CALCULATION OF THE COMPOSITE HARDNESS FROM THE ISOTHERMAL DIAGRAM

By

Rodrigo J. Mattos

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Signed: ______________________
Rodrigo J. Mattos

Golden, Colorado
Date: April 11, 1972

Approved: ______________________
Walter L. Bradley
Thesis Advisor

Golden, Colorado
Date: APRIL 11, 1972

____
John P. Hager
Head, Department of
Metallurgical Engineering

A B S T R A C T

A method for calculating the composite hardness of heat treated steel based on the Scheil's theory of the fractional nucleation for calculating the beginning of the transformation on continuous cooling and on the assumption that

$$f(t)= 1-\exp(-\frac{\pi}{3}N_V G^3 t^4)$$

describes the general shape of the transformation curve as a function of time for each temperature, was tested. In particular, the method has been used to calculate the hardness along a Jominy bar and across the diameter of round bars (Grossman test) quenched in three different quenching mediums.

For the three steels examined, AISI 1095, 4140, and 9260 types, the hardenability curves calculated in this way were found to be in very reasonable agreement with those determined experimentally.

CONTENTS

A C K N O W L E D G M E N T S

The author is deeply indebted to Dr. Walter L. Bradley, Associate Professor of Metallurgical Engineering, who suggested the problem for investigation and who gave his guidance and assistance throughout this work.

Sincere appreciation to my father José Bolivar who supported my professional studies and to my wife Martha Noria for her limitless patience and understanding.

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INTRODUCTION

The metallurgist has two tools to study the hardenability of a steel: (1) the isothermal transformation diagram and (2) the end-quench hardenability test or Jominy test.

In most of the commercial practices, the heat treatment of the steel is carried out through continuous cooling; therefore the use of the isothermal transformation diagram is very limited. It provides only a way of estimating the transformations that have taken place in the steel during the heat treatment. On the other hand, the end-quench hardenability test is used to correlate positions on the hardenability bar with positions in pieces of different shapes. Unfortunately, the end-quench test does not give information about the transformations in the steel.

It will be helpful for the metallurgist to have a link between the isothermal transformation diagram and the end-quench hardenability test.

This thesis is an effort in trying to correlate the isothermal transformation diagram and the end-quench hardenability test. In particular, the method for prediction of the hardness along the end-quench specimen and across the diameter of round bars from the isothermal diagram was studied for three steels.

REVIEW OF THE LITERATURE

Hardenability Tests

The earliest test for hardenability involved quenching a piece of steel and fracturing it. These earliest tests were concerned with texture and the accompaying observation as to the depth of hardening; however, these tests were not standardized. The first hardenability standardization was carried out in 1926; and as before, they attempted to measure the depth of hardening and the fracture appearance(1).

In 1936, Bain and Davenport introduced the custom of showing the depth of hardening of a quench round bar with the use of a symmetrical U-curve; they explored the hardness along a number of radii and averaged these values to obtain the mean gradation along a radius. In this investigation the limit of the hardened zone is defined to be the position of 50% martensite, and, as Grossman (1) points out, this position is not intended to imply that the depth of hardening to 50% martensite is necessarily the depth of most importance to the metallurgist. The intent is only to point out that such a depth can be measured more easily and perhaps with greater precision than at some other percentage of martensite.

The rapid change in structure at the 50% martensite position leads to another measure of hardenability that turns out to be most useful: it is known as the "critical size." Grossmann[2] defined the critical size as the size which is just half-hardened (half-martensite) at the center.

In 1938, Jominy and Boegehold[3] reported a test for carburizing steels. The test consisted of preparing a specimen 1 in. in diam and 3 in. in length. The piece was then carburized and placed in a fixture where it was quenched on its lower end by a stream of water impinging on that position from below. The hardenability or depth of hardening would be indicated along the piece by the distance over which it was hardened due to quenching. The criterion of hardenability employed in this instance was the distance along the piece which hardened fully.

The following year, Jominy[4] showed that the same principle of end-quenching could be readily extended to include the noncarburizing steel. Today, this test has been standardized by the A.S.T.M.[5]

Cooling Criteria for Hardenability

All the tests for hardenability described before involve the quenching of a piece of steel and then measuring the depth to which it hardened. The depth of hardening is the manifestation of the hardenability behavior of the steel.

For the correlation of different kinds of tests and in particular the U-test and the Jominy test, attempts have been made to describe the hardenability of a steel in terms of the rate at which that steel must be cooled if it is to harden.

Several ways have been proposed for describing the rate of transformation of a piece of steel that has been quenched.

Scheil[6] developed the theory of the "fractional nucleation" to predict the start of transformation under non-isothermal conditions. If the incubation period at temperature T is t sec, a specimen held at this temperature for a period of t_1 sec (where t_1 is less than t) may be said to have undergone a fractional nucleation of t_1/t. It was postulated by Scheil[6] that a thermal treatment corresponding to a sum of all fractions equal to unity will bring the steel to the point of commencement of the austenite decomposition. This may be applied to an infinite number of separate Scheil fractions, corresponding to a continuous cooling condition. The expression then is

$$\sum_{T_o}^{T_e} \frac{t_1}{t} = 1$$

By the use of this expression, the time and temperature at which transformation should start may be calculated from a knowledge of the time-temperature curve followed by the specimen during cooling. The summation begins at temperature T_e, at which austenite becomes supercooled, and it continues until the fractional sum reaches unity at some lower temperature T_o.

Grange and Kiefer(7), studying the decomposition of austenite on continuous cooling in relation to the isothermal diagram and assuming a constant cooling rate, developed a method to derive the continuous transformation diagram (Figure 1). A cooling curve of M^oF/sec is drawn on the isothermal diagram, starting from the A_1 (eutectoid) temperature if the transformation product is the eutectoid microconstituent (pearlite or bainite); from the A_3 temperature if the product is primary ferrite; or from the A_{cm} if it is proeutectoid cementite.

The cooling curve in Figure 1 intersects the curve

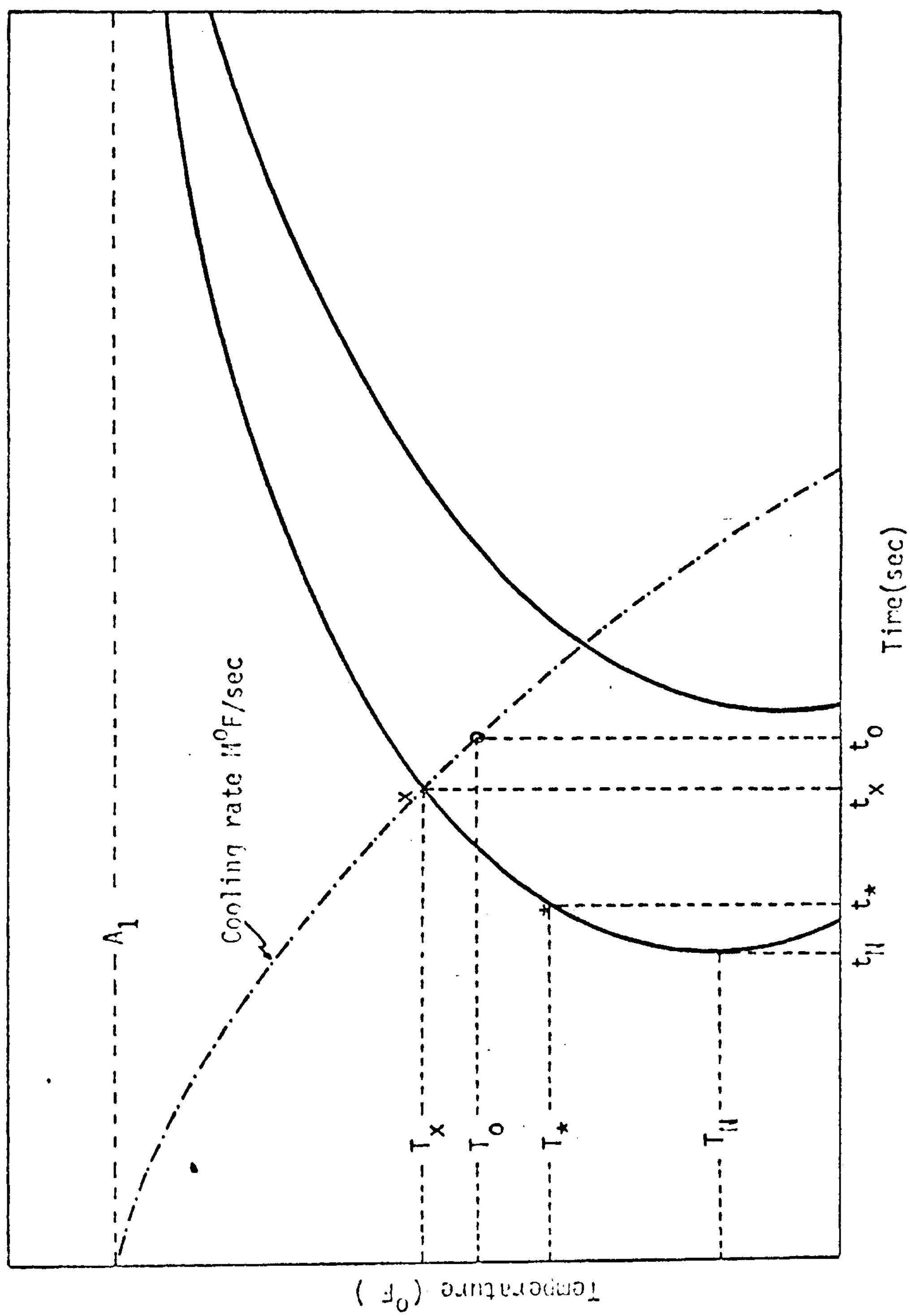


Figure 1. Method of Grange and Kiefer for calculating the continuous cooling transformation diagram.

representing the start of isothermal transformation at point x corresponding to a temperature T_x and a time t_x. After the heated metal has been cooling for t_o seconds, an arbitrary lower temperature T_o (on the cooling curve) is chosen. Two basic assumptions are proposed by Grange and Kiefer in regard to the transformation between the points x and o:

1) The extent of transformation of austenite from the start of cooling to the temperature T_x is the same as if the steel had been quenched rapidly from the austenitizing temperature to T_x.

2) On cooling through the limited temperature range T_x to T_o, the amount of transformation is approximately equal to that which would transform isothermally at the mean temperature $T^*=\frac{1}{2}(T_x+T_o)$ in the time interval $t^*=t_o-t_x$.

The same authors showed how to calculate the critical cooling rate of any steel. The critical cooling rate is defined as the lowest rate of cooling which will cause full hardening of any steel (100% martensite). A curve representing this critical constant rate of cooling will intercept a portion of the "nose" of the isothermal diagram (Figure 1). This curve can be estimated by the method proposed by them for relating cooling transformation to the isothermal diagram. They found that the critical constant-cooling rate can be simply approximated directly from the isothermal diagram as follows:

1) Locate point N (Figure 1) at the "nose" of the beginning line of the isothermal diagram, that is, at the temperature and time where the beginning of transformation is most rapid.

2) Calculate the critical constant rate (R) by substitution in the formula,

$$R = \frac{A_e - T_N}{1.5\ t_N}$$

where,

A_e= equilibrium transformation temperature (A_{e3} when N is on the ferrite beginning line, A_e, otherwise)

T_N= temperature at point N

t_N= time interval at point N

The factor 1.5 was based upon the observation that the time interval for cooling from the equilibrium temperature to T_N at the critical constant rate was approximately 50 percent greater than t_N. The chief objection to this method of judging hardenability lies in the fact that it is based on what is often the least accurately determined portion of the isothermal diagram, namely, the beginning line at the "nose."

Moore[8], using the Scheil fractional nucleation theory in a medium-alloy steel, found very good correlation between the observed and calculated start of transformation, particularly in the upper bainite range.

Grange and others[9] determined experimentally the continuous cooling transformation diagram in a Ni-Cr-Mo steel of eutectoid carbon content. The derived beginning of transformation on continuous cooling of the same steel by the methods of Scheil and Grange and Kiefer has more or less the correct shape but lies toward the left and above the measured continuous cooling diagram. The discrepancy is greatest in the bainite region. Thus, for this particular steel all the methods that have been proposed for predicting transformation behavior on continuous cooling from isothermal data were unsatisfactory.

Correlation Between the Jominy Test and Quenched Round Bars

Several workers have tried to correlate the end-quench test and the U-test in terms of hardness or cooling characteristics.

Asimow and others[10], using as a criterion for correlation the half-temperature time, which is the time to cool from the quenching temperature halfway down to that of the quenching medium[11], showed that it is possible to predict from the results of the Jominy test what the hardness distribution will be on the cross-section of a quenched round bar.

The same authors, on the basis of the above principle, found that it is possible to estimate the ideal critical diameter from the results of the hardness distribution curve on the Jominy bar when the position of 50% martensite in the Jominy bar is known.

Weinman and others[12] employed as cooling criterion the time to cool from 1350°F to some lower temperature. They obtained the cooling curves of a 2-in. round bar of a 9450 steel at 3/4 of the radius and at center, and the cooling curves for the corresponding Jominy positions. These curves coincide quite well and the hardness is comparable. However, the same investigators found that these curves did not always coincide. When this happened, longitudinal and transverse segregation was found in the quenched bars. As a result, a difference of 11 Rockwell-C units in hardenability between the center and near the surface of the Jominy bar were found. At the present time, there is some doubt about the coincidence of the cooling curve followed by some point in the Jominy bar and the equivalent point in a round bar. As Troiano[13] states, "the transformation characteristics are always the same (for the same steel); but the shape and the cooling curves will change with different section size, destroying correlation, regardless of what criterion of equivalence may be employed."

Carney[14], employing the half-temperature time criterion observed, that for several steels tested, the end-quench bar yields hardness up to 12 Rockwell-C units higher than the quench rounds at positions of equal half-temperature time. The same results were observed with the 1350°F-T criterion.

PROPOSED METHOD FOR CALCULATING THE COMPOSITE HARDNESS

The proposed method for calculating the composite hardness from the isothermal diagram and the cooling curve followed by a chosen point in the Jominy specimen which had been previously austenitized is based on the following assumptions:

1) Scheil fractional nucleation for calculating the beginning of the transformation on continuous cooling holds.

2) The transformation curve as a function of time and for a given temperature has the shape given by the expression[16]:

$$f(t) = 1 - e^{-(\pi/3) N_v G^3 t^4}$$

where:

$f(t)$ = fraction transformed

N_v = rate of nucleation, expressed in number of nuclei per unit of time per unit of volume.

G = rate of radial growth, expressed in units of length per unit of time.

t = time in seconds.

The above expression is true on these assumptions:

A) The reaction proceeds by nucleation and growth;

B) The rates of nucleation and growth remain constant throughout the reaction;

C) Nucleation is exclusively at grain boundaries;

D) The matrix is composed of spherical grains, and

E) The nodules grow only into the grain in which the nuclei originated and do not cross grain boundaries.

Each of these transformation curves for every temperature is implicitly given in the isothermal transformation diagrams for every steel when knowledge is had on the points where 1%, 50%, and 99% of the austenite had been isothermally transformed.

3) The hardness of the transformed product is the weighted average hardness of the constituents formed at different temperatures throughout the cooling.

As an example, a cooling curve which was taken at a distance of 1/8 in. from the quenched end of a Jominy bar of a 1095 steel is superimposed on the isothermal transformation diagram as shown in Figure 2. In plotting the

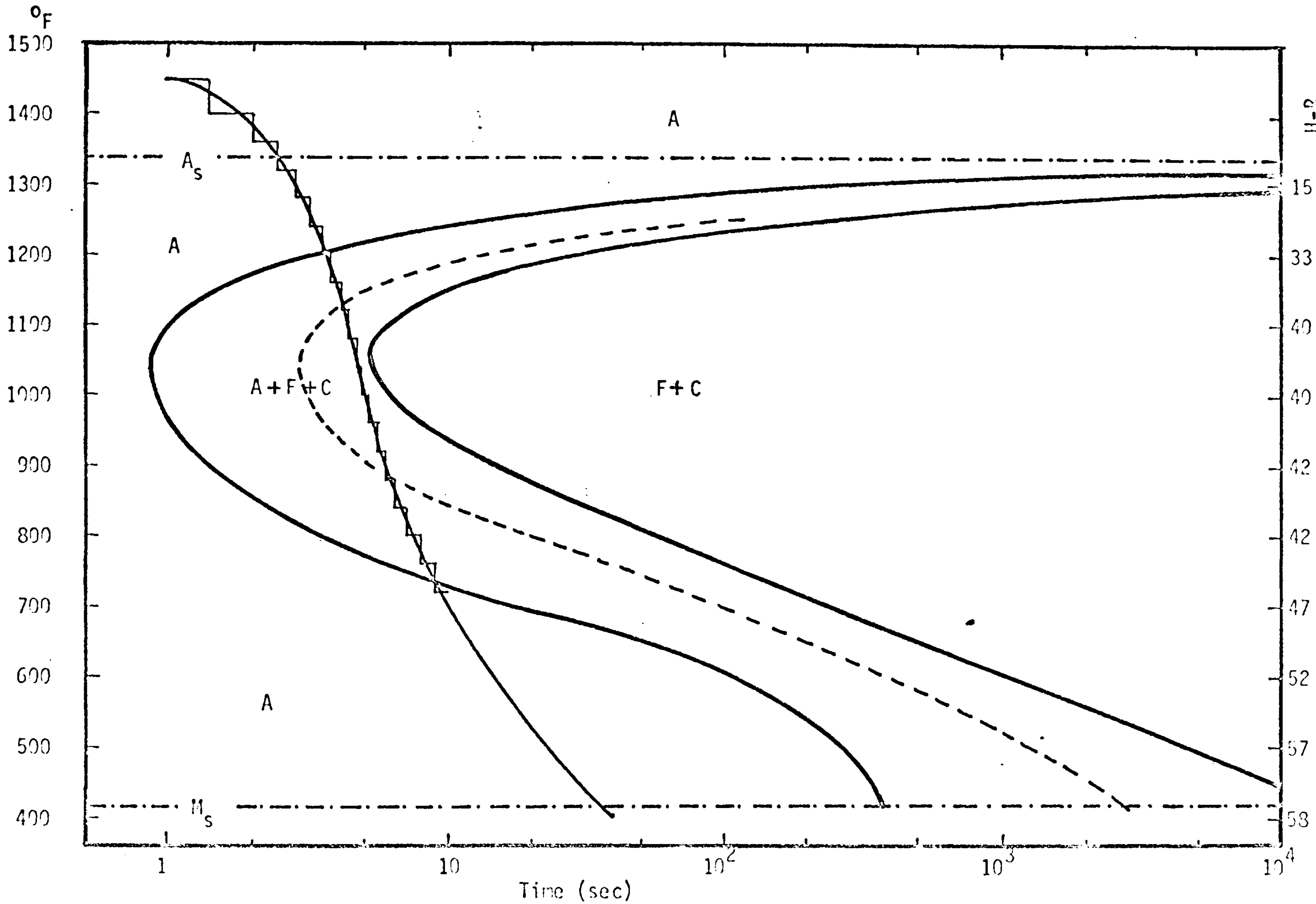


Figure 2. Cooling curve at a point 1/8 in. from the quenched end in a Jominy specimen. 1095 steel.

cooling curves, a problem exist in deciding the zero for the beginning of the cooling. Grange and others[17] found that for a eutectoid alloy steel, the exposure time of the austenite in the range 1700°F to 1450°F has no significant effect in the rate of subsequent transformation at temperatures lower than 1450°F. In their work, several specimens were austenitized at 1700°F and cooled at different rates from 1700 to 1450°F, but at the same rate from 1450 to 70°F. Upon examination of the specimens, they found that all the specimens had the same hardness and microstructure despite the variation in the rate of cooling through the 1700 to 1450°F range. On this basis, the time to cool from the austenitized temperature to 1450°F is not taken into account for the three steels studied.

The steps of the calculation of the composite hardness are as follows:

1) The point where 1% the transformed product is formed continuous cooling is calculated on the basis of Scheil's hypotesis, as shown in Table 1. At this point, 1060°F and 3.70 sec, 1% of austenite has been transformed, which has a hardness of 40.8 Rockwell-C. This hardness corresponds to the last fraction transformed.
2) For the plotting of the isothermal reaction curves for temperatures below 1060°F, the points

TABLE 1

Steps for the calculation of 1% of transformed product on the basis of Scheil hypotesis

Temperature Interval (^{o}F)	Mean Temperature(^{o}F)	Δt (sec)	$\sum\Delta t$ (sec)	t(1%) (sec)	$\Delta t/t(1\%)$	$\sum\Delta t/t(1\%)$
1450-1400	1425	0.50	0.50			
1400-1360	1380	0.60	1.10			
1360-1320	1340	0.50	1.60			
1320-1280	1300	0.30	1.90	350.0	0.0008	0.0008
1280-1240	1260	0.30	2.20	30.0	0.0100	0.0108
1240-1200	1220	0.30	2.50	6.4	0.0468	0.0576
1200-1160	1180	0.30	2.80	2.5	0.1200	0.1776
1160-1120	1140	0.30	3.10	1.4	0.2140	0.3916
1120-1080	1100	0.30	3.40	1.0	0.3000	0.6916
1080-1040	1060	0.30	3.70	0.9	0.3333	1.0249

where 1%, 50%, and 99% of the isothermally transformed austenite are read from the isothermal transformation diagram, are shown in Table 2. with these data, the isothermal reaction curves are plotted on the same semilogarithmic scale as the isothermal transformation diagram, but the transformed fraction is plotted on the ordinate instead of temperature, as shown in Figure 3.

3) The residence time of a given point in the Jominy specimen at each temperature interval is translated to the corresponding reaction curve and the fraction transformed at this temperature is read. Also, by interpolation the hardness of the transformed product at each temperature is taken from the isothermal transformation diagram. The composite hardness is the sum of the fractions transformed at each temperature times the corresponding hardness for the constituents formed at that temperature, as shown in Table 3. From the results of Table 3, we can see that 37% of the austenite was transformed to pearlite, and 63% was transformed to martensite, which has a 66- Rockwell-C hardness at room temperature.

TABLE 2

Points where 1%, 50% and 99% Of transformed products are taken from the isothermal transformation diagram.

Temperature Interval(^{o}F)	Mean Temperature(^{o}F)	Δt (sec)	$\sum\Delta t$ (sec)	t(1%) (sec)	t(50%) (sec)	t(99%) (sec)
1040-1000	1020	0.30	4.00	0.90	3.00	5.40
1000-960	980	0.40	4.40	0.96	3.30	7.00
960-920	940	0.30	4.70	1.10	4.00	9.40
920-880	900	0.50	5.20	1.40	5.40	15.00
880-840	860	0.50	5.70	1.90	8.20	25.00
840-800	820	0.70	6.40	2.70	15.00	42.00
800-760	780	0.80	7.20	4.20	30.00	74.00
760-720	740	1.00	8.20	8.00	54.00	130.00

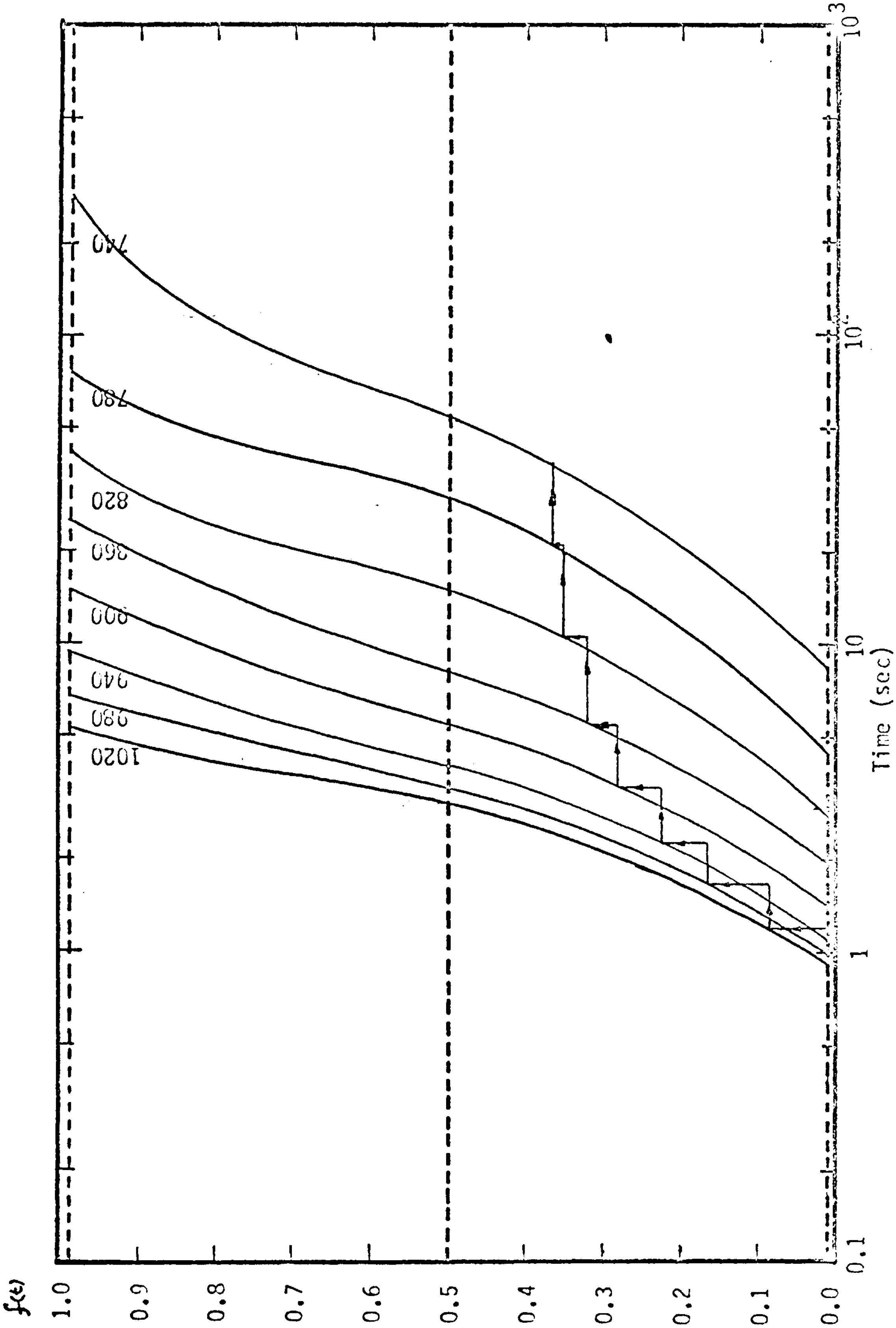


Figure 3. Isothermal reaction curves and steps for the calculation of the composite haedness.

TABLE 3

Calculation of the composite hardness

Mean Temperature (°F)	Total transformed at mean temperature	Austenite transformed at mean temperature, f(t)	Hardness of transformed product. ($H-R_c$)	$f(t) \times (H-R_c)$
1060	0.010	0.010	40.8	0.408
1020	0.085	0.075	41.6	3.120
980	0.170	0.085	42.0	3.570
940	0.220	0.050	42.0	2.100
900	0.280	0.060	42.0	2.520
860	0.320	0.040	42.0	1.680
820	0.350	0.030	42.0	1.260
780	0.370	0.020	43.0	0.860
740	0.380	0.010	45.0	0.450
		$\sum f(t) = 0.370$		$\sum f(t) \times (H-R_c) = 15.968$

The composite hardness is deduced thus:

Weigh average hardness from the steps of the reaction, austenite → pearlite. . .	15.968
Weigh average hardness from the steps of the reaction, austenite → martensite. .	41.580
Composite hardness	$57.548\text{-}R_c$

EXPERIMENTAL PROCEDURE

For testing the validity of the proposed method for calculating the composite hardness, two type of tests were used in this investigation: the Jominy test and the Grossman test, both of which were run on the same kind of steels.

The following steps were carried out during the course of this investigation:

1) Selection of the steels based on their chemical composition
2) Preparation of the test specimens
3) Measure of temperature and cooling curves
4) Heat treatment
5) Hardness determination
6) Metallographic studies

Selection of the Steel Based on Their Chemical Composition

Three steels, whose chemical composition corresponds to the 1095, 9260, and 4140 AISI type, were used in this research. The criterion for the selection of these steels was that they are representative of the carbon-steels group and alloy-steels group.

The chemical composition of each of these steels is as follows:

1095 Steel

C : 0.95 %

Mn: 0.42 %

P : 0.016 %

S : 0.046 %

Si: 0.15 %

9260 Steel

C : 0.58 %

Mn: 0.84 %

P : 0.013 %

S : 0.030 %

Si: 1.95 %

Ni: 0.03 %

Cr: 0.06 %

Mo: 0.02 %

4140 Steel

C : 0.43 %

Mn: 1.00 %

P : 0.015 %

S :	0.022	%
Si:	0.20	%
Cr:	0.98	%
Mo:	0.18	%

Preparation of the Test Specimens

The steels under study were received in 2- and 1¼-in.-diam bars in the hot-rolled condition at which the test specimens for the Jominy and Grossman tests were prepared.

Jominy Test Specimens: Round bars of 1-in. in diam and 4-in. in length were cut and machined from the 2-in. or 1¼-in.- diam bars.

For accommodation of the thermocouples, 0.1065-in.-diam holes (drill N^{o} 36) were drilled transversally in the test specimen to a depth of 7/8 in. Carney in his study(14) found very little difference between readings of temperature measured at different transverse depths.

For the avoidance of a significant loss of mass, only two holes per test specimen were drilled.

For the fastening of the thermocouples and the test specimen in the quenching fixture, a ring of 1-in. I.D by 1¼-in. O.D with holes to pass the thermocouples insulator tubes was fixed with screws on the upper end of the specimen. Also, for easier and faster transfer of the specimen from the furnace to the quenching fixture, a wire with the shape of an inverted U was screwed into two holes made on the ring.

Figure 4 shows the specimen used for the Jominy test.

Grossman Test Specimens: For the 4140 and 1095 steels, bars of 2-in. in diam and 8-in. in length were used. For the 9260 steel, bars of $1\frac{1}{4}$-in. in diam and 4-in. in length were used.

Thermocouples were accommodated in holes of 0.1065-in. diam (drill N° 36) drilled axially and at several distances from the center of the specimens to a depth midway along the length of the specimen.

Figure 5 shows the Grossman test specimen.

Measure of Temperature and Cooling Curves

Chromel-Alumel thermocouples of 24-gage wire were placed inside of porcelain insulator tubes of 0.094-in. diam. The whole assembling was inserted in the holes previously made on the test specimens and fixed fast by means of screws on the ring (Jominy test specimen) or by tying them with cromel wire to the U-shape wire (Grossman test specimen).

The temperature and cooling curves were recorded by two high-speed recorders: (1) a Honeywell model Electronic 194 recorder with two channels and (2) a H-W Packard model 680 with a single channel used at a chart velocity of

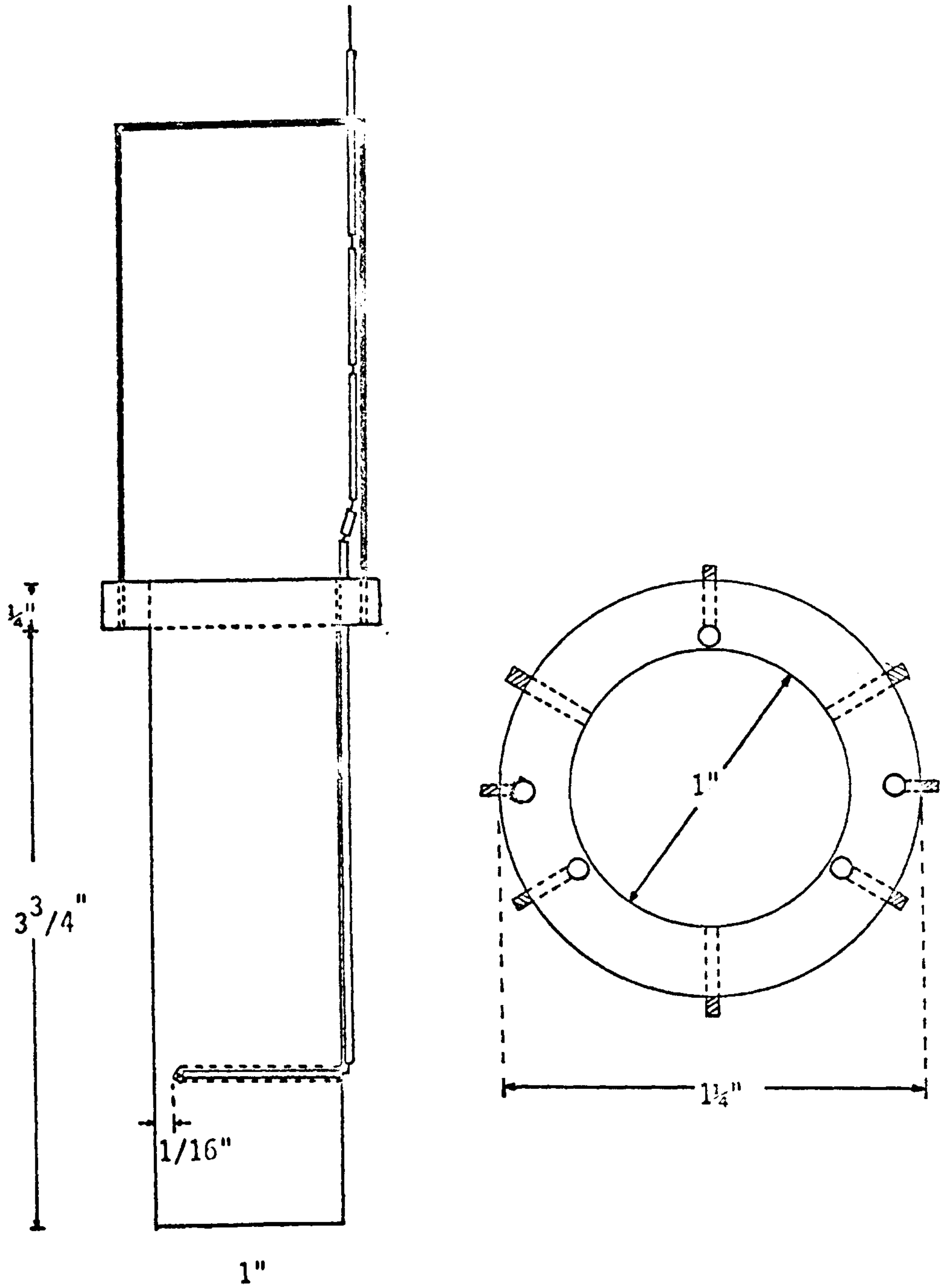


Figure 4. Jominy test specimen.

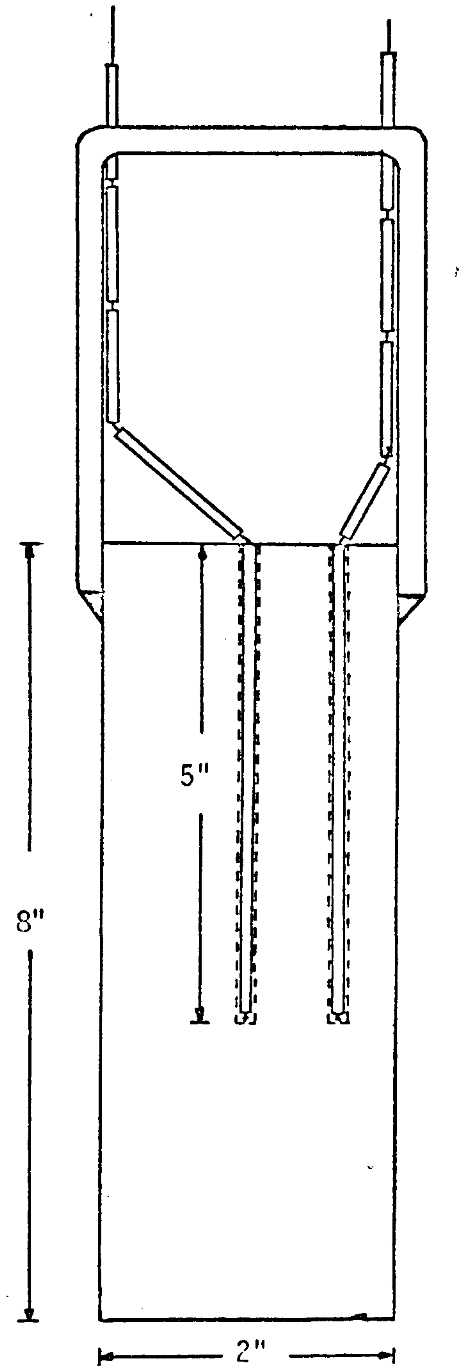


Figure 5. Grossman test specimen.

12 in./min for the first one and a velocity of 8 in./min for the second one.

Heat Treatment

Jominy Test: For the minimizing of oxidation and decarburization, the specimens were placed inside small boxes made up of stainless steel. Inside of the boxes, the specimens were surrounded with steel chips and small pieces of charcoal.

The specimens were heated in a glo-bar furnace, and placed in there when the furnace attained the austenitizing temperature, 1600°F for the three steels studied. The holding time of the steels at this temperature was 30 min.

After the austenitizing treatment, the specimens were removed from the furnace rapidly and quenched in water in the standard Jominy device[4, 5]. At this time, three operations were performed in the following order:

1) Set the recorders at the specified velocity.
2) Take the specimen from the furnace and place it in the Jominy device.
3) Open the water valve of the quenching fixture.

The time spent in the last two operations was not more than 5 sec. The specimens were quenched for 10 min, then, they were taken from the quenching fixture and completely inmersed in water.

This procedure was done following the recommendation of Birtalon and others[15]. They found that if reproductibility is to be achieved in the Jominy test, the following points should be observed:

1) The transfer time of the specimen from the furnace to the fixture is important because it affects the specimen surface temperature drop during this transfer, and the surface temperature at the time the quench is started, influences the rate of cooling of the surface. This transfer must be accomplished in 3 to 7 seconds.
2) The test bar should not form a scale to the point that the scale flakes from the bar during the quenching. When this happens, the end-quench test loses reproductibility.
3) The quench fixture should be designed to permit quick and accurate centering of the quench-end of the specimen over the water spray. This should be done in order to attain a uniform water flow over the quench-end and to avoid impingement of the water spray along the bar.

Grossman Test: Specimens were heated in the glo-bar furnace without protection against oxidation and decarburization. After the furnace attained the austenitizing temperature (1600°F), the specimens were placed in it and held at this temperature for 90 min for the 2-in.-diam

4140 and 1095 bars, and 30 min for the $1\frac{1}{4}$-in.-diam bar of 9260 steel.

After the austenitizing treatment, the specimens were rapidly removed from the furnace and quenched in the following way: 4140 steel, quenched in still air; 1095 steel, quenched in water without agitation; and 9260, quenched in quenching oil A without agitation.

The time spent in the quenching operation varied from a few minutes for the 1095 steel to an hour for the 4140 steel. The same three operations carried out in the Jominy test were also followed in this test.

Hardness Determination

Jominy Test Specimens: The quenched specimens were longitudinally ground with grinding belts along two opposite generatrices to a depth of an 1/16 in. Because the heating up of the specimens had to be avoided, the grinding belts were cooled with abundant water.

With this surface preparation, Rockwell-C hardnesses were taken at distances of 1/16 in. in the two opposite faces. Since several test specimens were used to take the cooling curve at different positions along the Jominy bar, hardness determination was done in each of them and the results of each point were averaged.

Grossman Test Specimens: The quenched specimens were sectioned with a water-cooled abrasive wheel at the points where the thermocouples were located. Special care was taken in this operation due to the possibility of burning out the sample.

The samples were then ground down with belts sander which were water-cooled, until a flat surface was obtained.

Rockwell-C hardness readings were taken along several diameters of each sample at intervals of 1/8 in. The readings at equivalent radius of each sample were averaged.

Metallographic Studies

The Jominy test specimens were cut at a distance of 1½ in. from the quenched end with a water-cooled abrasive wheel. The generatrix faces, where Rockwell-C hardness readings were taken previosly, were repolished. The polishing treatment consisted of these steps: (1) grinding with belts; (2) grinding with emery papers 1, 0, 00, 000, and 0000; (3) polishing with alumina N° 1 and AB selyt cloth; and (4) polishing with alumina N° 3 and AB selvyt cloth.

The Grossman test specimens were repolished with the grinding belts at the surface where the Rockwell-C hardness was taken. The polishing treatment of the samples was the same as that for the Jominy test specimens.

The etching reagents used on the specimens were sodium metabisulfite (1 g $Na_2S_2O_5$, dilute to 100 ml with distilled water) and 2% nital.

The microscopic studies were conducted on a Bausch & Lomb metallograph and on a Vickers Projection microscope.

All this work was conducted in the Physical Metallurgy laboratory facilities of the Metallurgical Engineering Department of the Colorado School of Mines.

RESULTS

1095 Steel

Jominy Test: Cooling curves were obtained at points along the axis of the Jominy test specimen at distances of 1/8, 1/4, 1/2, 3/4, 1, 1¼, 2, 2¼ in. from the quenched end (Figures 6 and 7). The cooling curves for points at 2, 2¼, and 2½ in. from the quenched end show that at slow rates of cooling there was heat evolution due to the change of phase, austenite to pearlite, when the steel reached the beginning line (1% transformation) of the continuous cooling transformation diagram.

A graph of the measured and calculated hardness in Rockwell-C units versus distance from quenched end of the Jominy test specimen was made (Figure 8). A maximum difference of 4 Rockwell-C units was found between the measured and calculated hardness at a point 1/4 in. from the quenched end. In general, the calculated hardness line lies at plus or minus 3 Rockwell-C units from the

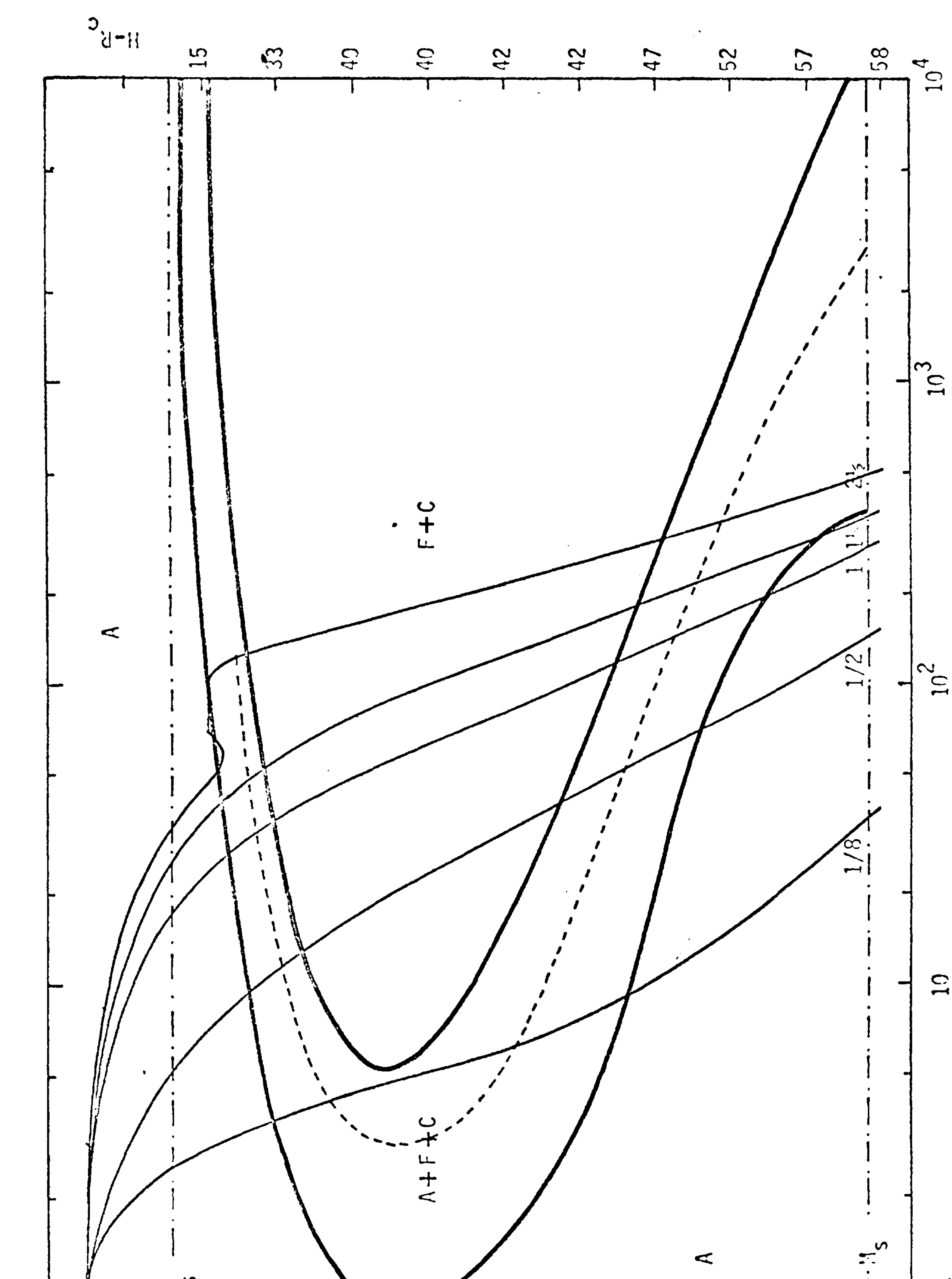


Figure 6. Cooling curves at distances of 1/8, 1/2, 1, 1½, and 2½ in. from the quenched end of a Jominy specimen. 1095 steel.

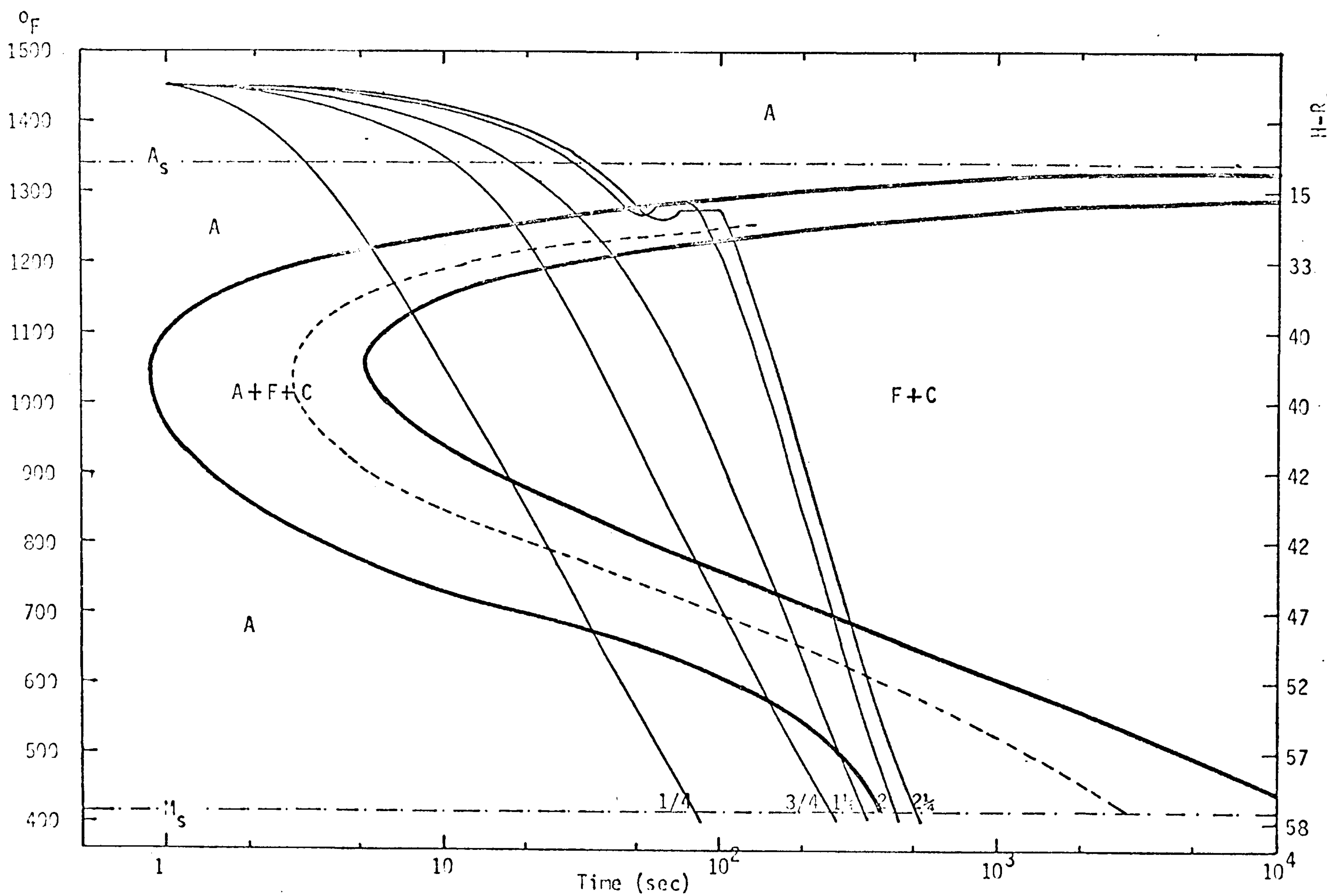


Figure 7. Cooling curves at distances of 1/4, 3/4, 1½, 2, 2¼ in. from the quenched end of a Jominy specimen. 1095 steel.

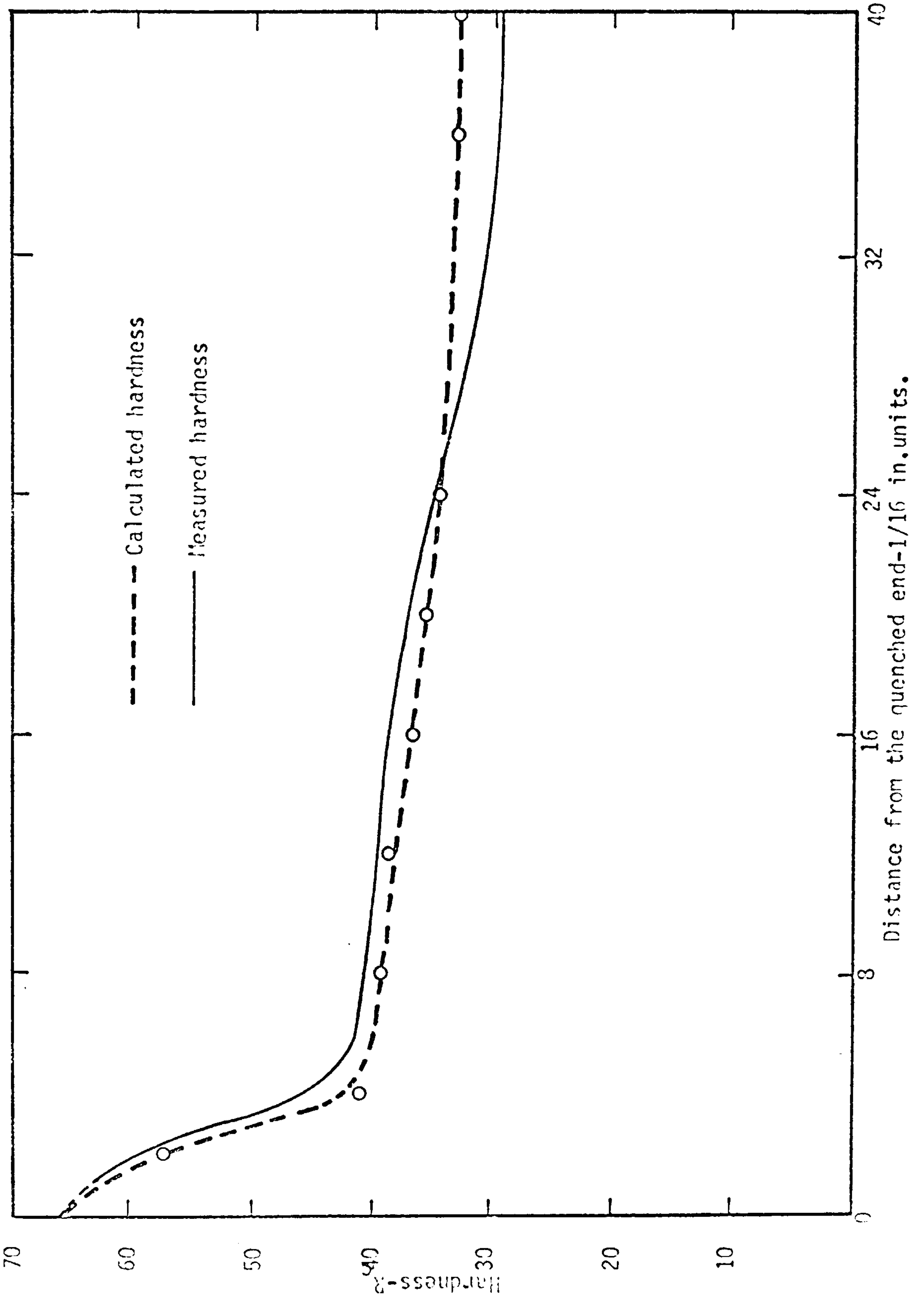


Figure 8. Jominy curve, 1095 steel.

measured hardness.

Grossman Test: Cooling curves were obtained at points across the diameter of a 2-in.-diam bar at distances of 0/8, 3/8, 4/8 and 6/8 in. from the center of the bar which was quenched in water without agitation (Figure 9).

A graph of the measured and calculated hardness in Rockwell-C units versus distance from the center of the bar is shown in Figure 10. At the point 4/8 in. from the center of the bar, the calculated hardness is 4 Rockwell-C units below the measured hardness whereas at the point 6/8 in. from the center of the bar, the calculated hardness is 4.5 Rockwell-C units above the measured hardness.

The results show in Figure 8 and Figure 10 demonstrate that the proposed method for calculating the composite hardness gives very accurate results for the steel studied since a small difference (4.0 Rockwell-C units) between the predicted and calculated hardness was found.

Metallographic Studies: The progress of the transformation along the Jominy test specimen is shown in Figures 11, 12, 13, 14, 15, and 16. It was observed that a very sudden change in the microstructure occurs at distances between 1/8 in. and 7/32 in. from the quenched end where the structure changes from 100% martensite (1/8 in.) to 100% pearlite (7/32 in). This observation

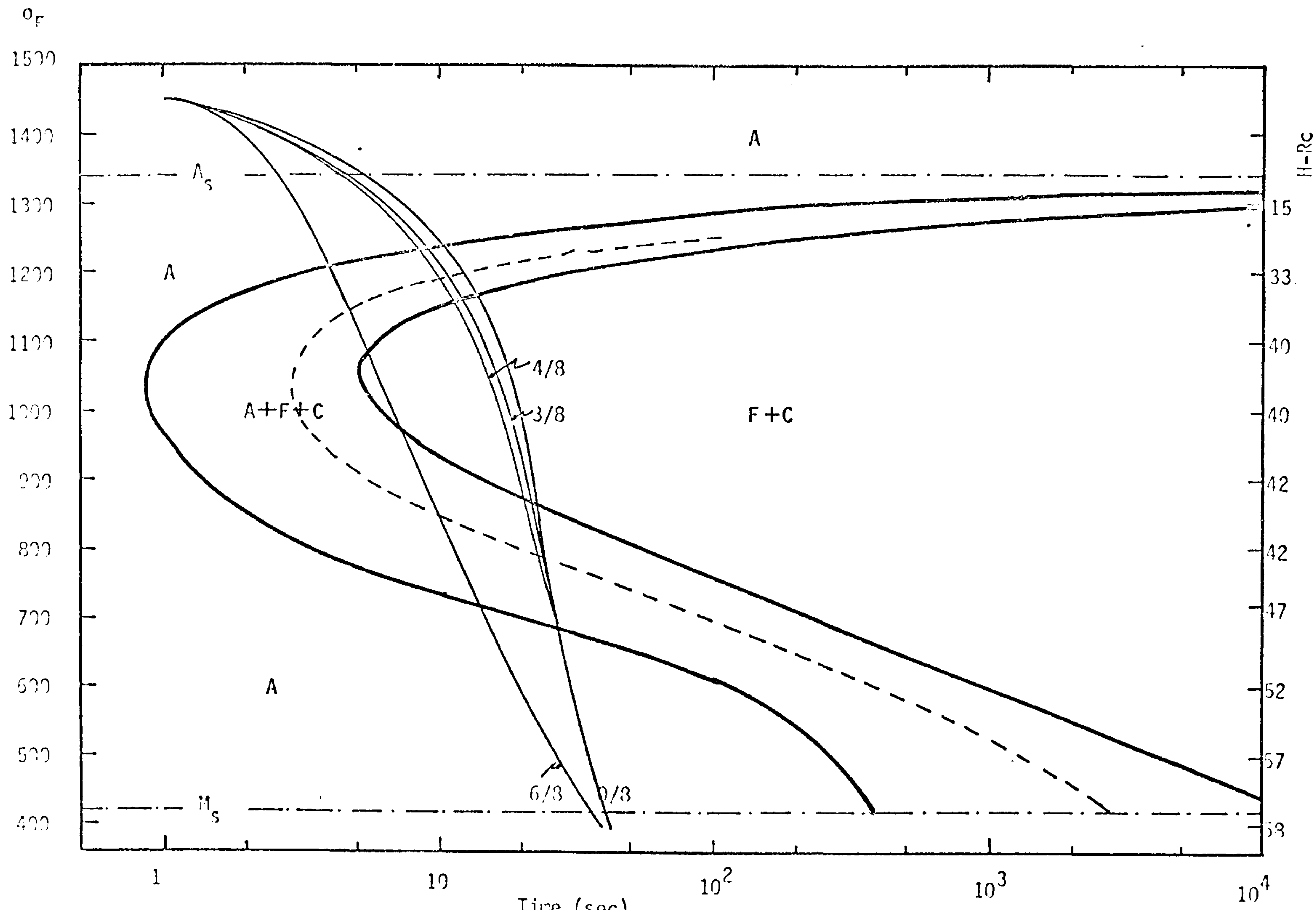
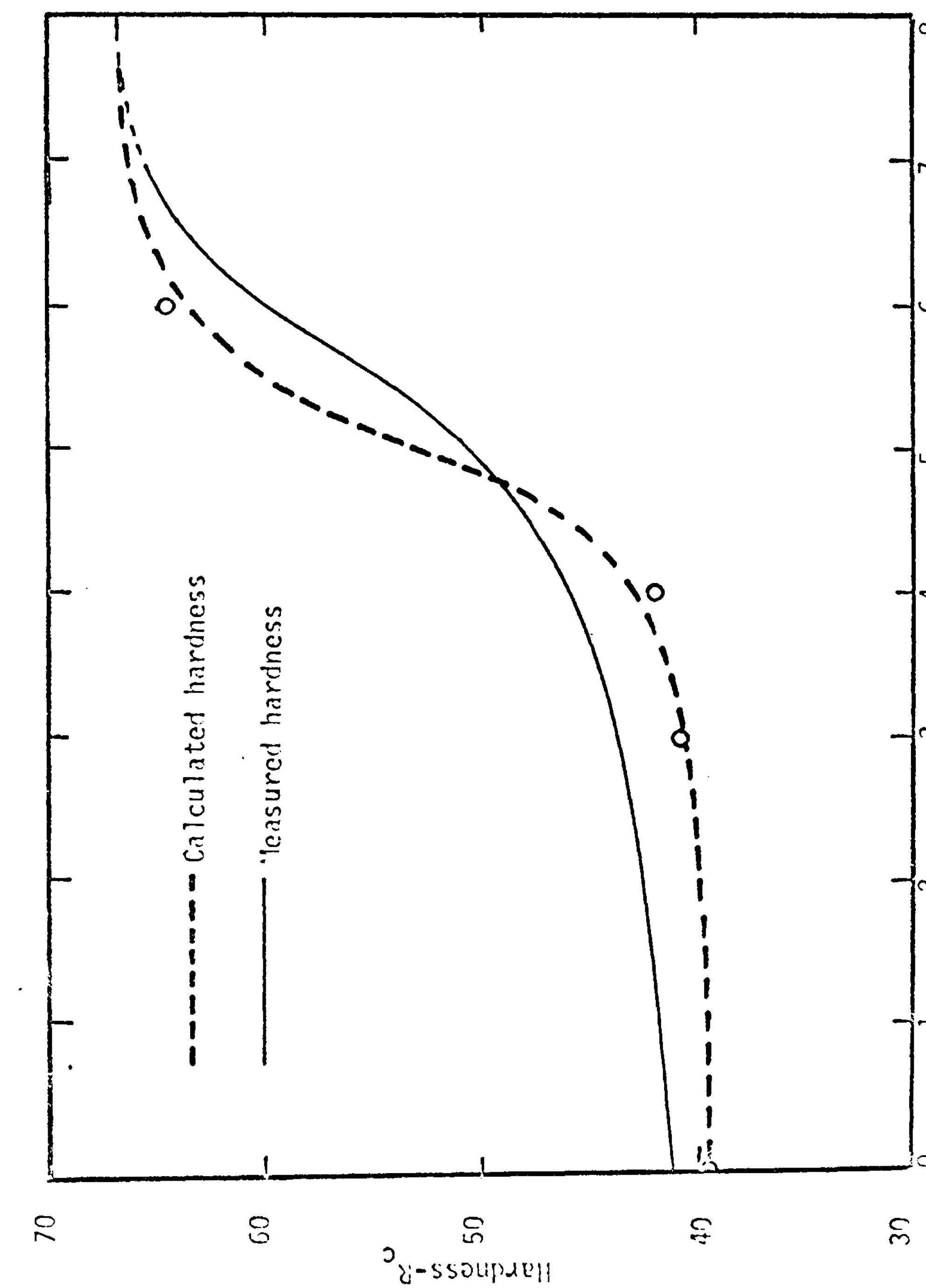


Figure 9. Cooling curves at distances of 0/8, 3/8, 4/8, and 6/8 in. from the center of a 2-in. diam bar quenched in water. 1095 steel.



Distance from the center -1/8 in. units.

Figure 10. Grossman curves. 1095 steel.

Figure 11. Microstructure at 1/8 in. from the quenched end of the Jominy bar. 1095 steel 100% martensite. X570.

Figure 12. Microstructure at 1/8 in. from the quenched end of the Jominy bar. Same area as shown in Figure 11. 1095 steel. 100% martensite. X 1320.

Figure 13. Microstructure at 5/32 in. from the quenched end of the Jominy bar. 1095 steel. Martensite and pearlite. X 570.

Figure 14. Microstructure at 5/32 in. from the quenched end of the Jominy bar. Same area as shown in Figure 13. 1095 steel. One pearlite nodule and martensite. X 1320.

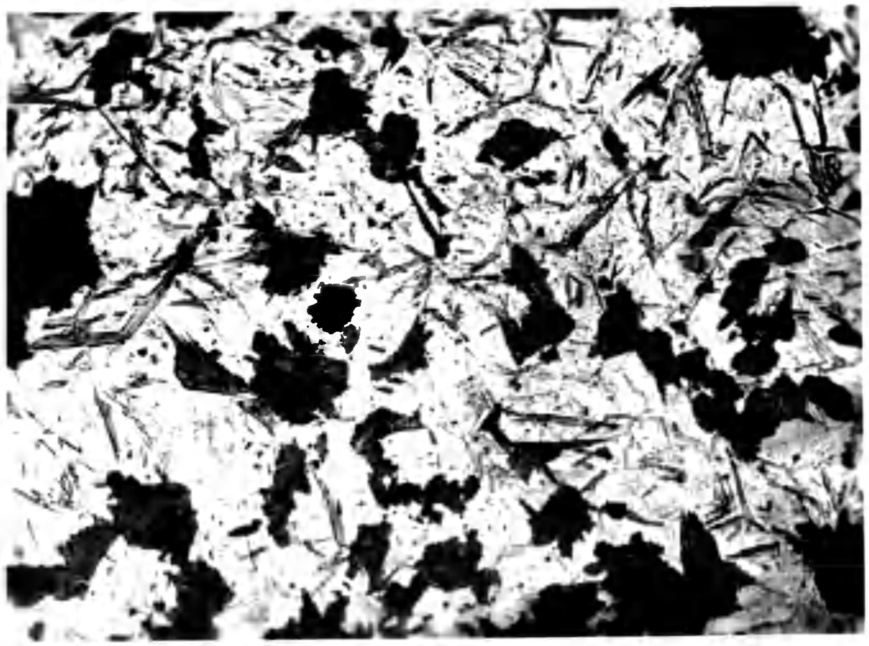


Figure 15. Microstructure at 3/16 in. from the quenched end of the Jominy bar. 1095 steel. Pearlite and martensite. X 570.

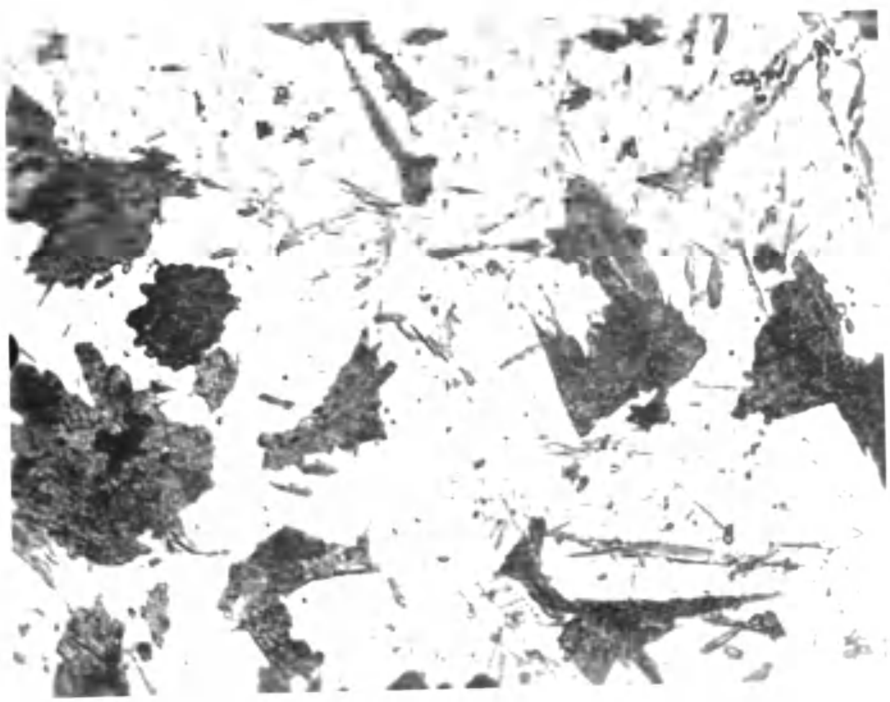


Figure 16. Microstructure at 3/16 in. from the quenched end of the Jominy bar. Same area as shown in Figure 15. 1095 steel. Pearlite and martensite. X 1320.

is in agreement with a both the calculated and measured hardness curves where the hardness changes from 57 to 40 Rockwell-C units for the respective points. The same sudden change in the microstructure was also found in the 2-in.-diam bar.

The proposed methods for calculating the composite hardness also allows the prediction of the relative amount of microconstituents. Attempts to determine the percentages of each phase were made. The results obtained with the lineal analysis method[18] for determination of the relative amount of phases present indicates a discrepancy of 15% of the values predicted by the proposed method. This discrepancy was believed to be due to the difficulty in determining whether the structure of the platelets seen under the microscope were complete martensitic, or a mixture of martensite and bainite, or martensite and pearlite.

<u>4140 Steel</u>

<u>Jominy Test:</u> Cooling curves were measured at points along the axis of the Jominy test specimen at distances of 1/4, 1/2, 3/4, 1, 1¼, 2, 2¼, and 2½ in. from the quenched end. These cooling curves are shown in Figures 17 and 18.

None of the measured cooling curves for this steel show the flat part presented by some of the cooling curves for the 1095 steel. This should be due to the fact that

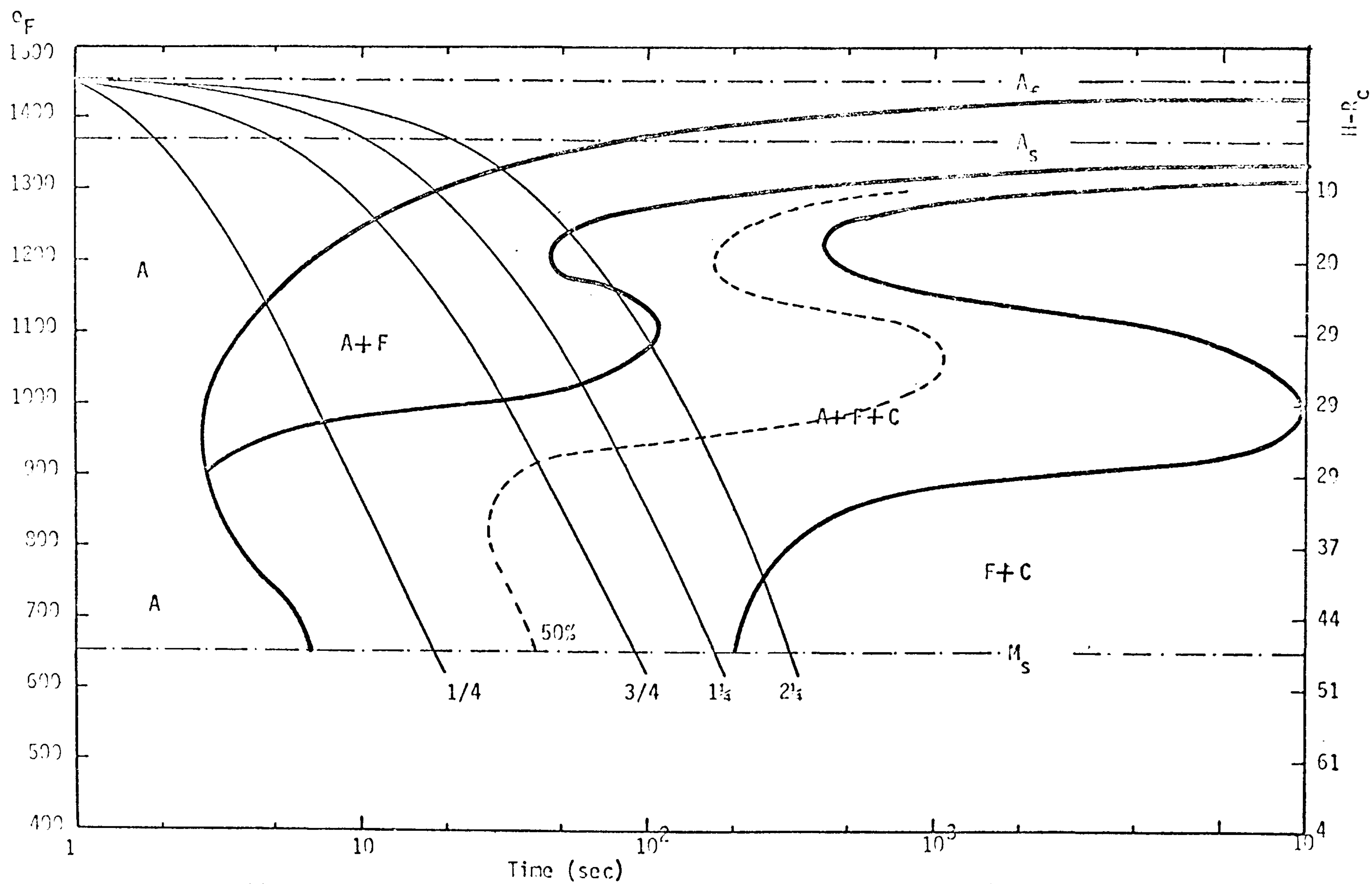


Figure 17. Cooling curves at 1/4, 3/4, 1¼, and 2¼ in. from the quenched end of a Jominy specimen. 4140 steel.

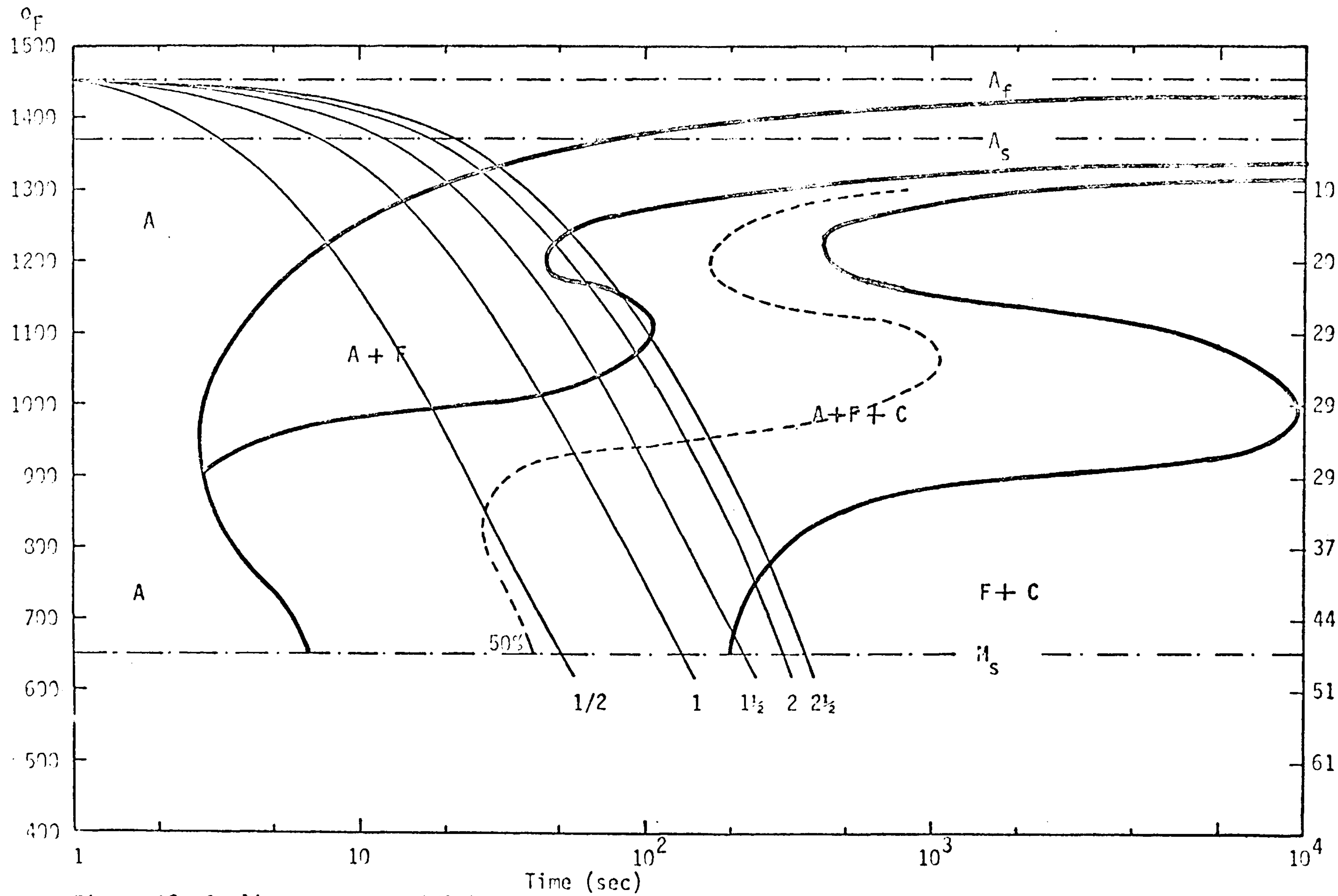


Figure 18. Cooling curves at 1/2, 1, 1½, 2, and 2½ in. from the quenched end of a Jominy specimen. 4140 steel.

none of them crossed the divisory line, austenite pearlite, in the continuous cooling transformation diagram.

A graph of the measured and calculated hardness in Rockwell-C units versus distance from the quenched end of the Jominy test specimen is shown in Figure 19. For distances between zero and 3/4 in. from the quenched end, the calculated hardness curve almost coincides (1.0 Rockwell-C unit) with the measured hardness curve; it lies above the measured hardness curve by 2.0 Rockwell-C units for distances between 1.0 and 2.0 in. from the quenched end. At distances between 2.0 and 2.5 in. from the quenched end, the calculated hardness curve lies 1.0 Rockwell-C unit above the measured hardness curve, and for distances larger than 2.5-in. from the quenched end, there is a tendency for both curves to coincide.

Grossman Test: Cooling curves were measured at points across the diameter of a 2-in.-diam bar at distances of 0/8, 2/8, 3/8, 4/8, 6/8 and 7/8 in. from the center of the bar which was quenched in still air. The cooling curves for all of the points measured were the same as shown in Figure 20.

A plot of the measured and calculated hardness in Rockwell-C units versus distance from center of the bar is shown in Figure 21. The calculated hardness curve lies

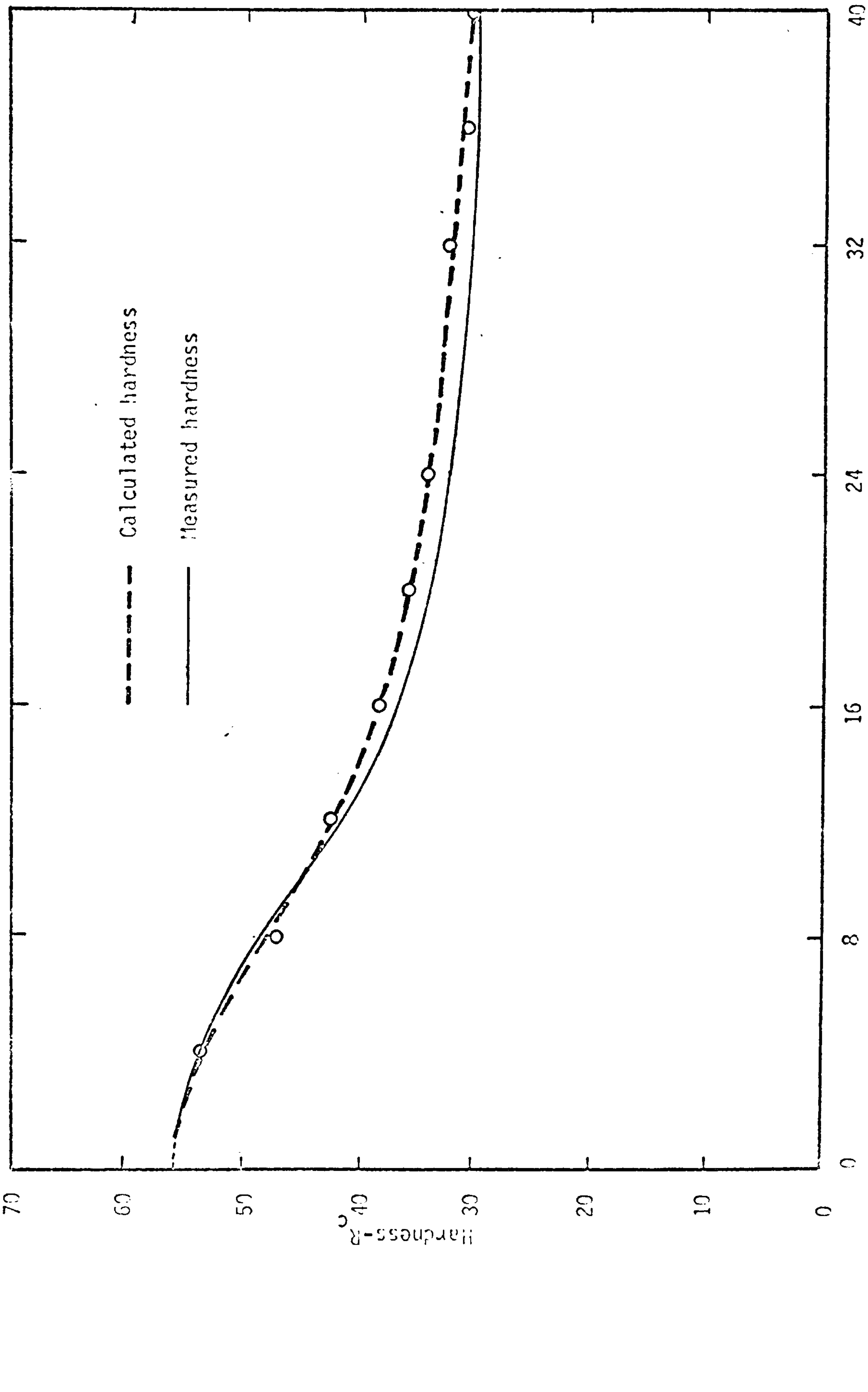


Figure 19. Jominy curve. 4140 steel.

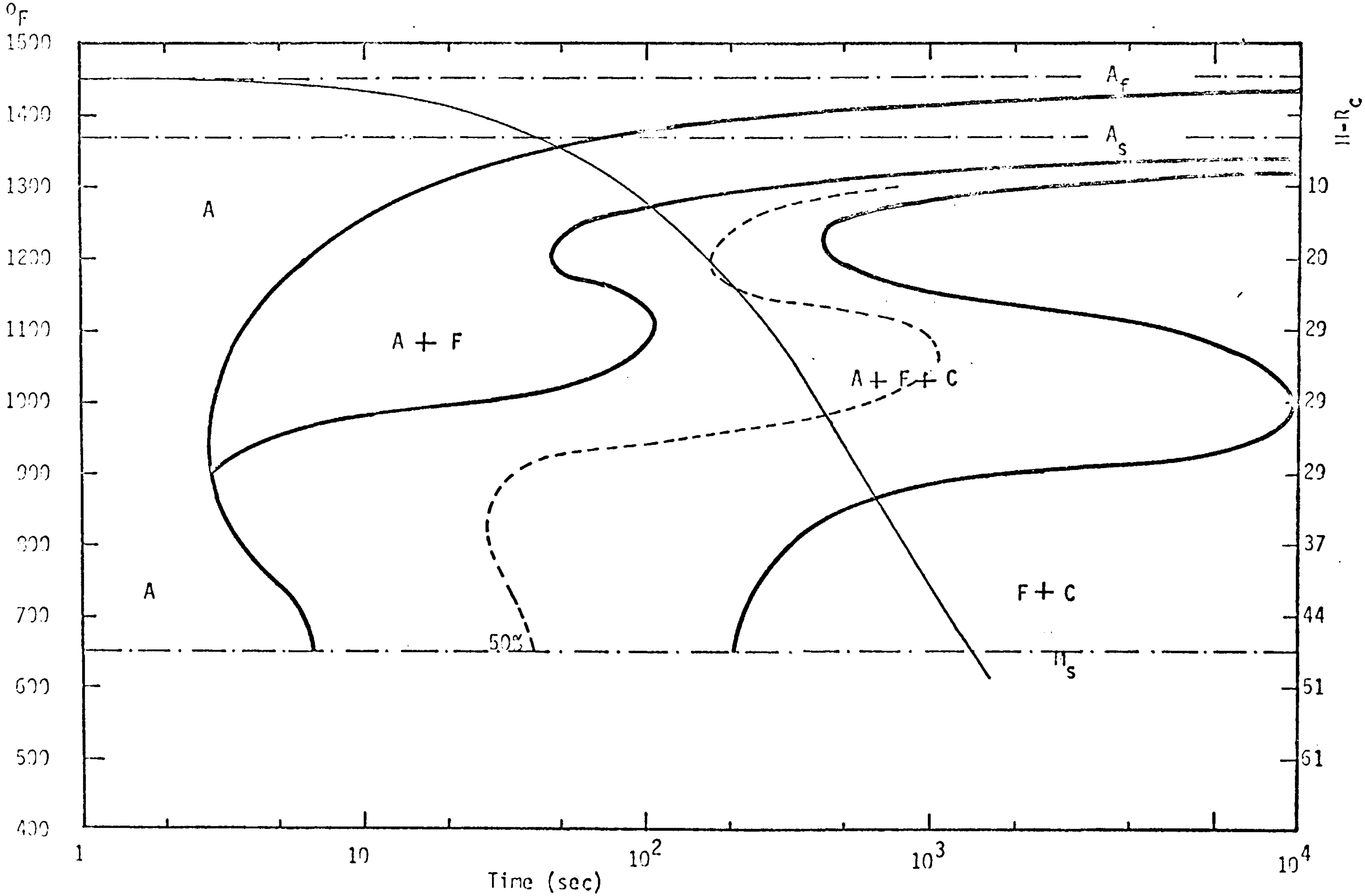
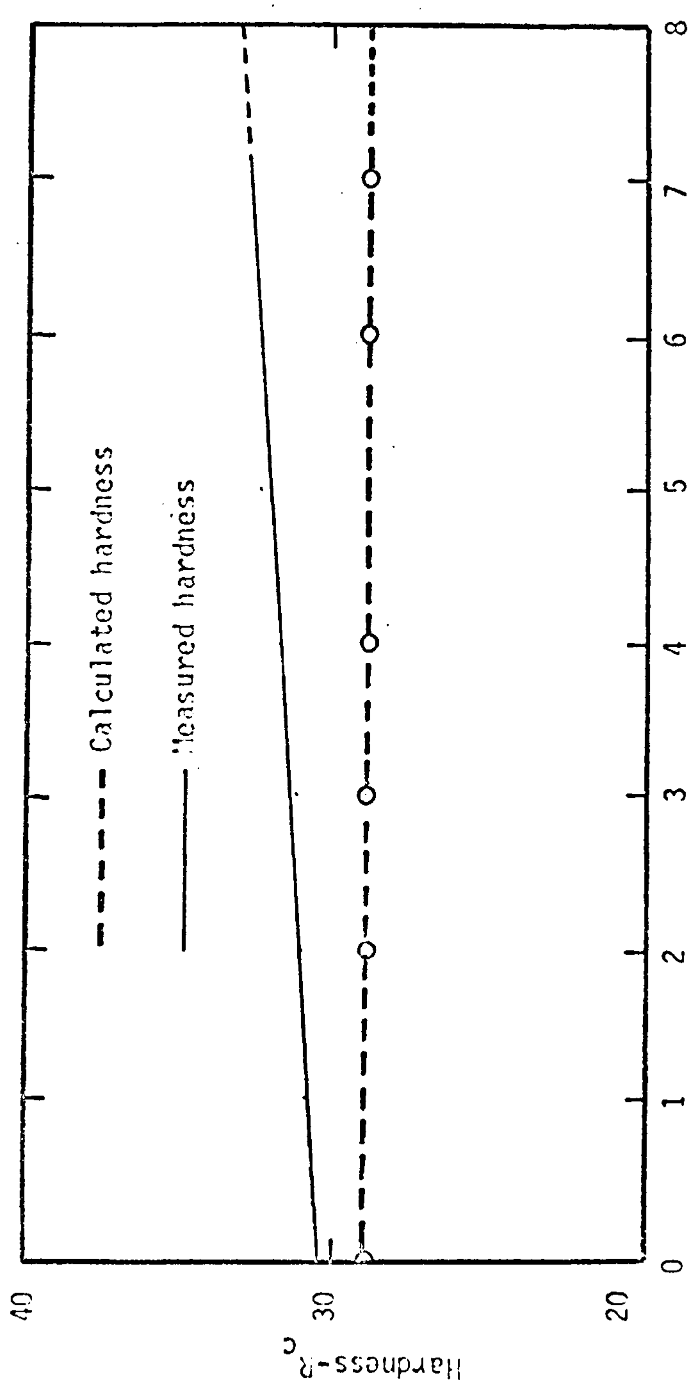


Figure 20. Cooling curves at distances of 0/8, 2/8, 3/8, 4/8, 6/8, and 7/8 in. from the center of a 2-in. diam bar quenched in still air. 4140 steel.



Distance from the center-1/8 in. units.

Figure 21. Crossman curves. 4140 steel.

below the measured hardness curve by 1.5 Rockwell-C units at the center of the bar and by 4.0 Rockwell-C units at a distance of 7/8 in. from the center of the bar.

The results obtained in both the Jominy test and in the Grossman test show a very good agreement between the calculated and measured hardness for this steel.

Metallographic Studies: The progress of the transformation along the Jominy test specimen is show in Figures 22, 23, 24, 25, and 26. As the photomicrographs show, the amount of bainite was gradually increasing from a few percent at 1/2 in. from the quenched end to a structure almost completly bainitic at 1¼ in. from the quenched end.

The use of the lineal analysis method for determination of the relative percentages of each phase failed again in this steel. As the microstructures show, even working at relative high magnifications, the identification of each phase was very difficult and a high degree of uncertainty exist in this identification.

9260 Steel

Jominy Test: Cooling curves were obtained at points along the axis of the Jominy test specimen at distances of 1/8, 1/4, 1/2, 1, 1¼, 2, and 2¼ in. from the quenched

Figure 22. Microstructure at 1/4 in. from the quenched end of the Jominy bar. 4140 steel. 100% martensite. X 1320.

Figure 23. Microstructure at 1/2 in. from the quenched end of the Jominy bar. 4140 steel. Martensite and bainite (dark). X 1320.

Figure 24. Microstructure at 3/4 in. from the quenched end of the Jominy bar. 4140 steel. Martensite and bainite (dark). X 1320.

Figure 25. Microstructure at 1 in. from the quenched end of the Jominy bar. 4140 steel. Mostly bainite (dark) and small quantities of martensite. X 1320.

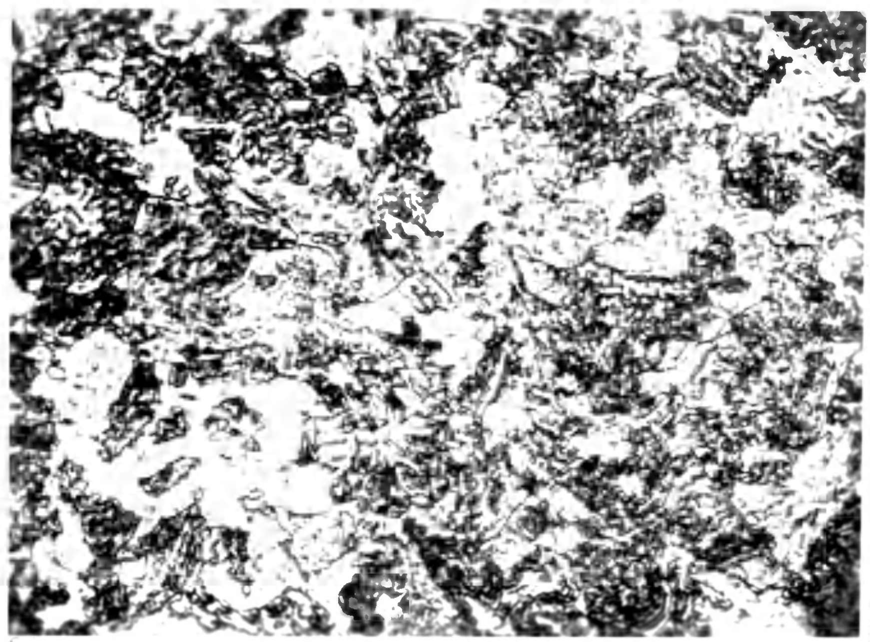


Figure 26. Microstructure at 1¼ in. from the quenched end of the Jominy bar. 4140 steel. Mostly bainite and a few percents of martensite. X 1320.

end. These cooling curves are shown in Figures 27 and 28. The cooling curves for the points $1\frac{1}{2}$, 2, and $2\frac{1}{4}$ in. from the quenched end present a flat part near the line of 99% of transformation in the isothermal transformation diagram. The same shape of curves was also found in the 1095 steel. The same reasoning used to explain this change in the shape of the cooling curves for the 1095 steel is also valid for the 9260 steel.

The measured and calculated hardness in Rockwell-C units was plotted as a function of the distance from the quenched end of the Jominy test specimen (Figure 29). For distances between 5/16 in. and 3/4 in. from the quenched end, the calculated hardness curve lies above the measured hardness curve. At the point 1/2 in. from the quenched end, a difference of 9 Rockwell-C units between the calculated and measured hardness was found. For distances larger than 3/4 in. from the quenched end, the measured and calculated hardness curves practically coincide.

Grossman Test: Cooling curves were obtained at points across the diameter of a $1\frac{1}{4}$-in.-diam bar at distances of 0/8, 1/8, 3/8, and 9/16 in. from the center of the bar which was quenched in quenching oil without agitation (Figure 30).

A plot of the measured and calculated hardness in Rockwell-C units versus distance from the center of the

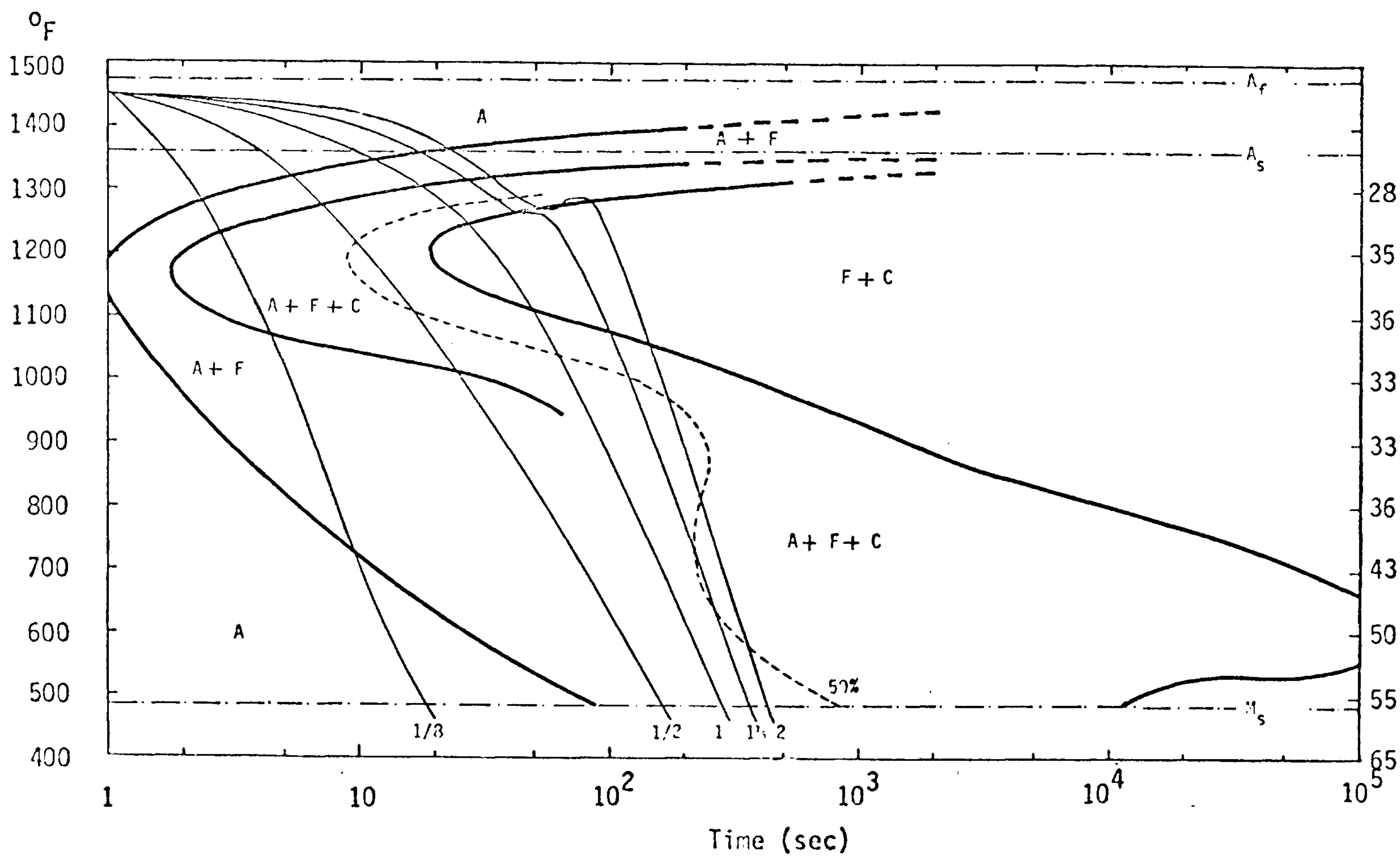


Figure 27. Cooling curves at distances of 1/8, 1/2, 1, 1½, and 2-in. from the quenched end of a Jominy specimen. 9260 steel.

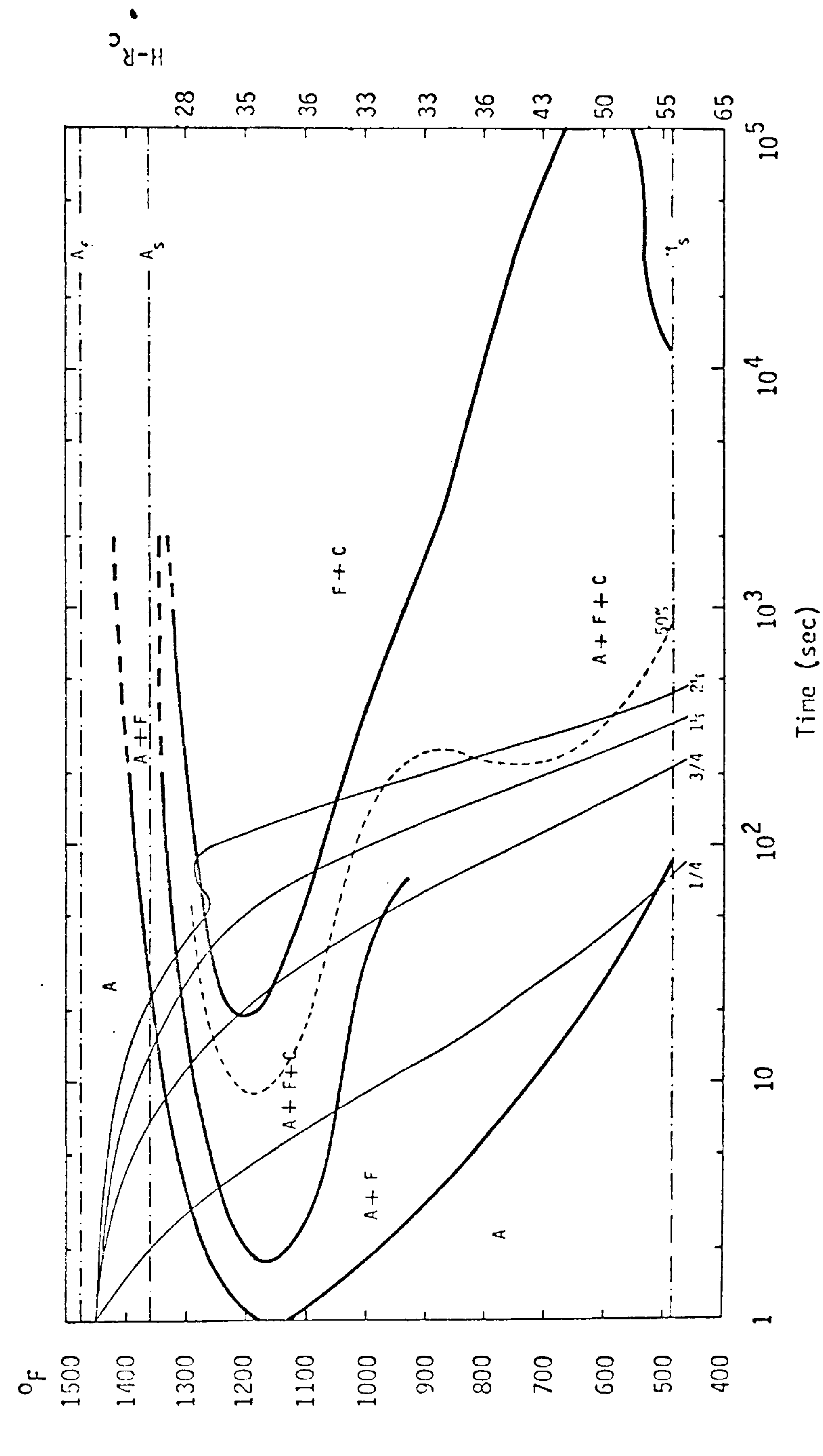


Figure 28. Cooling curves at distances of 1/4, 3/4, 1¼, and 2¼ in. from the quenched end of a Jominy specimen. 9260 steel.

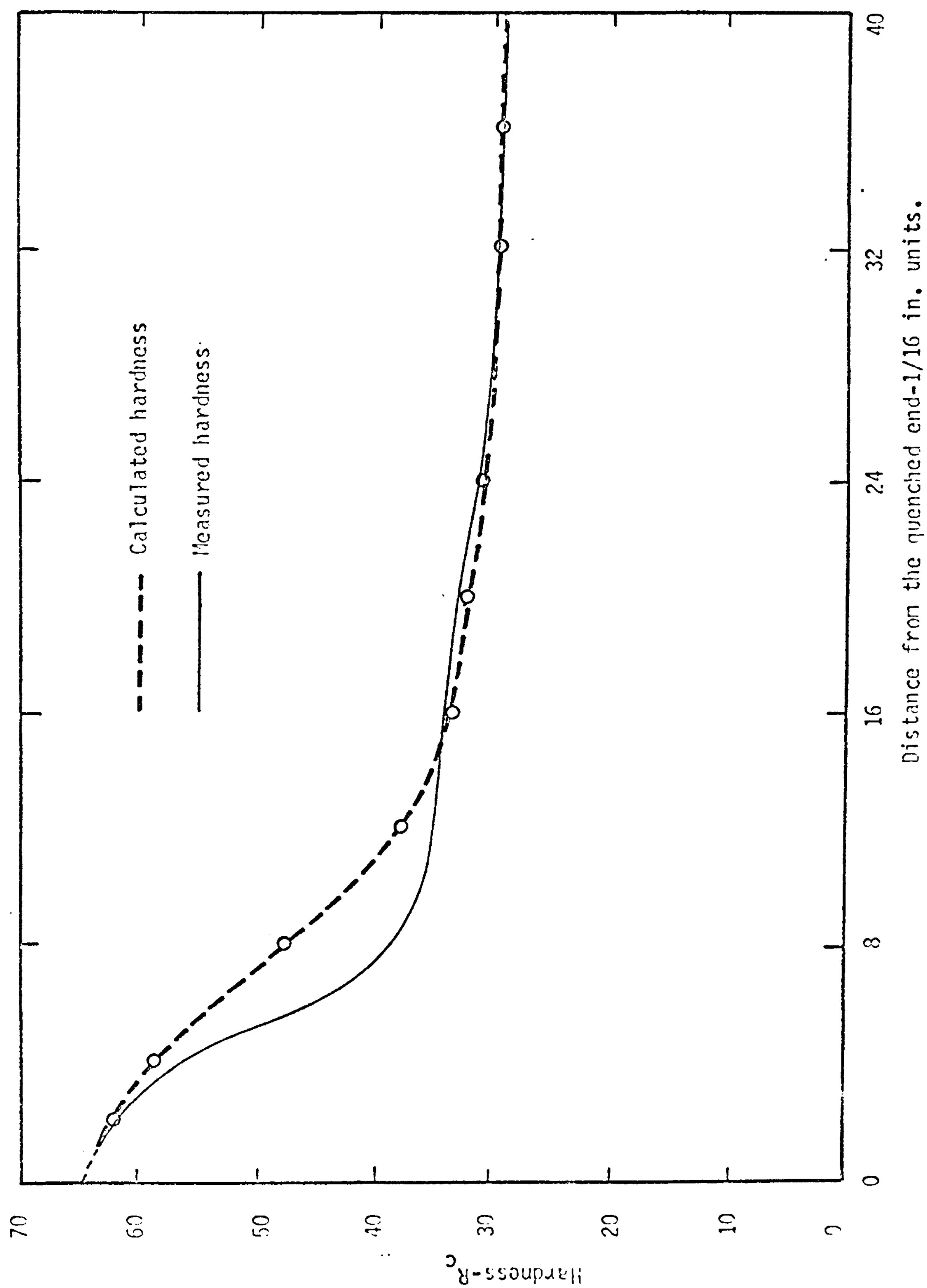


Figure 29. Jominy curves. 9260 steel.

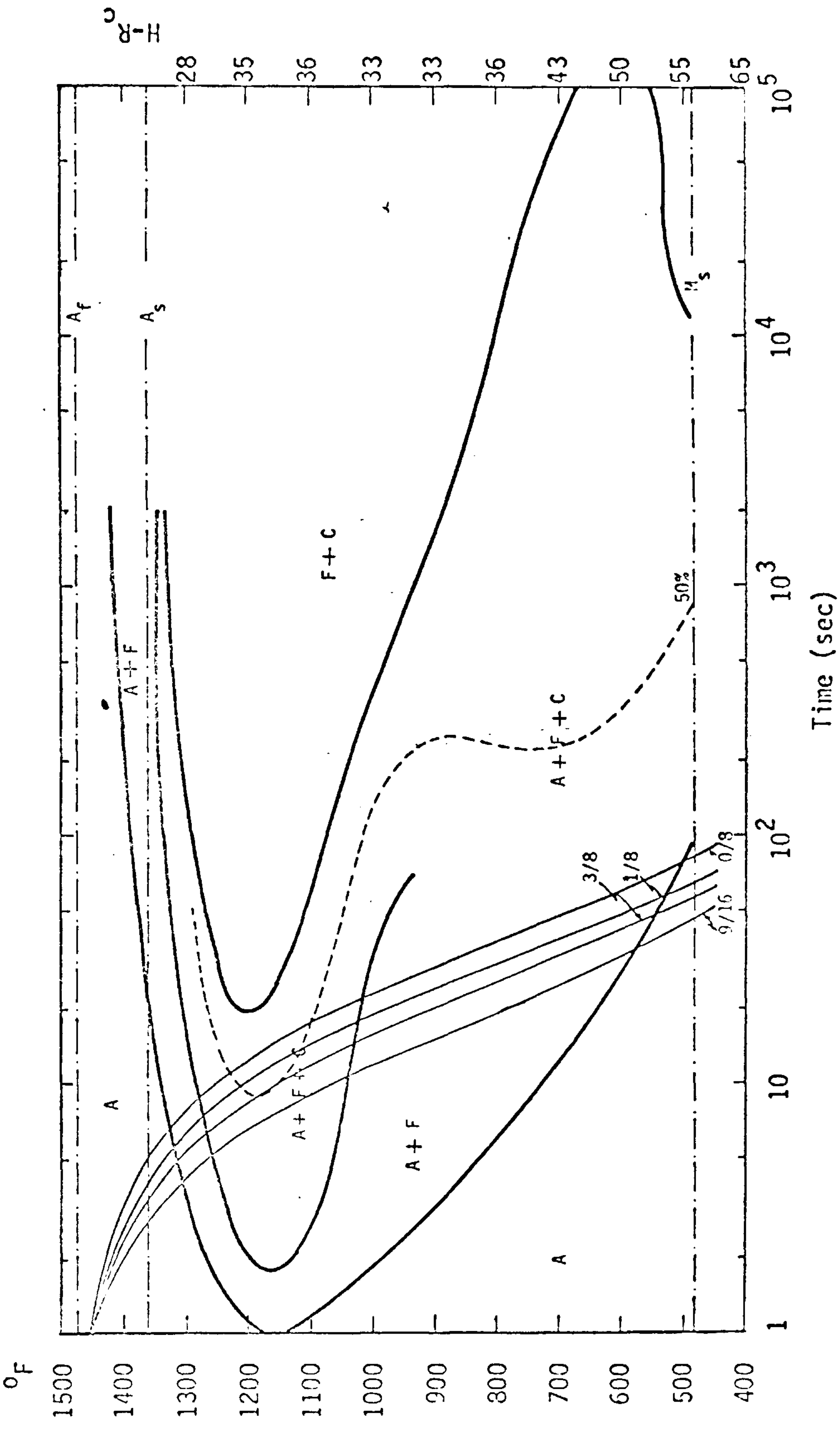


Figure 30. Cooling curves at 0/8, 1/8, 3/8, and 9/16 in. from the center of a 1¼-in. diam bar quenched in oil. 9260 steel.

bar is shown in Figure 31. The calculated hardness curve lies above the measured hardness curve by 5.5 Rockwell-C units at the center of the bar and by 4.0 Rockwell-C units at a distance of 9/16 in. from the center of the bar..

Metallographic Studies: The progress of the transformation along the Jominy test specimen is shown in Figures 32, 33, 34, 35, 36, 37, 38, and 39. At distance of 1/4 in. from the quenched end, ferrite started to nucleate at the grain boundaries of the prior austenite grains as shown in Figure 32 and Figure 33. This finding confirms al least in part one of our previous assumptions, namely, that the nucleation is exclusively at the grain boundaries. For distances farther than 1/4 in. from the quenched end, pearlite is formed (Figures 34 and 35) and increases in quantity as long as the distance from the quenched end is increased. At 3/4 in. from the quenched end the transformation is wholly to pearlite.

Correlation Between Jominy Test and Grossman Test in Terms of the Ideal Critical Diameter.

From the data obtained, it was possible to correlate the ideal critical diameter calculated from the Jominy test to the ideal critical diameter calculated from the Grossman test for the 1095 and 9260 steels. The cooling curve obtained at the center of the round bars of the Grossman

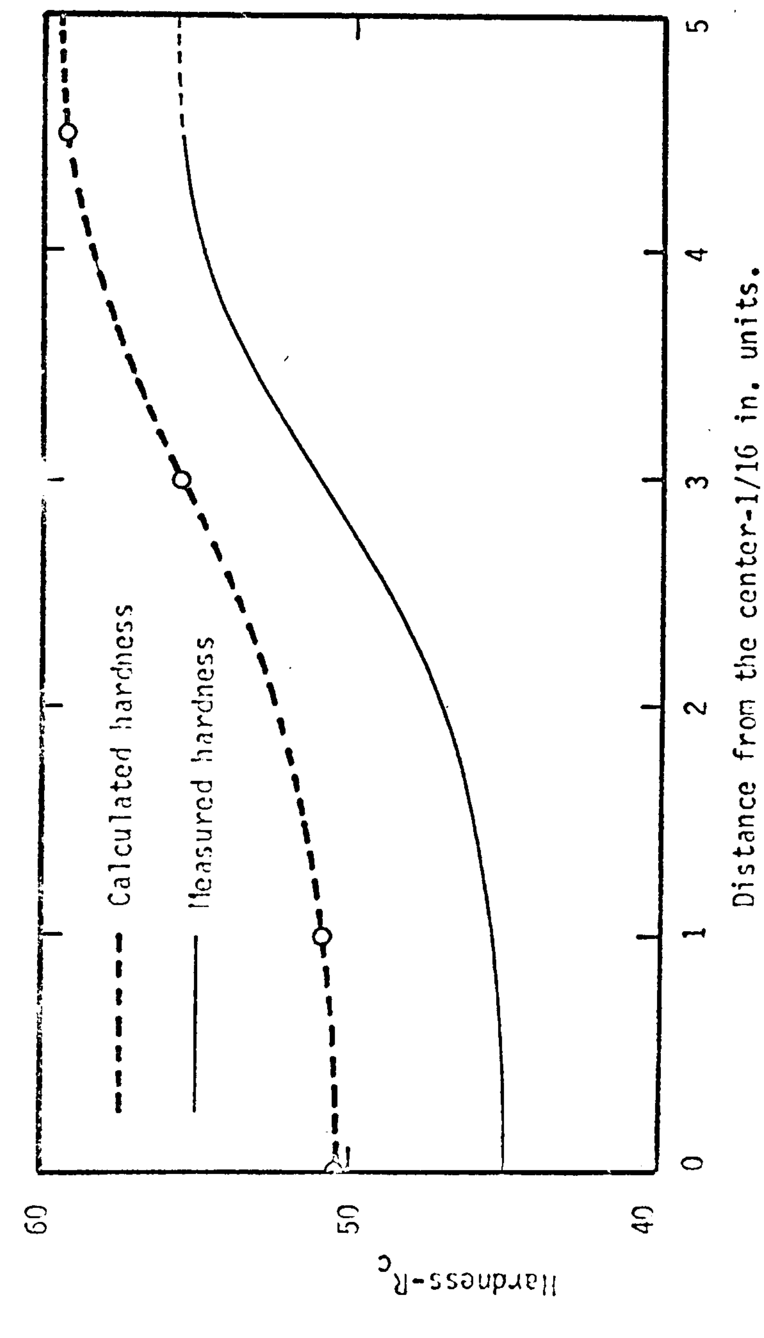


Figure 31. Grossman curves. 9260 steel.

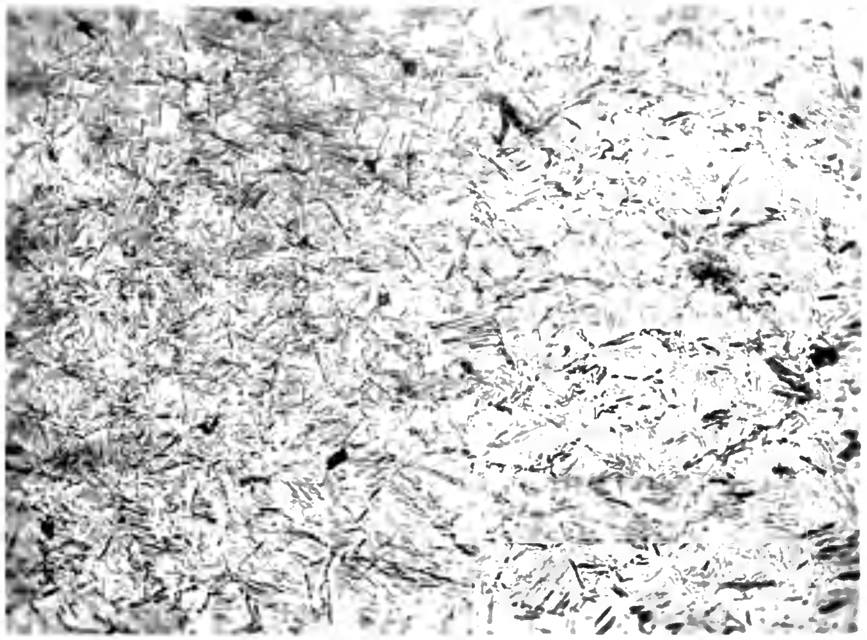


Figure 32. Microstructure at 1/4 in. from the quenched end of the Jominy bar. 9260 steel. Martensite and small pools of ferrite nucleated in prior austenite grain boundaries. X 570.

Figure 33. Microstructure at 1/4 in. from the quenched end of the Jominy bar. 9260 steel. Same area as in Figure 32. Martensite and ferrite pools. X 1320.

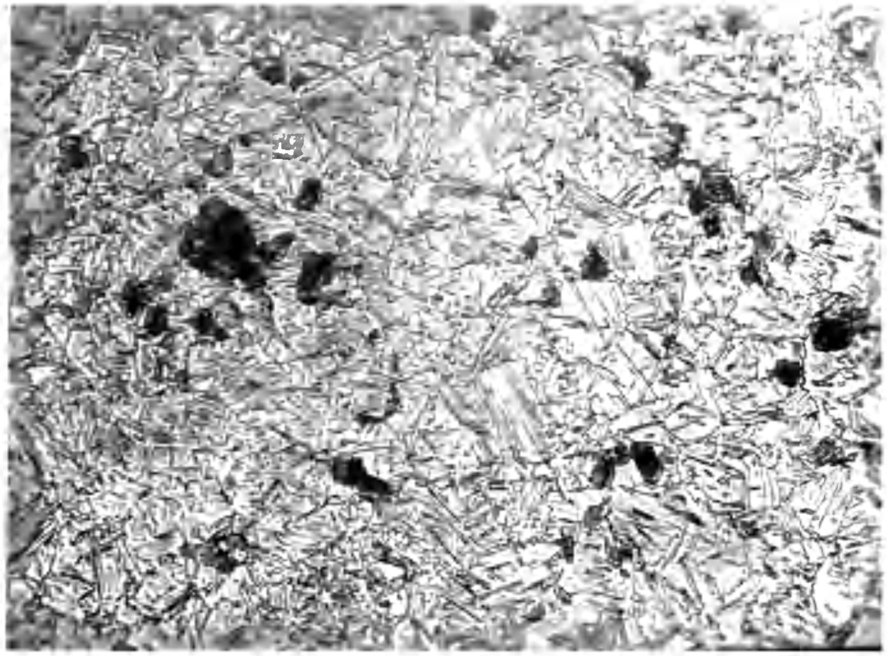


Figure 34. Microstructure at 3/8 in. from the quenched end of the Jominy bar. 9260 steel. Martensite, pearlite and ferrite. X 570.

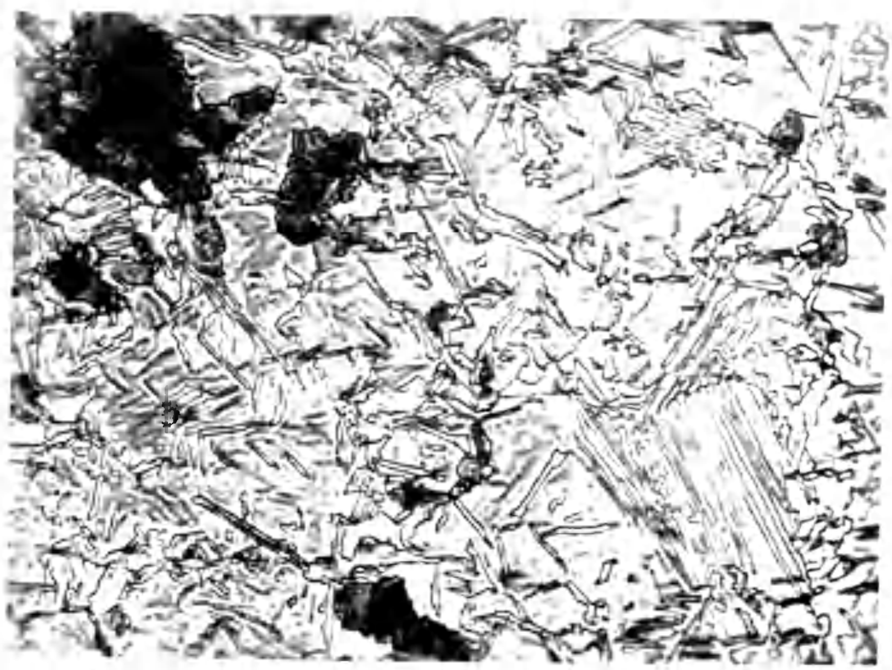


Figure 35. Microstructure at 3/8 in. from the quenched end of the Jominy bar. Same area as in Figure 34. 9260 steel. Martensite, pearlite and ferrite. X 1320.

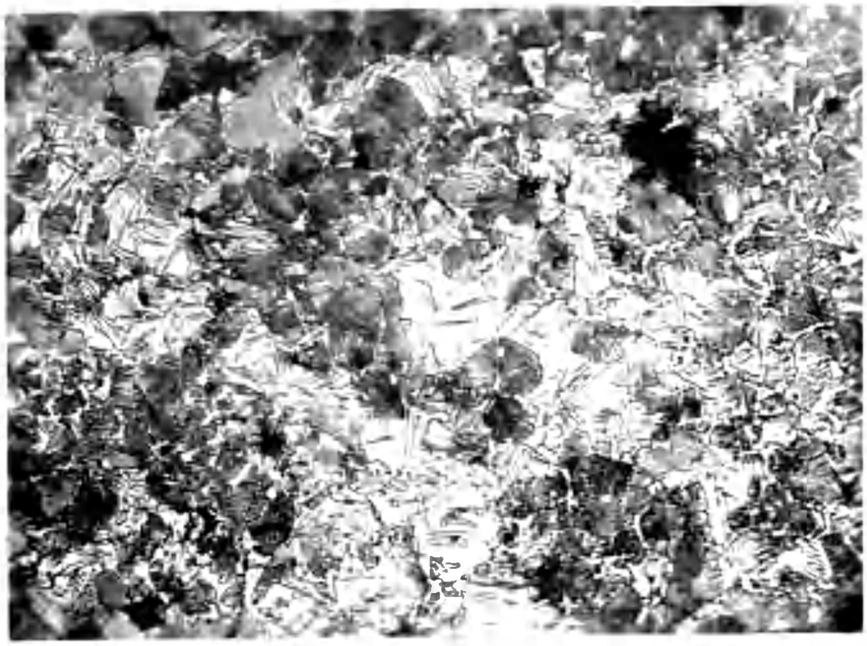


Figure 36. Microstructure at 1/2 in. from the quenched end of the Jominy bar. 9260 steel. Larger amounts of pearlite (dark), martensite and ferrite. X 570.

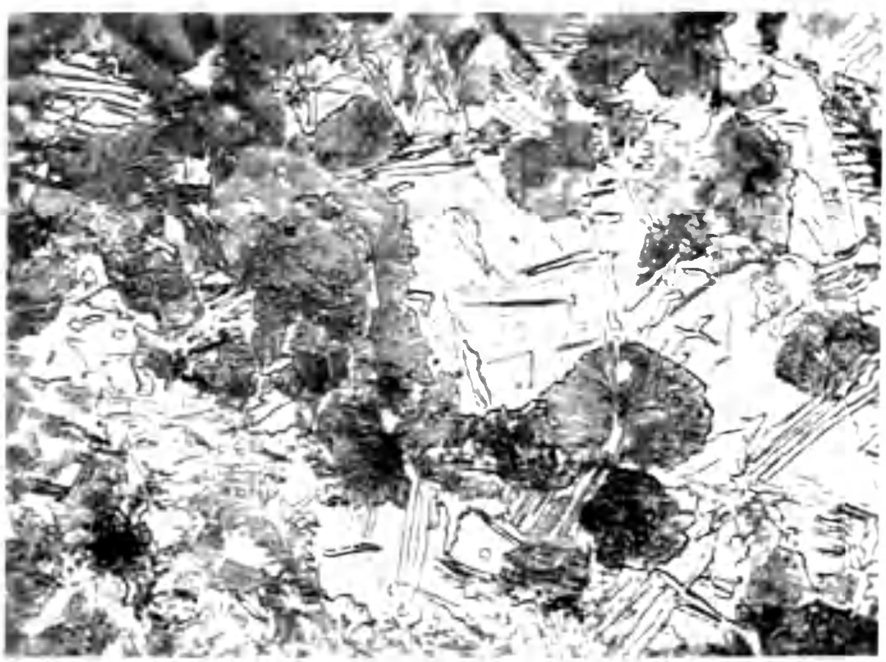


Figure 37. Microstructure at 1/2 in. from the quenched end of the Jominy bar. Same area as in Figure 36. 9260 steel. Pearlite, martensite and ferrite. X 1320.

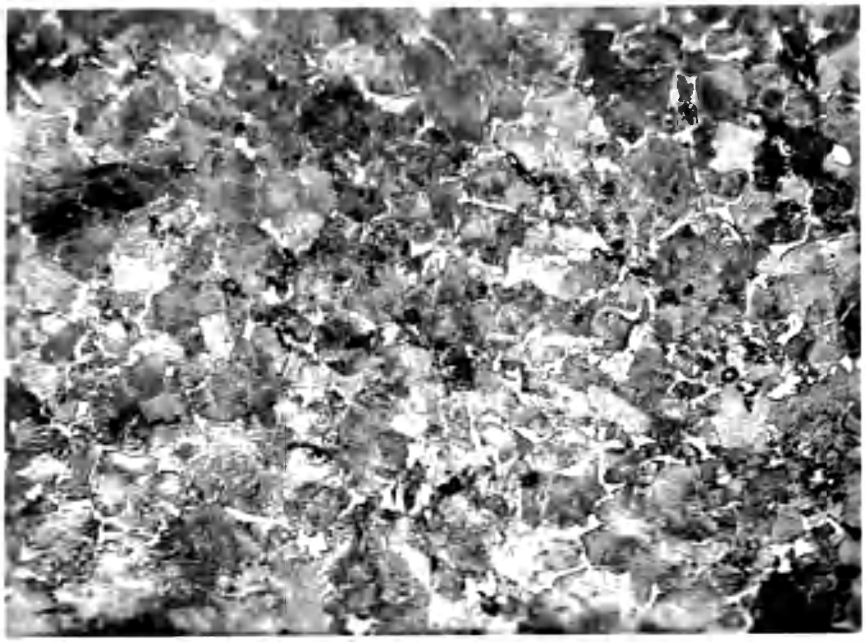


Figure 38. Microstructure at 3/4 in. from the quenched end of the Jominy bar. 9260 steel. Complete transformation. Pearlite and ferrite. X 570.

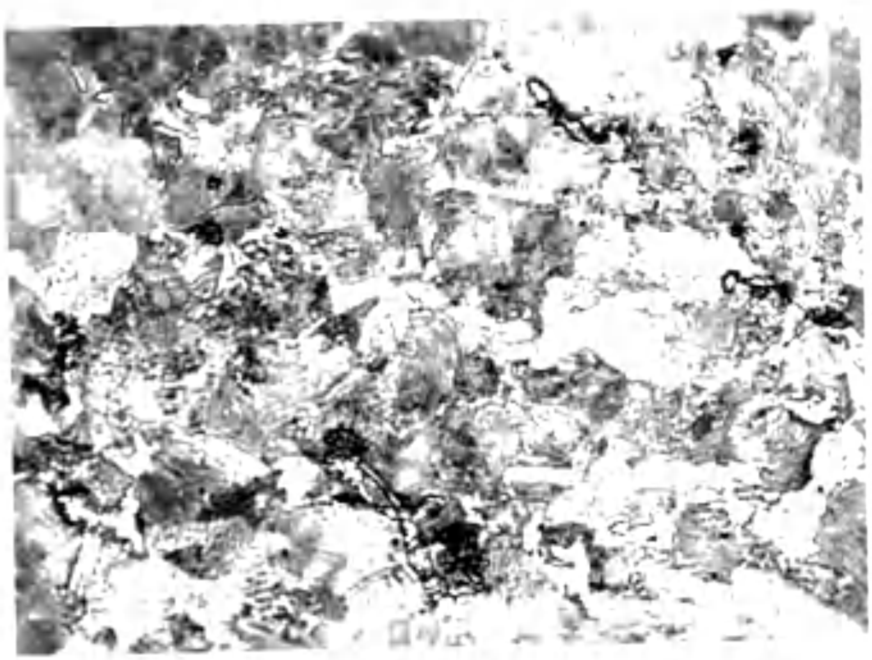


Figure 39. Microstructure at 3/4 in. from the quenched end of the Jominy bar. Same area as in Figure 38. Complete transformation. Pearlite and ferrite. X 1320.

test was compared with the cooling curves obtained along the axis of the Jominy bar until a coincidence of a cooling curve from the Jominy bar with the cooling curve obtained at the center of the Grossman test specimen was found. It was assumed that these two equivalent curves should give the following results:

1) Identical ideal critical diameters as calculated by the method of Lamont[19] and of Grossman[1].

2) Identical hardnesses.

It was found that for the 1095 steel, the cooling curve at the center of the 2-in.-diam bar coincided in most of the intervals where the transformation took place, with the cooling curve at 1/2 in. from the quenched end in the Jominy bar. The ideal critical diameter calculated from the Jominy bar by Lamont's method yields an ideal critical diameter of 2.9 in.. The ideal critical diameter calculated by the Grossman's method from the round bar yields 2.9 in., on the assumption that the severity of quench was one. The hardness reading at these two points was 41 Rockwell-C units.

In the case of the 9260 steel no coincident cooling curves were found, but by interpolation between the experimentally obtained curves at 1/2 in. and 3/4 in. from the quenched end, it was estimated that a cooling curve at 5/8 in. from the quenched end coincided with the cooling curve obtained at the center of the $1\frac{1}{4}$-in.-diam bar of the Grossman test. The ideal critical diameter calculated from the Jominy test by Lamont's method yields an ideal critical diameter of 3.4 in.. The ideal critical diameter calculated by the Grossman's method from the round bar yields 3.36 in., on the assumption of a value of 0.2 for the severity of quench. The hardness reading obtained at 5/8 in. from the quenched end of the Jominy bar was 36 Rockwell-C units, whereas the hardness at the center of the $1\frac{1}{4}$ in. diam bar was 45 Rockwell-C units. No satisfactory explanation was found for this discrepancy in the hardness values at these two points.

The 4140 steel was cooled in still air. Since the cooling rate at the center of the 2-in.-diam bar was slower than the slowest cooling rate obtained in the Jominy bar (at $2\frac{1}{2}$ in. from the quenched end), it was not possible to compare the cooling curve obtained at the center of the round bar with any of the cooling curves obtained along the Jominy bar.

C O N C L U S I O N S

1) The method proposed in the present research for the calculation of the composite hardness from the isothermal transformation diagram has enabled the hardness along a Jominy bar and across the diameter of round bars to be calculated. For the three steels studied, AISI 1095, 4140, and 9260 types, the hardenability curves calculated for the proposed method were found to be in reasonable agreement with those determine experimentally.

2) In theory, the method also permits the prediction of the relative amount of microconstituents in steels which have been heat treated. However, no confirmation of this point was possible due to the lack of an effective method for calculating the percentage of phases present.

LITERATURE CITED

1. Grossman, M.A., Elements of hardenability: American Society for Metals, Cleveland, Ohio, p. 1-42, (1952).

2. Grossman, M.A., and Bain E.C., Principles of heat treatment: American Society for Metals, Metals Park, Ohio, p. 75-127, (1964).

3. Jominy, W.E., and Boegehold, A.L., A hardenability test for carburizing steel: Trans. ASM, v. 26, p. 574-579, (1938).

4. Jominy, W.E., Hardenability tests, in Hardenability of alloy steels: American Society for Metals, Cleveland, Ohio, p. 66-94, (1939).

5. A.S.T.M., Standard method of end-quench test for hardenability of steel, American Society for Testing and Material, p. 169-176, (1971).

6. Scheil, E., Initiation time of the austenite transformation: Archiv Eisenhuttenwesen (in German), v. 8, p. 565-567, (1935).

7. Grange, R.A., and Kiefer, J.M., Transformation of austenite on continuous cooling and its relation to transformation at constant temperature: Trans. ASM, v. 32, p. 85-116, (1941).

8. Moore, P.T., Anisothermal decomposition of austenite in a medium-alloy steel: Jour. Iron and Steel Inst., v. 177, p. 305-311. (1954).

9. Grange, R.A., and others, Austenite transformation and incubation in an alloy steel of eutectoid carbon content: Trans: ASM, v. 51, p. 495-516, (1959).

10. Asimow, M., and others, Correlation between Jominy test and quenched round bars: Jour. SAE, v. 49, no 1, p. 283-293, (1941).

11. Grossman, M.A., and others, Hardenability-its relation to quenching and some quantitative data, in Hardenability of alloy steels: American Society for Metals, Cleveland, Ohio, p. 124-196, (1939).

12. Weinnan, E.W.., and others, A correlation of end-quench test bars and round in terms of hardness and cooling characteristics, Trans. ASM, v. 44, p.803-844, (1952).

13. Troiano, A.R., and Kinger, L.J., Limitations of the end-quench hardenability test: Trans. ASM, v. 44, p. 775-802, (1952).

14. Carney, D.J., Another look at quenchants, cooling rates and hardenability: Trans. ASM, v. 46, p. 882-927, (1954).

15. Birtalon, John, and others, Thermal reproductibility of the end-quench test: Trans. ASM, v. 46, p. 928-947, (1954).

16. Johnson, W.A., and Mehl, R.F., Reaction kinetics in process of nucleation and growth: Trans. AIME, v. 135, p. 416-458, (1939).

17. Grange, R.A., and others, Austenite transformation and incubation in an alloy steel of eutectoid carbon content: Trans. ASM, v. 51 p. 495-516, (1959).

18. Gifkins, R.C., Optical microscopy of metals: American Publishing Company, Inc., New York, p. 168-175, (1970).

19. Lamont, J.L., How to estimate hardening depths in bars: Iron Age, Oct. 14, p. 64-70, (1943).