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TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

AN INVESTIGATION OF THREE FERRITIC STEELS FOR HIGH-TEMPERATURE APPLICATION

by

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SUMMARY

This report presents the progress made in an investigation of the relationship between types of heat treatment and the elevated-temperature properties of low-alloy ferritic steels for high-temperature applications. The work period covered by the report was from December 15, 1955 to March 15, 1956.

Complete data from a survey of the effect of hardness level on the high-temperature properties of several typical microstructures of a Cr-Ni-Mo (SAE 4340) steel and a 1.25Cr-0.75Si-0.5Mo-0.25V ("17-22-A"S) steel are presented.

Survey creep and rupture tests were run on several structures which were tempered to a hardness of 350 BHN (± 20 BHN) so that comparisons could be made with the results of previous identical tests performed on the same structures tempered to a hardness of 300 BHN (± 20 BHN). The results indicated that all structures of the "17-22-A"S steel increased in strength properties at the higher hardness level. The increase was substantial at 700° and 900°F, but only slight at 1100°F. The ductility was invariably lower at the higher hardness level. The results of the tests on the SAE 4340 steel indicated that the only significant changes in strength properties occurred in the oil-quenched, martensitic structure. In this structure, the increase in hardness produced moderate increases in strength at 700° and 900°F and slight decreases in strength at 1000°F. The other 4340 structures experienced no significant increases or decreases in strength.

The general heat-treating characteristics of the new "17-22-A"V (1.25Cr-0.75Si-0.5Mo-0.8V) steel were established in the form of an approximate isothermal transformation diagram. The diagram and photomicrographs of four isothermal structures -- as well as the oil-quenched and the normalized structures -- are are presented.

Preliminary experiments designed to produce structures of mixed bainites in all three subject steels are described. The specific heat-treating conditions selected for 4340 and "17-22-A"V are presented, as well as photomicrographs of the resulting mixed bainitic structures.

INTRODUCTION

This progress report, the second report issued under Air Force Contract No. AF 33(616)-3239, covers work done from December 15, 1955 to March 15, 1956.

The present investigation is a continuation of previous work done at the University of Michigan for the Wright Air Development Center concerning the fundamentals of heat treatment of ferritic steels for service at elevated temperatures in such spplications as jet engines and airframes. The major items presented in the report include:

1. Complete data from the survey of the comparative high-temperature properties of 4340 and "17-22-A"S steels at 300 and 350 Brinell hardness levels.

2. The general relationships between heat treatment and structure have been established for the new steel added for the present contract, "17-22-A"V steel, in the form of an approximate isothermal transformation diagram.

3. Based on this diagram, a number of the treatments have been carried out to prepare specimens for creep and rupture tests.

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. 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 steels being studied in the current phase of the investigation include a Ni-Cr-Mo (SAE 4340) steel, a 1.25Cr-0.75Si-0.5Mo-0.25V ("17-22-A"S) steel, and a 1.25Cr-0.75Si-0.5Mo-0.8V ("17-22-A"V) steel. The phases of research to be included in the investigation include: (1) completion of work initiated under the previous contract on the effect of higher hardness level on the high tempera-

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* References are given at the end of the report

ture properties of several typical structures for the three steels; (2) a general survey of the relationship between properties and structures of the new, higher stre "17-22-A"V steel; (3) determination of the influence of transformation over a range of temperatures, using stepwise isothermal transformations in the bainitic range for all three steels; (4) an evaluation of the effect of an homogenization normaliz prior to final heat treatment; 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 high temperature properties and microstructures.

TEST MATERIALS

The SAE 4340 steel being used is the same heat that was used in the previous work. Additional "17-22-A"S and "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 subject steels were reported by the manufacturers to be as follows:

Steel	Heat	C	Mn	Si	Cr	Ni	Mo	V
SAE 4340	19053	0.40	0.70	0.30	0.78	1.75	0.26	-
"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

PROCEDURES

The procedures employed during the period covered by this report may be described under three topics: Effect of Hardness Level, General Survey of the Response of "17-22-A"V Steel to Heat Treatment, and Development of Mixed Bainitic Structures. These correspond to items (1), (2), and (3), respectively, listed in the Introduction.

Effect of Hardness Level

The procedure followed in studying the effect of hardness level on the elevated-temperature properties was described in detail in the First Progress Report, dated December 15, 1955. Briefly, several typical microstructures for each steel were selected for creep-rupture testing at the 350 BHN hardness level so that comparisons could be made with exactly similar tests which had been conducted at the 300 BHN hardness level under the previous contracts.

The microstructures selected for testing at the 350 BHN level were necessarily limited to those having an "untempered" hardness considerably above the 350 BHN level. For the SAE 4340 and "17-22-A"S steels the structures selected were:

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

These were suitably tempered to produce a hardness of 350 BHN. Survey type creep and rupture tests were then conducted in the temperature range of 700° to 1100°F.

The details of the heat treatments used to produce these structures at the 350 BHN (± 20 BHN) hardness level are given in Table I.

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

Isothermal Transformation Diagram:

As the initial step toward an understanding of the heat-treating characteristics of the new 1.25Cr-0.75Si-0.5Mo-0.8V ("17-22-A"V) steel, the (approximate) isothermal transformation diagram was determined. The work involved in the "S" curve determination constituted a major part of the experimental work accomplished during the period covered by this report. The details of the procedure followed are given on the next page.

Approximately 100 samples were prepared by cutting 50 - 3/16-inch thick wafers from a 1-foot length of 1-inch round bar stock and then cutting each wafer in half. A small hole was drilled near the periphery of each sample so that it could be attached securely to the end of a 2-foot length of 14 gage chromel wire. The samples were divided into groups of 10, each group being used to follow the transformation of austenite at one given temperature.

The course of the decomposition or transformation of austenite at any given temperature was determined as follows: A group of ten samples was put into an electrically heated furnace (air atmosphere) at 1850°F. After 30 minutes the samples were withdrawn from the austenitizing furnace and quenched into an agitated molten salt bath maintained at the given transformation temperature by external electric resistance coils. At various, predetermined times throughout the course of the transformation a sample was withdrawn from the salt bath and quenched in water. The transformation times were selected with the aid of the "S" curve for "17-22-A"S steel which is somewhat similar in composition to "17-22-A"V. Each sample was numbered after it was quenched from the salt bath. The semi-circular wafers were again cut in half so that the freshly cut surface could be polished for metallographic examination. All ten samples were mounted in a single bakelite mount, hand polished, etched with 2% nital, and examined under the microscope with magnifications up to X1000 diameters. It was assumed that the sample in which the first trace of transformation product was visible at X1000D and the sample in which the last trace of martensite* was visible at X1000D corresponded to the initiation and completion of the transformation. The transformation times of these two samples were plotted on a temperature vs. log transformation time diagram.

This procedure was repeated for each group of 10 specimens, covering transformation temperatures from 600° to 1320°F in 100°F or less intervals.

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* Representing the last trace of untransformed austenite.

The curves drawn through all points representing the start and the finish of the transformation at each temperature constitute the isothermal transformation diagram.

Design of Heat Treatments:

The types of heat treatments used to produce the various microstructures of the low-alloy, ferritic steels previously studied for this investigation have included:

1. Oil Quenching and Tempering
2. Normalizing and Tempering
3. Isothermal Transformations to
    a. Upper Pearlite
    b. Middle Pearlite
    c. Lower Pearlite
    d. Upper Bainite
    e. Middle Bainite
    f. Lower Bainite

Structural differences within these basic treatments which have been studied include variations in:(1) final tempered hardness for all structures; (2) austenitizing temperature for the oil-quenched and the normalized (0.8-inch rounds) structures; and (3) effective section size (0.8-inch and simulated 3- and 6-inch diameter rounds) for the normalizing or air-cooling treatment. It is planned to include all of these in the "17-22-A"V survey.

The procedures followed in selecting the specific conditions for the heat treatments were as follows:

1. The same section sizes as were used in the previous studies were selected, i.e., 0.8-inch rounds for oil quenching and normalizing, and 0.4-inch rounds for the isothermal transformations. Insulating firebrick cylinders will be used around 0.8-inch rounds to simulate the air cooling of 3- and 6-inch dia-

meter rounds.

2. Previous work on "17-22-A"V on a different project indicated that for normalizing, an austenitizing temperature of 1850°F gave better properties than 1750° or 1800°F. On this basis, 1 hour at 1850°F was selected as the standard austenitizing treatment for normalizing. To eliminate austenite composition, homogeneity, and grain size as a variable in the basic microstructures, the same austenitizing conditions were selected for the oil-quenched and the isothermally transformed structures.

3. The transformation temperatures and times for the isothermal heat treatments were selected by means of the isothermal transformation diagram determined for this heat of "17-22-A"V.

4. The tempering conditions used to bring each structure to the final desired hardness level were selected with the aid of tempering curves (hardness vs. time at constant temperature). Each tempering curve was determined by cutting a representative, heat-treated bar into a number of slugs suitable for hardness testing and tempering the slugs for various times at a constant tempering temperature. The tempering temperatures were selected on the basis of past experience with a similar steel but containing less vanadium.

Development of 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) 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 gained through a study of mixed bainitic structures of known composition -- that is -- composition with respect to kind (as determined by the temperature at which they were formed) and amount (volume percent) of the bainites present. It was also thought that certain controlled mixtures of bainite might be found to possess high-temperature properties which are superior to those of any of the bainitic structures tested thus far.

The suggested heat treatment for producing mixed bainitic structures was simply to use two or more transformation temperatures in a stepwise, isothermal treatment. Specifically, the sample would be austenitized in the usual way, quenched into a salt bath at a relatively high bainitic temperature, held until the transformation has progressed the desired amount, quenched into a second salt bath at a lower bainitic temperature, held until the transformation has progressed the desired additional amount, and so on until the sample contained the desired mixture of bainites.

The isothermal transformation diagrams may be used in selecting the transformation temperatures (which determine the types of bainite in the structure, but the transformation times which will produce the desired amounts of the various bainites must be determined by quenching out a series of samples at each of the lower, subsequent transformation temperatures and examining them metallographically.

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

on which deformation the strength was based on.

Lower Pearlite (Tempered):

1. At 700° and 900°F, the creep and total deformation properties were both superior for the harder condition.

2. At 1100°F the 350 BHN structure was stronger than the 300 BHN structure with respect to rupture, creep, and total deformation; but it was inferior with respect to ductility. The difference was much greater at the lower stresses suggesting the possibility that the low stress data for 300 BHN material is abnormally low and should be checked.

Upper Bainite (Tempered):

1. The harder structure had substantially higher strength at 700° and 900°F. At 1100°F there was little difference between the two hardness levels.

Middle Bainite (Tempered):

1. At 700° and 900°F the material at the higher hardness level showed marked superiority with respect to creep and total deformation strengths.

2. The rupture data at 1100°F showed little or no difference in strengths at 41,000 psi, but at 19,000 psi the 350 BHN structure was somewhat superior. The 350 BHN material exhibited inferior ductility as usual.

3. The creep and total deformation at 1100°F pointed in every instance toward the harder structure as being slightly superior.

Lower Bainite (Tempered):

1. The 350 BHN structure tested at 700° and 900°F was greatly superior to the 300 BHN structure with respect to creep and total deformation strengths.

2. At 1100°F the 350 BHN structure had only slightly higher rupture, creep and total deformation strengths. The ductility of the harder material was inferior as usual.

SAE 4340 Steel

Oil Quenched and Tempered:

1. At 700° and 900°F the 350 BHN structure had the better creep and total deformation strengths.

2. At 1000°F the softer structure proved to be somewhat superior with respect to rupture, creep, and total deformation strengths.

3. The ductility at 1000°F was unexpectedly high for the 350 BHN material - running from 10 to 80 percent higher than that for the 300 BHN material.

Normalized and Tempered:

1. At 700°F the 350 BHN material had inferior creep strength and superior total deformation strengths.

2. At 900°F the 350 BHN structure had superior creep strength and inferior total deformation strengths.

3. In all cases at 1000°F the material at the higher hardness level exhibited inferior rupture, creep, and total deformation properties and superior ductility.

Lower Bainite (Tempered):

1. The structure at the higher hardness level showed lower creep and total deformation strengths at 700°F.

2. At 900°F the 350 BHN material exhibited superior rupture and creep strengths but somewhat inferior total deformation strengths.

3. The data at 1000°F indicated that the harder structure had somewhat superior short-time rupture and creep strengths, but slightly inferior total deformation strengths.

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

Isothermal Transformation Diagram:

The approximate isothermal transformation diagram is presented in Figure 1. The general shape of the diagram is characteristic for this type of steel. That is, it shows the ferrite and pearlite region (upper curves) separated from the bainite region (lower curves) by a considerable range of temperature in which the austenite will not begin to decompose even after relatively long time periods.

It is of interest to note that the very short times to the start of the bainite reaction below 900°F would limit the depth to which this steel can be fully transformed to martensite.

Another interesting result of the isothermal study was the fact that the isothermal pearlite observed in this heat of "17-22-A"V did not have a well-defined lamellar structure. While a few instances were found in which the eutectoid mixture was somewhat lamellar, most of the time the eutectoid was simply a local area darkened by a concentration of minute spheroids of carbides.

Microstructural studies revealed that austenitizing treatments of 30 to 60 minutes at 1850°F left a trace of the original carbides undissolved. The diagram of Figure 1 therefore is based on material austenitized at a temperature slightly below that required for complete solution of carbide.

Design of Heat Treatments:

The specific heat-treating conditions for "17-22-A"V which have been selected to date include four isothermal treatments based on the isothermal transformation diagram, and the standard oil quenching and the normalizing treatments. The heat treatments are summarized on the following page:

Structure	Section Size	Heat Treatment
Oil Quenched	0.8-inch round	1 hr. at 1850°F, Oil Quenched
Normalized	0.8-inch round	1 hr. at 1850°F, Air Cooled
Lower Pearlite	0.4-inch round	1 hr. at 1850°F, Isothermally Transformed at 1200°F for 5 hrs., Water Quenched
Upper Bainite	0.4-inch round	1 hr. at 1850°F, Isothermally Transformed at 850°F for 2 hrs., Water Quenched
Middle Bainite	0.4-inch round	1 hr. at 1850°F, Isothermally Transformed at 750°F for 0.3 hrs., Water Quenched
Lower Bainite	0.4-inch round	1 hr. at 1850°F, Isothermally Transformed at 650°F for 0.2 hrs., Water Quenched

Specific tempering conditions have been determined only for the oil-quenched and the normalized structures at the 350 BHN hardness level. The tempering curves for these two structures are presented in Figures 2 and 3. On the basis of the curves, the tempering treatment selected for both the oil quenched and the normalized bars was 2 hours at 1250°F.

Photomicrographs of the oil-quenched and the normalized structures are shown in Figure 4. The oil-quenched bar was essentially 100% martensite. There were, however, a few spears of bainite at about the mid-radius of the 0.8-inch round. At the center of the round the martensite at 100 diameters appeared as varying light and dark areas. This is believed to be due to chemical inhomogeneity.

The normalized bar was 100% bainitic. At 1000 diameters magnification the structure appeared quite similar to middle bainite. At 100 diameters the effect of chemical inhomogeneity again appeared as alternate light- and dark-etching areas.

Photomicrographs of lower pearlite and upper, middle, and lower bainite are presented in Figures 5 and 6. The pearlite formed isothermally at 1200°F did not exhibit a definite lamellar structure. Rather, the eutectoid mixture appeared simply as small areas of closely grouped spheroids of carbide. The eutectoid areas comprised approximately 5 percent of the microstructure--the remainder being ferrite.

The upper, middle, and lower bainite structures were similar to those observed in the "17-22-A"S steel. At the higher temperature (850°F) the transformation to bainite seemed to stop after the first hour or two, making it necessary to include about 40% martensite in the structure. At the lower temperatures (750° and 650°F) the reaction went to completion in a relatively short time, giving finer and more acicular bainite the lower the transformation temperature.

Development of Mixed Bainitic Structures

The preliminary experiments used in selecting the specific heat-treating conditions for the mixed bainitic structures yielded the following results:

Steel	Heat Treatment	Microstructure
SAE 4340	1 hr. at 1750°F, Isothermally Transformed Stepwise at 850°F for 1 hr. and 650°F for 1 hr., Water Quenched	60% Upper Bainite + 40% Lower Bainite
"17-22-A"V	1 hr. at 1850°F, Isothermally Transformed Stepwise at 850°F for 5 min. and 650°F for 45 min. Water Quenched	60% Upper Bainite + 40% Lower Bainite
"17-22-A"S	1 hr. at 1750°F, Isothermally Transformed Stepwise at 900°and 700°F. The transformation times have not yet been determined.	

Photomicrographs of the mixed bainitic structures for SAE 4340 and "17-22-A"V are presented in Figure 7. The two kinds of bainite are readily distinguishable at X1000D in the 4340 steel but not in the "17-22-A"V.

DISCUSSION

Effect of Hardness Level

Strength properties of the various structures in the "17-22-A"S steel at the 350 BHN hardness level were generally higher than those observed at the 300 BHN hardness level. The differences were substantial at 700° and 900°F; however, at 1100°F the differences, even though fairly consistent, were so small as to be hardly significant. In no case was there any indication of a substantial reduction in strength values as the hardness was raised from the 300 BHN to the 350 BHN level.

At 1100°F, the harder material generally compared more favorably in the longer time, lower stress tests. The reverse might have been the case if greater instability from higher hardness had been a factor. It is important to note, however, that the specimens which ruptured at 1100°F all showed lower elongation and reduction of area for the harder material.

One factor which ought to be considered in judging the final significance of the results for "17-22-A"S is that two heats of steel were involved in the comparison. All except three of the tests at 300 BHN were on specimens from Heat No. 24797. The other three tests at 300 BHN and all of the tests at 350 BHN were on specimens from Heat No. 10420. However, because the data of the three "common heat" comparisons invariably followed the same trends shown by the "different heat" comparisons, it is quite certain that the differences between heats were not large enough to affect the trend of the influence of hardness.

The results for the SAE 4340 steel are not so easily generalized. It is clear, however, that in none of the structures tested was the 350 BHN material either greatly superior or inferior to the 300 BHN material. The only comparisons in which the 350 BHN material exhibited (moderately) higher strength values consistently were for the tempered martensite structure at 700° and 900°F. For the most part, however, the harder material was observed to have lower strength values as frequently as it was observed to have higher strength values.

The lack of a general superiority of the 4340 steel at 350 BHN over the same steel at 300 BHN is attributed to structural instability. It can be seen from Table I that the tempering conditions used to obtain a hardness of 350 BHN were much less severe than those used to obtain a hardness of 300 BHN. The result was that in 9 of the 13 tests conducted at the 350 BHN hardness level, the testing temperature was equal to or greater than the tempering temperature. It is quite likely that the continued tempering of these specimens during testing resulted in a lowering of their strength values.

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

There are several items concerning the determination and the applicability of the isothermal transformation diagram which need some discussion.

The term "approximate", as applied to the isothermal transformation diagram, was intended to mean simply that certain portions of the diagram are not well defined because of insufficient data. The accuracy of the individual data with respect to the measured temperatures and times and the metallographic examinations was considered to be good. Specifically, (1) the austenitizing temperature was controlled to within ± 5°F of 1850°F, (2) each transformation temperature was controlled to within ± 3°F of the nominal value, (3) the transformation times were measured to within ± 1 second for the short times and to within ± 1 minute for the long times, and (4) two observers agreed upon the results of the metallographic examinations of the "borderline" samples.

In using any isothermal transformation diagram it is important to note what austenitizing conditions were used in determining the diagram. The reason for this is that the positions of the lines in the diagram may be shifted considerably by large variations in the composition, homogeneity, and grain size of the austenite. Since the temperature and time of the austenitizing treatment are the major factors governing these properties of the austenite, it is important to know the austenitizing treatment used in the determination of the diagram. Heat to heat variations in chemical composition and the other production variables can also affect the transformation diagram.

In view of these considerations, it is advised that the isothermal transformation diagram herein presented was determined for Timken Heat Number 11833 of the "17-22-A"V steel austenitized at 1850°F for 30 to 60 minutes, starting from the as-furnished (hot-rolled) condition, and that under any conditions varying greatly from these the diagram must be considered as being only a "first approximation".

Several check tests were run using an austenitizing time of 60 minutes rather than 30 minutes. No difference in the transformation times could be detected between the 30 and 60 minute austenitizing treatments. No checks were made on the effect of varying the austenitizing temperature, but it is estimated that the given transformation diagram would be relatively accurate for austenitizing temperatures as low as 1800° or 1750°F and as high as the coarsening temperature.

The microstructures of "17-22-A"V which have been developed thus far are somewhat similar to the corresponding structures in the "17-22-A"S steel. The most salient difference in appearance is the much finer grain size of "17-22-A"V. In this connection it is interesting to note that the austenitizing temperature for "17-22-A"V was 100°F higher than that used for "17-22-A"S. The persistence of the fine grain structure of the "17-22-A"V at high temperatures is attributed to the effectiveness of undissolved carbide particles as grain growth inhibiters.

Another notable difference between the two "17-22-A" steels was that on normalizing the 0.8-inch rounds, the "17-22-A"S steel was about 85% bainite plus 15% martensite, while the "17-22-A"V was 100% bainite.

The shapes of the tempering curves (see Figures 2 and 3) for the oil-quenched and the normalized structures of "17-22-A"V indicated the presence of secondary hardening effects. This is what would normally be expected in a steel containing appreciable amounts of carbon and vanadium.

Development of Mixed Bainitic Structures

The microstructures observed in the specimens which were isothermally transformed stepwise in the bainitic range were surprisingly different for 4340 and "17-22-A"V. In the 4340 steel, the high- and low-temperature forms of bainite are readily distinguishable; whereas, in the "17-22-A"V steel the two forms of bainite can hardly be distinguished. In Figure 7, the darkest as well as the lightest areas in the 4340 micro are the lower bainite; the medium-dark areas are the upper bainite. This illustrates the difficulty in identifying the various types of bainite in a single specimen with the aid of the microscope alone. The identification of the bainites in Figure 7(a) was accomplished by observing a series of four samples which had been transformed 0, 15, 30, and 60 minutes, respectively, at 650°F after the initial transformation at 850°F for 1 hour.

CONCLUSIONS

Effect of Hardness Level

1. Strength properties of the various structures in the "17-22-A"S steel at the 350 BHN hardness level were generally higher than those observed at the 300 BHN hardness level. The differences at 700° and 900°F were substantial; however, at 1100°F the differences were so small as to be hardly significant.

2. The 350 BHN structures in "17-22-A"S steel at 1100°F tended to compare more favorably in the longer time, lower stress tests.

3. Without exception the ductility of the "17-22-A"S steel at fracture was lower at the higher hardness level.

4. Strength properties of the oil-quenched and tempered structure in the SAE 4340 steel at 700° and 900°F were increased moderately as the hardness level was raised from 300 BHN to 350 BHN. At 1000°F, however, the same structure was somewhat inferior at the higher hardness level.

5. The strength properties of the other structures in the SAE 4340 steel were not consistently different at the two hardness levels.

FUTURE WORK

Future work will consist primarily of completing the heat treating and machining of specimens, and conducting the planned program of creep and rupture testing.

The other phases of the investigation involving the study of the effect of (1) a prior normalize and (2) double heat treatments will be started in the near future.

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", Proposed Wright Air Development Center Technical Report 55-388 (September, 1955).

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 "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 III

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	~~0.0015~~ .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 0.0188	-	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	-

.06

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

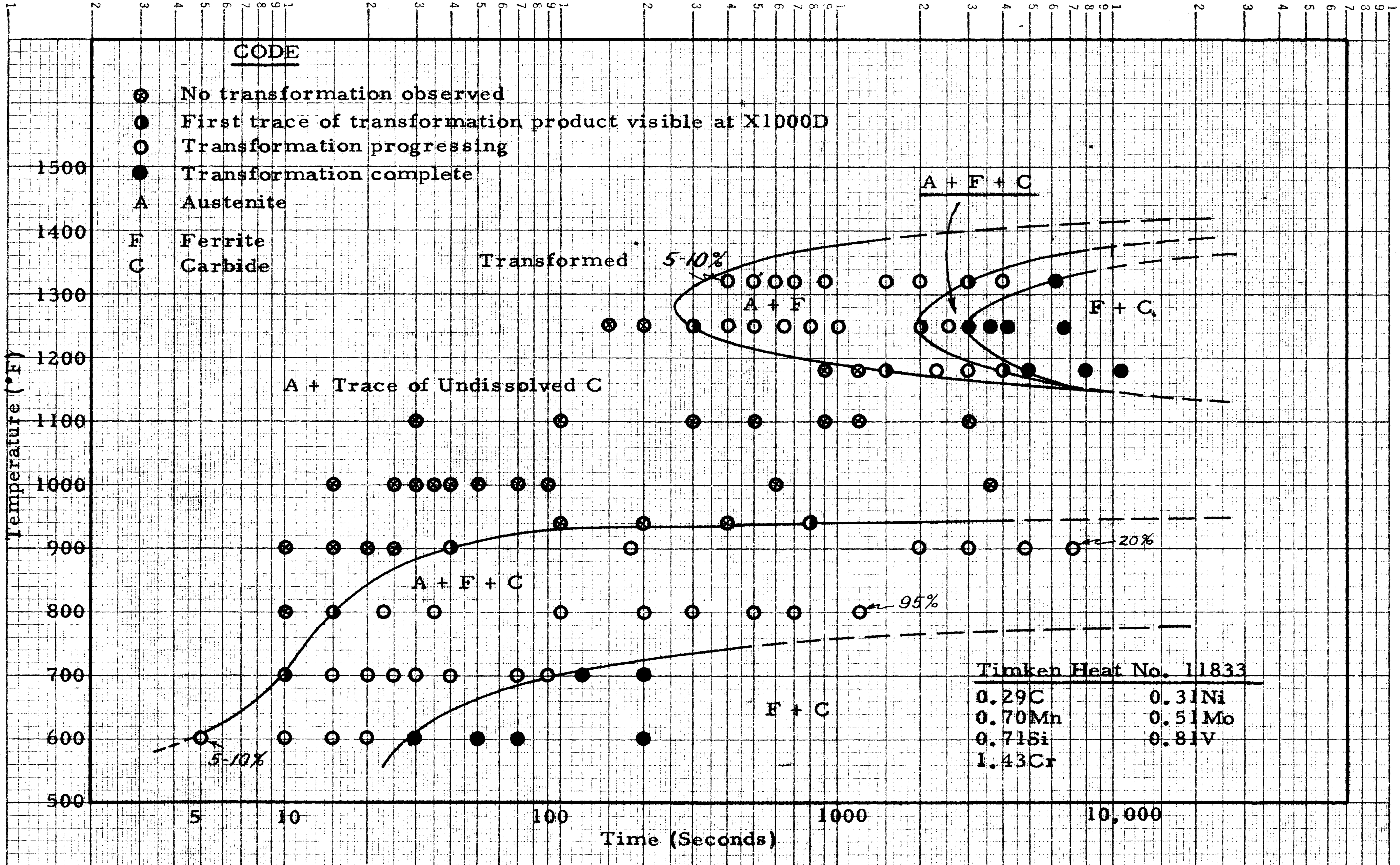


Figure 1. - Isothermal Transformation Diagram for "17-22-A"V Steel Austenitized at 1850°F. (Grain Size 9-10).

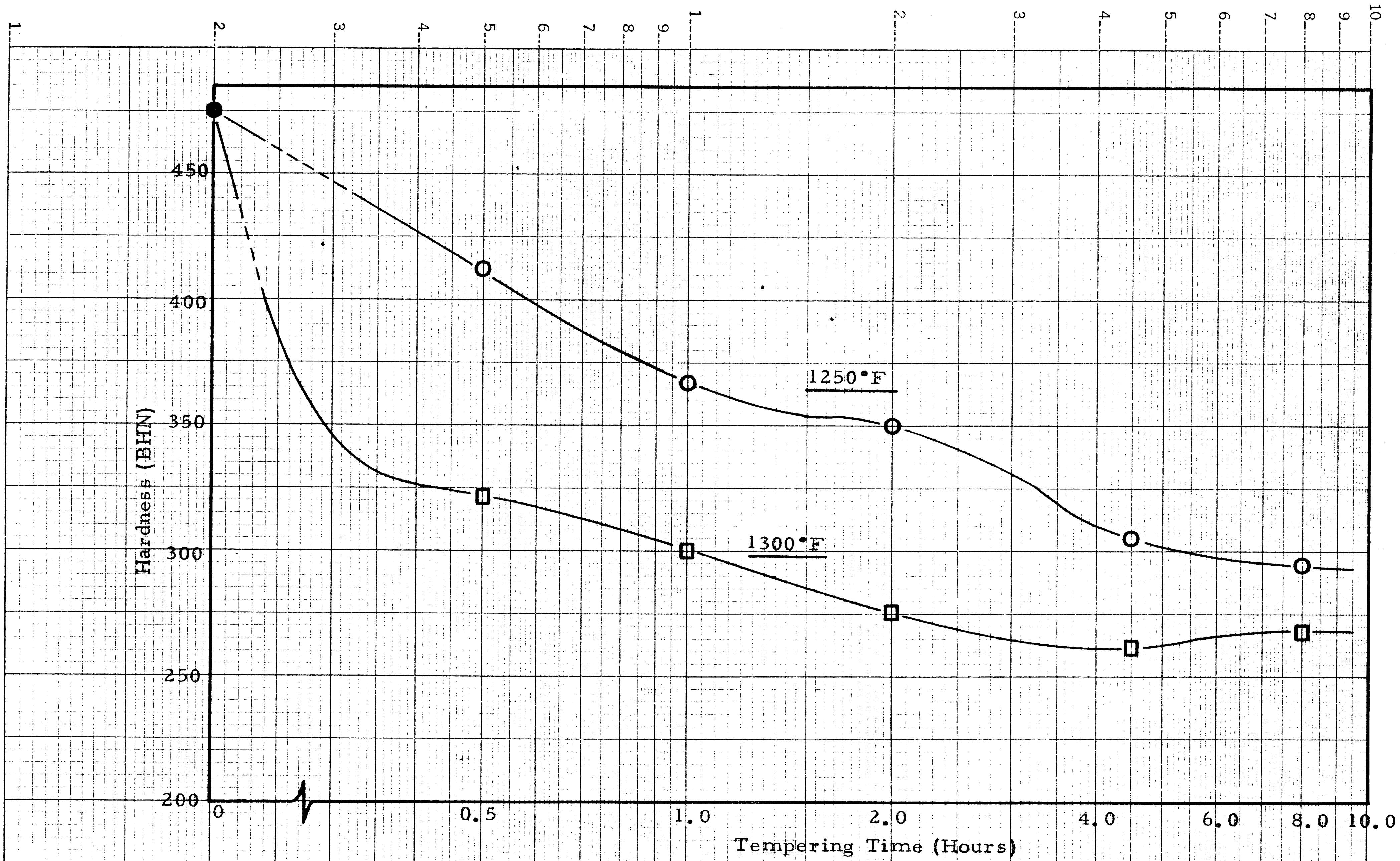


Figure 2. - Tempering Curves for 0.8-inch Rounds of "17-22-A"V Steel Oil Quenched from 1850°F.

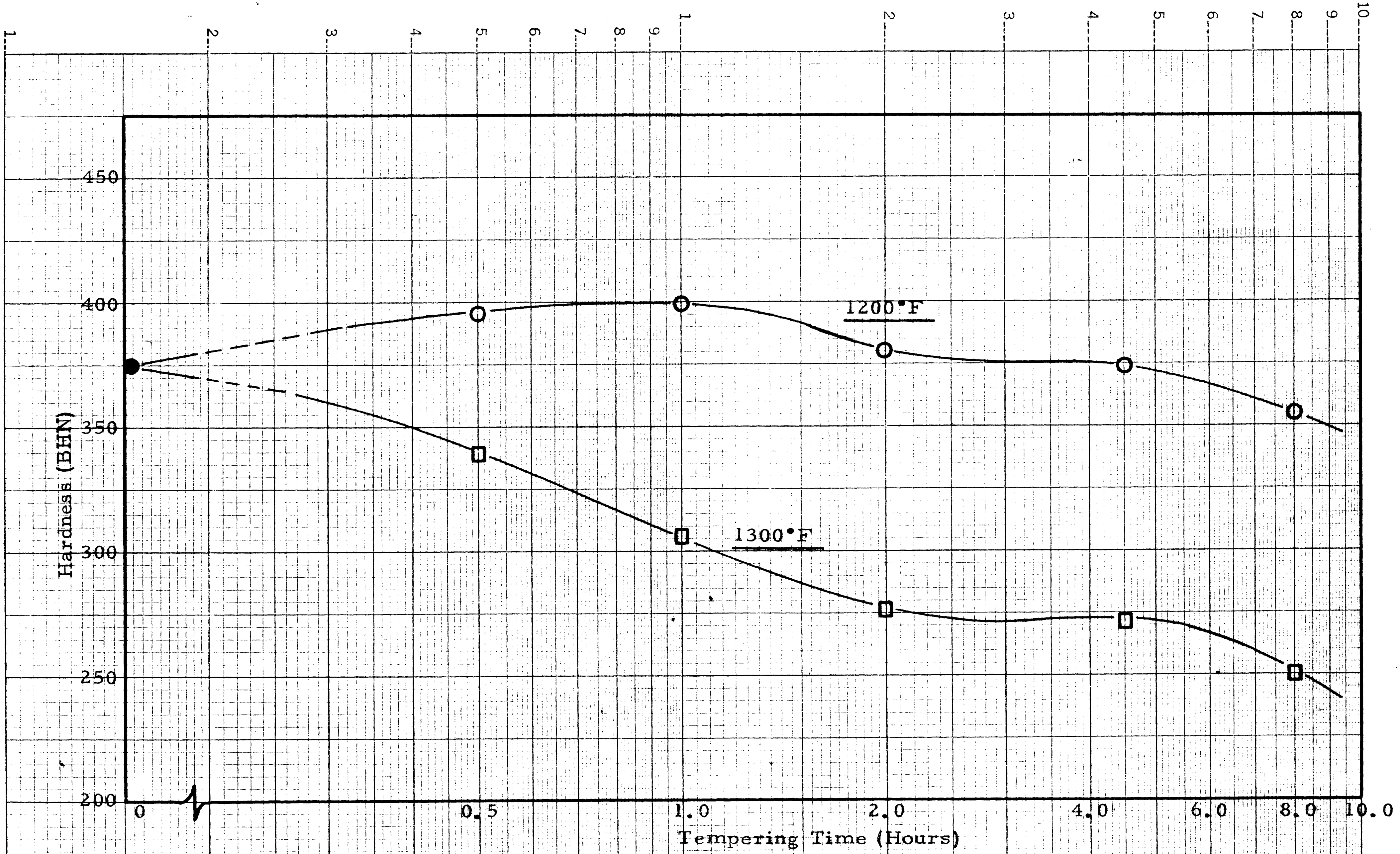
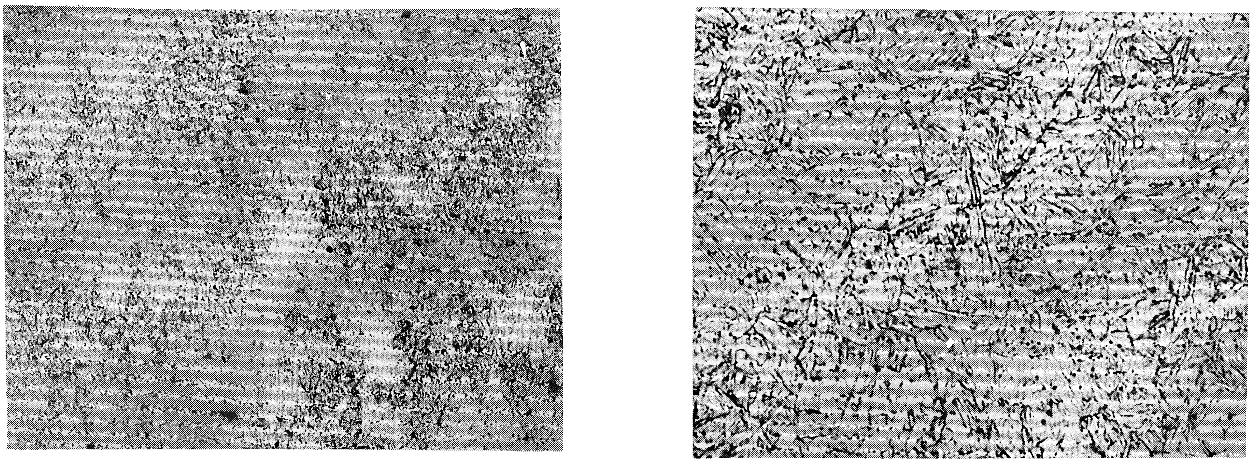


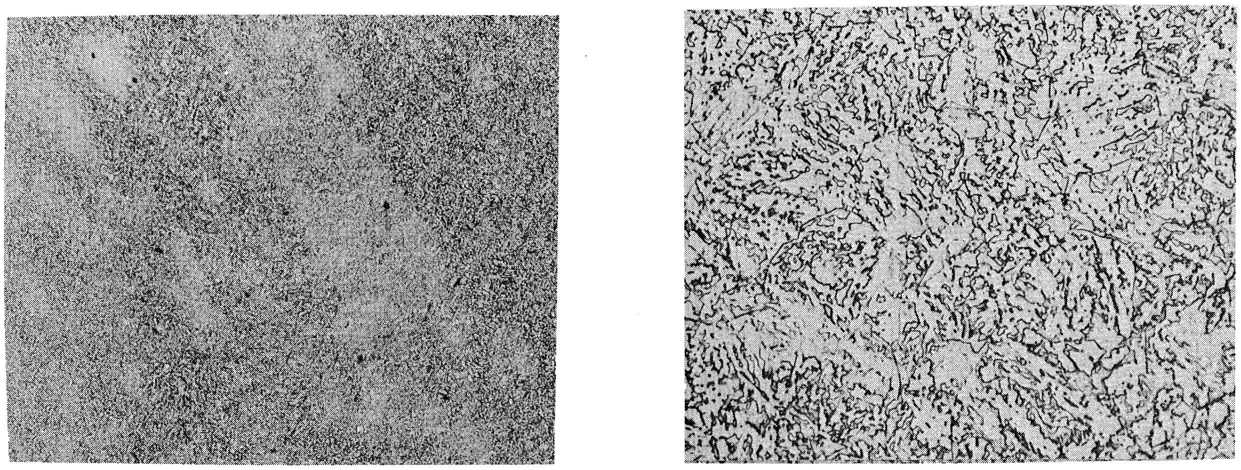
Figure 3.- Tempering Curves for 0.8-inch Rounds of "17-22-A"V Steel Normalized from 1850°F.

Pictures are with Phil Coldren

X100D X1000D



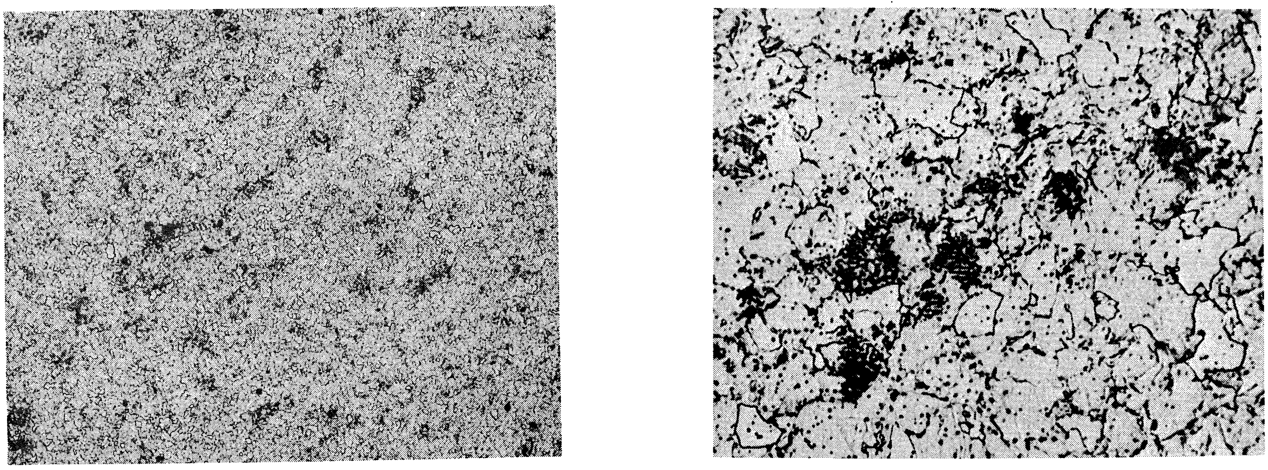
(a) Oil quenched from 1850°F - 476 Avg. BHN



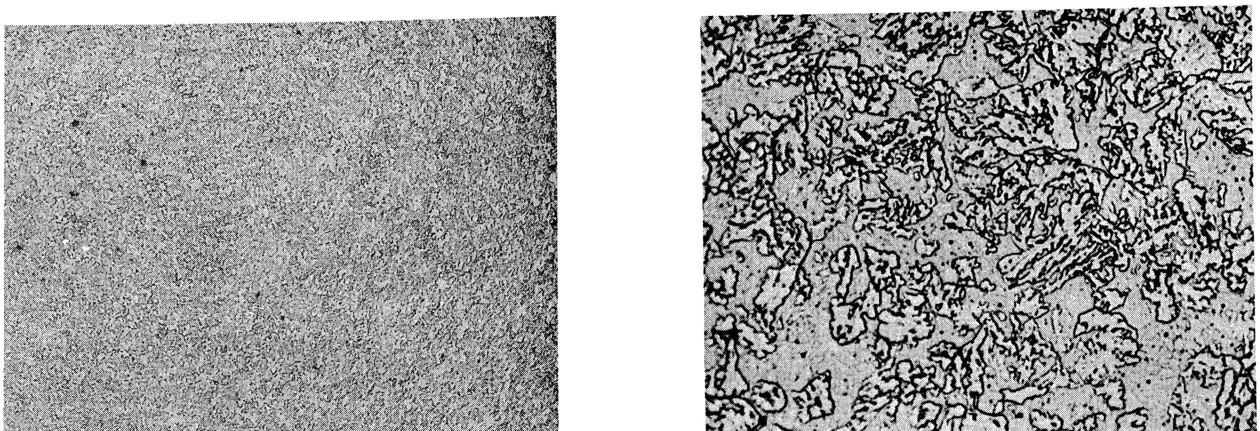
(b) Normalized from 1850°F - 374 Avg. BHN

Figure 4. - "17-22-A"V Bar Stock (a) As Oil Quenched from 1850°F and (b) As Normalized from 1850°F.

X100D X1000D

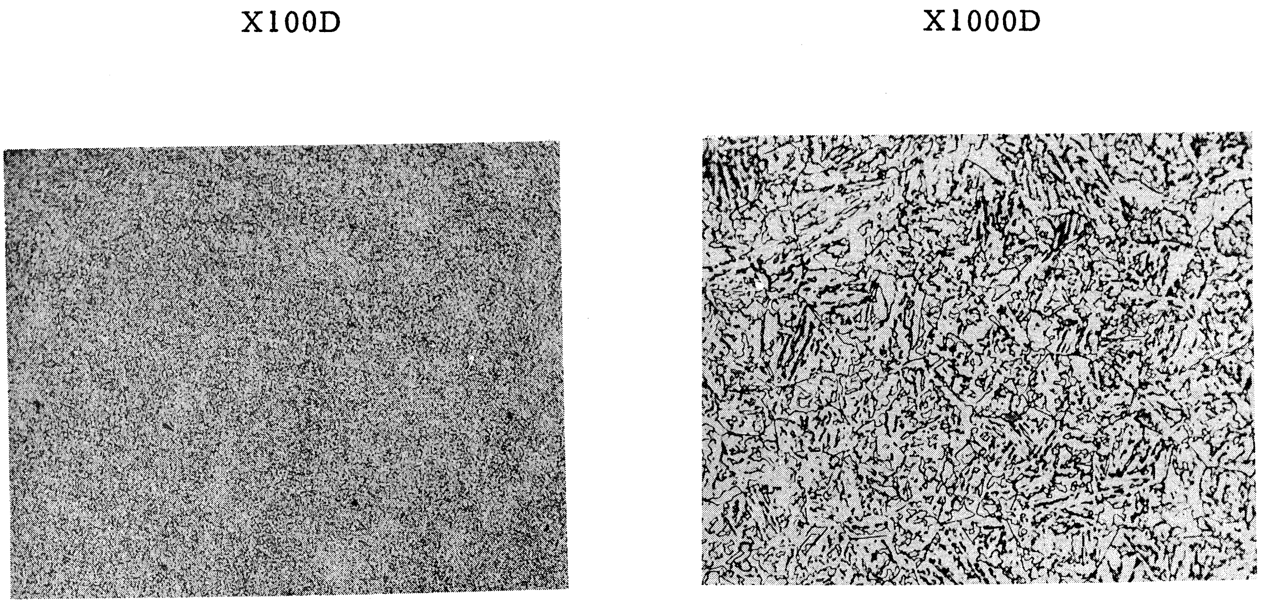


(a) Isothermally-transformed at 1200°F for 5 hrs. 5% Lower Pearlite + 95% Ferrite.

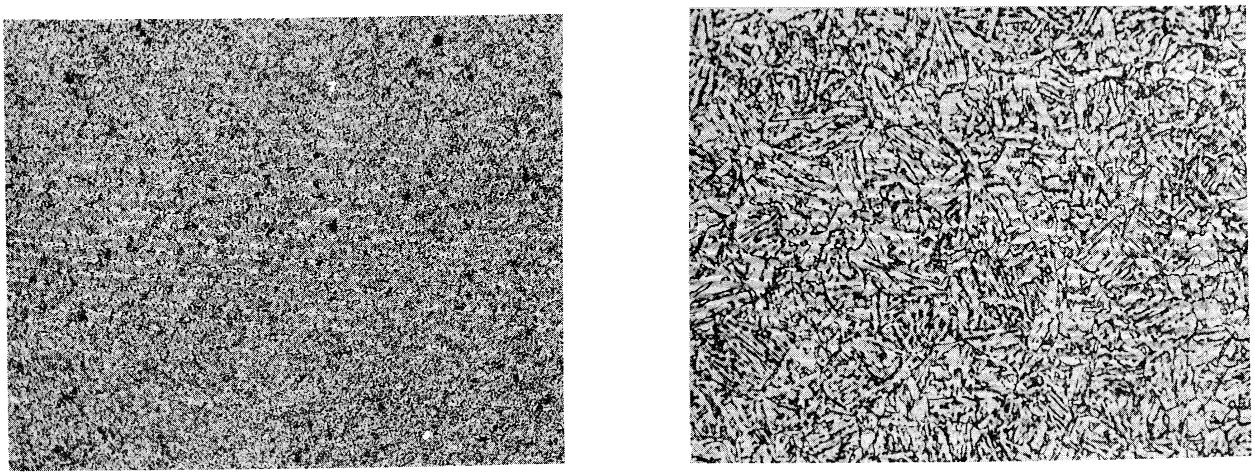


(b) Isothermally transformed at 850°F for 2 hrs. 60% Upper Bainite + 40% Martensite.

Figure 5. - "17-22-A"V Bar Stock as Transformed Isothermally to (a) Lower Pearlite and (b) Upper Bainite.

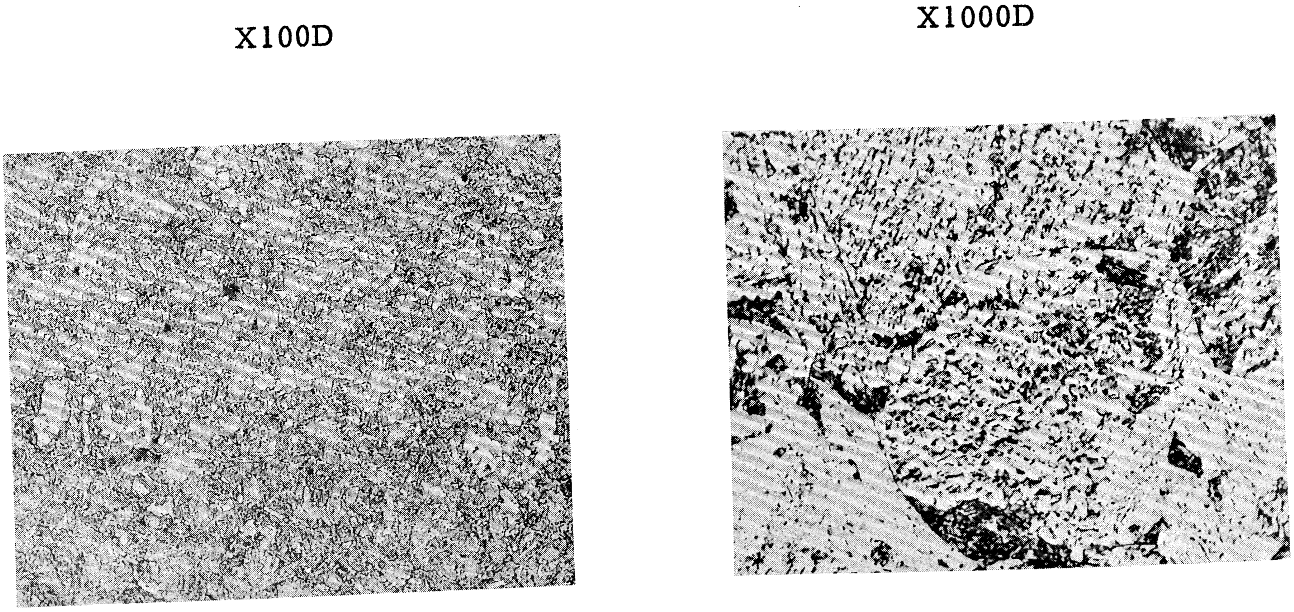


(a) Isothermally transformed at 750°F for 18 min. 100% Middle Bainite.

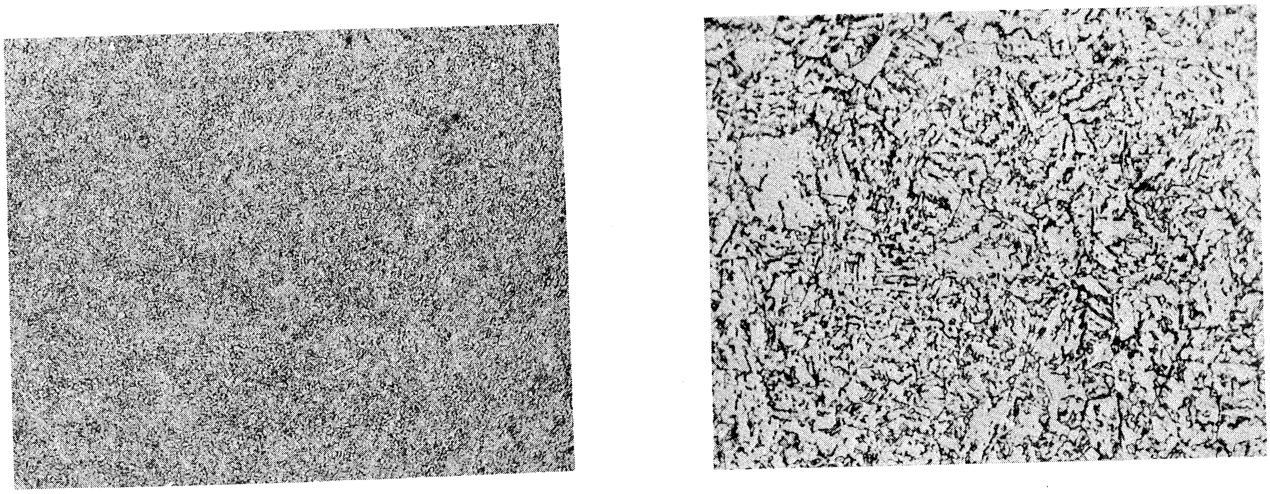


(b) Isothermally transformed at 650°F for 12 min. 100% Lower Bainite.

Figure 6. - "17-22-A"V Bar Stock as Transformed Isothermally to (a) Middle Bainite and (b) Lower Bainite.



(a) SAE 4340, isothermally transformed stepwise at 850°F for 1 hr. and 650°F for 1 hr. 60% Upper Bainite + 40% Lower Bainite.



(b) "17-22-A"V, isothermally transformed stepwise at 850°F for 5 min. and 650°F for 45 min. 60% Upper Bainite + 40% Lower Bainite.

Figure 7. - Mixed Bainitic Structures as Produced in SAE 4340 and "17-22-A"V by Stepwise Isothermal Transformations in the Bainitic Range.