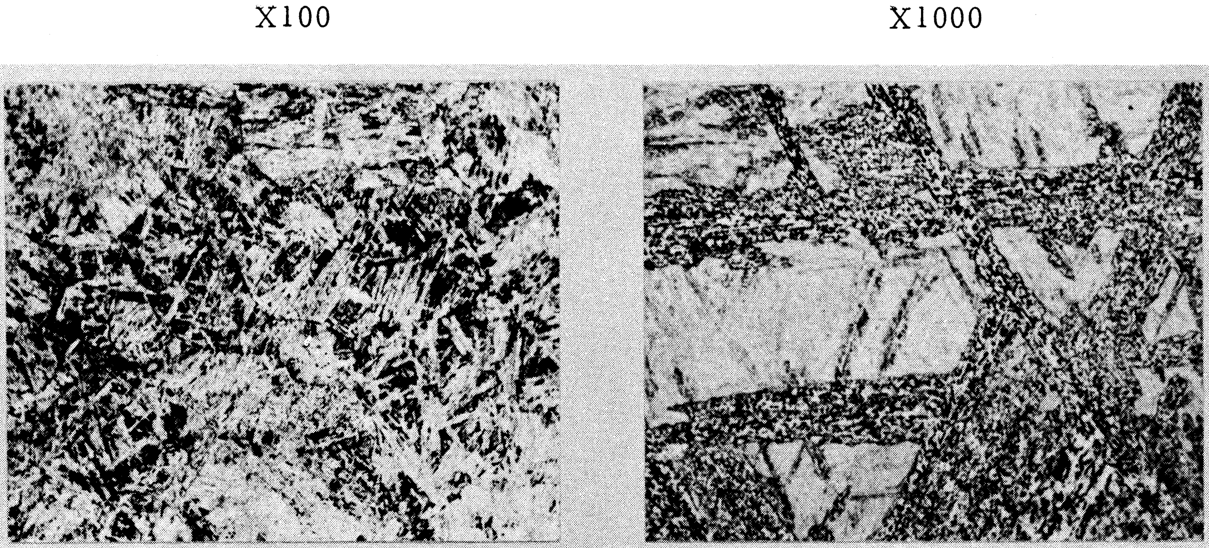


(c) Same As in (b) + Tempered 2.5 Hours at 1200°F. Avg. BHN - 293

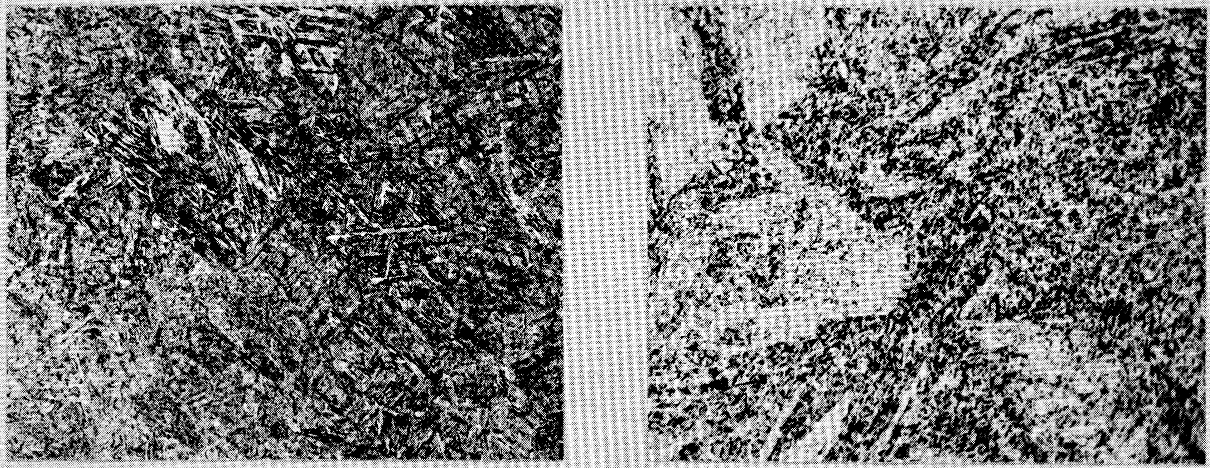


(d) Same As in (c) + Creep Tested 1004 Hours at 1000°F and 12,000 psi. BHN - 270

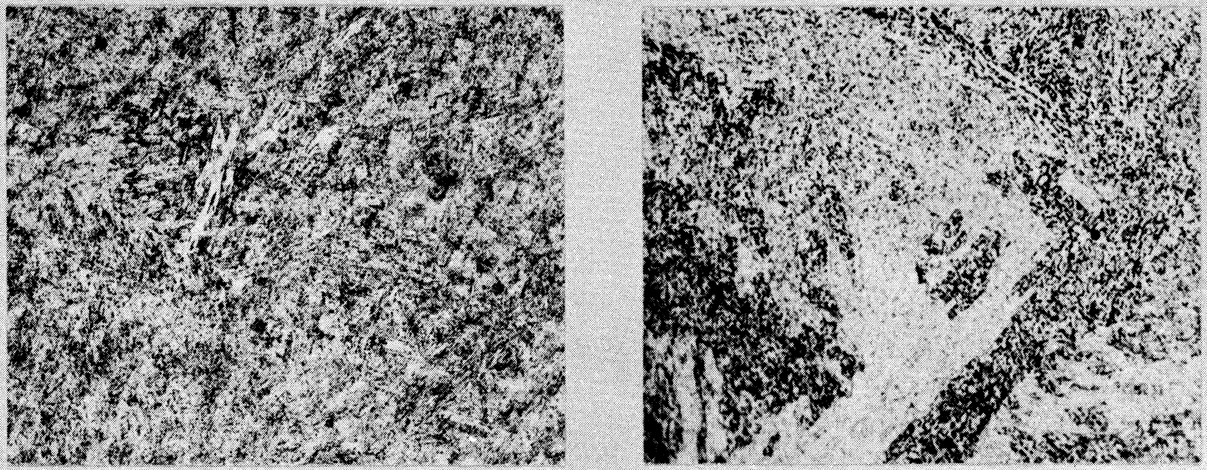
Figure 40. - Concluded.



(a) Air Cooled from 2100°F to 1800°F and then Hot Rolled 25 Percent in One Pass. Avg. BHN - 366



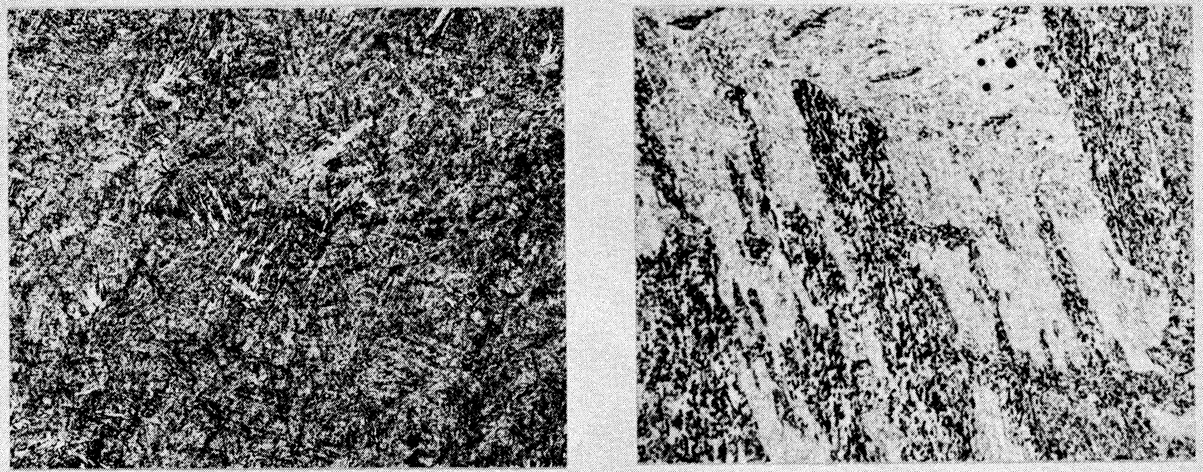
(b) Same As in (a) + Tempered 2.25 Hours at 1200°F. Avg. BHN - 297



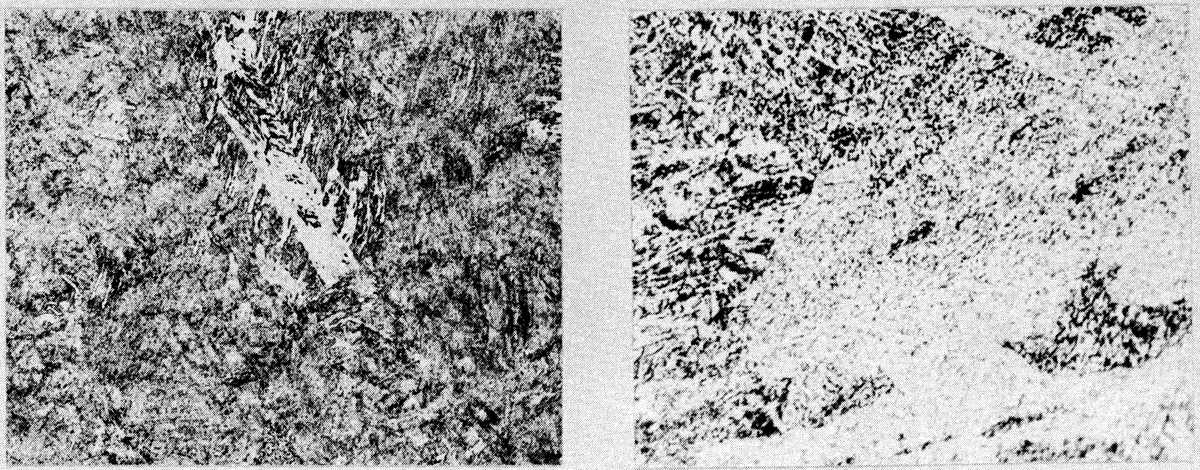
(c) Same As in (b) + Creep Tested 932 Hours at 1000°F and 12,000 psi. BHN - 269

Figure 41. - SAE 4340 Bar Stock (a) As Air Cooled from 2100°F to 1800°F and then Hot Rolled, (b) As Tempered to 300 BHN, and (c) After Creep Tested at 1000°F.

(a) Hot Rolled 25 Percent in Three Passes during Air Cooling from 2100°F to 1800°F. Avg. BHN - 386



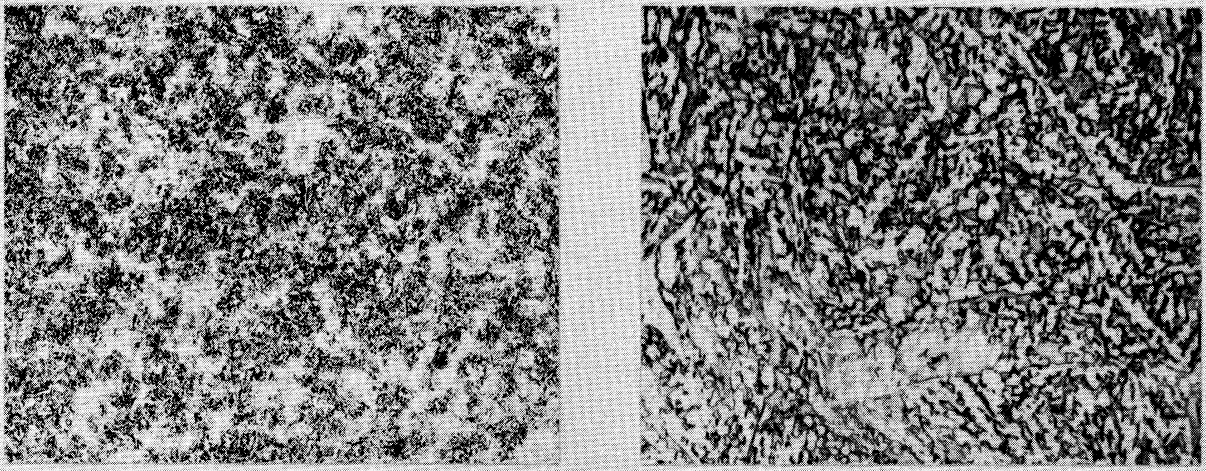
(b) Same As in (a) + Tempered 2.25 Hours at 1200°F. Avg. BHN - 297



(c) Same As in (b) + Creep Tested 932 Hours at 1000°F and 12,000 psi. BHN - 265

Figure 42. - SAE 4340 Bar Stock (a) As Hot Rolled during Air Cooling from 2100°F to 1800°F, (b) As Tempered to 300 BHN, and (c) After Creep Tested at 1000°F.

X100 X1000


(a) Hot Rolled 25 Percent in One Pass at 1800°F.

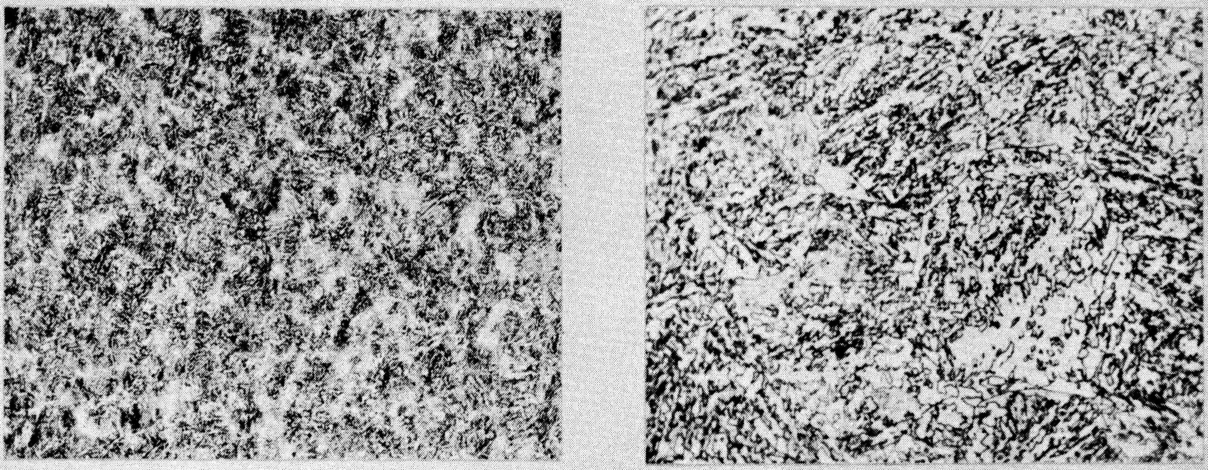
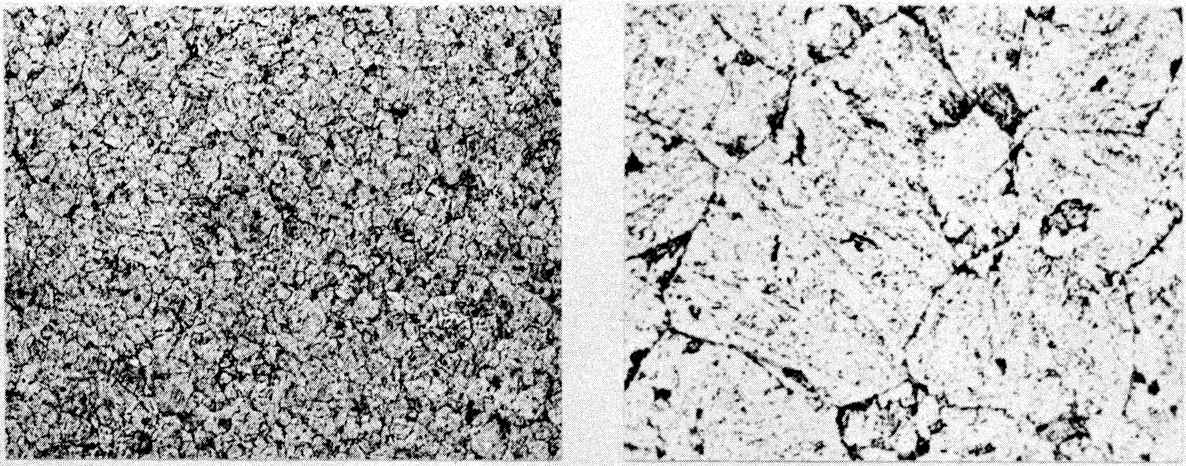
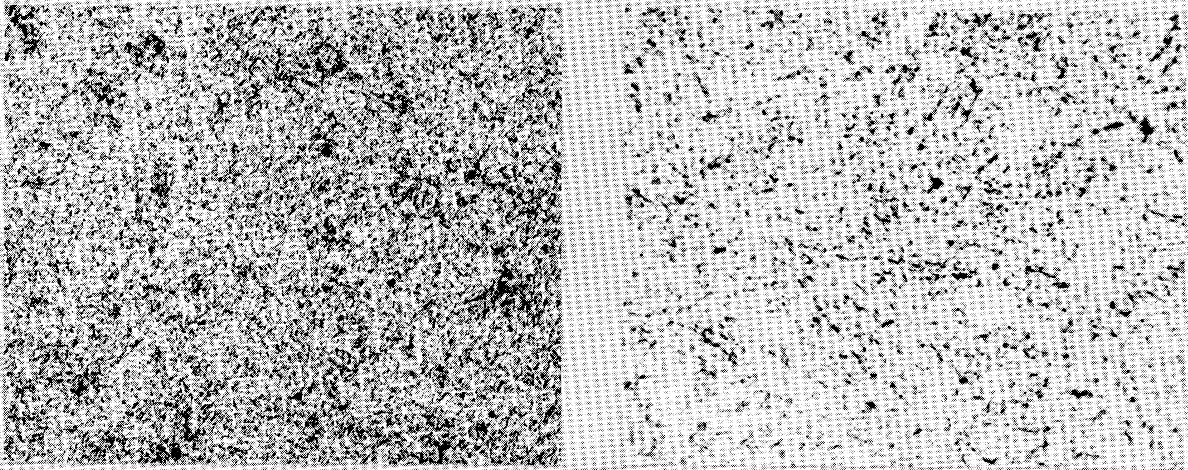

(b) Same As in (a) + Air Cooled from 1750°F. Avg. BHN - 331

Figure 43. - "17-22-A"S Bar Stock (a) As Hot Rolled at 1800°F, (b) As Normalized from 1750°F, (c) As Tempered to 350 BHN, and (d) After Creep Tested at 1100°F.



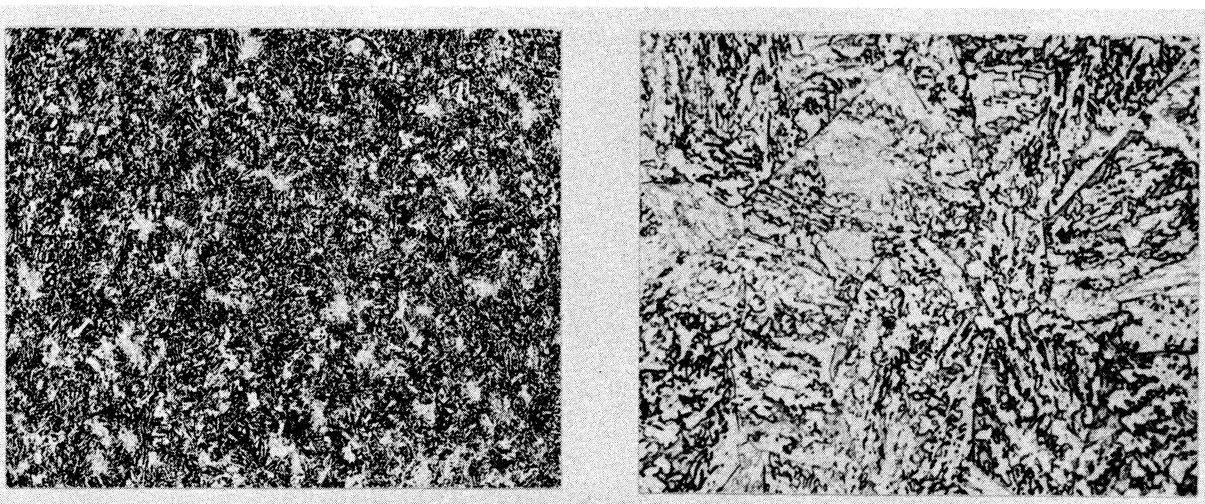
(c) Same As in (b) + Tempered 2 Hours at 1200°F. Avg. BHN - 342



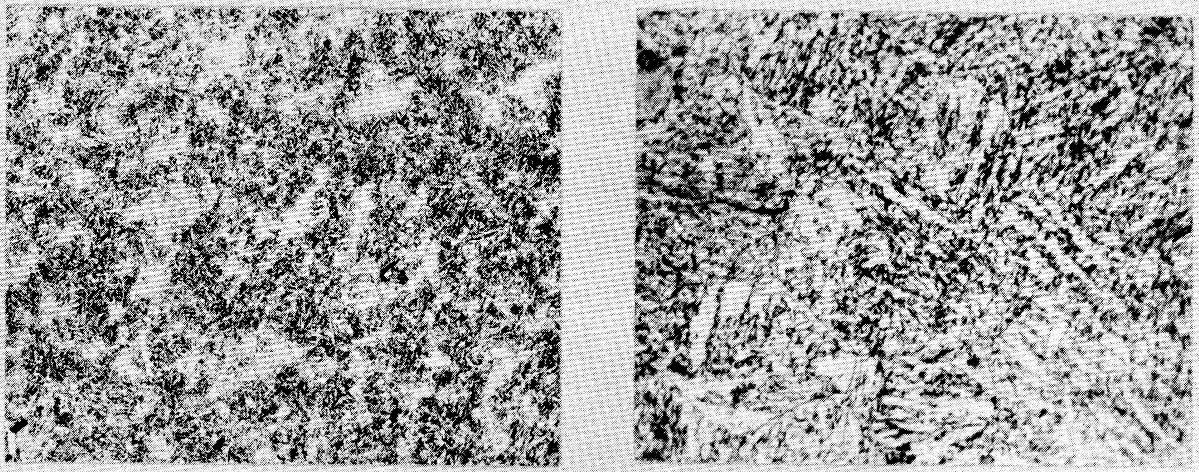
(d) Same As in (c) + Creep Tested 980 Hours at 1100°F and 19,000 psi.
BHN - 238

Figure 43. - Concluded.

X100 X1000



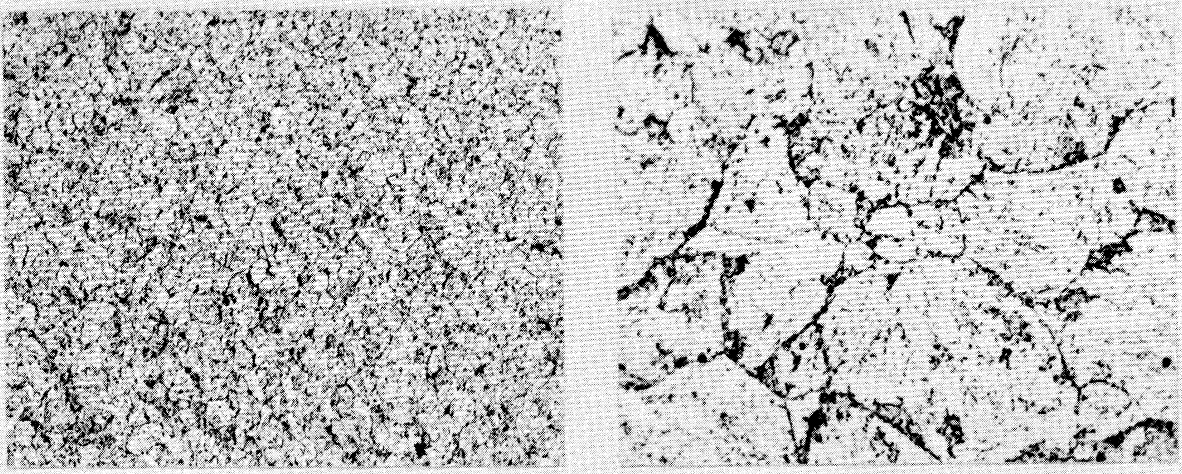
(a) Hot Rolled 25 Percent in One Pass at 2000°F.



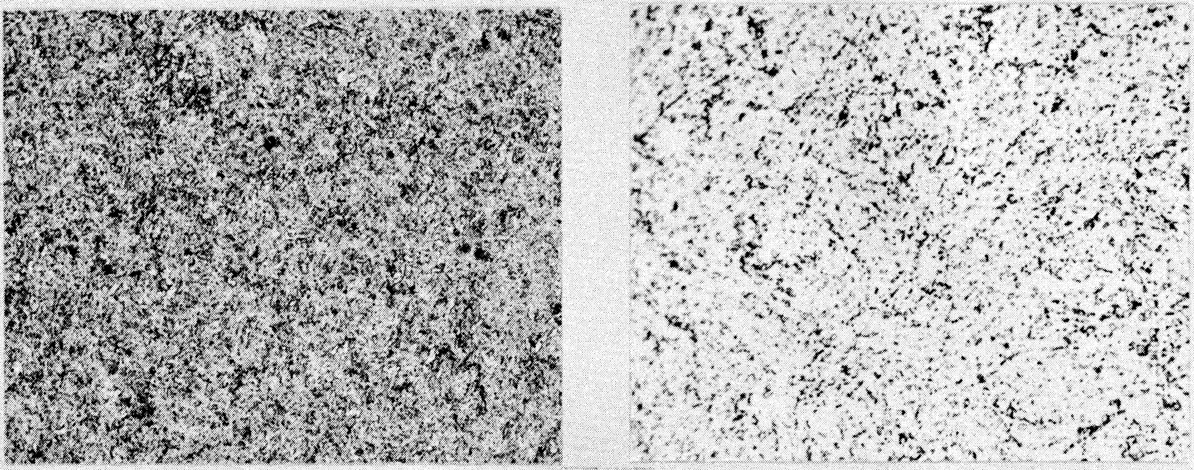
(b) Same As in (a) + Air Cooled from 1750°F. Avg. BHN - 329

Figure 44. - "17-22-A"S Bar Stock (a) As Hot Rolled at 2000°F, (b) As Normalized from 1750°F, (c) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.

X100 X1000



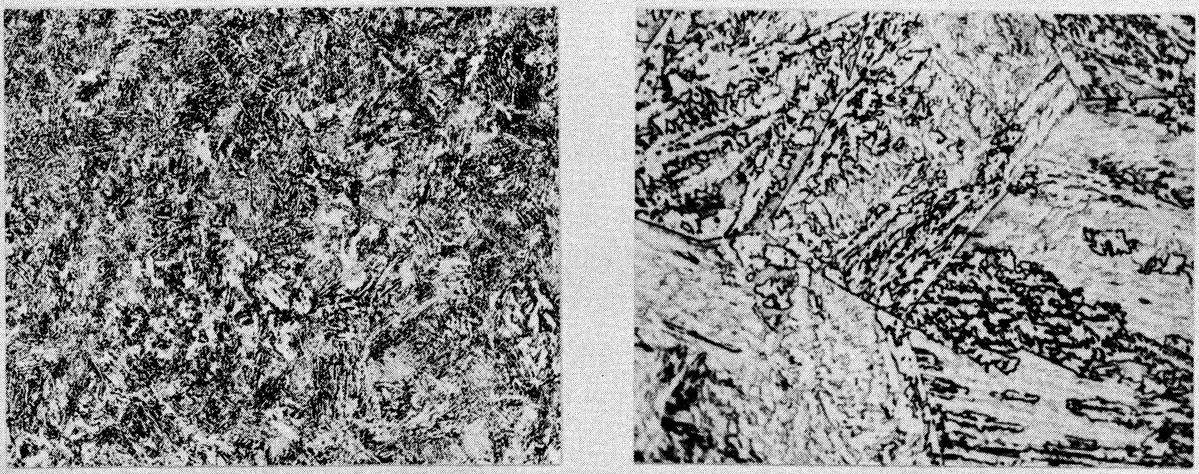
(c) Same As in (b) + Tempered 2 Hours at 1200°F. Avg. BHN - 350



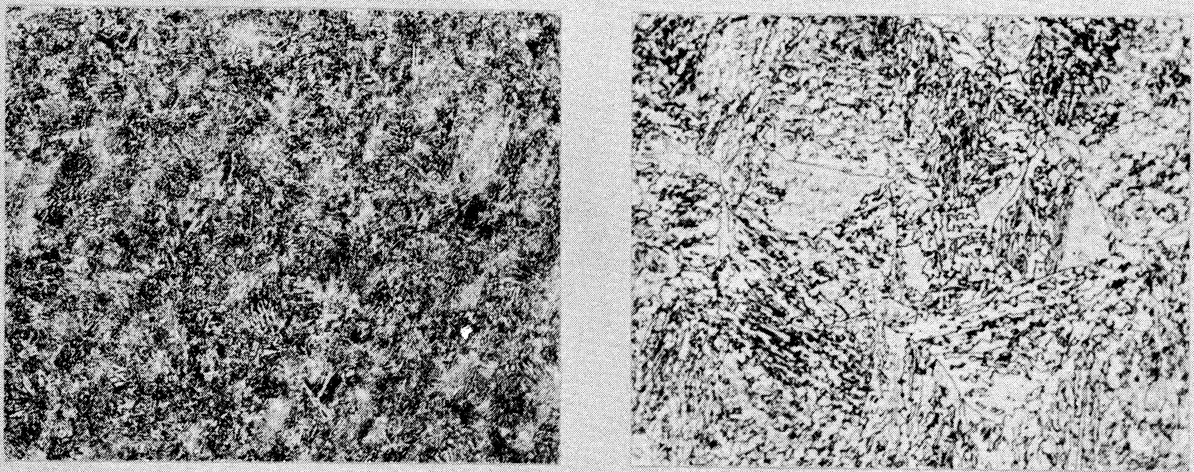
(d) Same As in (c) + Creep Tested 861 Hours at 1100°F and 19,000 psi. BHN - 249

Figure 44. - Concluded.

X100 X1000



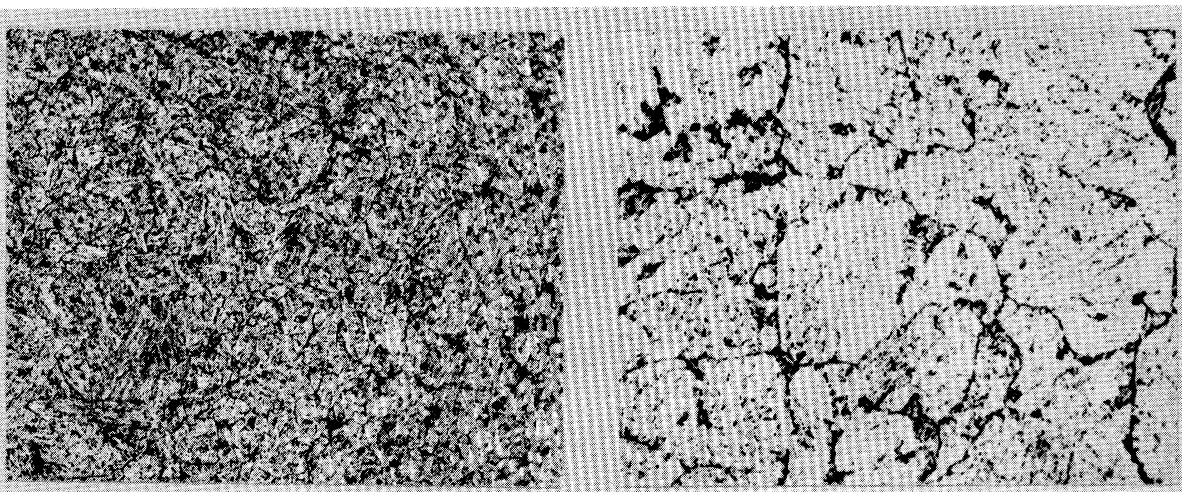
(a) Hot Rolled 25 Percent in One Pass at 2200°F.



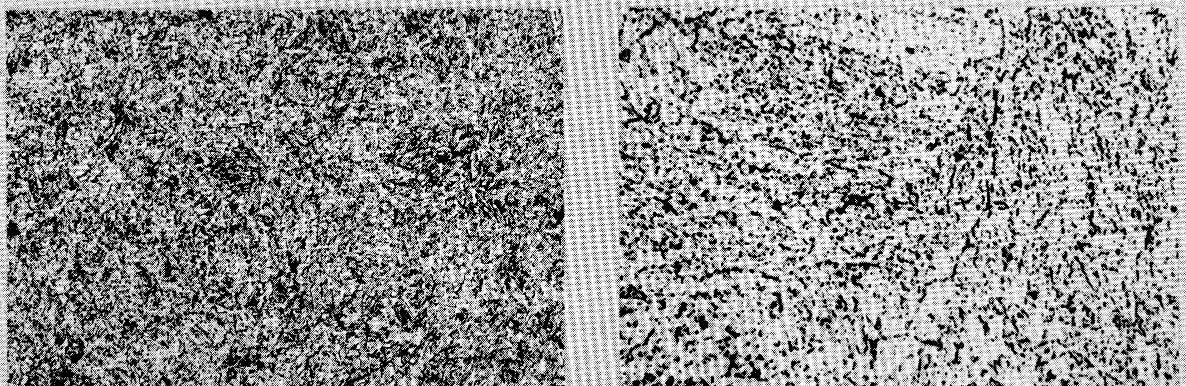
(b) Same As in (a) + Air Cooled from 1750°F. Avg. BHN - 332

Figure 45. - "17-22-A"S Bar Stock (a) As Hot Rolled at 2200°F, (b) As Normalized from 1750°F, (c) As Tempered to 350 BHN, and (d) After Creep Tested at 1100°F.

X100 X1000

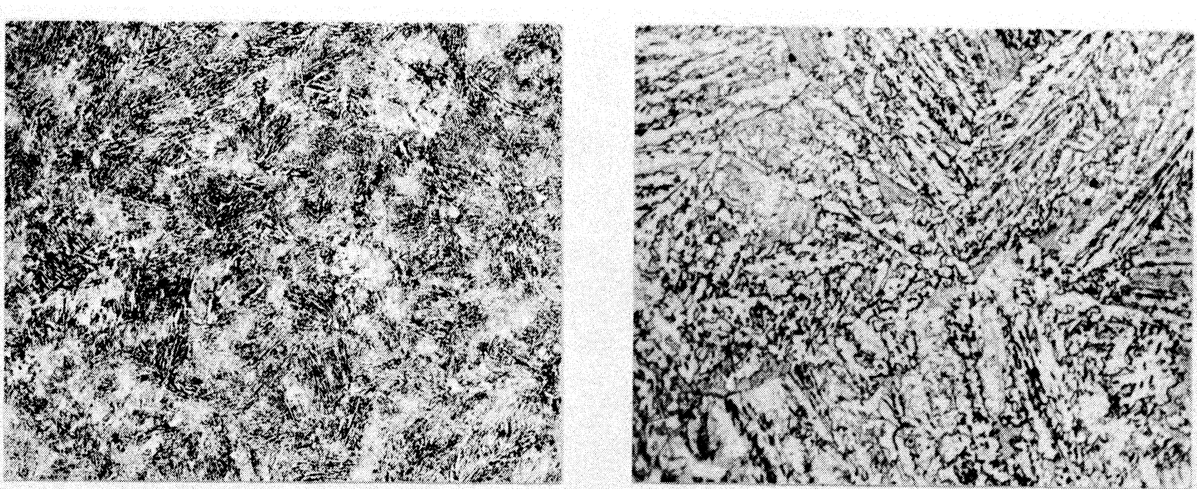


(c) Same As in (b) + Tempered 2 Hours at 1200°F. Avg. BHN - 344

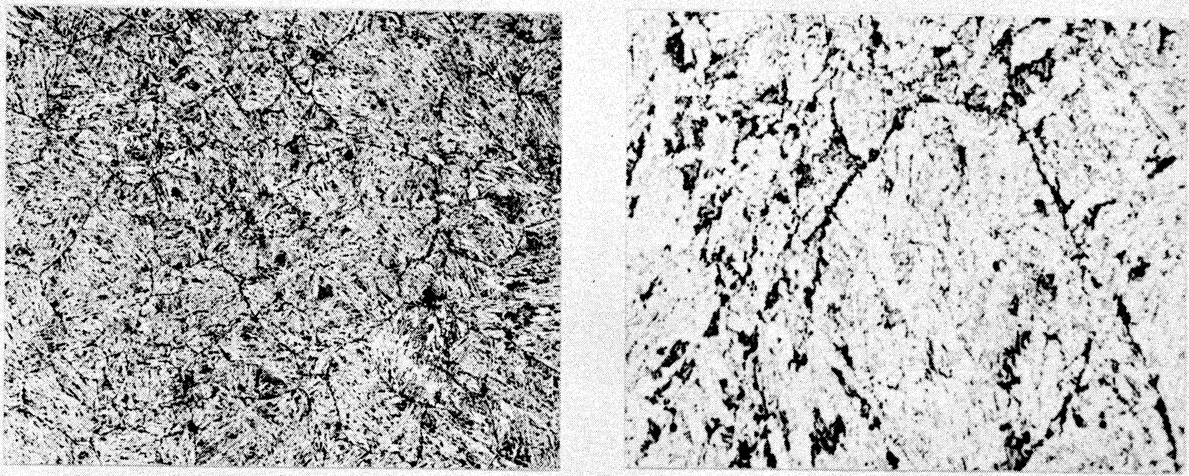


(d) Same As in (c) + Creep Tested 861 Hours at 1100°F and 19,000 psi.
BHN - 252

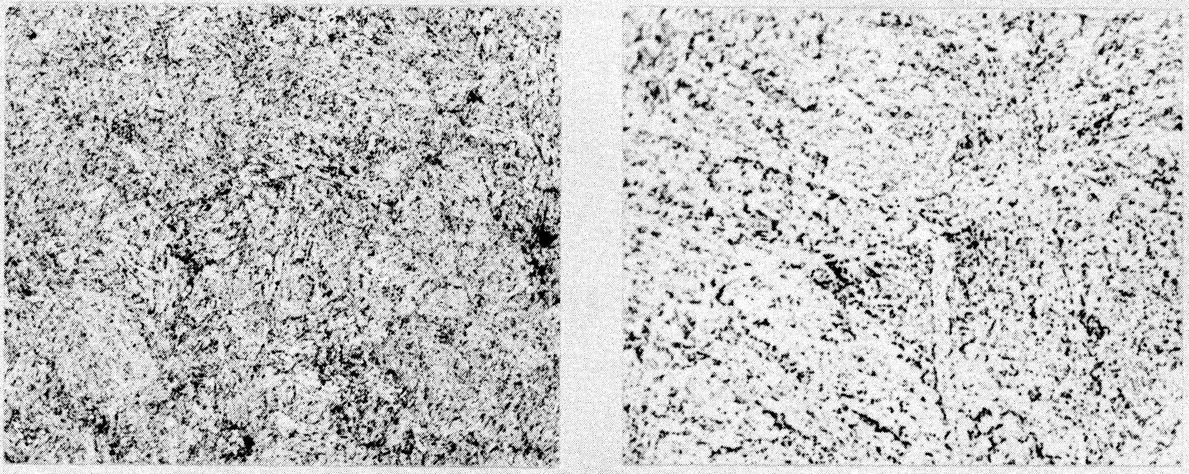
Figure 45. - Concluded.



(a) Air Cooled from 2100°F to 1800°F and then Hot Rolled 25 Percent in One Pass. Avg. BHN - 334

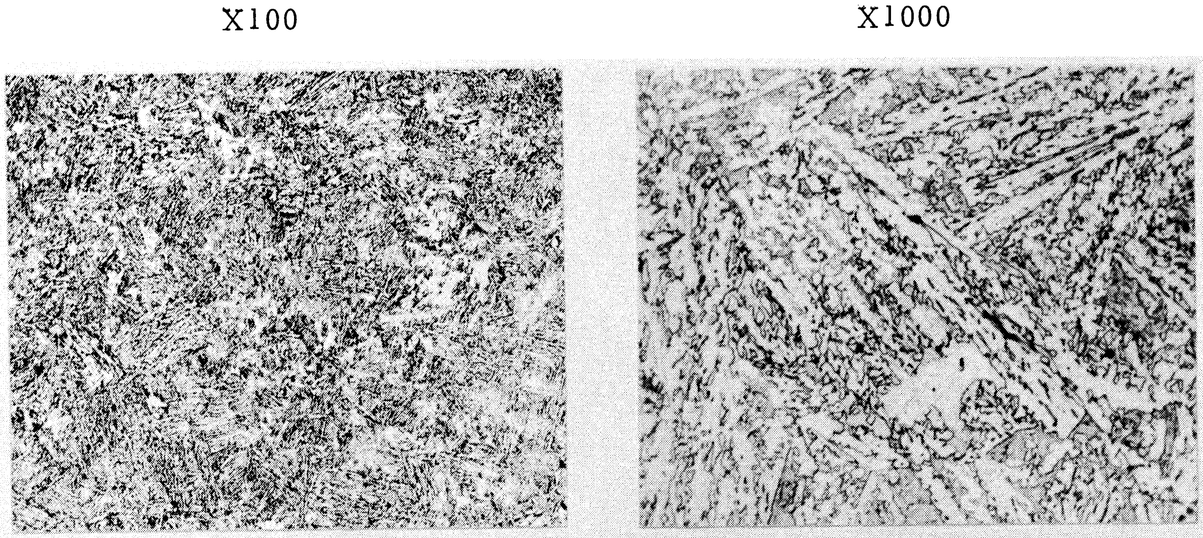


(b) Same As in (a) + Tempered 2 Hours at 1200°F. Avg. BHN - 347

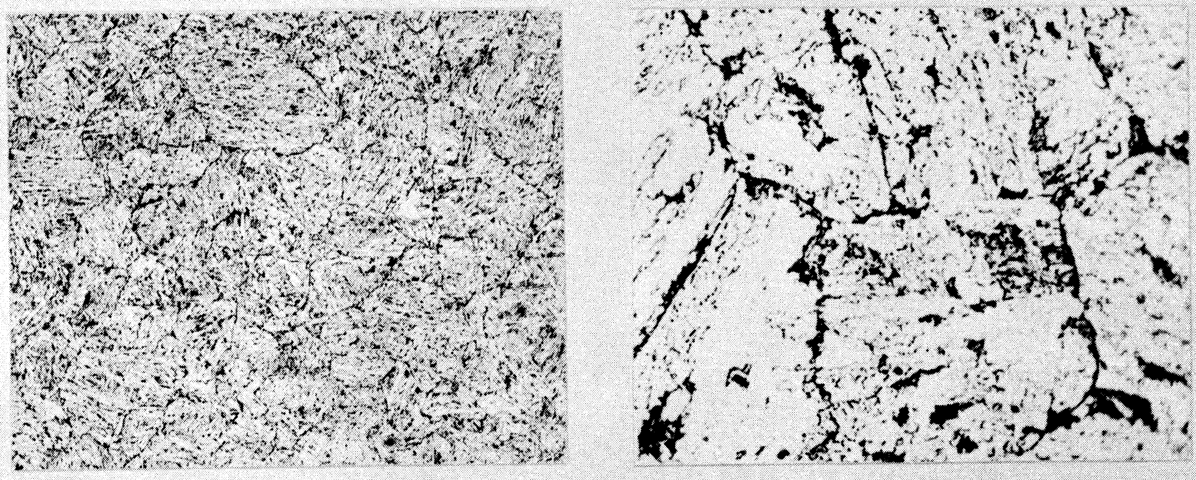


(c) Same As in (b) + Creep Tested 1077 Hours at 1100°F and 19,000 psi. BHN - 256

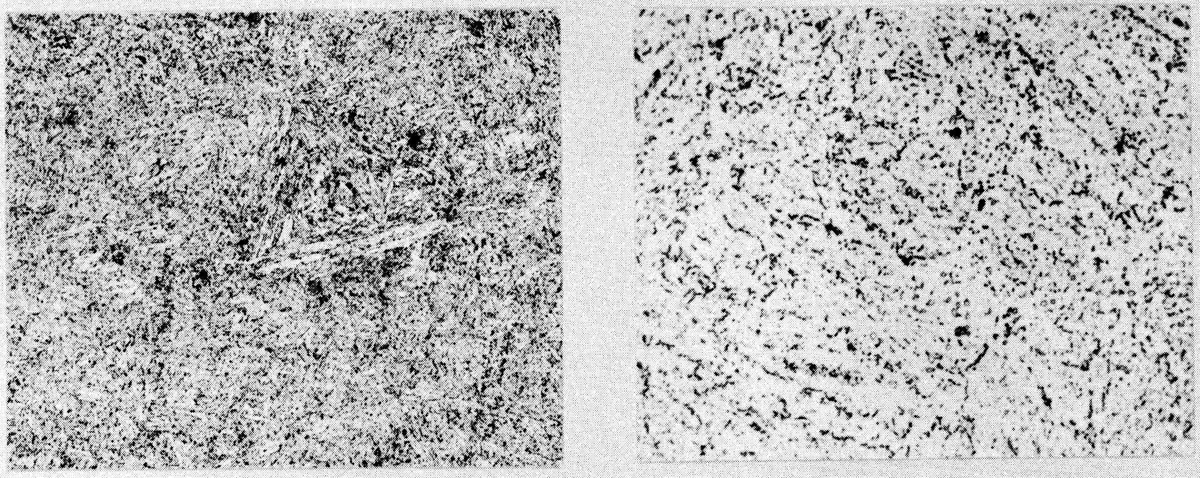
Figure 46. - "17-22-A"S Bar Stock (a) As Air Cooled from 2100°F to 1800°F and then Hot Rolled, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Hot Rolled 25 Percent in Three Passes during Air Cooling from 2100°F to 1800°F. Avg. BHN - 330



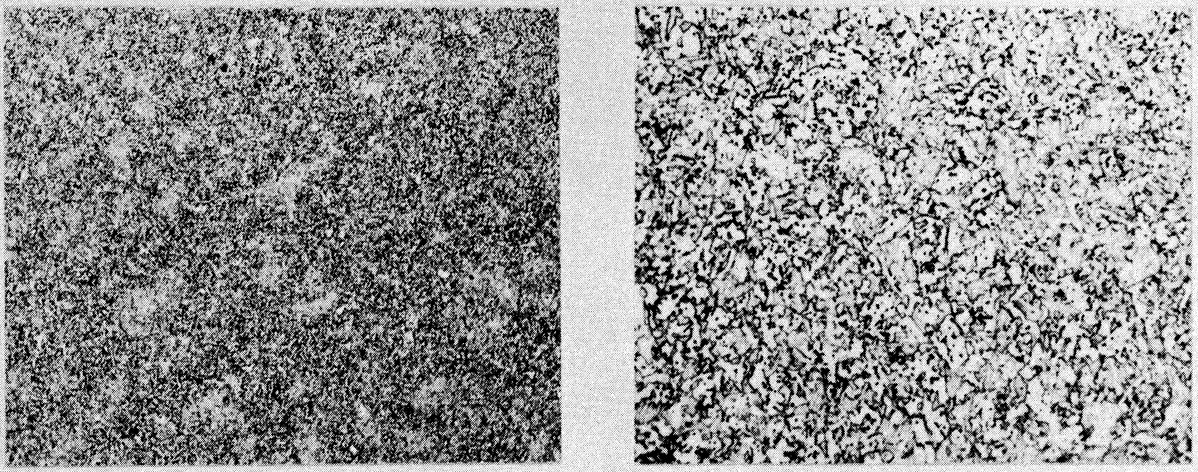
(b) Same As in (a) + Tempered 2 Hours at 1200°F. Avg. BHN - 352



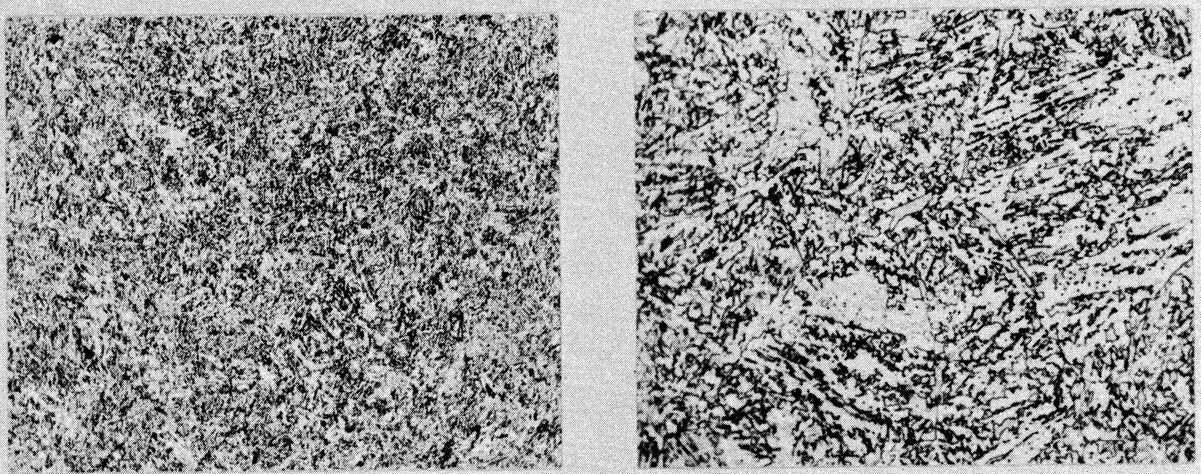
(c) Same As in (b) + Creep Tested 931 Hours at 1100°F and 19,000 psi. BHN - 265

Figure 47. - "17-22-A"S Bar Stock (a) As Hot Rolled during Air Cooling from 2100°F to 1800°F, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.

X100 X1000



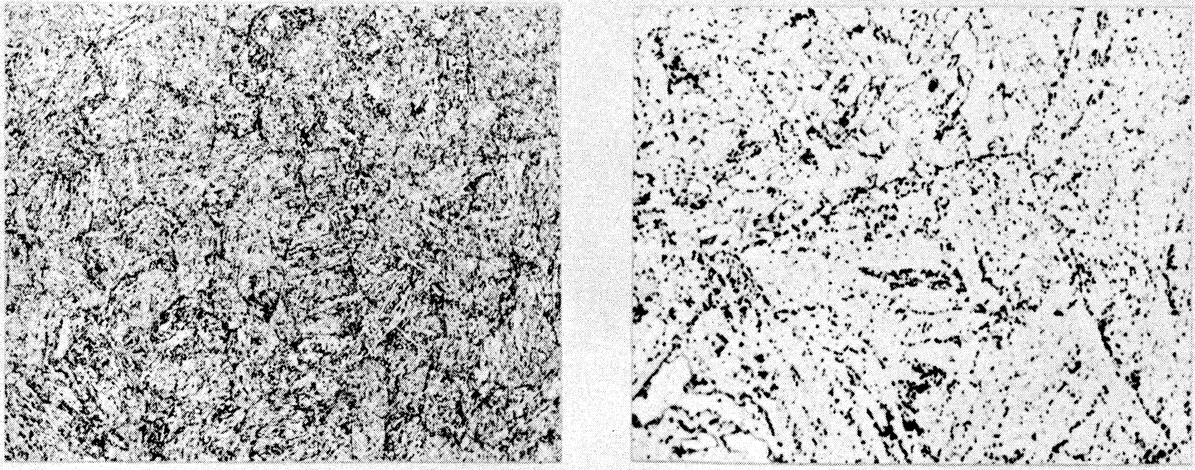
(a) Hot Rolled 25 Percent in One Pass at 1800°F.



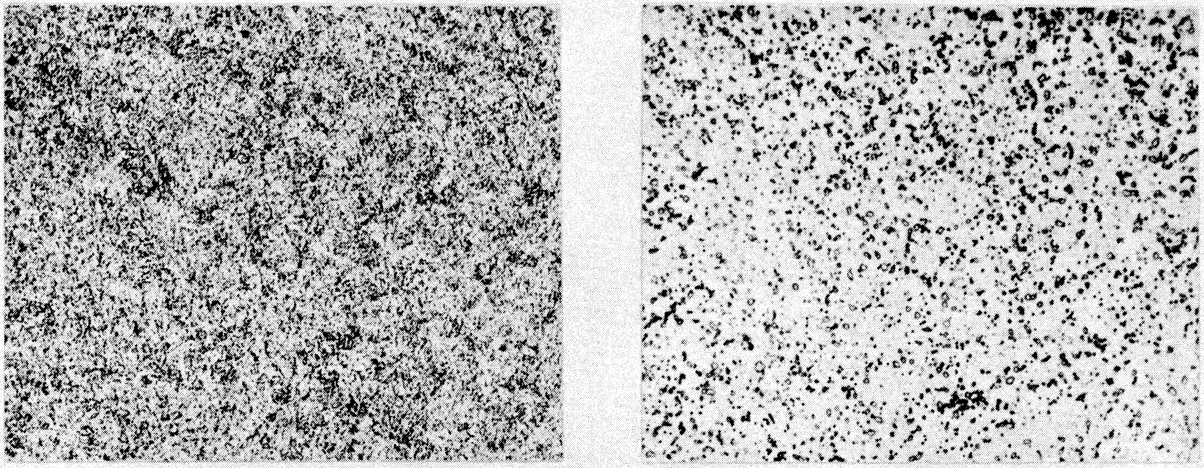
(b) Same As in (a) + Air Cooled from 1850°F. Avg. BHN - 360

Figure 48. - "17-22-A"V Bar Stock (a) As Hot Rolled at 1800°F, (b) As Normalized from 1850°F, (c) As Tempered to 350 BHN, and (d) After Creep Tested at 1100°F.

X100 X1000



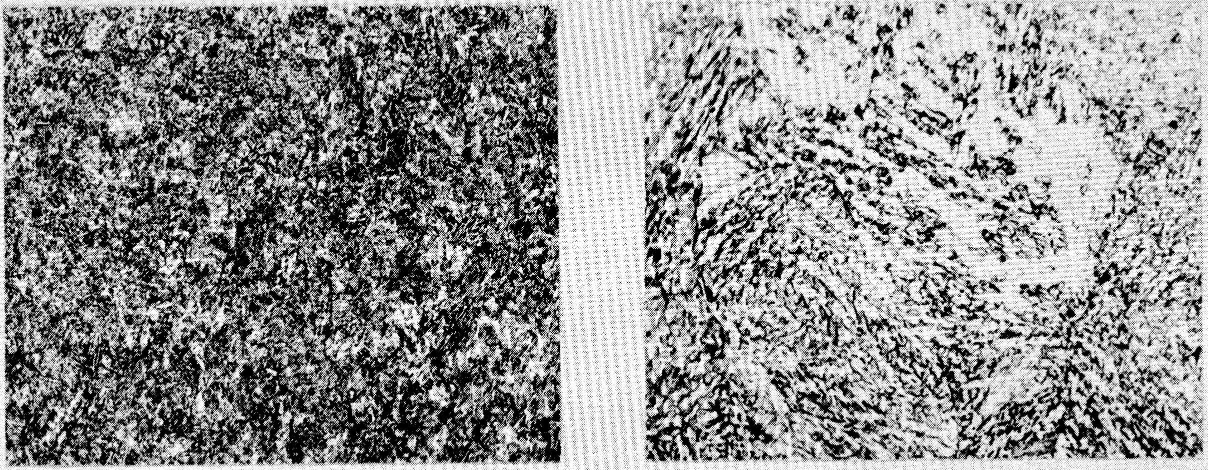
(c) Same As in (b) + Tempered 1.75 Hours at 1250°F. Avg. BHN - 350



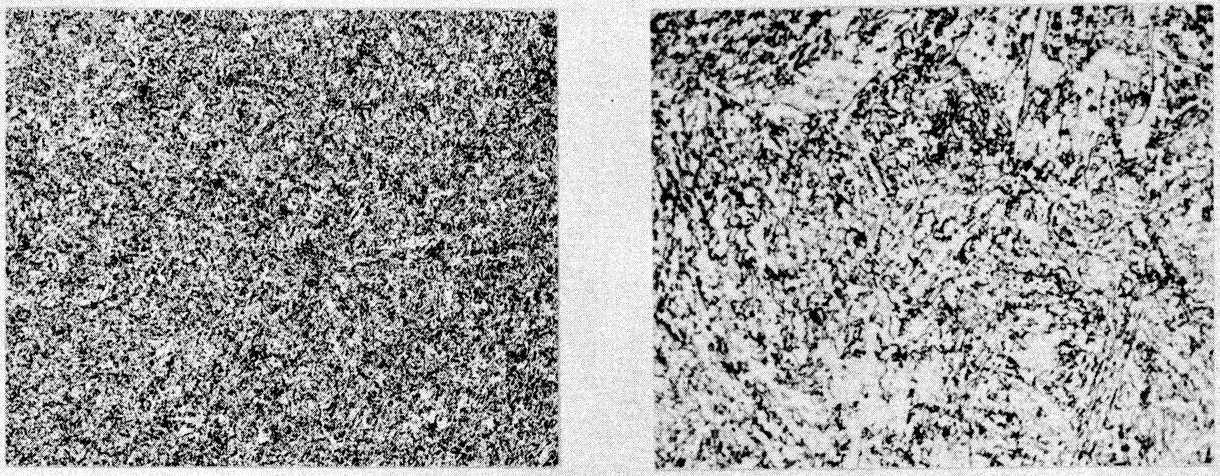
(d) Same As in (c) + Creep Tested 934 Hours at 1100°F and 19,000 psi. BHN - 270

Figure 48. - Concluded.

X100 X1000



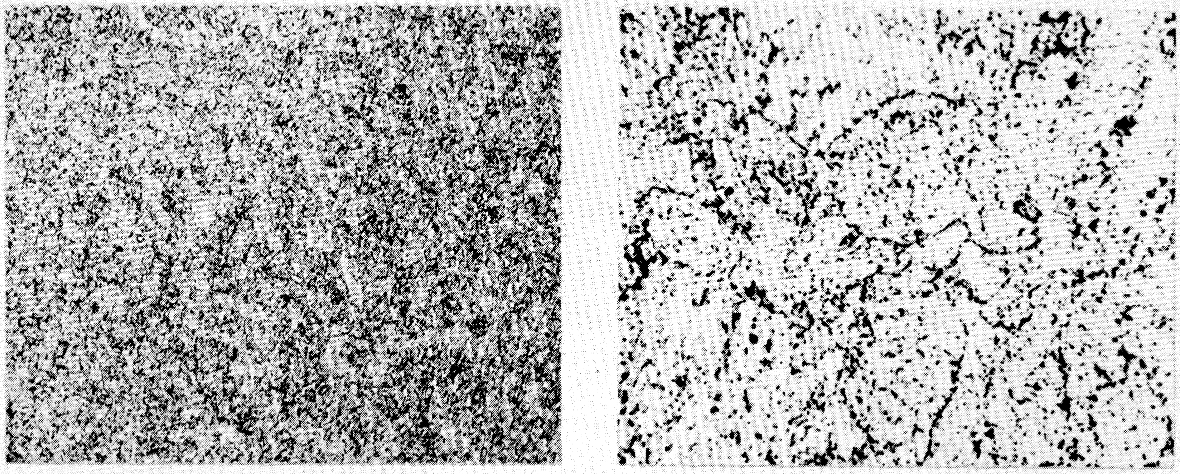
(a) Hot Rolled 25 Percent in One Pass at 2000°F



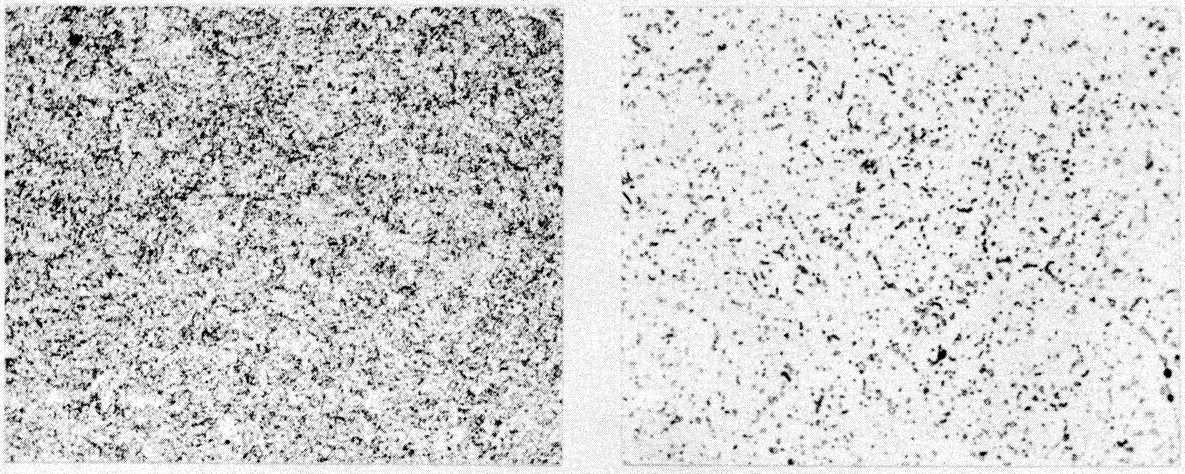
(b) Same As in (a) + Air Cooled from 1850°F. Avg. BHN - 376

Figure 49. - "17-22-A"V Bar Stock (a) As Hot Rolled at 2000°F, (b) As Normalized from 1850°F, (c) As Tempered to 350 BHN, and (d) After Creep Tested at 1100°F.

X100 X1000



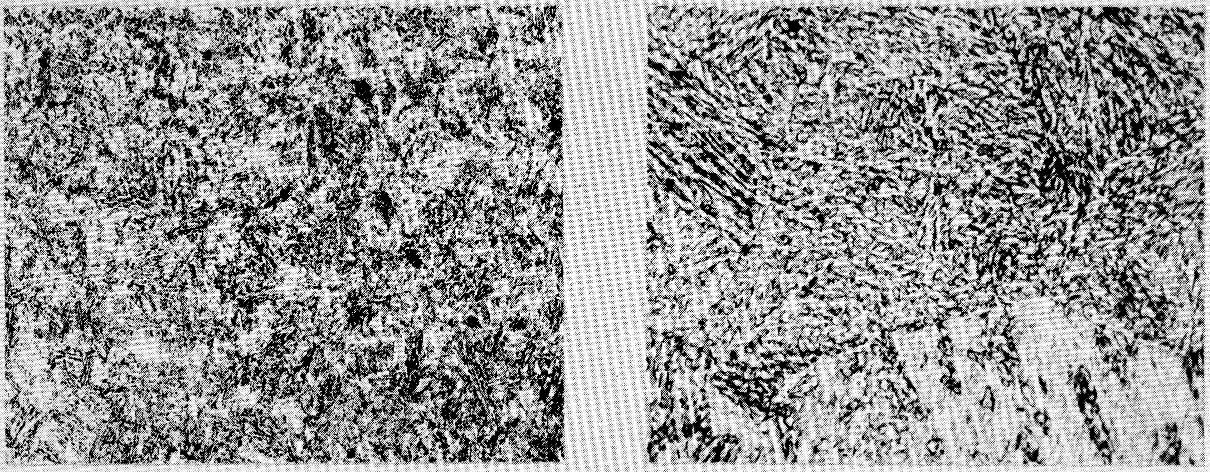
(c) Same As in (b) + Tempered 1.5 Hours at 1250°F. Avg. BHN - 355



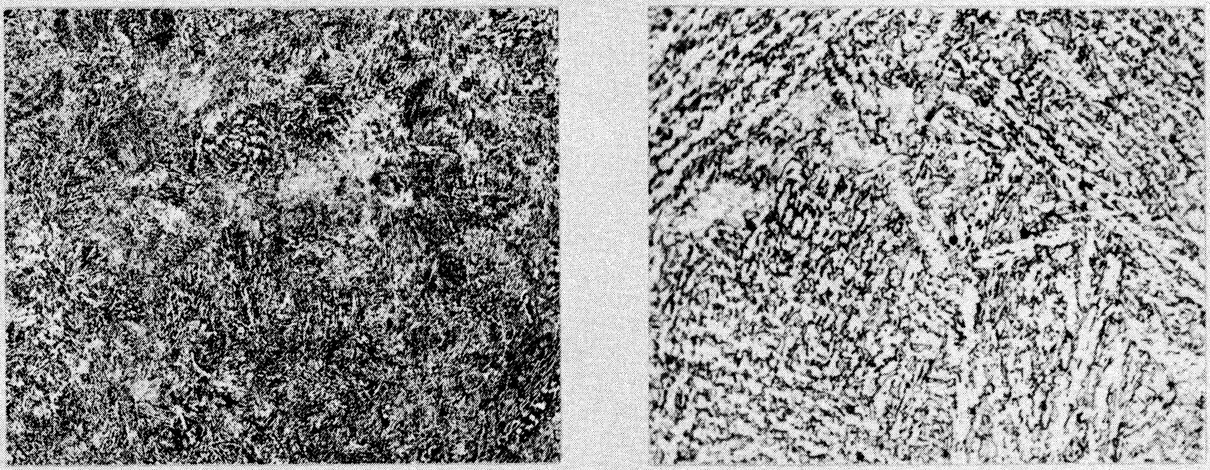
(d) Same As in (c) + Creep Tested 962 Hours at 1100°F and 19,000 psi. BHN - 254

Figure 49. - Concluded.

X100 X1000



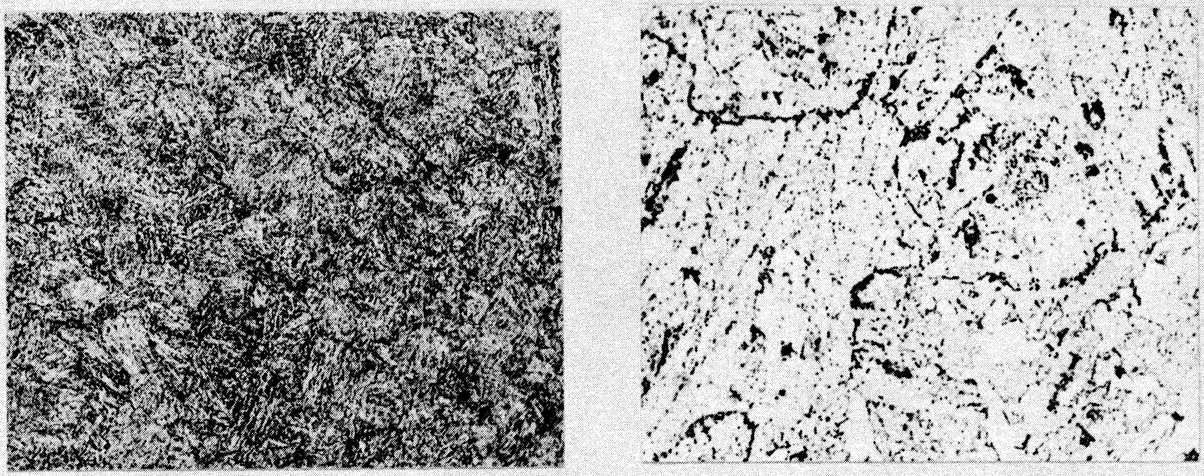
(a) Hot Rolled 25 Percent in One Pass at 2200°F



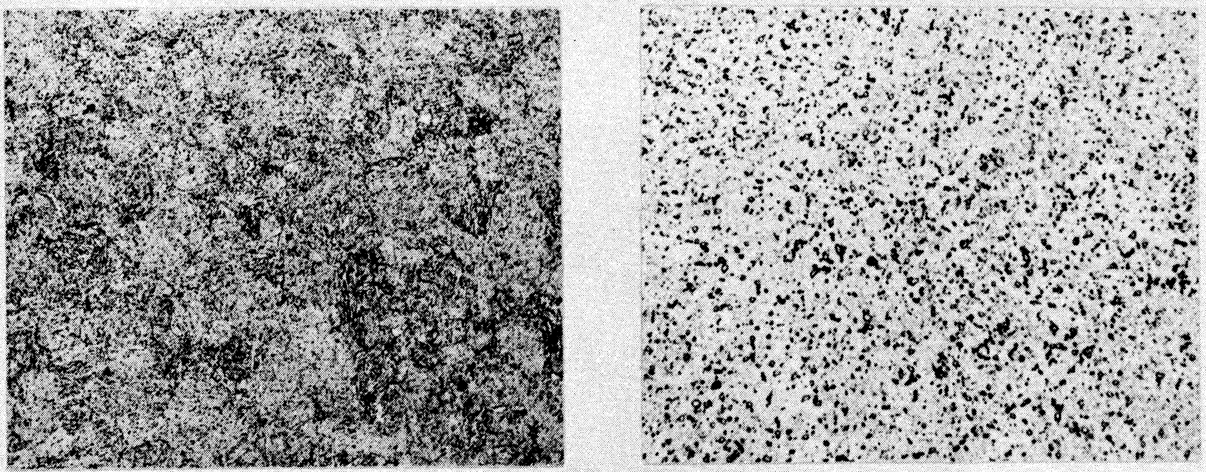
(b) Same As in (a) + Air Cooled from 1850°F. Avg. BHN - 365

Figure 50. - "17-22-A"V Bar Stock (a) As Hot Rolled at 2200°F, (b) As Normalized from 1850°F, (c) As Tempered to 350 BHN, and (d) After Creep Tested at 1100°F.

X100 X1000

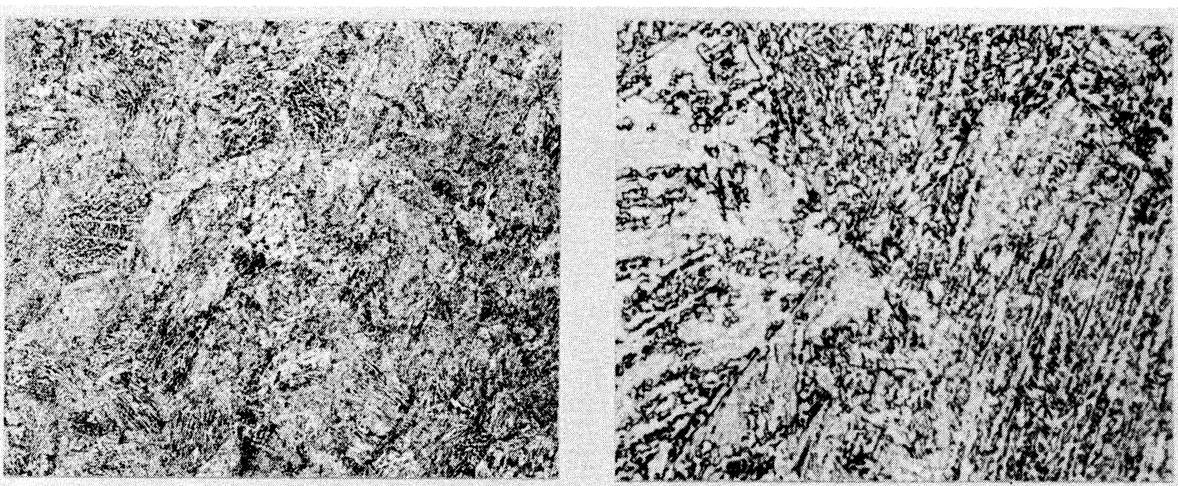


(c) Same As in (b) + Tempered 1.25 Hours at 1250°F. Avg. BHN - 350

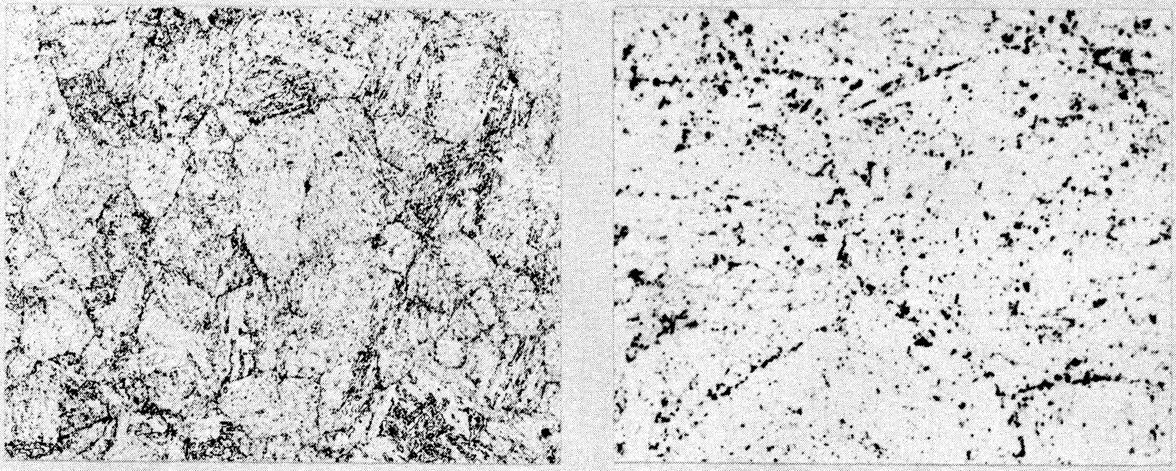


(d) Same As in (c) + Creep Tested 964 Hours at 1100°F and 19,000 psi. BHN - 259

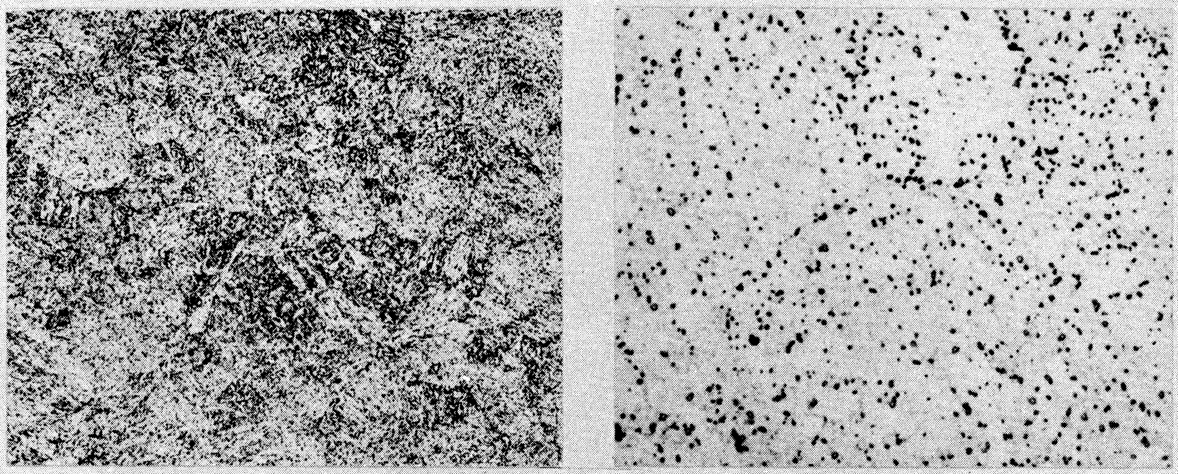
Figure 50. - Concluded.



(a) Air Cooled from 2200°F to 1900°F and then Hot Rolled 25 Percent in One Pass. Avg. BHN - 381

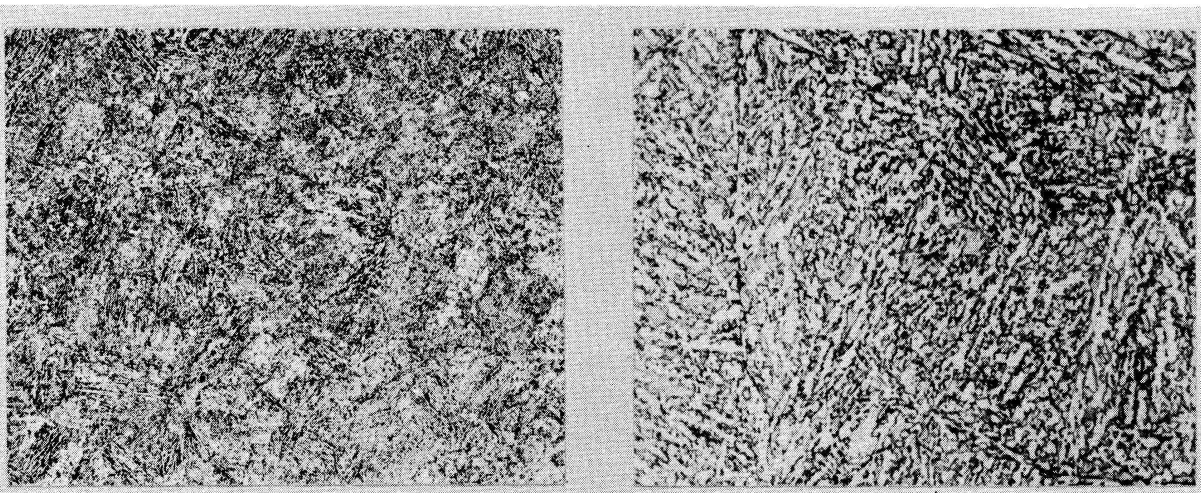


(b) Same As in (a) + Tempered 2.5 Hours at 1250°F. Avg. BHN - 358

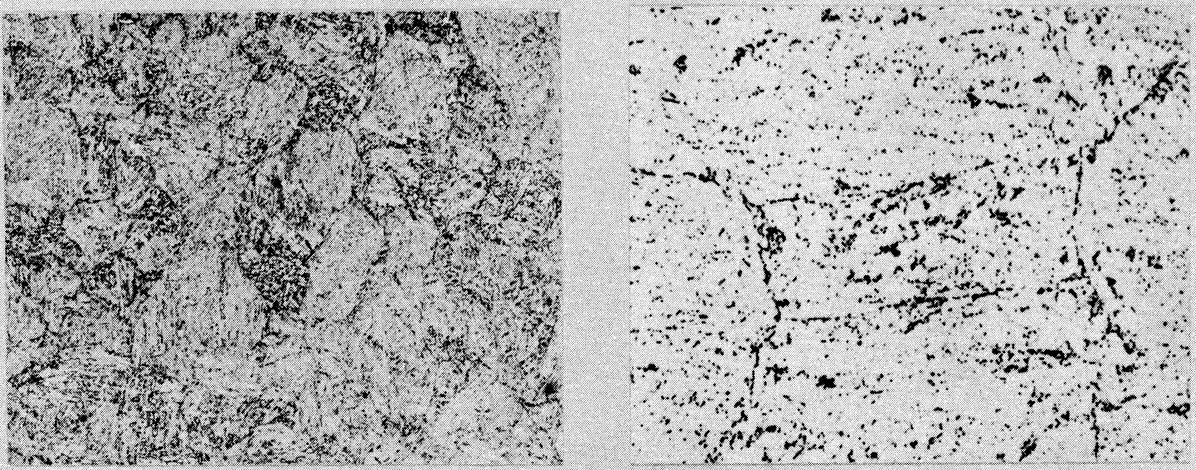


(c) Same As in (b) + Creep Tested 1414 Hours at 1100°F and 19,000 psi. BHN - 262

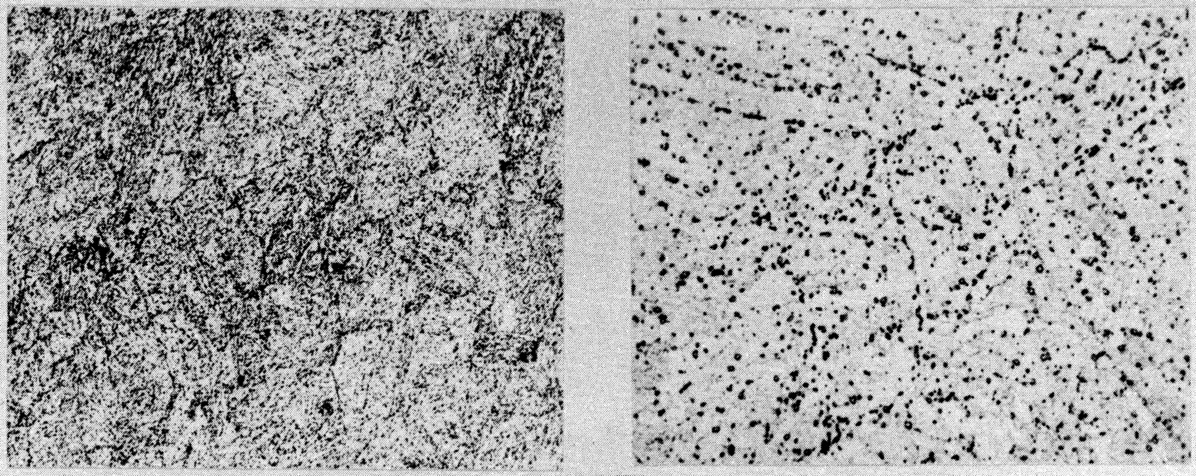
Figure 51. - "17-22-A"V Bar Stock (a) As Air Cooled from 2200°F to 1900°F and then Hot Rolled, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.



(a) Hot Rolled 25 Percent in Three Passes during Air Cooling from 2200°F to 1900°F. Avg. BHN - 386



(b) Same As in (a) + Tempered 2.75 Hours at 1250°F. Avg. BHN - 342



(c) Same As in (b) + Creep Tested 1846 Hours at 1100°F and 19,000 psi. BHN - 257

Figure 52. - "17-22-A"V Bar Stock (a) As Hot Rolled during Air Cooling from 2200°F to 1900°F, (b) As Tempered to 350 BHN, and (c) After Creep Tested at 1100°F.

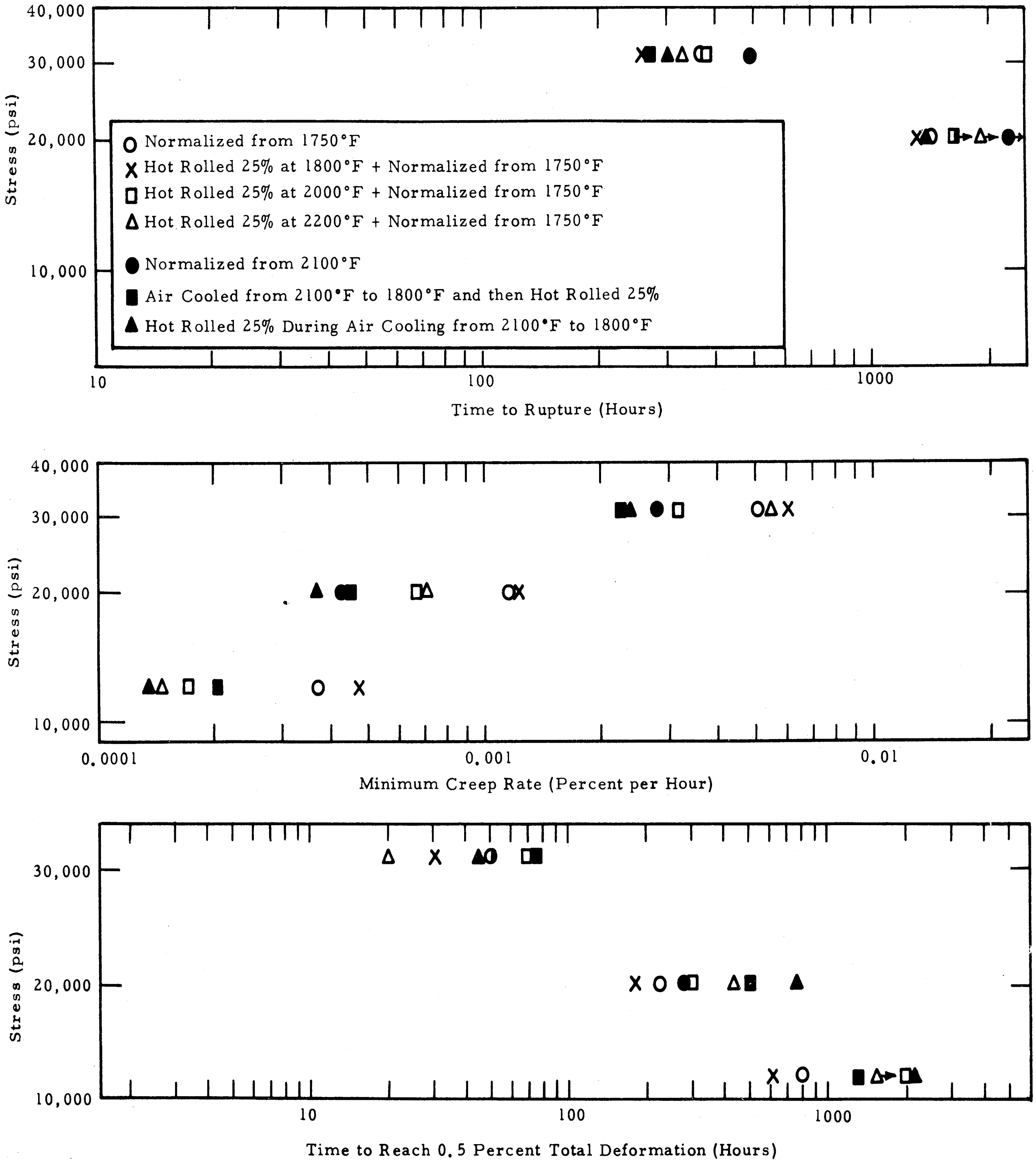


Figure 53. - Influence of Hot-Rolling Conditions on the Stress-Time to Rupture, Stress-Minimum Creep Rate, and Stress-0.5-Percent Total Deformation Time Relationships for SAE 4340 Steel at 1000°F.

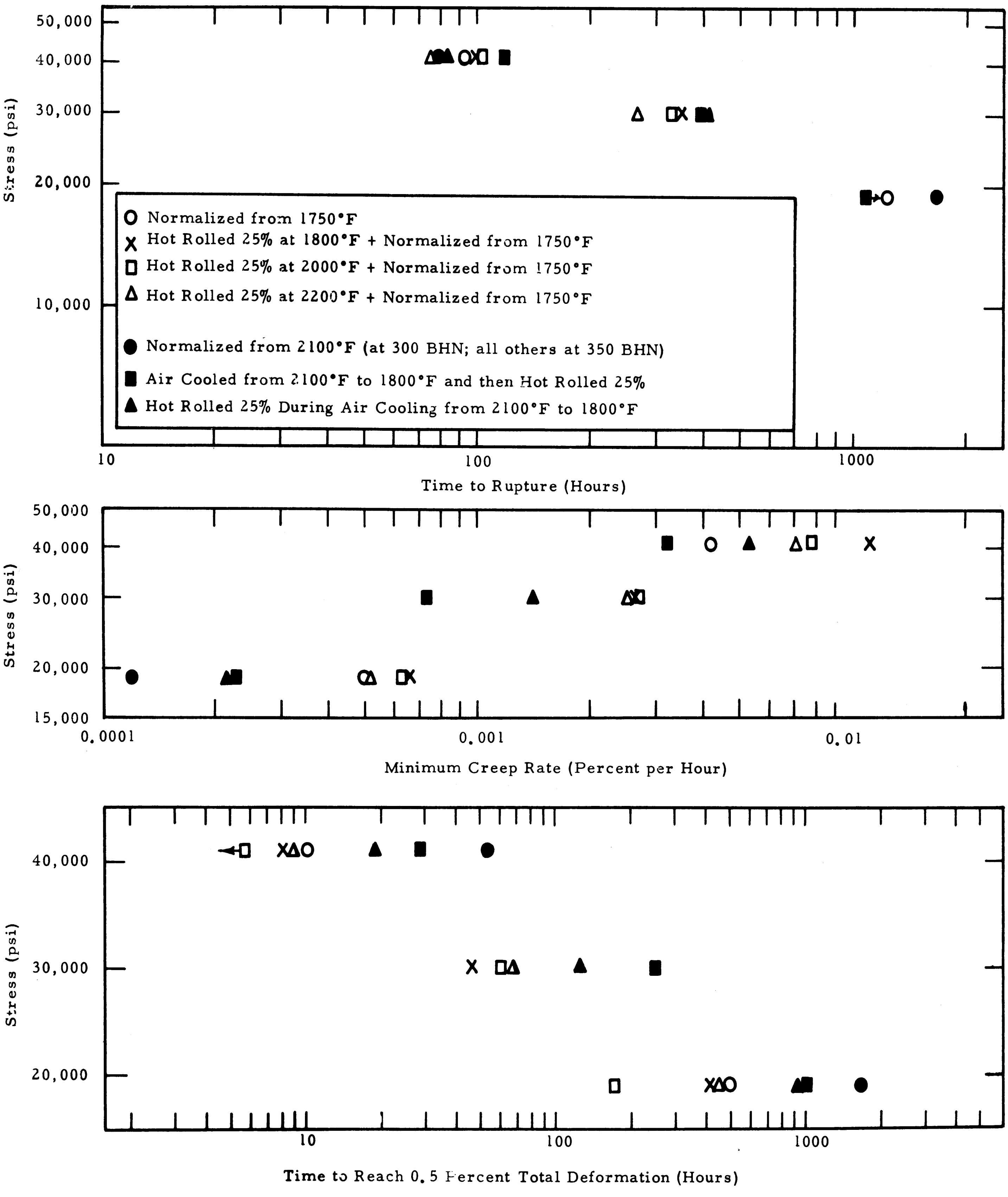


Figure 54. - Influence of Hot-Rolling Conditions on the Stress-Time to Rupture, Stress-Minimum Creep Rate, and Stress-0.5-Percent Total Deformation Time Relationships for "17-22-A"S Steel at 1100°F.

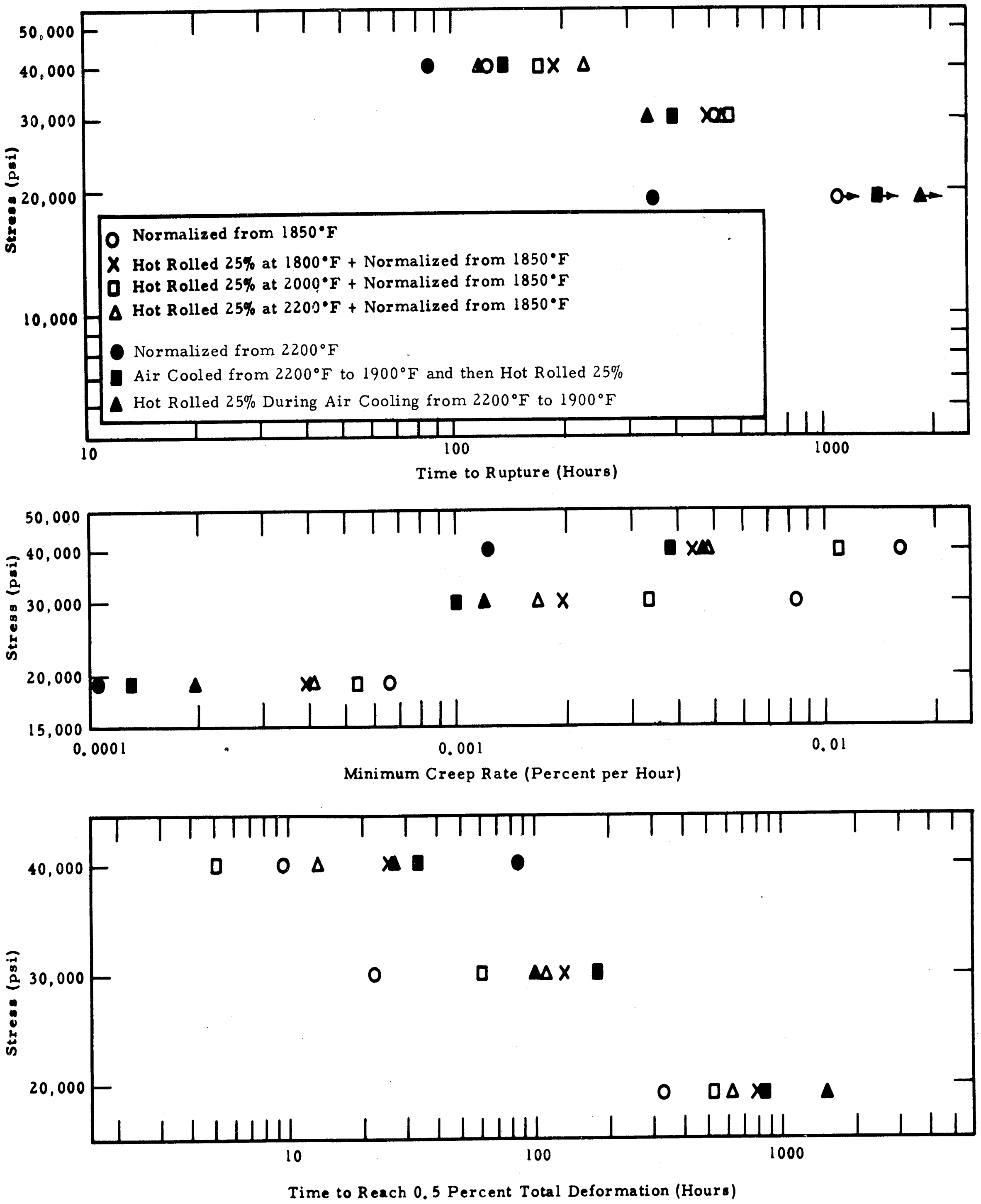


Figure 55. - Influence of Hot-Rolling Conditions on the Stress-Time to Rupture, Stress-Minimum Creep Rate, and Stress-0.5-Percent Total Deformation Time Relationships for "17-22-A"V Steel at 1100°F.