CONTINUOUS COOLING TRANSFORMATION DIAGRAM FROM MODIFIED END-QUENCH METHOD

by

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CONTINUOUS COOLING TRANSFORMATION DIAGRAM, FROM MODIFIED END-QUENCH METHOD

I. INTRODUCTION

Before World War II when the industrial production in the United States reached its peak, industry demanded from the steel manufacturers many different types of steel for very specialized uses. As a natural consequence of this demand, the market was flooded with many types of steel that required varied amounts of alloys. The SAE classification of steels at this time showed the number of types to be in the hundreds. However, with our entering into the war the source of supply of many of the alloys used was completely cut off. As a direct reaction to this, the N.E. (National Emergency) steels were developed. In the development of the N.E. steels it was found that the physical properties of many of the steels could be duplicated by one steel with the proper heat treatment. Due to this investigation the number of steels produced today (according to SAE classification) is less than a hundred. Even though the types of steel manufactured today are many less, the rigid requirements of industry are still met. If this then is the case, just what is meant by the important process we classify as "heat treatment".

"Heat treatment of steel" in its broadest sense

refers to any process involving heating and cooling of the solid metal by which the properties of the steel are altered without any intentional alteration of its chemical composition (2). The object then of heat treatment is to produce mechanical or physical properties that make the steel better adapted for industrial use. To better understand the process involved in heat treatment, one must first become intimately familiar with the theory of heat treatment.

II. THEORY OF HEAT TREATMENT

There is a voluminous amount of material written on the heat treatment of steels, but the universal conception can be classified into four basic concepts. First, if a steel is heated to a temperature above its critical range, it undergoes definite internal changes. Second, if the steel that has been heated to this temperature is allowed to cool naturally, it will tend to revert back to its normal condition. Third, if the steel is to revert back to its original condition, a sufficient amount of time must elapse during the cooling period so that the internal changes that took place during heating will have time to reverse themselves. Fourth, if the steel is allowed to cool more rapidly than the internal changes can reverse themselves, certain modifications of the original structure will be brought about (9). These modifications alter the physical properties of the material.

In order to predict the internal changes that result on either heating or cooling the Iron-Carbon Equilibrium Diagram has been devised. The Iron-Carbon diagram is useful in the study of parts one, two, and three of the above theory on heat treatment. What then, the question is asked, is used in the study of part four to determine the modifications in the original structure due to abnormal cooling? Ten years ago metallurgists would have answered

that it is by the utilization of the Bain S-Curve. Many metallurgists today would still answer by utilization of the Bain S-Curve. However, the one purpose of this thesis is to point out discrepancies and limitations of the Bain S-Curve, and is an attempt to present a continuous cooling Transformation Diagram as a supplement to be used with the S-Curve in predicting the modifications brought about by abnormal cooling. A second, and main, objective is to present a laboratory procedure to be followed whereby a continuous cooling Transformation Diagram can be obtained by any well-equipped metallography laboratory. In order to present this part a typical steel has been chosen and the technique carried out to completion.

III. THE BAIN S-CURVE AND ITS LIMITATIONS

Austenite, the resulting unstable product when steel is treated above the critical temperature, can be transformed into different constituents depending on the temperature and time at which the transformation takes place. The amount of transformation corresponding to different times and temperatures has been plotted, and the resulting curve has oftentimes been referred to as a TTT-Curve--"Time, Temperature, and Transformation"--or the Bain S-Curve, after one of the early pioneers in this field. To fully appreciate the limitations of the curve, knowledge of the method of obtaining the curve should first be understood.

A certain heat of steel is made up into test specimens which are thin and small. The object here is an attempt to get a piece whose entire volume will react instantaneously to the same variations in temperature. The pieces are then austenitized at a specified temperature, attempting here to obtain complete homogeneity and a specified grain size. The specimens are then quenched to some predetermined temperature and allowed to remain for varying degrees of time; the time varies from a fraction of a second to hours. From here they are quenched in brine which freezes the structure. Upon metallographic examination the time that transformation begins and ends

can be determined. A plotting of these points will yield the TTT-Curve or Bain S-Curve (7).

This test also provides the information in regard to the nucleation period, which is important in heat treating. This time delay is useful as it defines the "critical cooling rate". Critical cooling rate is the maximum rate at which the steel can cool and still be transformed into martensite.

Some of the limitations in the utilization of the TTT-curve should be apparent from the above discussion, but for emphasis the major ones should be pointed out. The TTT-curve, even though made for one type of steel, cannot justifiably be used for the same steel as no two heats are ever the same. However, it is useful in predicting trends in a steel. When complete homogenization and grain size are specified, it is doubtful if these conditions can be duplicated. The curve was based on the small specimens whose whole volume reacted to changes in temperature, which makes it inconceivable that pieces of a larger volume will also react in the same way.

How then can the structure of this piece actually be predicted and controlled by the TTT-curve? If the critical cooling rate was less than the maximum specified, the question again arises as to how to control the properties of the material. It should be obvious that the metallurgist requires information about transformation

during continuous cooling as a profitable supplement to aid in the study and perfection of heat treating. Many methods have been devised whereby the conventional S-curve can be modified to take care of rapid continuous cooling, but the best method on the horizon appears to be a transformation diagram based on continuous cooling itself (6). The idea appears to be a natural conclusion, but at the present time very few data are available based on this type of work. The old adage appears to be rather apt in this case: "You can't see the trees for the forest."

IV. LABORATORY PROCEDURE FOR DEVELOPMENT OF TRANSFORMATION DIAGRAM DURING CONTINUOUS COOLING

The laboratory test procedure for development of the transformation diagram during continuous cooling logically falls into five basic operations. The method employed utilizes a modified end-quench technique, using the standardized Jominy test specimens and test apparatus (1).

The synopsis of the test procedure is as follows:

A. Development of Continuous Cooling Curves

Cooling curves were obtained for various positions along the test bar. In this test the distances from the end at 1/8 inch, 1/4 inch, and in eighths up to one inch, 1⅛ inch, 1⅜ inch, 2 inches, and 2⅜ inches were used as station marks. A chromel-alumel thermocouple was used and was secured in position by drilling a 1/16 inch hole 1/16 inch deep. In order to insure a sealed joint the hole was peened closed. The specimen was heated up to 1700 F and quenched in the Jominy test stand. Cooling curves of time vs. temperature were then obtained.

B. Size of Specimens

Standard Jominy test bars were machined to size as specified in the ASTM specifications for the Jominy End-Quench Hardenability Test. For this test twenty

specimens of SAE 4142 steel were used (1).

C. Heat Treating the Specimens

The twenty prepared specimens were heated in a furnace up to a temperature of 1700 F making certain the bars were protected from decarburization by surrounding them with charcoal. Then various specimens were placed in the Jominy test stand and quenched for various periods of time. In the test they were quenched in increments of 10 seconds up to and including 200 seconds. After being quenched in the Jominy test apparatus, they were requenched in ice water as a final quench.

D. Rockwell Hardness Traverse

The specimens were prepared for the Rockwell Hardness Tester by grinding diametrically opposite flats 0.015 inch deep. Rockwell "C" hardness readings were taken in the usual manner by using the Equitrom to space the various readings.

E. Metallographic Examination of Specimens

The specimens were prepared for metallographic examination, so the point at which transformation begins could be determined.

V. LABORATORY METHOD FOR DEVELOPING CONTINUOUS COOLING CURVES

The laboratory test setup for the development of the continuous cooling curves can be seen in Figure 1.

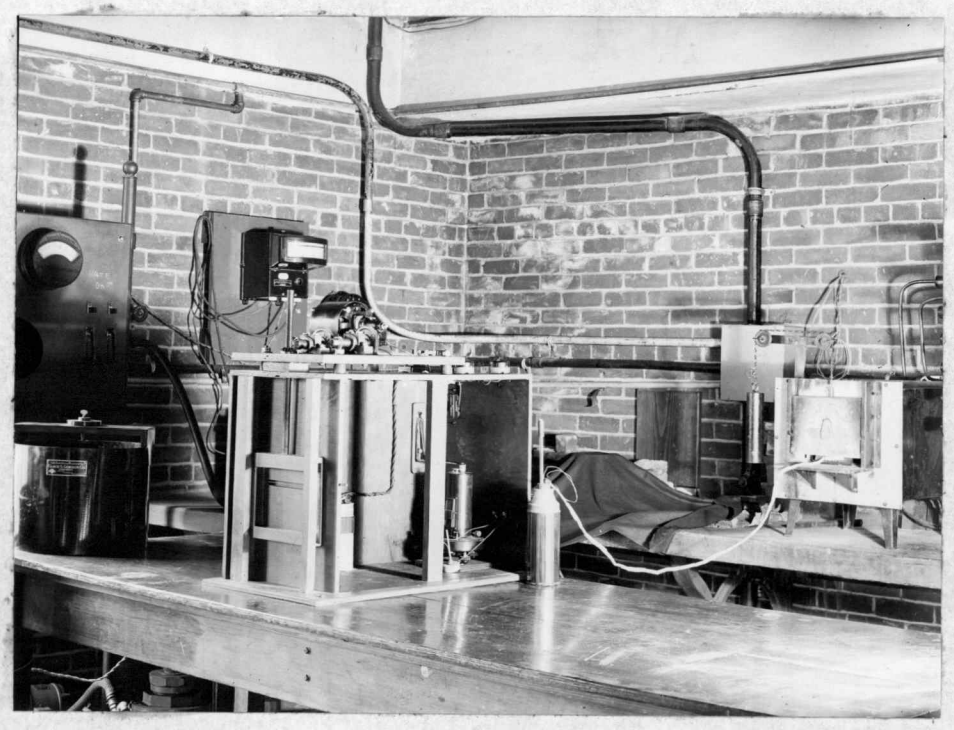

Figure 1. Overall picture of the test setup used in developing the continuous cooling curves and for the heat treating of the specimens.

In Figure 1 the furnace that was used can be seen on the far right. It has an automatic control which was set for 1700 F. The thermocouple can be seen attached to the specimen which constitutes the hot junction. From the hot junction the couple goes to the thermos bottle which was

kept at 32 F as a cold junction reference temperature. Leads from here go to the deflection galvanometer, which has a mirror that casts a beam of light on a photographic plate at the far end of the box. The light source for the mirror on the galvanometer was derived from a bulb (not visible but opposite the galvanometer). Two dry cells supplied the current. The motor on the top of the box actuated through the reduction gears the vertical movement of the photographic plate.

After being held in the furnace for 120 minutes, the specimen was placed in the Jominy test apparatus for quenching. This apparatus can be seen at the far left in the picture. The water supply for the quench was obtained from a water reservoir that was maintained at room temperature. The water was run through a pump to the Jominy apparatus and then drained back to the tank. The water reservoir and pump are not visible in the picture. Also not visible is the tank containing the ice water that was used to quench the specimens after the alloted time in the Jominy test apparatus.

Actual running test procedure consisted of: Turning on the light source to the galvanometer and turning on the motor. Next, remove the specimen and put it in the Jominy test apparatus, and then turn on the water. This was followed by an iced quench after proper time in the apparatus.

Before the test could be started, the component parts had to be calibrated. The only elements affected were the thermocouple and the time-temperature relationship for the galvanometer and the motor. The thermocouple was calibrated in the usual manner of using the freezing temperatures of pure metals for calibration points. Results of this calibration appear in Table I. It can be seen the couple is within the allowable limit of error of ± 5%.

Table I.

Calibration of Thermocouple (Chromel Alumel)

	Freezing °C (Act.)	MV	Freezing Pt. Couple	% Error
B P Water	212.0	8.6	212	0
Tin	231.9	9.4	232	0.04
Lead	327.4	13.5	332	1.42
Zinc	419.4	17.4	424	1.11
Antimony	630.0	25.5	614	2.54
Aluminum	660.0	27.5	662	0.34

In order to determine the time-temperature relationship for the apparatus the following method was used. The furnace was brought up to 100 F with the thermocouple in place. When equilibrium conditions were established, the light on the galvanometer was turned on.

This gave a point on the photographic film. This was done for a series of temperatures with the net result the film was calibrated with the furnace and galvanometer for various temperature increments. The time coordinates on the ordinate were done in much the same manner for 10-second intervals. Once the film was developed all that was necessary to determine points on the continuous cooling curves was to place the calibration film over the curve and read the data.

A typical cooling curve as obtained from the apparatus can be seen in Figure 2. The data for all the curves can be found on Page 16.

The results from this part of the investigation can be seen in graphical form in Figure 3 on Page 15. Along with the continuous cooling curves, the cooling rate can be obtained at any desired reference temperature by merely taking the slope at that point. The cooling rates yield desirable information in designing of heat treatments. The cooling curves shown here are for the surface area; however, they can be determined for various other positions within the specimen by several common methods.

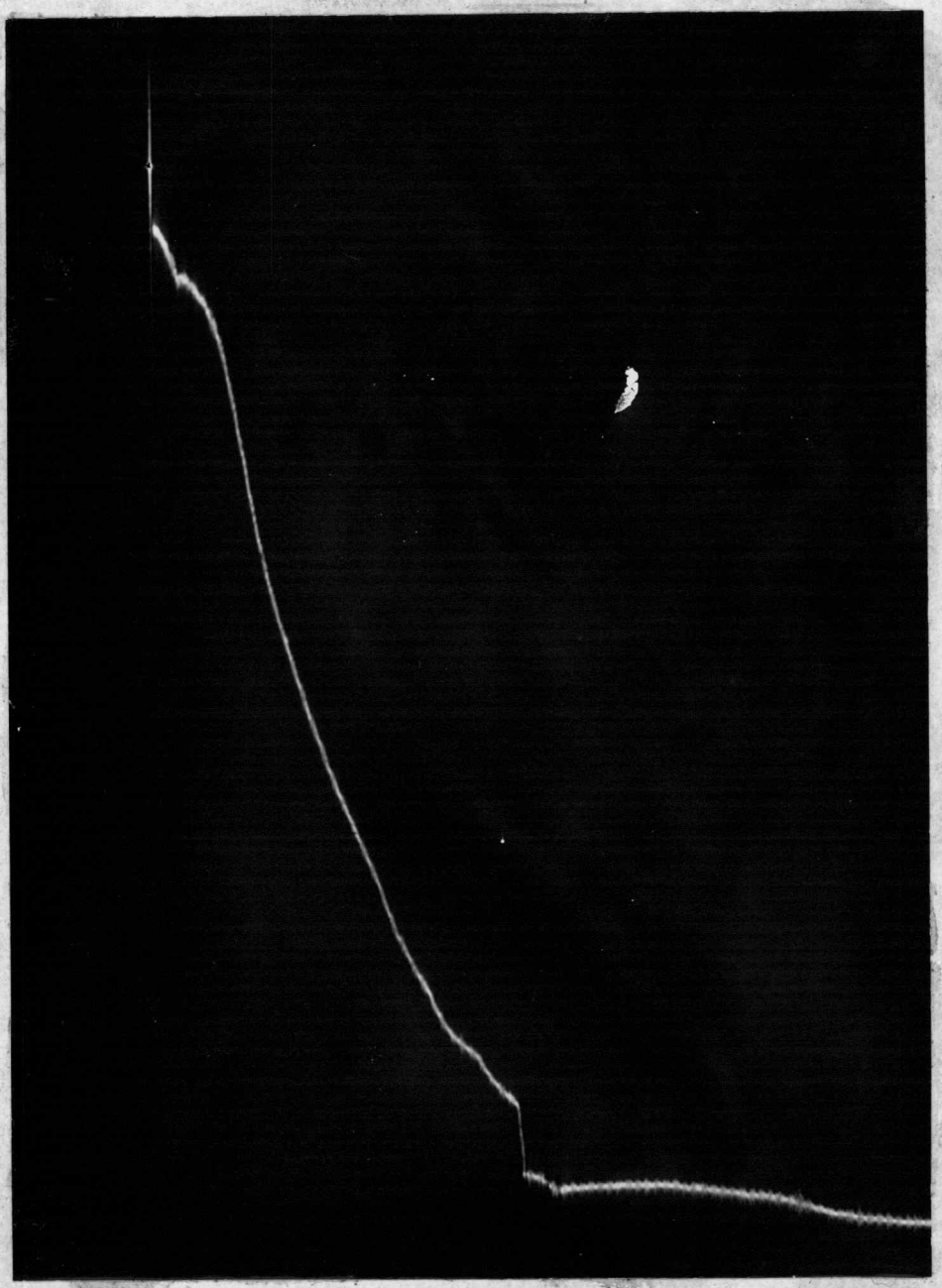

Figure 2. Typical cooling curve as obtained from the test apparatus for the 7/8 inch station

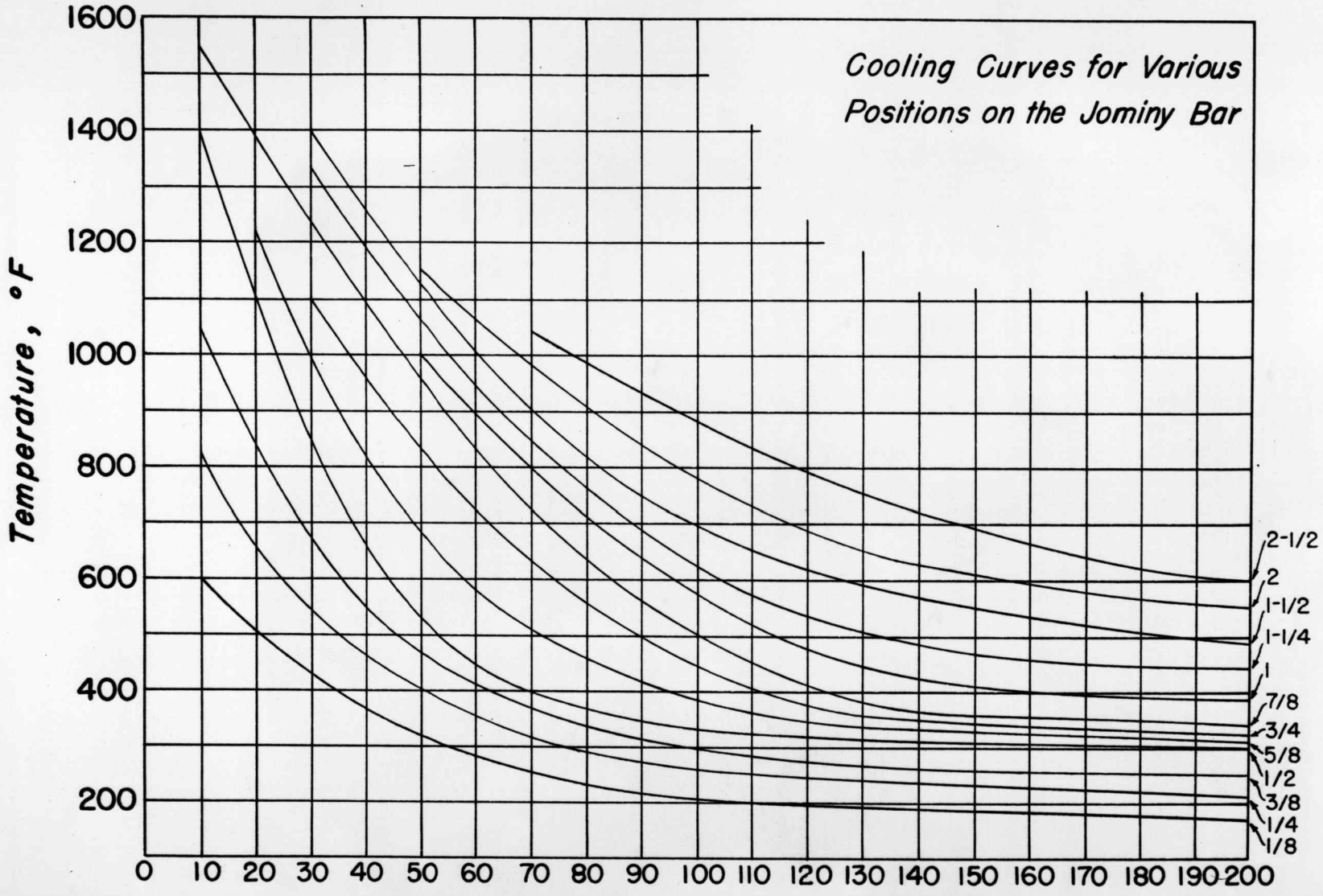
Cooling Curves for Various Positions on the Jominy Bar
Temperature, °F
1600
1400
1200
1000
800
600
400
200
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Interval Cooled in Jominy End-Quench Machine, Seconds
2-1/2
2
1-1/2
1-1/4
1
7/8
3/4
5/8
1/2
3/8
1/4
1/8
Distance From End of Specimen for Respective Cooling Curve, in.

Figure 3.

COMPILED DATA FOR CONTINUOUS COOLING CURVES

	Temperatures at Various Positions from End of Test Bar											
TIME	1/8	1/4	3/8	1/2	5/8	3/4	7/8	1"	1¼	1½	2"	2½
10	600	825	1050	1400	1450	1500	1550	1575	1600	1600	1600	1600
20	520	700	910	1150	1300	1350	1400	1410	1420	1410	1420	1415
30	430	550	675	850	1000	1100	1250	1285	1330	1400	1375	1500
40	380	500	570	675	880	960	1125	1150	1180	1240	1200	1440
50	315	400	470	500	680	830	950	1000	1060	1120	1150	1290
60	260	360	420	460	600	740	840	900	970	1000	1085	1140
70	250	320	370	400	510	630	720	800	850	900	970	1040
80	240	295	330	380	470	580	670	720	790	820	900	980
90	220	270	310	340	420	500	560	640	690	740	840	930
100	210	260	295	335	400	485	530	590	660	700	790	880
110	200	250	280	325	360	410	475	520	570	660	740	830
120	195	245	275	320	345	380	430	480	540	620	690	790
130	190	240	270	320	330	350	365	440	510	590	650	750
140	185	235	265	320	330	345	360	430	485	560	635	725
150	180	230	260	315	325	345	360	410	470	540	615	690
160	180	225	255	315	325	335	355	405	460	530	590	670
170	180	225	255	310	320	330	355	400	450	520	570	640
180	175	220	250	310	320	330	350	395	445	410	560	620
190	175	215	250	305	315	325	350	390	440	495	550	600
200	170	210	250	300	310	320	330	380	440	490	550	600

VI. ROCKWELL "C" HARDNESS TRAVERSE

In Part D of the test procedure the hardness numbers were obtained in the usual manner. The equipment used can be seen in Figure 4.

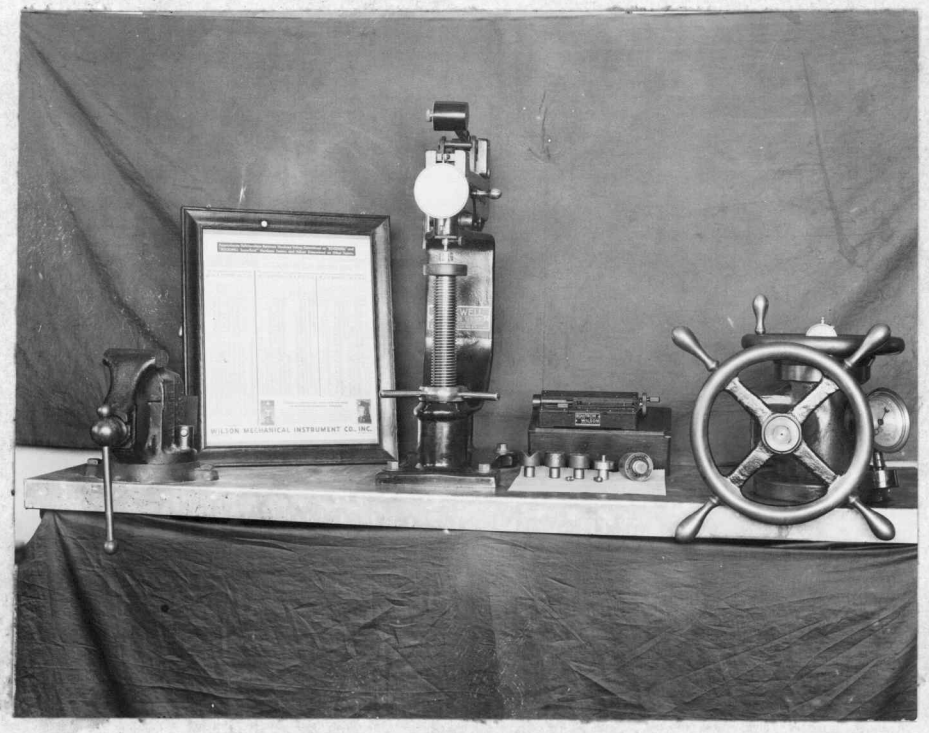

Figure 4. Test setup used in determining the Rockwell "C" hardness numbers.

The actual Rockwell tester used can be seen in the center of the picture. A 150-kg load was used in the determination of the hardness numbers. The Equitron shown just to the right of the tester is a jig that facilitates the setting of the specimen for 1/16-inch increments. The chart on the extreme left is used in the conversion of

Rockwell numbers to Brinell hardness numbers. The trend of the hardness numbers gives a good indication as to when transformation takes place. In some instances it has been used as the only method of determining the beginning and end of transformation for S-curves. For this particular test both the hardness numbers and the micrographic examination served as a check on each other for the determination of the beginning of these transformation points.

The data sheet for the Rockwell "C" Hardness Numbers appears on Page 21. In Figure 5, Page 19, the hardness numbers are placed on the continuous cooling curves and hardness contour lines drawn in. Figure 6, Page 20, shows the hardness surveys at different times of quench in the Jominy test apparatus. It can be seen that the time scale on the right hand side in all cases is 3 seconds greater than the time on the left hand side. This 3 seconds represents the time to remove the specimen from the furnace and put it in the test apparatus.

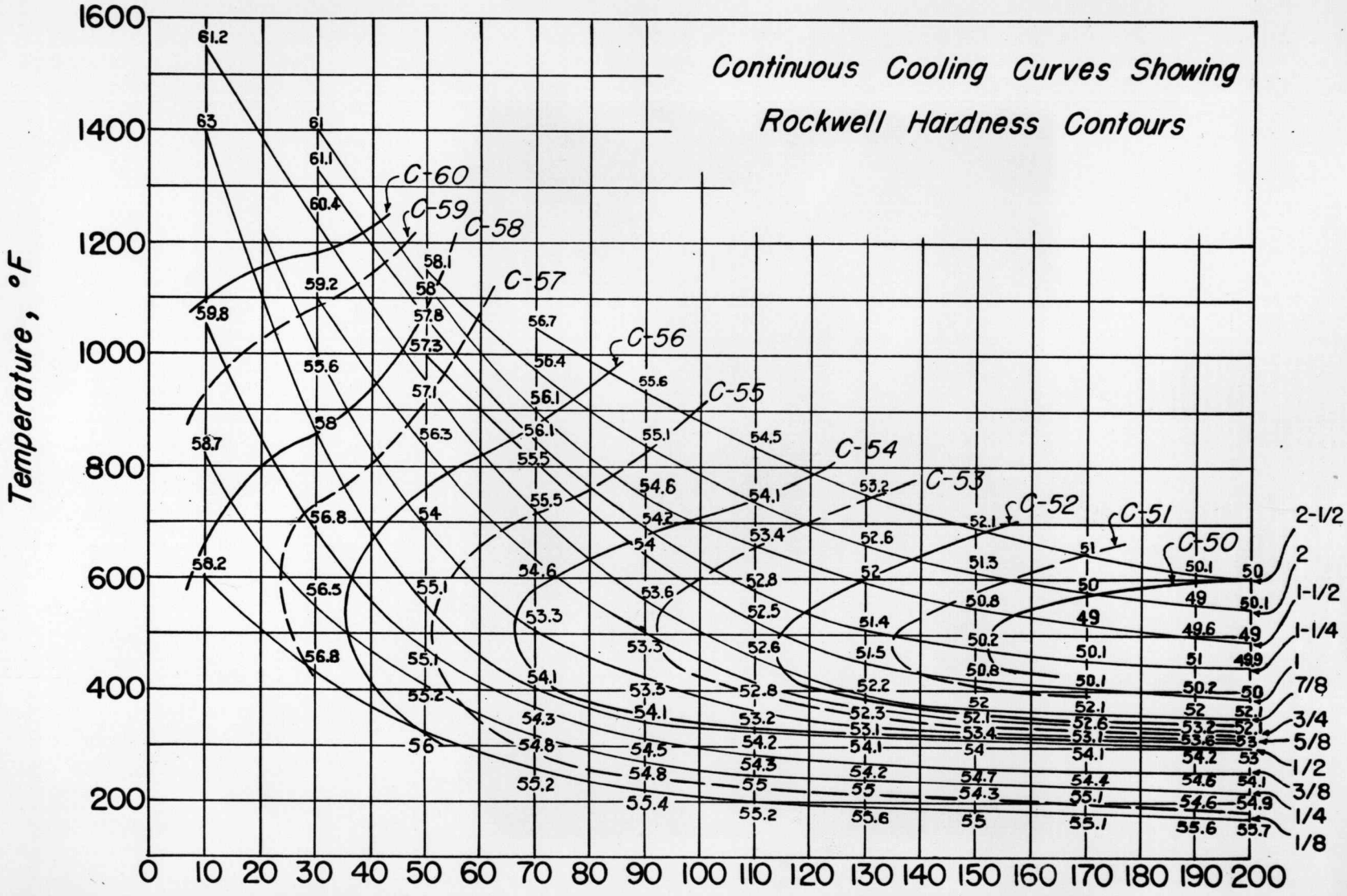
Continuous Cooling Curves Showing
Rockwell Hardness Contours
C-60
C-59
C-58
C-57
C-56
C-55
C-54
C-53
C-52
C-51
C-50
Temperature, °F
1600
1400
1200
1000
800
600
400
200
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Interval Cooled in Jominy End-Quench Machine, Seconds
Distance From End of Specimen for Respective Cooling Curve, in.
2-1/2
2
1-1/2
1-1/4
1
7/8
3/4
5/8
1/2
3/8
1/4
1/8

Figure 5.

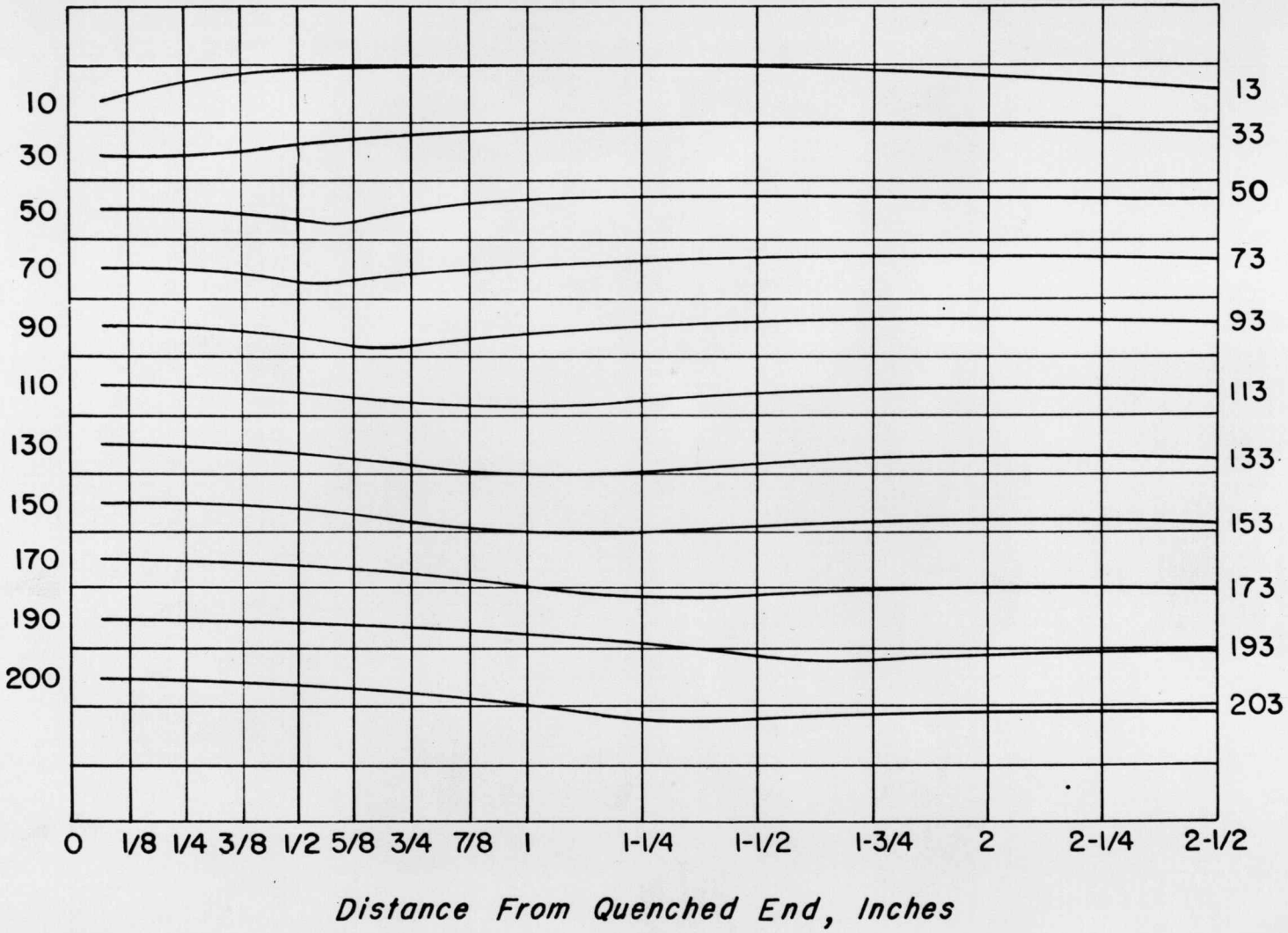
Hardness Surveys on Representative End-Quench Bars of SAE 4142 Steel
Interval Cooled in Jominy End-Quench Machine, Seconds
10
30
50
70
90
110
130
150
170
190
200
Total Time, Furnace to Brine Quench, Seconds
13
33
50
73
93
113
133
153
173
193
203
0
1/8
1/4
3/8
1/2
5/8
3/4
7/8
1
1-1/4
1-1/2
1-3/4
2
2-1/4
2-1/2
Distance From Quenched End, Inches

Figure 6.

COMPILED DATA FROM ROCKWELL "C" HARDNESS TEST

	Distance from End of Bar											
TIME	1/8	1/4	3/8	1/2	5/8	3/4	7/8	1"	1¼	1½	2"	2½
10	58.2	58.7	59.8	63.0	58.5	62.1	61.2	59.8	60.3	61.8	61.0	60.2
20	57.3	57.2	58.2	59.6	60.4	62.0	61.3	60.3	61.1	62.1	60.0	62.2
30	56.8	56.5	56.8	58.0	55.6	59.2	60.4	61.0	61.1	61.0	60.5	60.2
40	56.5	55.8	55.8	56.0	57.1	58.1	58.7	59.0	59.6	58.1	60.5	60.8
50	56.0	55.2	55.1	55.1	54.0	56.3	57.1	57.3	57.8	56.7	58.1	60.0
60	55.6	54.8	54.6	54.5	54.7	55.4	56.0	56.5	56.7	56.4	56.8	57.0
70	55.2	54.8	54.3	54.1	53.3	54.6	55.5	55.5	56.1	55.8	56.4	56.8
80	55.3	54.6	54.5	54.1	53.5	53.6	54.0	54.8	55.0	55.1	55.3	55.8
90	55.4	54.8	54.5	54.1	53.3	53.3	53.6	54.0	54.2	54.5	55.1	55.6
100	55.3	55.0	54.6	54.1	53.2	52.2	52.6	52.8	53.2	54.1	53.8	54.8
110	55.2	55.0	54.3	54.2	53.2	52.8	52.6	52.5	52.8	53.0	54.1	54.5
120	55.4	54.7	54.5	54.1	53.8	52.6	51.9	51.8	52.0	52.6	53.0	54.0
130	55.6	55.0	54.2	54.1	53.1	52.3	52.2	51.5	51.4	52.0	52.6	53.2
140	55.5	54.4	54.6	54.1	52.9	52.2	52.9	52.0	51.7	51.3	51.4	52.6
150	55.0	54.3	54.7	54.0	53.4	52.1	52.0	50.8	50.2	50.8	51.3	52.1
160	55.0	54.1	54.6	54.5	54.1	53.6	52.1	50.6	50.1	50.0	50.6	51.5
170	55.1	55.1	54.4	54.1	53.1	52.6	52.1	50.1	50.1	50.0	50.0	51.0
180	55.4	54.6	54.1	54.1	53.2	52.4	52.0	50.0	51.1	49.6	49.6	50.0
190	55.6	54.6	54.6	54.2	53.6	52.2	52.0	50.2	51.0	49.0	49.0	50.1
200	55.7	54.9	54.1	54.3	53.0	52.1	52.1	50.0	49.9	49.9	50.1	50.0

VII. METALLOGRAPHIC EXAMINATION OF TEST SPECIMENS

In Part E the specimens were polished and prepared for metallographic examination in the usual way. Figure 7 shows a picture of the Bausch & Lomb metalloscope that was used.

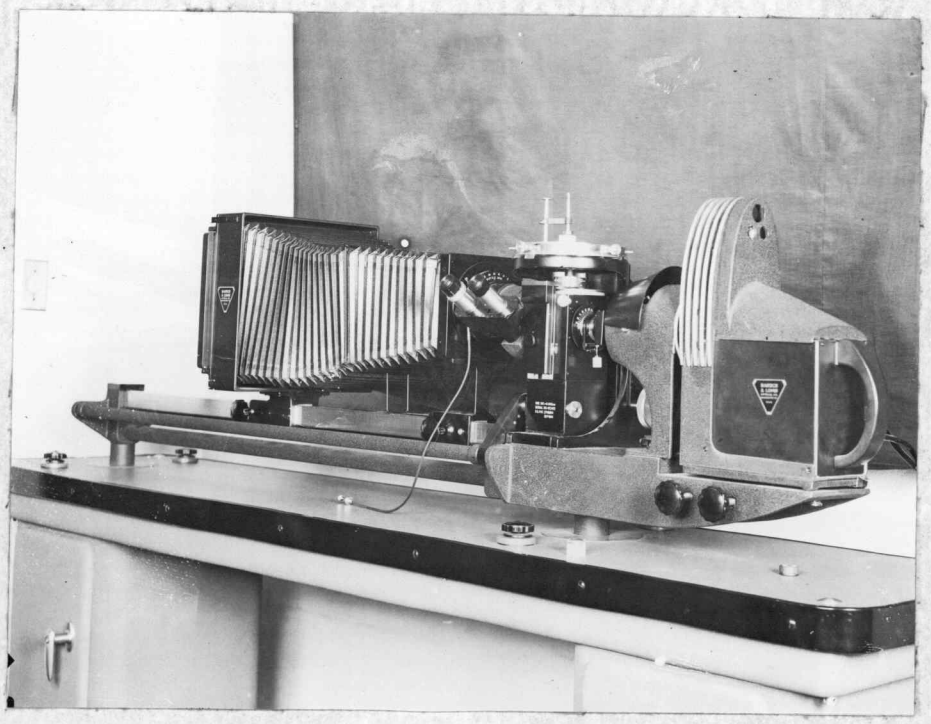

Figure 7. Bausch & Lomb metalloscope used to determine the points of transformation in the steel.

In the final preparation of the specimens the test bars were etched and repolished three times in order to remove any effects of cold working that might have

entered into the polishing procedure. This precaution was particularly necessary as cold worked metal can oftentimes be misconstrued for bainite. The etching reagent used in all cases was 10% nital. Although this etching reagent will etch in relief in lieu of picral, which stains the surface, it was used as the photomicrographs were all taken at a comparatively low magnification 1000X.

Results of the photomicrographic study appear in Figures 8 through 17. The photomicrographs show various types of structures for different stations on the Jominy test bar for different periods of quench. The study is very interesting as the basic structures are of three types: martensite alone; combination of martensite and ferrite; or various combinations of martensite, ferrite, and bainite. It is interesting to note that none of the cooling rates were slow enough to bring about any pearlite structures. However, unresolved pearlite appears in the form of primary troostite.

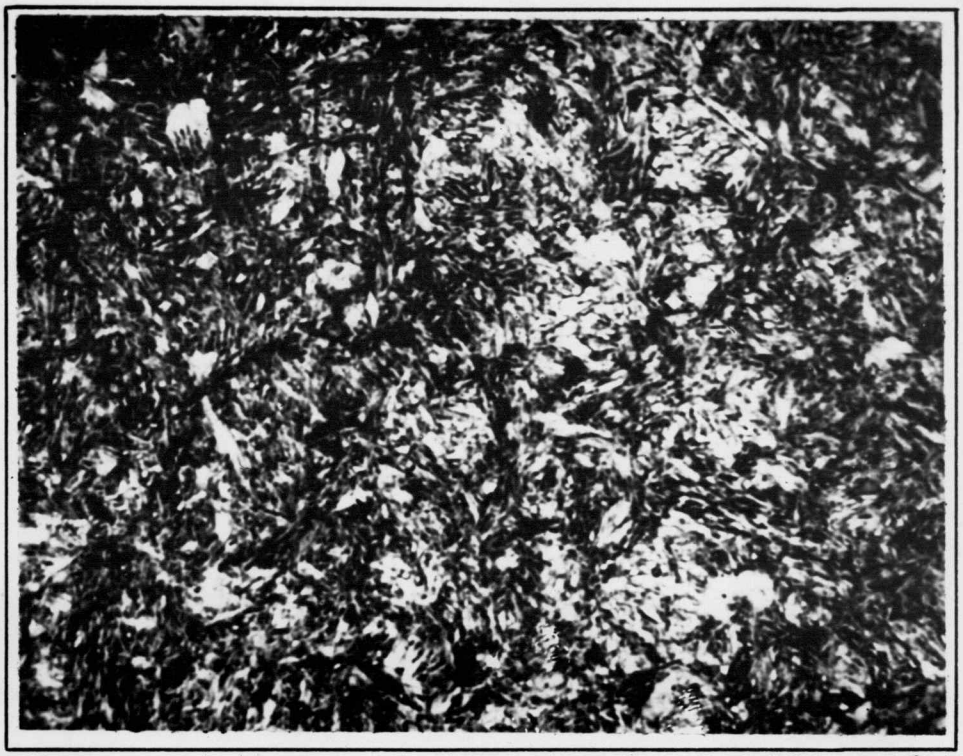

Figure 8. Mixture of martensite, ferrite and bainite. Taken $2\frac{1}{2}$ inches from end of specimen quenched for 200 seconds.

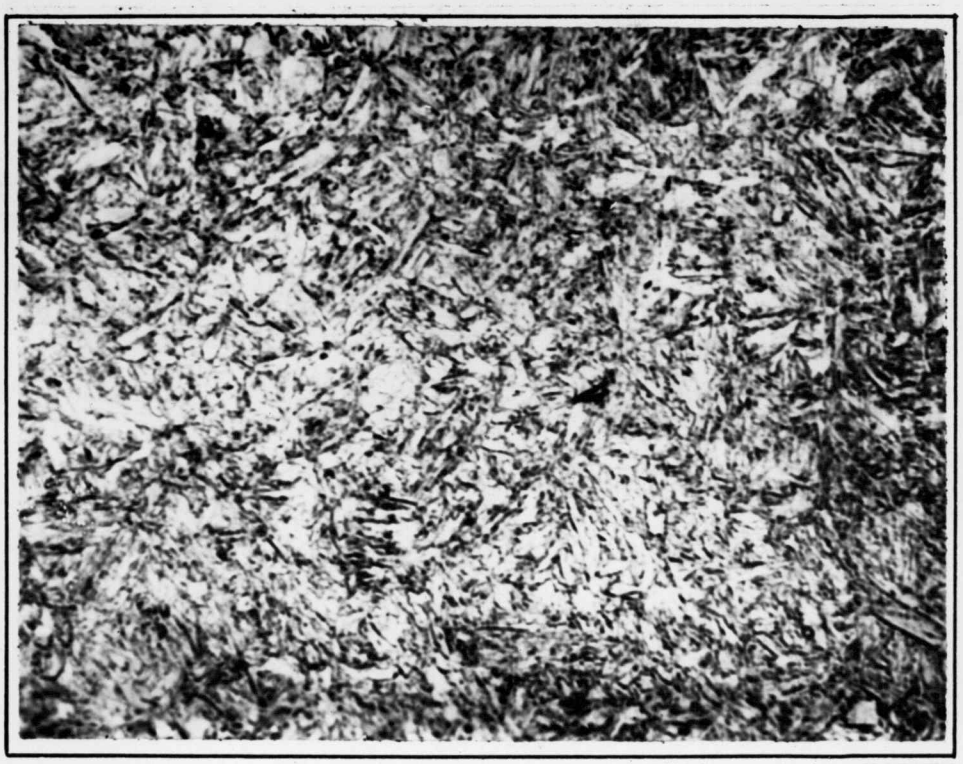

Figure 9. Almost all martensite area. Shows small amounts of ferrite. Taken 3/8 inch from end of specimen quenched for 10 seconds.

Figure 10. Mixture of martensite, ferrite and bainite. Taken 1/2 inch from end of specimen quenched for 140 seconds.

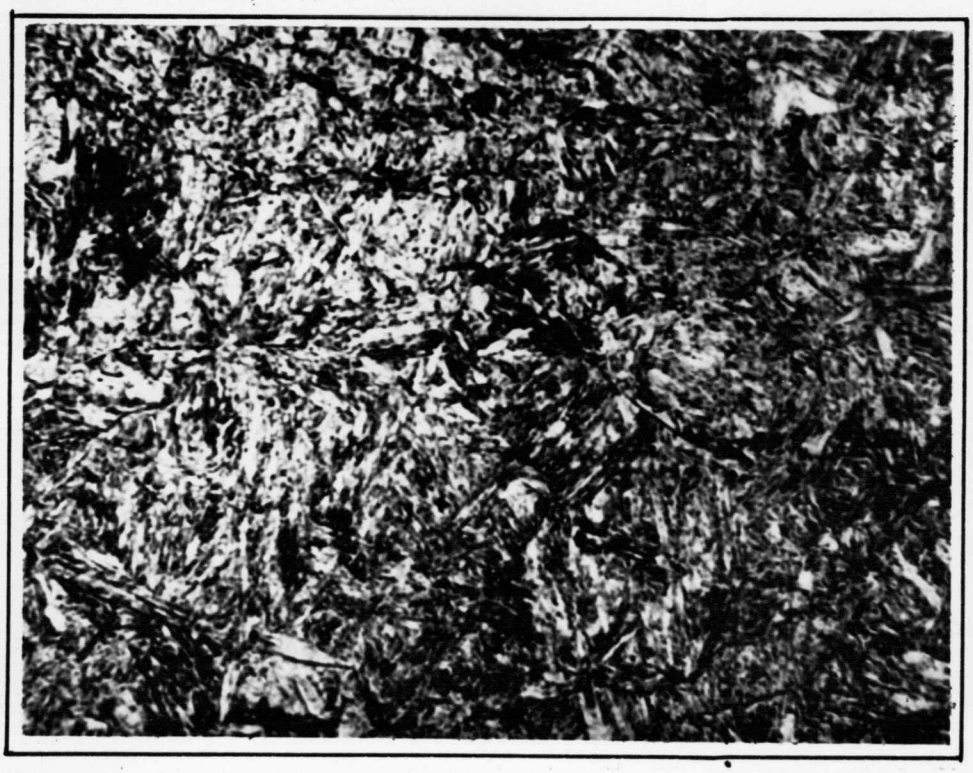

Figure 11. Same basic microstructure as Fig. 10 but slightly more martensite. Taken 1/4 inch from end of specimen quenched for 20 secs.

Figure 12. Mixture of martensite, ferrite and bainite. Taken 1/4 inch from end of specimen quenched for 80 seconds.

Figure 13. Mixture of martensite, ferrite and bainite. Taken 3/8 inch from end of specimen quenched for 20 seconds.

Figure 14. Shows ferrite and martensite Rockwell "C" 60.8. Taken 1 inch from end of specimen quenched for 60 seconds.

Figure 15. Mixture of martensite, ferrite, and bainite Rockwell "C" 49.5. Taken 1½ inch from end of specimen quenched for 160 seconds.

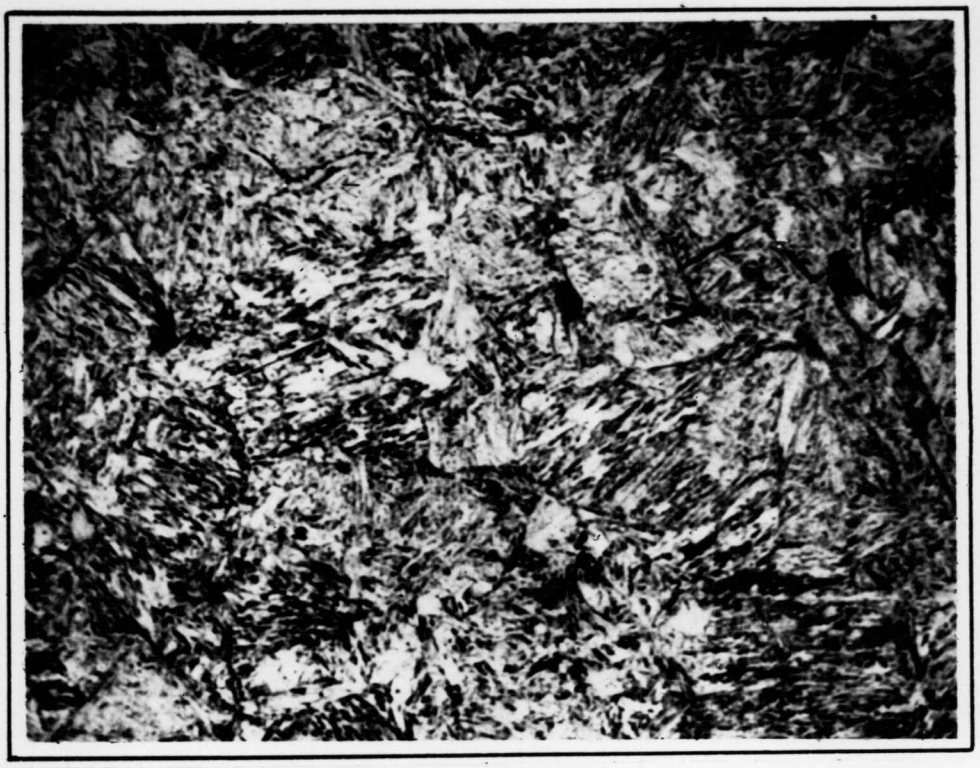

Figure 16. Mixture of martensite, ferrite and small amounts of bainite. Taken 3/4 inch from end of specimen quenched for 40 seconds.

Figure 17. Mixture of martensite, ferrite and bainite. Taken $1\frac{1}{2}$ inch from end of specimen quenched for 180 seconds.

VIII. DISCUSSION OF RESULTS

The results of the five combinations of laboratory procedures can be combined into one overall curve which will yield the desired Transformation Diagram during continuous cooling. The results of this combination can be found in Figure 18, Page 35.

To analyze the results of the study, it is felt that each part of the investigation should be analyzed individually, and then the project should be surveyed in general.

In analyzing the results of the cooling curves several things should be noted. The cooling curve, as shown in Figure 2, has a very peculiar reaction at the lower part of its temperature range. It is noted that there is a sudden drop in temperature of approximately 100 degrees with a very small lapse of time. This same thing appeared in all curves up to the one-inch station mark at which point the curve left the plate while still descending, so it was not known whether this continued through the entire range or not. Right after these series of points there appears to be a fairly isothermal reaction as can be seen from the curve. The reason as to why this type of reaction should occur always at the same temperature but not the same time is not clearly

understood. It could be due to the heat retained in the body during quenching, and at the observed point the built up residual heat in the bar overcomes the effect of the quench. As a result a rapid change in the temperature gradient results. After this, equilibrium conditions again exist and a smooth curve results.

In observing the overall plot of the cooling curves in Figure 3, it can be seen that this sudden drop in temperature does not effect the overall results as it appears at a temperature below the useful range of the curves. The curves themselves do not appear to be too consistent. One would expect an even temperature increment between curves; for instance, on the right hand side of the curve at the respective stations there appears to be a fairly even division up to 5/8 of an inch, then a bunching up of curves to the 7/8 inch station and thenfairly good distribution after that. A plot of distance vs. time at this point does plot up into a smooth curve. The data appear correct, but should be rechecked to determine if this is the actual trend. In general the results on the cooling curves appear to be very reliable. The test setup was responsive and accurate to the rapid changes in temperature.

In the quenching of the specimens for the Rockwell "C" Hardness Test all the specimens suffered

quenching cracks. This is rather common in the higher carbon steels especially when such a drastic quench as a water spray is used. If one wished to avoid cracks in quenching, martempering or a less drastic quench would probably eliminate the situation. These quenching cracks could be an aid in explaining some very erratic readings in the hardness tests. It was thought at first that erratic readings in the hardness traverse were due to tempering in the grinding process, but this was checked as recommended by ASTM for the Jominy test. As a general statement, however, none of the hardness testers is too reliable with the situation being further aggravated by not having a good definition of hardness itself.

In observing Figure 5, which shows the hardness contours, it can be seen that the end of the bar for the 10-second quenching time is softer than the other parts of the bar. This is a rather common type of occurrence in the high-alloy steels under a drastic quench. Due to their sluggishness some austenite is oftentimes retained. As the retained austenite is softer than martensite, a lower reading will result where one would expect the hardest reading at the end of the bar.

The hardness surveys in Figure 6 give a better graphical view of the trend in the transformation of the steel. Although the curves are not complete, the curves

as drawn show the steel will stand about a 50-second delay before it sags. The curves from 50 to 70 seconds at a distance from 1/4 inch to 1 inch from the quenched end show that this area has been cooled down into the nose of the S-curve by drainage of heat to the quenched end. However, it shows the air-cooled end was still austenite and responded fully to the ice water quench.

It was first thought that the Rockwell "C" hardness surveys would give the desired information as to when transformation of the steel occurred, but due to the unreliability of the data it was not used exclusively to determine the transformation points. The data were used in conjunction with the micrographic examination to determine the transformation points. The micrographic examination, which yielded the necessary information to determine the points of transformation, proved to be a rather exacting study. The specimens were examined under the metalloscope by panning from the quenched end. By this method it was possible to determine the approximate point at which transformation started. Then, knowing the point of transformation or distance from the quenched end and the time of quench to produce this transformation, the temperature at which transformation started could be determined. These points were plotted in Figure 18 along with the cooling curves. The curve is the final result

of the investigation and finds its greatest use in predicting the transformation of the steel during continuous cooling. The curve itself is not complete as all of the possible cooling rates that arise in heat treating are not represented. This curve should be expanded to cover the slower cooling rates that are representative of the normalizing and annealing cycles.

In the examination of Figure 19, which is a continuous cooling curve superimposed on an S-curve, it can be seen that when the material is continuously cooled, the transformation curve tends to displace itself down and to the right. This curve shows the basic difference between the TTT-curve and the curve for transformation during continuous cooling. In this set of curves for the SAE 4142 steel the difference in the time element is about three seconds. For other steels some investigators have found the difference to be as great as 75 seconds (7). This time delay is very important in that larger pieces can be more completely transformed to martensite than the TTT-curve would indicate. If the cooling rate is known, the Transformation Curve during continuous cooling would indicate just exactly the hardness that could be expected at any point in the piece.

The TTT-curve will not yield this information

directly. The end of transformation for the continuous cooling curve has not been determined in this particular test. Although the information would be useful, the design of the apparatus used would not be conducive to yield these results. The question of time is also important as complete transformation in many cases would require a period of many hours and, in some cases, days.

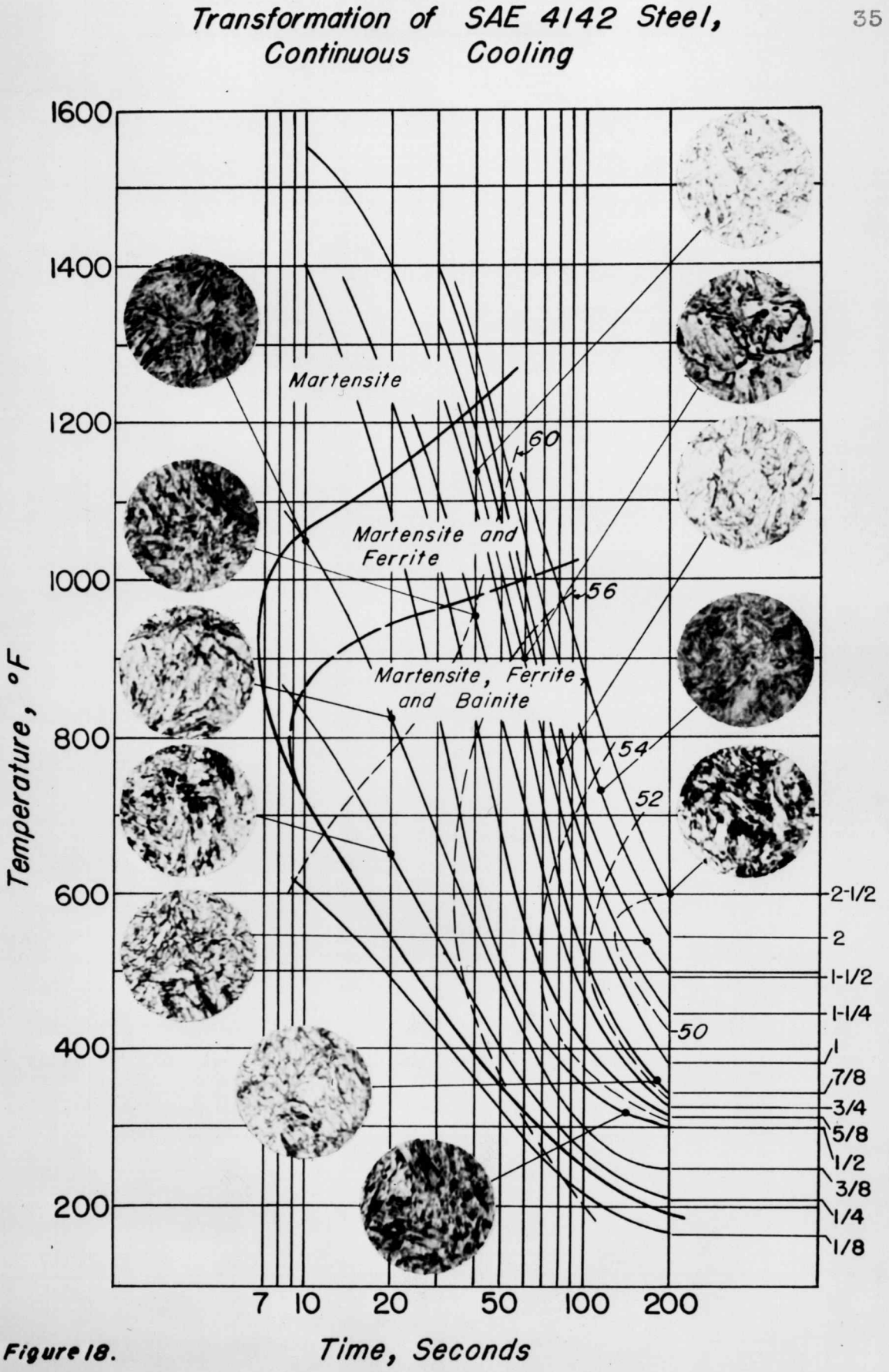
Transformation of SAE 4142 Steel,
Continuous Cooling
1600
1400
1200
1000
800
600
400
200
Temperature, °F
Martensite
Martensite and Ferrite
Martensite, Ferrite, and Bainite
60
56
54
52
50
2-1/2
2
1-1/2
1-1/4
1
7/8
3/4
5/8
1/2
3/8
1/4
1/8
7
10
20
50
100
200
Time, Seconds
Cooling Curves for Respective Stations on Jominy End-Quench Test Bar

Figure 18.

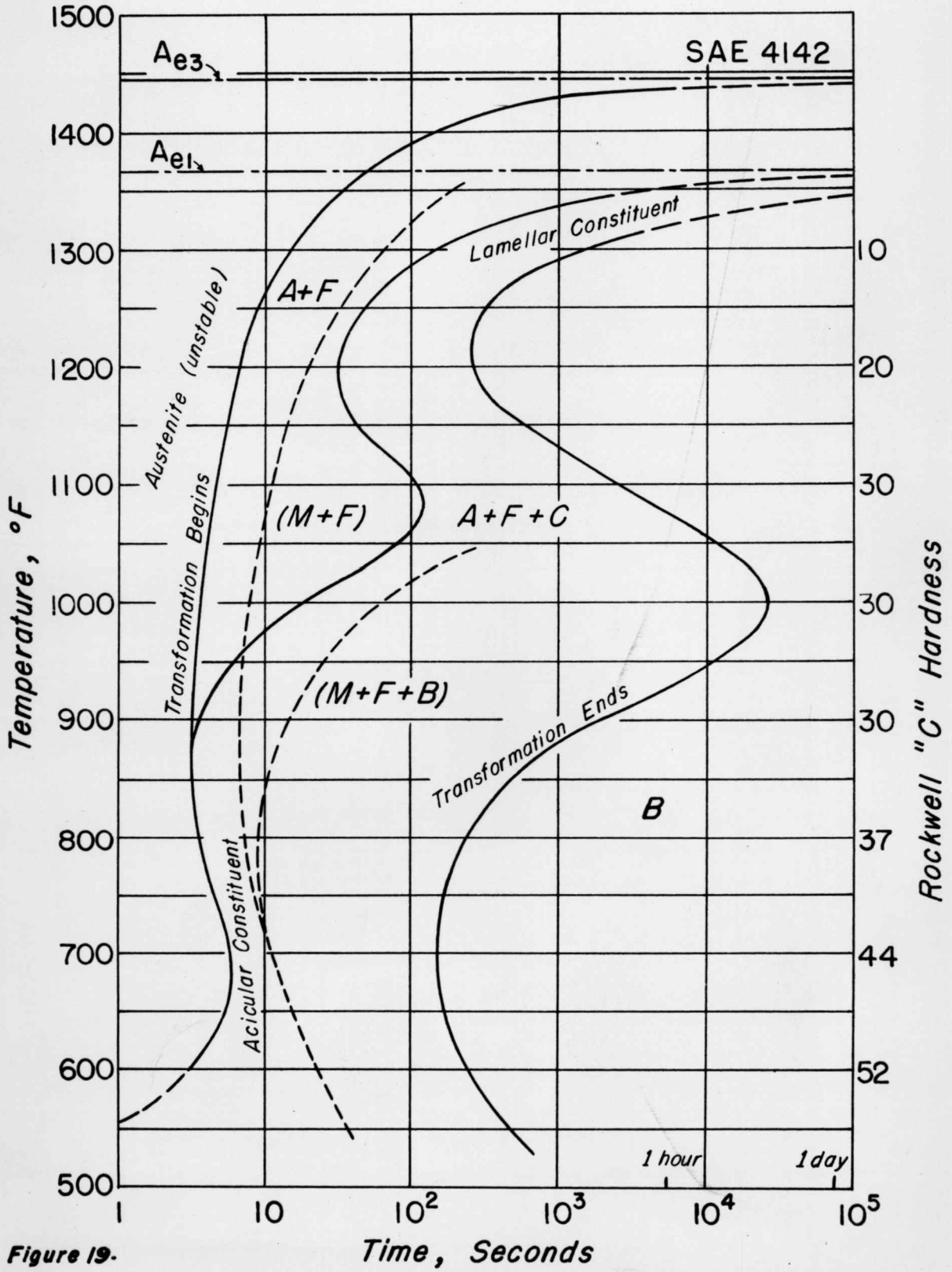
SAE 4142
A_{e3}
A_{e1}
Austenite (unstable)
Transformation Begins
Transformation Ends
Lamellar Constituent
Acicular Constituent
A+F
(M+F)
A+F+C
(M+F+B)
B
1 hour
1 day
Temperature, °F
Time, Seconds
Rockwell "C" Hardness
1500
1400
1300
1200
1100
1000
900
800
700
600
500
1
10
10^2
10^3
10^4
10^5
10
20
30
30
30
37
44
52

Figure 19.

IX. CONCLUSIONS

As previously stated, the objectives of this study were to devise a laboratory technique for the development of a transformation diagram during continuous cooling, and to develop a diagram using this technique and then point out the functions of this diagram as an aid in heat treating of materials. It was also felt necessary to justify the uses of the continuous cooling diagram in lieu of the limitations of the TTT-curve as an aid in heat treating.

The author feels that the objectives as set forth were successfully completed. At the present time the work that has been done in the field of transformation during continuous cooling is very limited. As a consequence the data obtained cannot be verified through the current literature. However, the trends indicate the data to be in accord with other investigations.

The author feels that the transformation diagram during continuous cooling will in time find its way into the field, and will penetrate the literature to the extent the TTT-curve does now. At the present time the idea is still new, but the standardization of the Jominy end-quench hardenability test, which forms the basis for this test, the continuous cooling type of curve should come into its own.

BIBLIOGRAPHY

1. American Society for Testing Materials Standards. End-Quenched Hardenability Test. ASTM, Part I, Metals, 1942 Ed. p. 1106-1113.

2. Bullens, D. K. Steel and Its Heat Treatment. John Wiley & Sons, Inc, New York, 1948. p 489.

3. French, H. J. The Quenching of Steels. American Society for Metals, 1930. p 176.

4. Gillmar, R. N. The Influence of Alloying Elements on the Critical Points of Steel, Transactions of the American Society for Metals, Vol 40, Dec 1942. p 1377-1404.

5. Grange, R. A. and Keifer, J. M. Transformation of Austenite on Continuous Cooling and Its Relation to Transformation at Constant Temperature. Transactions of the American Society for Metals, Vol 29, March 1941. p 85-114.

6. Liedholm, C. A. Structural Changes during Continuous Cooling, Metal Progress, vol 54, December 1948. p 94-9 and p 849-856.

7. Manning, G. K. and Lorig, C. H. The Relationships between Transformation at Constant Temperatures and Transformation during Cooling. AIME Tech Pub 2014, Metals Tech, Vol 13, June 1946. p 94-9.

8. Macral, F. R. Heat Treating Diagrams, Soc TTT-Curves. Metal Progress, Vol 48, October 1945. p 818-31.

9. Ryerson, Joseph T. Alloy Steel Reference Book. Section II, Heat Treatment of Alloy Steels. 2nd Edition, 1947. p 1-80.

10. Scott, H. The Origin of Quenching Cracks. Bureau of Standards, Scientific Paper 513, Vol 20, 1925. p 399-444.