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THIRD PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

AN INVESTIGATION OF THREE FERRITIC STEELS FOR HIGH-TEMPERATURE APPLICATION

by

A. P. Coldren

J. W. Freeman

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SUMMARY

This report describes the progress made in an investigation of the relationship between types of microstructure and the elevated-temperature, creep-rupture properties of low-alloy ferritic steels. The work period covered by the report was from March 15, 1956 to June 15, 1956.

Considerable tangible progress was made in the general survey of the response of "17-22-A"V steel to heat treatment. Complete details are presented of the heat treatments which were experimentally determined to produce a total of 17 different microstructures for creep-rupture testing. The heat treatments used in the study of mixed bainitic structures and the study of the effect of a prior homogenization normalize are also presented for the three subject steels ("17-22-A"V, "17-22-A"S, and SAE 4340).

The program of survey-type creep-rupture testing is well under way, with 65% of the test specimens either completed, in progress, or waiting for the next available testing units. Results have been obtained from a number of short-time rupture tests in each of three different studies. These data are too sparse to permit the drawing of any conclusions, so they are presented in the report without discussion. The observation is made, however, that the rupture times for the "17-22-A"V tests seem unexpectedly short.

Photomicrographs of many of the structures being tested are also presented with some discussion.

INTRODUCTION

This progress report, the second report issued under Air Force Contract No. AF 33(616)-3239, covers work done from March 15, 1956 to June 15, 1956.

The research work being done on this project is a continuation of a previous investigation done at the University of Michigan for the Wright Air Development Center concerning the fundamental relationships of microstructure of steels to properties at elevated temperatures. The three steels being studied currently include (1) a 1.25 Cr - 0.75 Si - 0.5 Mo - 0.8 V ("17-22-A"V) steel, (2) a 1.25 Cr - 0.75 Si - 0.5 Mo - 0.25 V ("17-22-A"S) steel, and (3) a Ni - Cr - Mo (SAE 4340) steel.

The major items presented in this report include:

1. Details of most of the heat treatments used to produce the various microstructures to be creep-rupture tested.

2. Photomicrographs of most of the structures produced to date.

3. Rupture data from the few rupture tests completed thus far in the investigation.

The previous work involved surveys of the high-temperature properties of several low-alloy, ferritic steels in the form of forged rotor wheels and in the form of bar stock given various continuous cooling and isothermal heat treatments to produce specific microstructures. The results of these studies are to be found in WADC Technical Reports 53-277-Part I, 53-277-Part II, and 55-388 (References 1, 2, and 3). The phases of research originally planned under this contract included: (1) completion of work initiated under the previous contract on the effect of hardness level on the high-temperature properties of several typical structures for each of the three steels; (2) a general survey of the relationship between properties and structures of the "17-22-A"V steel;

(3) determination of the influence of transformation over a range of temperature, using stepwise isothermal transformations in the bainitic range for the three subject steels; (4) an evaluation of the effect of an homogenization normalize prior to the final heat treatment of the three steels; and (5) a study of the effect of various double heat treatments to determine possible prior history effects on response to heat treatment as measured by microstructures and by high-temperature properties.

TEST MATERIALS

At the completion of the study of the effect of hardness level on creep and rupture properties the supply of SAE 4340 steel was exhausted. Since additional stock from the same heat was unavailable, material from a different heat (No. D-14064) was supplied gratis by the Universal-Cyclops Steel Corporation. Additional "17-22-A"S and the "17-22-A"V stock for work under the present contract were both supplied gratis by the Timken Roller Bearing Company.

The chemical compositions of the steels were reported by the manufacturers to be as follows:

Steel	Heat No.	C	Mn	Si	Cr	Ni	Mo	V
SAE 4340	19053	0.40	0.70	0.30	0.78	1.75	0.26	----
SAE 4340	D-14064	0.40	0.80	0.27	0.82	1.67	0.32	----
"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

PROCEDURE

The Procedure, Results, and Discussion sections of this report will each be subdivided under the following headings: (1) General Survey of the Response of "17-22-A"V Steel to Heat Treatment, (2) Mixed Bainitic Structures, and (3) the Effect of a Prior Homogenization Normalize. These correspond to items

(2), (3), and (4), respectively, listed in the Introduction. The Study of the Effect of Hardness Level was completed for SAE 4340 and "17-22-A"S and was reported in the Second Progress Report (Reference 4). The hardness level study for "17-22-A"V will be incorporated in the General Survey of the Response of "17-22-A"V Steel to Heat Treatment.

General Survey of the Response of "17-22-A"V Steel to Heat Treatment

Briefly, the original plan for surveying the response of "17-22-A"V to heat treatment was: (1) to determine the approximate isothermal transformation diagram, (2) to produce typical microstructures by the appropriate isothermal and continuous cooling heat treatments, (3) to determine by survey type creep and rupture tests the relative strengths of these structures in the temperature range of 700° to 1100°F, and finally, (4) to correlate the creep and rupture data with the observed microstructures.

The approximate isothermal transformation diagram has been determined and was presented in the Second Progress Report (Reference 4). Based on this diagram, five isothermal heat treatments were selected so that typical "pure" isothermal structures could be studied. The usual treatments of air cooling (normalizing) and oil quenching were also included as basic treatments, giving a total of seven basic microstructures. Modifications of the basic structures were effected by variations in (1) the final tempered hardness, (2) the rate of continuous cooling as controlled by section size, and (3) the austenitizing temperature. The modifications of the seven basic structures brought the total number of structures to seventeen. The specific heat treatments for these seventeen structures are considered in the Results section.

The basis on which the high-temperature properties of the seventeen structures are to be compared is the data obtained from single, survey-type creep-rupture tests run under the following conditions:

Testing Temperature (°F)	Stress (psi)	Type of Test
700	115,000	Creep
900	70,000	Creep
1100	40,000	Short-Time Rupture
1100	19,000	Creep

These conditions were selected partly on the basis of previous work done at 1000° and 1100°F on this heat of "17-22-A"V for a different project, and partly on the assumption that this steel would have strengths at 700° and 900°F comparable to those of the "17-22-A"S steel. The main comparison of data from the creep tests on the various structures is based on the times to reach specified total deformations; whereas, the primary data for comparison from the short-time rupture tests are the rupture times. Minimum creep rates are also reported. Creep tests are the main basis of comparison at the lower temperature because there is little time dependency for rupture and because rupture strengths of interest are above the yield strength.

The correlation of the creep and rupture data with the metallographic observations will necessarily be of a qualitative nature because the data are so limited for survey purposes. In general the purpose will be to classify various structures according to strength as a function of temperature. It is planned that three representative metallographic samples shall be prepared for each structure. The first sample shall be of the initial structure prior to tempering; the second shall be of the tempered structure; and the third sample shall be from a completed creep specimen. A comparison of the second and third samples will show any major changes in the microstructure which might have occurred during creep testing.

Mixed Bainitic Structures

Basically, the interest in the development of microstructures containing a mixture of the upper and lower-temperature forms of bainite resulted from the knowledge that bainitic structures formed during continuous cooling (as in normalizing small sections of alloys of the type being considered) are made up of an intimate mixture of bainites formed over a range of temperature. It was felt that one step toward an understanding of these structures could be achieved through the development and study of mixed bainitic structures.

The suggested type of heat treatment for producing mixed bainitic structures was simply to use two or more transformation temperatures in a stepwise, isothermal treatment. The control of the type and amount of bainites would be achieved through control of the temperatures and times of each isothermal step, respectively. Specifically, the sample would be austenitized in the usual way, held until the desired amount of bainite had formed, transferred directly to a second salt bath at a lower bainitic temperature, held until the desired additional amount of bainite had formed, and so on until the sample contained the desired mixture of bainites.

For the sake of simplicity and to avoid excessive losses in time in securing additional equipment, structures containing only two types of bainite were selected for study under this contract. All three subject steels will be studied in this respect.

Effect of a Prior Homogenization Normalize

It is common practice to use a normalizing treatment prior to the final heat treatment. The purpose of the normalize is to minimize or eliminate (1) differences between heats resulting from differences in prior thermal histories and (2) chemical inhomogeneities. The prior normalize is often from an austenitizing temperature 50° to 100°F above the austenitizing temperature used for the final heat treatment. The purpose of this part of the investigation is to determine for the three subject steels whether the prior normalizing treatment appreciably affects the elevated-temperature properties as measured by creep and rupture test data.

The procedure adopted for this study was simply to repeat the testing of three typical structures for each steel, with everything being held constant except for the insertion of a normalizing treatment prior to the final heat treatment. The three structures selected were the oil-quenched (martensitic), normalized (non-isothermal bainite), and middle bainite (isothermal, medium bainite). The austenitizing temperature for the prior normalize was 100°F above that used for the final heat treatment.

RESULTS

It is to be emphasized that while the rate of progress of this investigation as measured by the amount of creep and rupture data produced has heretofore been rather slow, the current rate of creep-rupture testing is very high. Since May 15, 1956 30 tests have been completed. At the present time 43 tests are in progress, with 27 specimens ready to be started as soon as creep-rupture testing units become available. These 100 tests constitute about 65% of the originally planned program of testing.

General Survey of the Response of "17-22-A"V Steel to Heat Treatment

The specific conditions of heat treatment developed for each of the 17 structures are presented in Table I.

The results to date are primarily from the short-time rupture tests. The data are too sparse to permit any generalizations to be made at this time, so the following results are presented without comment, other than to note that the strength of the "17-22-A"V material seems abnormally low at 1100°F. Checks are in progress to attempt to determine the reason for this.

Structure	Nominal Hardness (BHN)	Temp (°F)	Stress (psi)	Rupture Time (hrs)	Elong. (%)	Red. of Area (%)
Oil Quenched	300	900	70,000	257.9	29.0	71.1
	350	900	70,000	>1200.3	---	---
	350	1100	40,000	43.4	17.0	48.8
	300	1100	30,000	83.7	27.5	64.1
	350	1100	30,000	177.5	23.5	47.8
	350	1100	19,000	1491.6	20.5	24.4
Normalized	350	1100	40,000	123.3	12.0	23.5
	300	1100	30,000	231.0	11.5	31.8
	350	1100	30,000	514.8	19.5	19.9
Middle Pearlite	250	1100	40,000	93.3	34.0	51.3
Lower Pearlite	300	700	115,000	101.7	17.0	59.0
	300	1100	40,000	89.2	35.0	39.6
	350	1100	40,000	138.8	18.0	21.8
Upper Bainite	300	900	70,000	230.3	27.0	69.7
	350	900	70,000	>1138.8	---	---
	300	1100	40,000	29.8	40.0	69.3
	350	1100	40,000	59.6	25.0	39.7
Middle Bainite	300	1100	40,000	75.6	22.0	35.9
	350	1100	40,000	89.0	35.0	42.0
Lower Bainite	300	700	115,000	239.5	16.0	60.5
	350	700	115,000	>979.7	---	---
	300	1100	40,000	102.7	24.0	43.5
	350	1100	40,000	201.8	19.6	23.8

Note: The symbol > means "greater than" and is used to indicate the time at which the test was discontinued.

Photomicrographs of 14 of the structures produced for the "17-22-A"V steel survey are presented in Figures 1 through 7. The following significant facts were revealed by the metallographic examinations:

1. The austenitizing treatment of 1 hour at 1850°F left numerous small carbide particles undissolved. The initial fine grain size (ASTM No. 9 - 10) of the hot-rolled bar stock was preserved because of the effectiveness of the carbide particles as grain growth inhibiters.

2. The section size of a normalized part can have a profound influence on the resulting microstructure--and hence, presumably, on the resulting strength

properties. For example, the microstructures of air-cooled 0.8-inch and simulated 3- and 6-inch rounds were 100% bainite, 90% bainite + 10% ferrite, and 5% bainite + 95% ferrite, respectively. (Figures 2 and 3)

3. The bainite in the normalized 0.8-inch round (Figure 2) appeared to be very similar to the isothermal, middle bainite (Figure 6).

Mixed Bainitic Structures

The specific heat treating conditions which were experimentally determined for each steel to produce approximately 50-50 mixtures of upper and lower bainite are presented in Table II.

There are no test results yet for the "17-22-A"S or "17-22-A"V steels. Only one rupture result can be reported for SAE 4340: At 1000°F and 31,000 psi the rupture time was 374.3 hours. This may be compared to rupture times of 389, 261, and 210 hours for upper, middle, and lower bainite, respectively, for exactly similar tests on Heat No. 19053. (The heat being tested currently is No. D-14064.) The "upper bainite" structure for Heat No. 19053 was actually 70 percent bainite plus 30 percent martensite.

The metallographic work is not quite complete for the mixed bainitic structures, so no photomicrographs are presented.

Effect of a Prior Homogenization Normalize

The conditions of heat treatment which have been determined for the study of the effect of a normalizing treatment prior to the final heat treatment are presented in Table II.

The only available rupture test results for this study are for the "17-22-A"S steel. These results are presented below, along with results from similar tests on material not given a prior normalize:

Structure	Test Temp (°F)	Stress (psi)	Rupture Time (hrs) No Prior Norm.	Prior Norm.
Oil Quenched	1100	41,000	52.7	42.8
Normalized	1100	41,000	92.8	106.2

These results were all from Heat No. 10420, and they are obviously too sparse to permit any drawing of conclusions at this time.

Photomicrographs for the structures being used in the prior normalize study are shown in Figures 8 and 9. The structures are for the "17-22-A"S and SAE 4340 steels only. The metallographic work on the "17-22-A"V steel is not yet finished.

DISCUSSION

General Survey of the Response of "17-22-A"V Steel to Heat Treatment

The only possible comment which could be offered at this time regarding the few rupture data for "17-22-A"V is that lower bainite appears to be the strongest of the structures tested at 1100°F thus far. Previous work of this type on "17-22-A"S and SAE 4340 (Reference 2) also indicated that the highest strengths were associated with the predominantly bainitic structures. The strength values in general, however, appears to be abnormally low for "17-22-A"V steel.

The metallographic studies of the various "17-22-A"V structures have thus far revealed two important facts which may be related to the high-temperature properties of this steel. The first is that for normalizing treatments the section size of the part has a very important bearing on the resultant microstructure--at least for the heat under consideration. Specifically, part sizes up to those corresponding to a 3- inch round will contain at least 90% bainite after air cooling from 1850°F, while part sizes up to those corresponding to a 6-inch round will contain up to 95% pro-eutectoid ferrite after air cooling from 1850°F. The rupture data on these structures are not yet available, but previous work has shown that bainite is superior to free ferrite with respect to high-temperature strength.

The second characteristic of this heat of "17-22-A"V which was shown by the metallographic work was that an austenitizing treatment of 1 hour at 1850°F left numerous, small carbide particles undissolved. Supposedly there are two ways in which the lack of complete carbide solution could affect the high-temperature strength of the steel: (1) the carbides tie up appreciable quantities of vanadium, molybdenum, chromium, and carbon which, if in solution, could strengthen the iron matrix; and (2) the carbide particles act as grain growth inhibiters and thus preserve the initially small grain size of the as-rolled stock. The fine grain structure may or may not have an appreciable effect on the high-temperature properties. Tests are planned for the oil-quenched and the normalized structures produced with an austenitizing treatment of 1 hour at 2000°F, and it is believed that the results of these tests will help to show the effect that undissolved carbides have on the strength of this particular steel.

The status of the work on the study of Mixed Bainitic Structures and the study of the Effect of a Prior Homogenization Normalize does not warrant any discussion of these studies at this time.

FUTURE WORK

Future work will consist largely of an analysis of the creep and rupture data which will soon be available. Metallographic work on the mixed bainitic structures remains to be finished, as well as the examination of representative, completed creep specimens.

The work on the double heat treatments will be considerably simplified with respect to heat treating because of the experience gained in the investigation up to now.

REFERENCES

(1) A. Zonder, A. I. Rush, and J. W. Freeman, "High Temperature Properties of Four Low-Alloy Steels for Jet-Engine Turbine Wheels", Wright Air Development Center Technical Report 53-277, Part I (November, 1953).

(2) A. I. Rush and J. W. Freeman, "High-Temperature Properties of Four Low-Alloy Steels for Jet-Engine Turbine Wheels", Wright Air Development Center Technical Report 53-277, Part II (February, 1955).

(3) K. P. MacKay, A. P. Coldren, A. I. Rush, and J. W. Freeman, "A Survey of the Effect of Austenitizing Temperature and Rate of Continuous Cooling on the Structure and 700° to 1200°F Properties of Three Low-Alloyed Steels", Wright Air Development Center Technical Report 55-388 (September, 1955).

(4) A. P. Coldren and J. W. Freeman, "An Investigation of Three Ferritic Steels for High-Temperature Application," Second Progress Report to Wright Air Development Center, Contract No. AF 33(616)-3239 (March 15, 1956).

TABLE I

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

Structure	Initial Heat Treatment	Average Hardness Before Tempering (BHN)	Tempering Treatment 300 BHN	Tempering Treatment 350 BHN	Average Final Hardness (BHN) 300 BHN	Average Final Hardness (BHN) 350 BHN
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	
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 (100% Bainite)	1 Hour at 2000°F, Air Cooled (0.8-in. Round)	384	4 hrs at 1250°F		349	
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	
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

* Timken Heat No. 11833

TABLE II

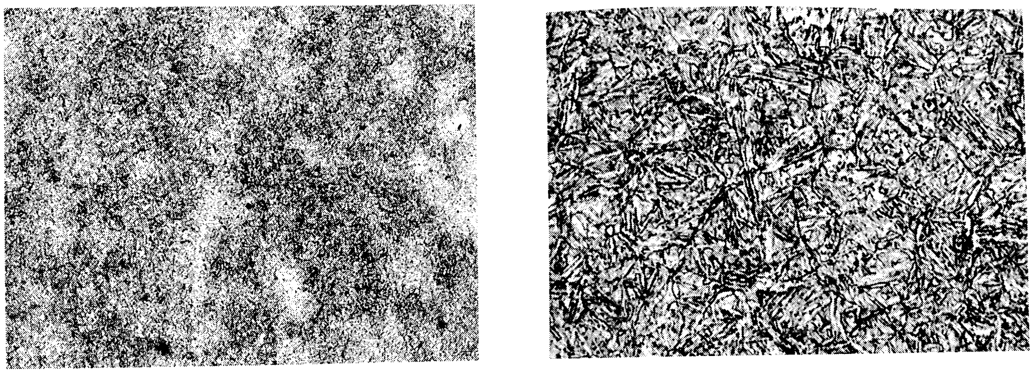
Structures and Heat Treatments Used in the Study of Mixed Bainites and the Study of the Effect of a Prior Homogenization Normalize for the "17-22-A"V, "17-22-A"S, and SAE 4340 Steels

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	a	a	a
	"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

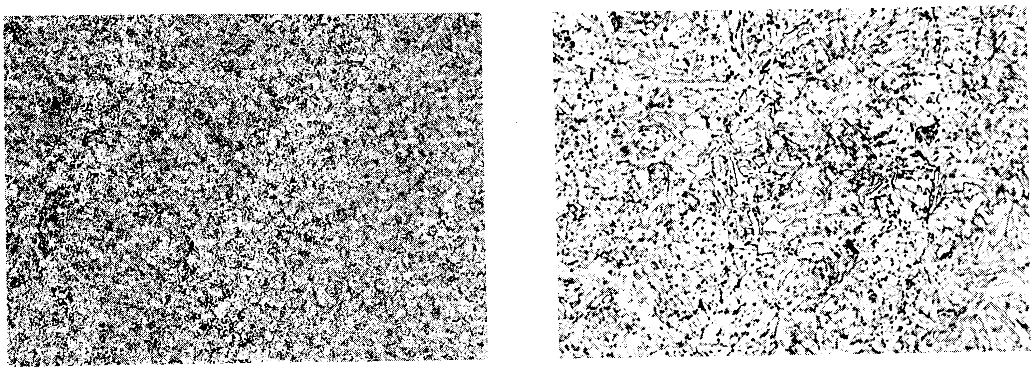
a - Not yet determined

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.

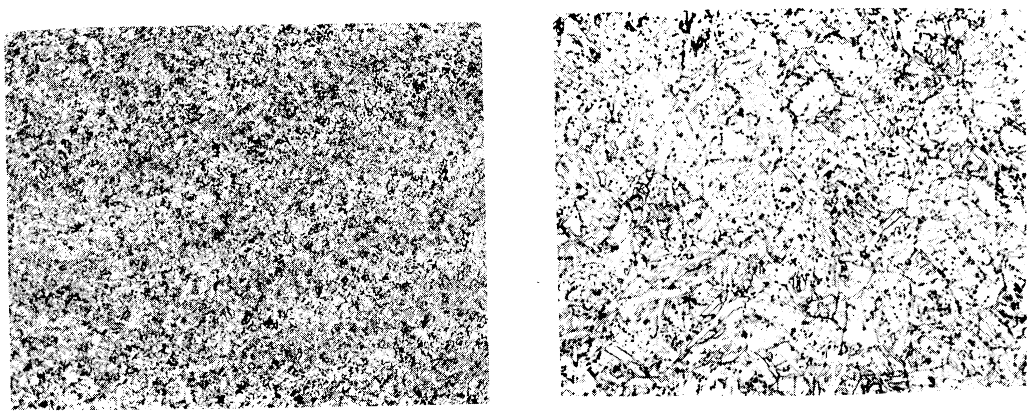
X100 X1000



(a) Oil Quenched from 1850°F (0.8-inch round). Average BHN - 476



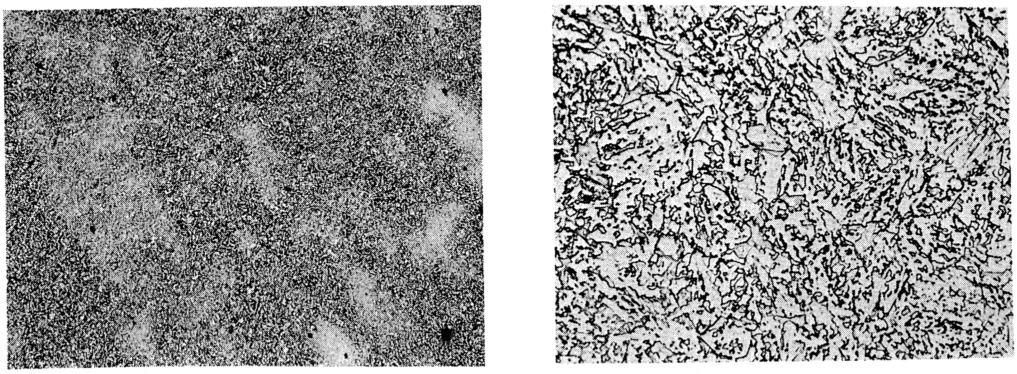
(b) Oil Quenched from 1850°F + Tempered 2 Hours at 1250°F. Average BHN-345



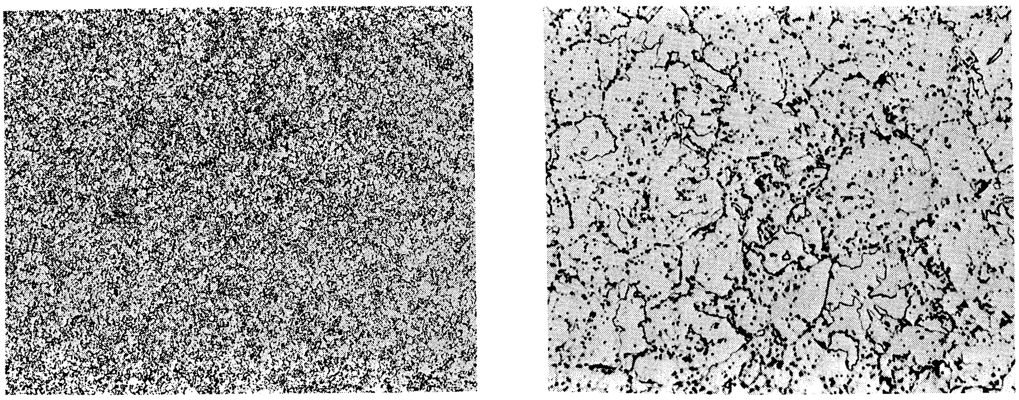
(c) Oil Quenched from 1850°F + Tempered 1 Hour at 1300°F. Average BHN-304

Figure 1 - "17-22-A" V Bar Stock (0.8-inch Round) (a) As Oil Quenched from 1850°F, (b) Tempered to 350 BHN, and (c) Tempered to 300 BHN.

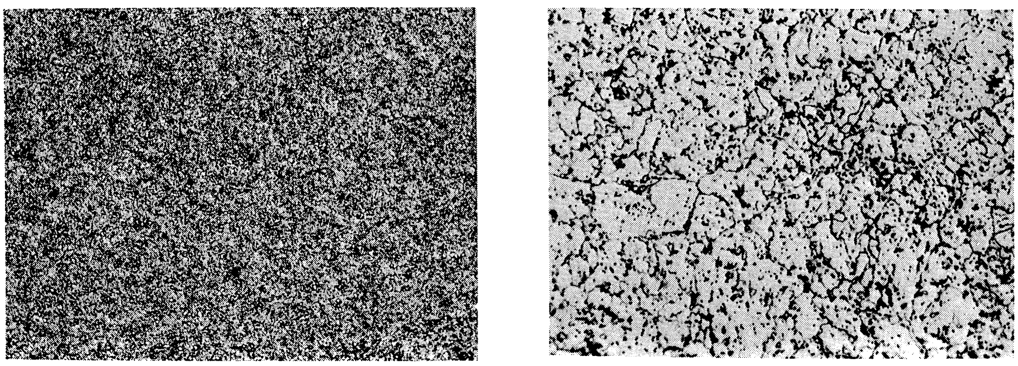
X100 X1000



(a) Air Cooled from 1850°F (0.8-inch round). Average BHN - 374



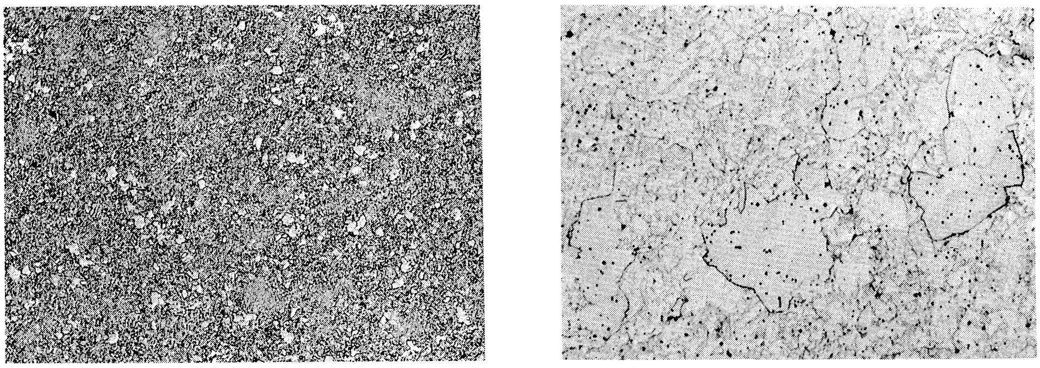
(b) Air Cooled from 1850°F + Tempered 2 Hours at 1250°F. Average BHN - 359



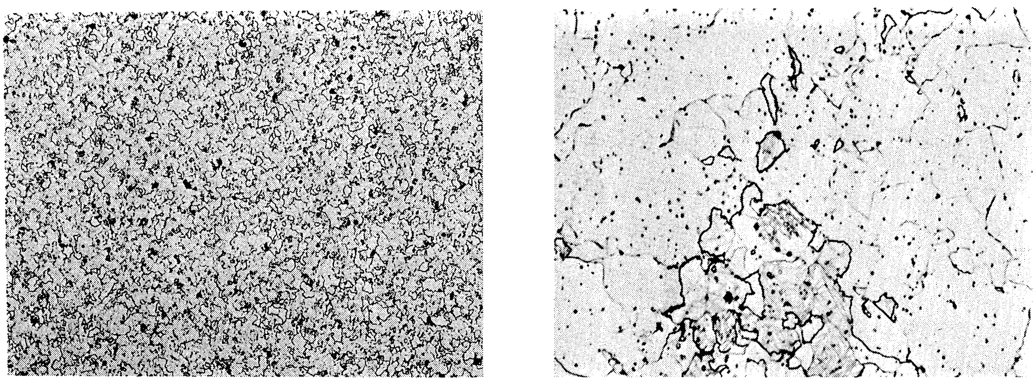
(c) Air Cooled from 1850°F + Tempered 1-1/3 Hours at 1300°F. Average BHN - 308

Figure 2 -"17-22-A" V Bar Stock (0.8-inch Round) (a) As Normalized from 1850°F, (b) Tempered to 350 BHN, and (c) Tempered to 300 BHN.

X100 X1000



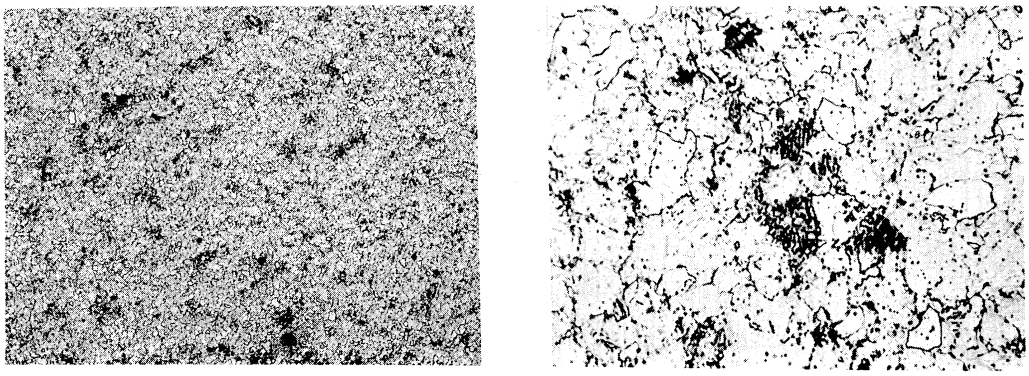
(a) Air Cooled from 1850°F in Firebrick Jacket to Simulate Cooling Cycle at Center of a 3-inch Round. Average BHN - 365



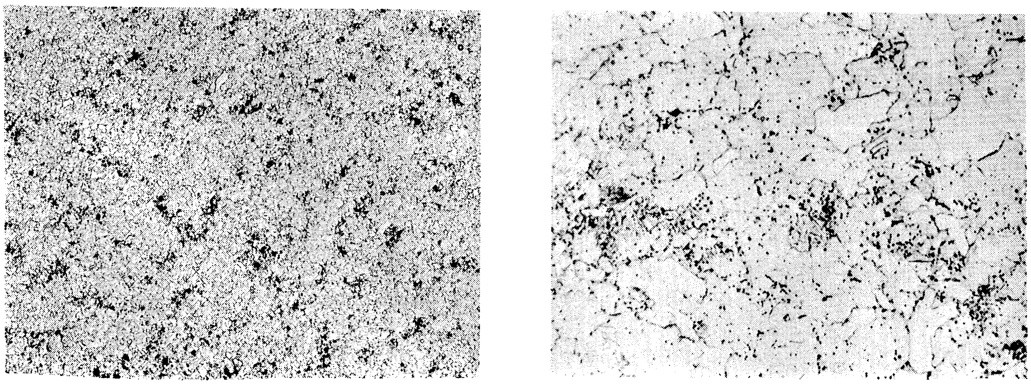
(b) Air Cooled from 1850°F in Firebrick Jacket to Simulate Cooling Cycle at Center of a 6-inch Round. Average BHN - 303

Figure 3 -"17-22-A" V Bar Stock As Normalized in (a) Simulated 3-inch Round, and (b) Simulated 6-inch Round.

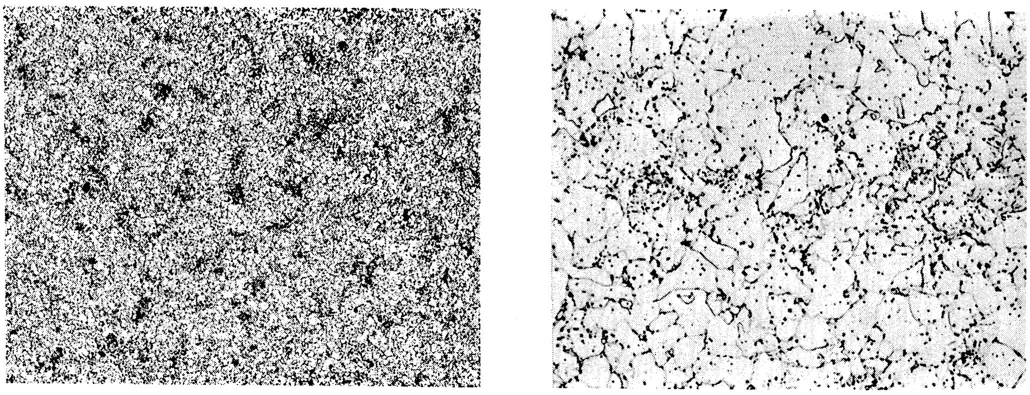
X100 X1000



(a) Isothermally Transformed to Lower Pearlite (0.4-inch Round).
Average BHN - 360



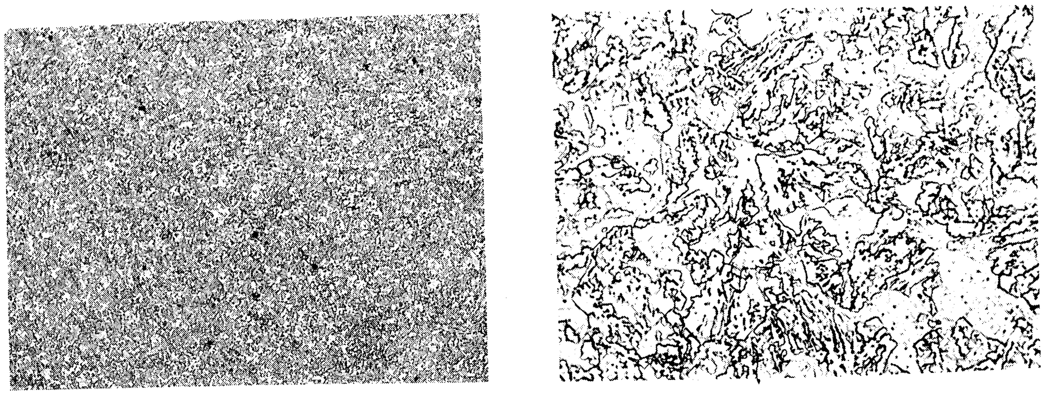
(b) Isothermally Transformed to Lower Pearlite + Tempered 1 Hour at
1200°F. Average BHN - 347



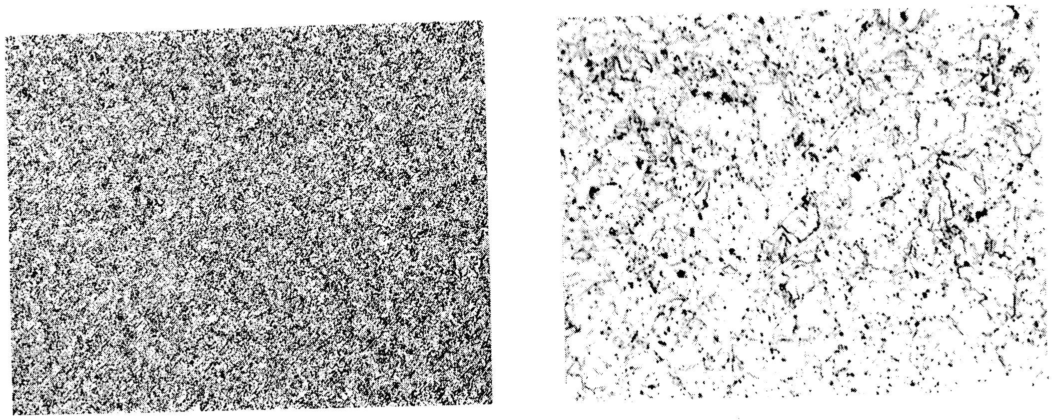
(c) Isothermally Transformed to Lower Pearlite + Tempered 1 Hour at
1300°F. Average BHN - 289

Figure 4 -"17-22-A" V Bar Stock (a) As Transformed to Lower Pearlite,
(b) Tempered to 350 BHN, and (c) Tempered to 300 BHN.

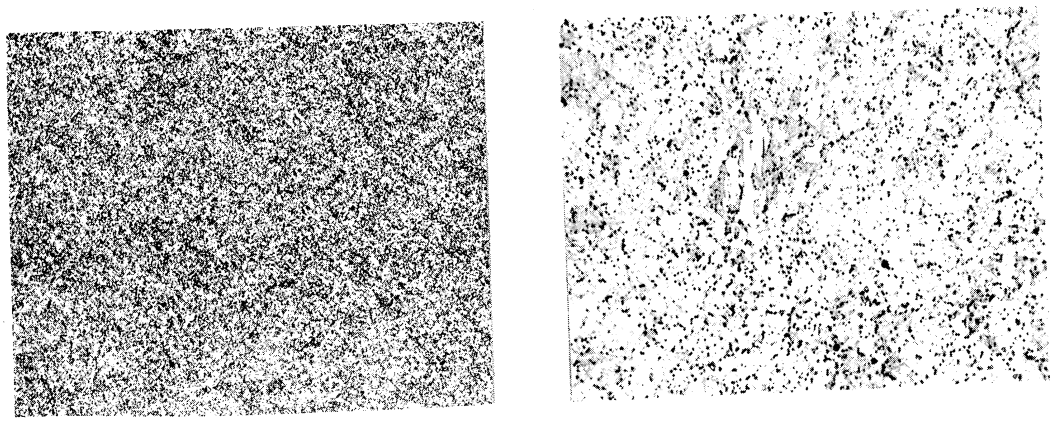
X100 X1000



(a) Isothermally Transformed to Upper Bainite (0.4-inch Round). Average BHN - 447



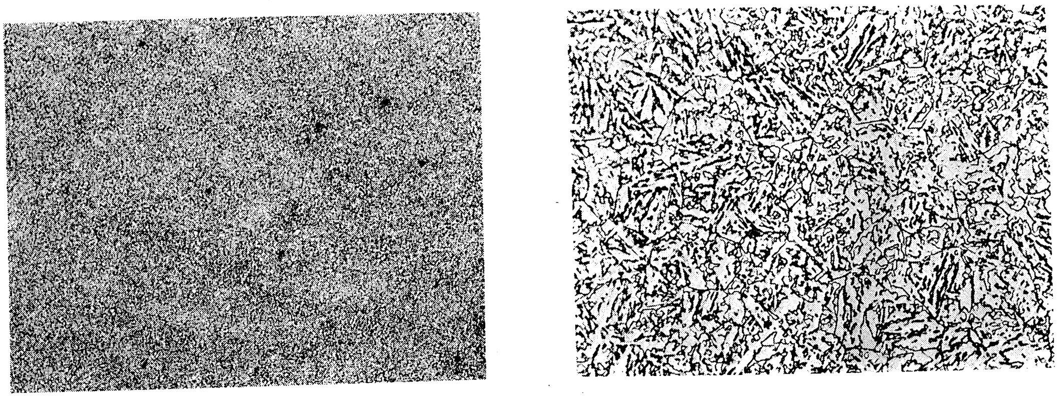
(b) Isothermally Transformed to Upper Bainite + Tempered 4-1/2 Hours at 1200°F. Average BHN - 348



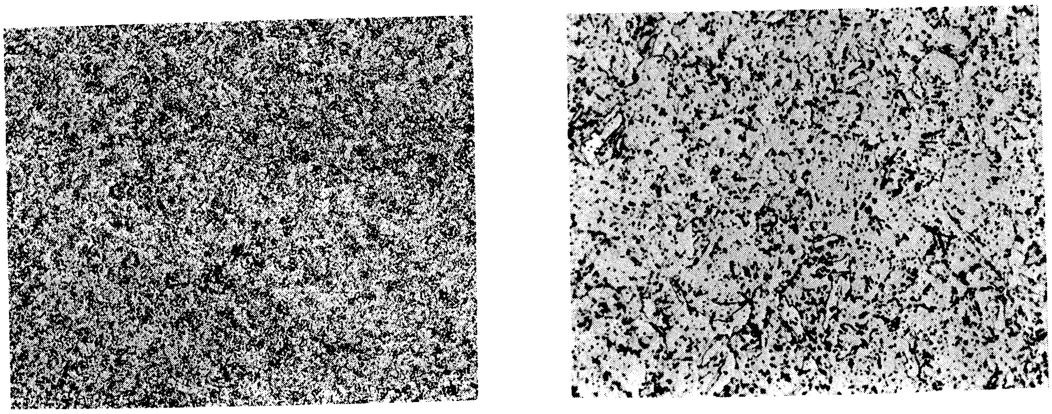
(c) Isothermally Transformed to Upper Bainite + Tempered 1-1/3 Hours at 1300°F. Average BHN - 290

Figure 5 - "17-22-A"V Bar Stock (a) As Transformed to Upper Bainite, (b) Tempered to 350 BHN, and (c) Tempered to 300 BHN.

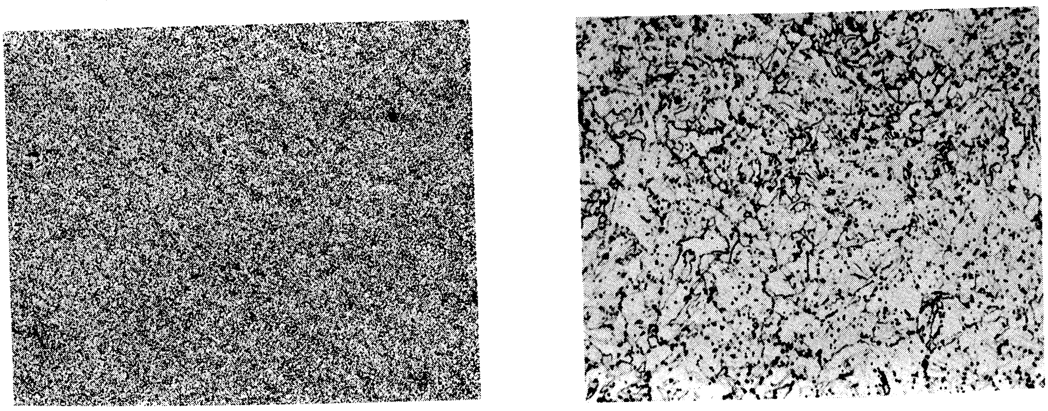
X100 X1000



(a) Isothermally Transformed to Middle Bainite (0.4-inch Round). Average BHN - 364



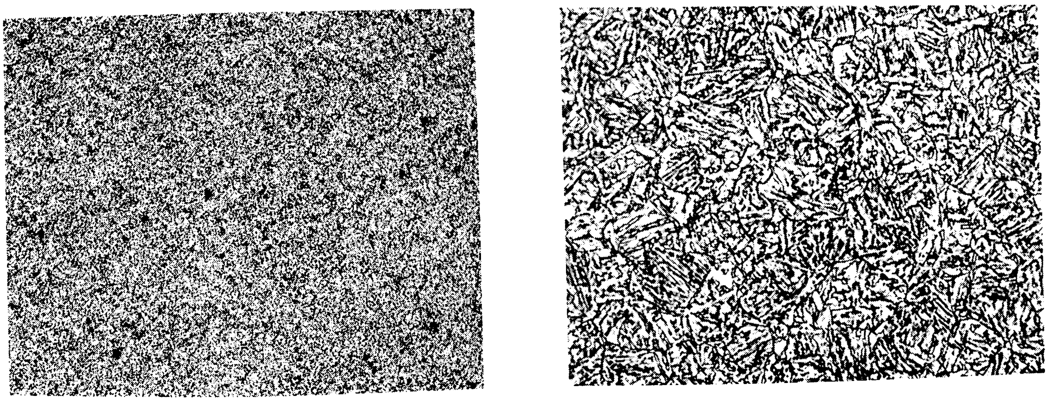
(b) Isothermally Transformed to Middle Bainite + Tempered 5 Hours at 1200°F. Average BHN - 338



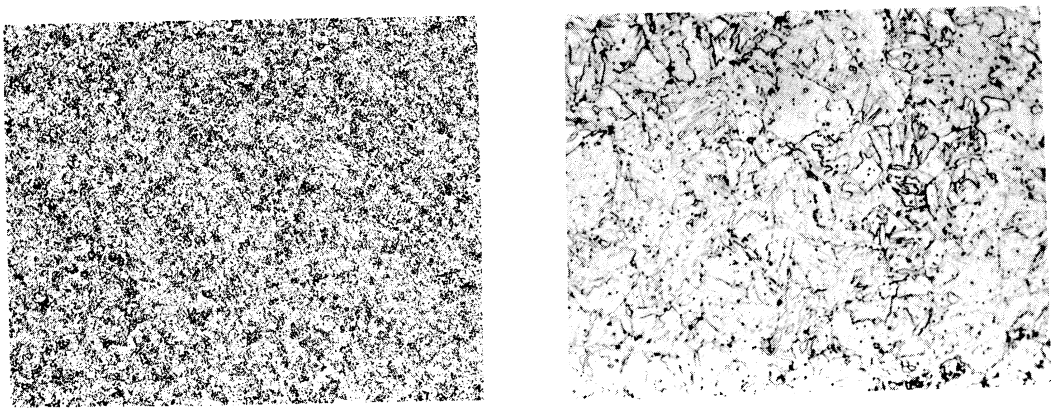
(c) Isothermally Transformed to Middle Bainite + Tempered 1 Hour at 1300°F. Average BHN - 298

Figure 6 -"17-22-A" V Bar Stock (a) As Transformed to Middle Bainite, (b) Tempered to 350 BHN, and (c) Tempered to 300 BHN.

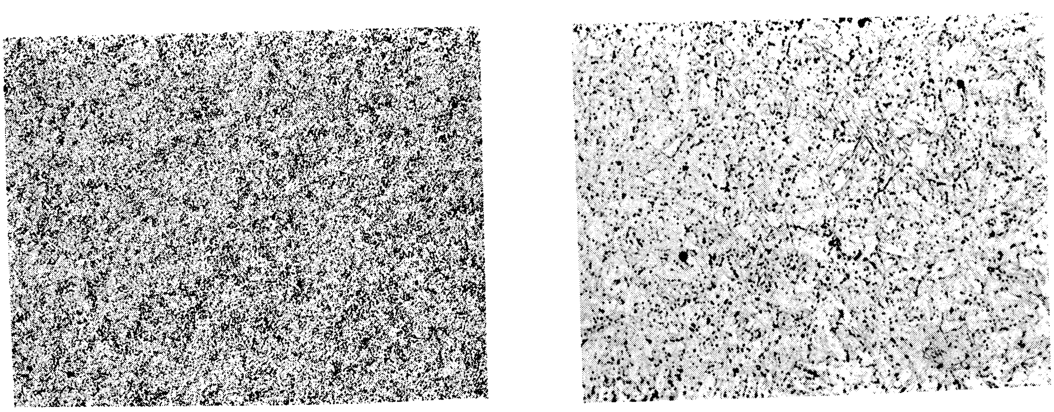
X100 X1000



(a) Isothermally Transformed to Lower Bainite (0.4-inch Round). Average BHN - 405



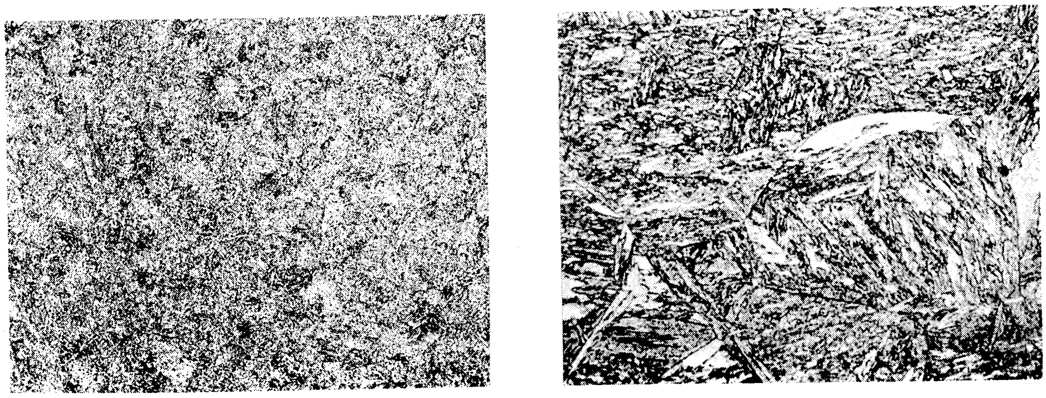
(b) Isothermally Transformed to Lower Bainite + Tempered 6 Hours at 1200°F. Average BHN - 348



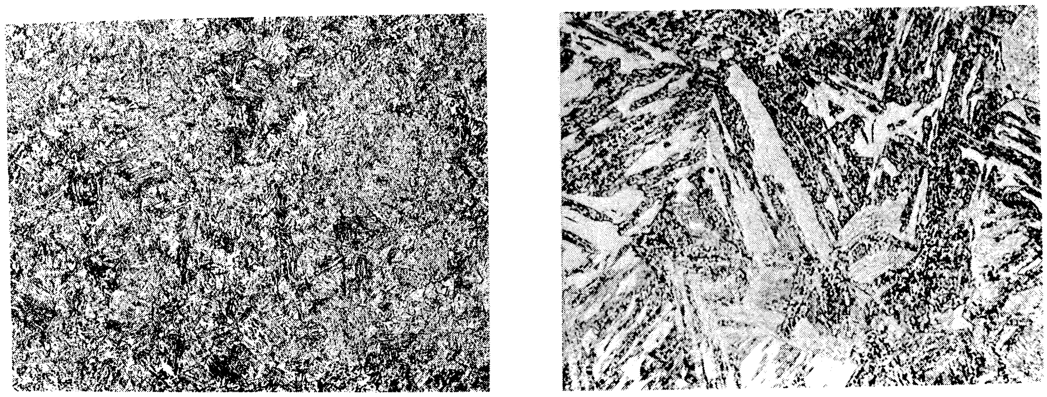
(c) Isothermally Transformed to Lower Bainite + Tempered 1-1/2 Hours at 1300°F. Average BHN - 294

Figure 7. - "17-22-A"V Bar Stock (a) As Transformed to Lower Bainite (b) Tempered to 350 BHN, and (c) Tempered to 300 BHN.

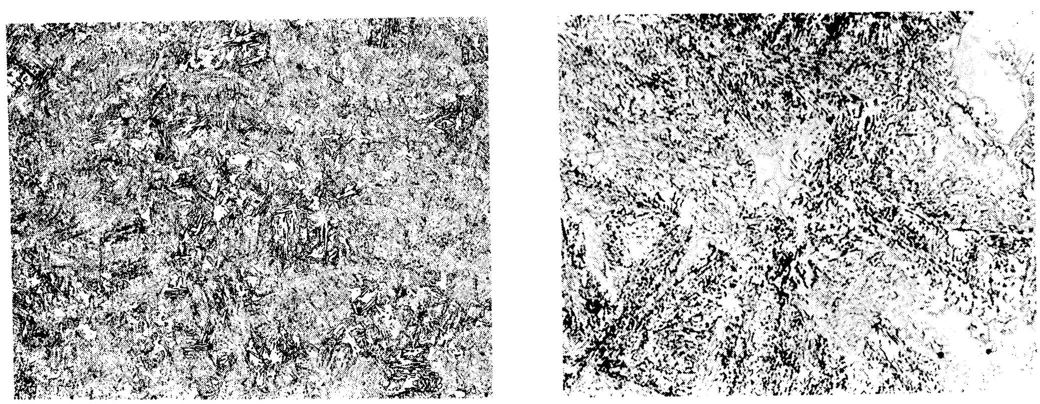
X100 X1000



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



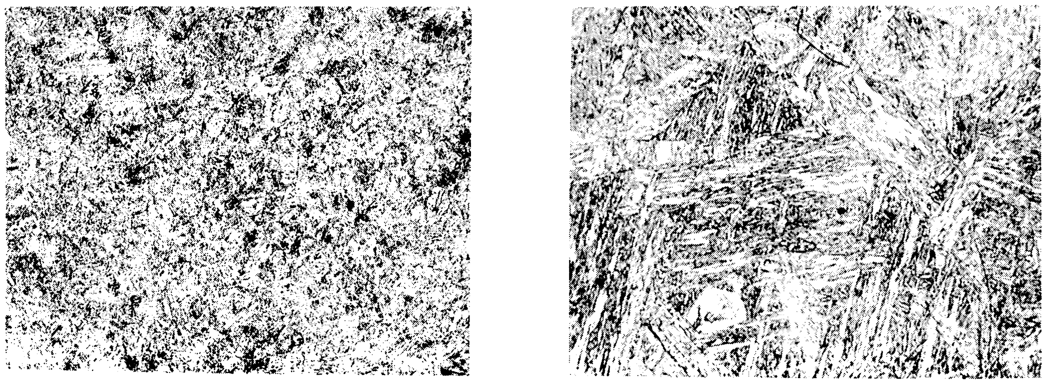
(b) Air Cooled from 1850°F + Air Cooled from 1750°F (0.8-inch Round).
Average BHN - 408



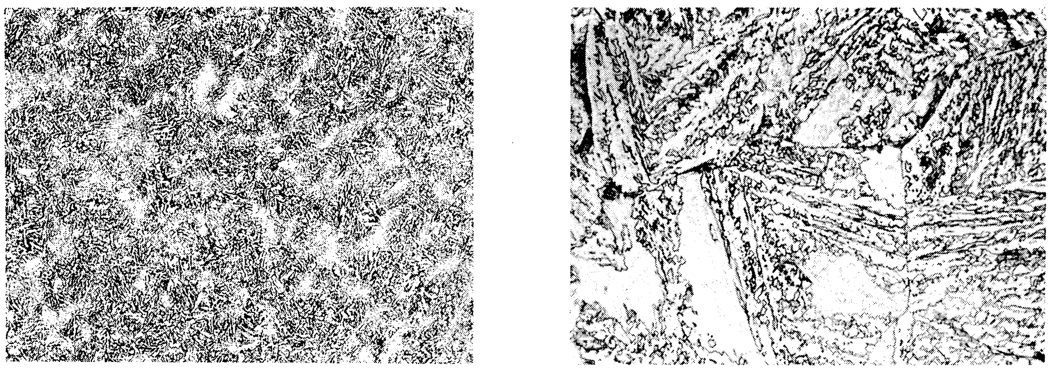
(c) Air Cooled from 1850°F (0.8-inch Round). + Isothermally Transformed to Middle Bainite from 1750°F (0.4-inch Round). Average BHN - 321

Figure 8. - SAE 4340 Bar Stock Normalized from 1850°F, Followed by (a) an Oil Quench from 1750°F, (b) a Normalize from 1750°F, and (c) an Isothermal Transformation to Middle Bainite (from 1750°F).

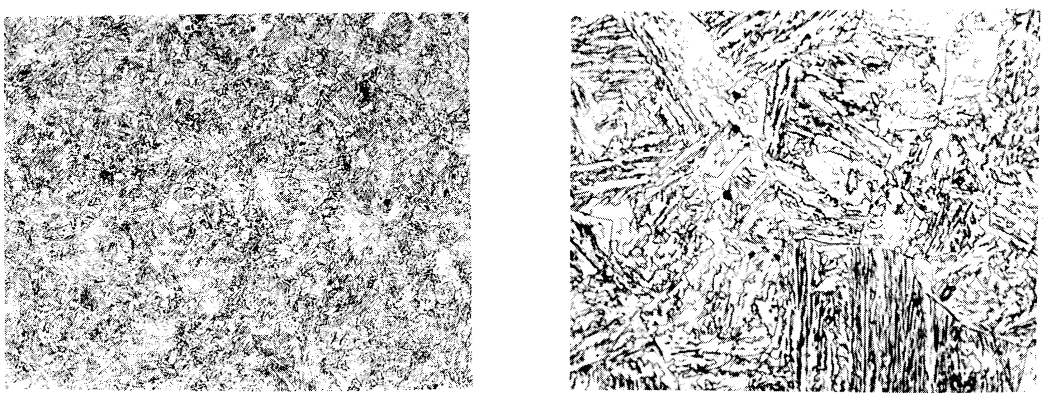
X100 X1000



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



(b) Air Cooled from 1850°F + Air Cooled from 1750°F (0.8-inch Round). Average BHN - 335



(c) Air Cooled from 1850°F (0.8-inch Round) + Isothermally Transformed to Middle Bainite from 1750°F (0.4-inch Round). Average BHN - 382.

Figure 9. - "17-22-A"S Bar Stock Normalized from 1850°F, Followed by (a) an Oil Quench from 1750°F, (b) a Normalize from 1750°F, and (c) an Isothermal Transformation to Middle Bainite (from 1750°F).