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An Experimental Study of the Effects of Welding on Cold-Worked and on Heat-Treated Steels as they Correlate to Tempering and Jominy Data

Kiran Patwari
Brigham Young University - Provo

AN EXPERIMENTAL STUDY OF THE EFFECTS OF WELDING ON COLD-WORKED AND ON HEAT-TREATED STEELS AS THEY CORRELATE TO TEMPERING AND JOMINY DATA

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CHAPTER I

INTRODUCTION

Since Bernardos of Russia in 1887 applied an electric arc to weld metals, welding has become an important method of fabrication in industry. The ever increasing use of welding on a still widening variety of materials demands more and more understanding of the basic mechanisms of welding.

Although much information has been obtained on soundness, tensile strength and other properties of a welded joint, much more is still required in order to understand fully the effects of welding on the parent metals. To illustrate this idea, recently, industrialists and researchers were asked for help by the Welding Research Council to define 205 welding problems faced by industry. The topic of this thesis treats only one of these problems, namely the effects of welding on cold-worked and heat-treated steels as they correlate to tempering and jominy data.

Many of the problems occurring during welding of a steel may be traced back to changes in various physical properties like strength, ductility, etc. A steel, uniformly welded, becomes softer in certain regions, and harder in others. The softening effect is called tempering. Tempering effects occur at some distance from the weld-bead. The hardening effects constitute a basic heat-treatment process, and they take place immediately adjacent to the weld-bead. The center line of the weld-bead is called the weld-axis and the region of metal which has its characteristics altered by the welding process is called the heat-affected zone (HAZ).

The basic problem in this thesis was to try to correlate the tempering and hardening effects of welding of a cold-worked and of a heat-treated steel with tempering and hardening data for these steels, as these data are usually specified. Tempering data is usually specified by tempering curves which are a plot of hardening versus tempering temperatures. Hardening data is usually specified by jominy end-quench curves. A jominy curve is a relation between the distance from the quenched end (in 1/16 in. increments) and hardness. The standard practice is to water-quench one end of the 1" dia., 4" long specimen. The cooling rate near the quenched end is quite high but it decreases rapidly with distance from the quenched end. Thus jominy distance represents cooling rates and the jominy curve represents a graph of cooling rates versus hardnesses, for a particular steel.

Cold working is defined as subrecrystallization plastic deformation of a metal. Recrystallization of a cold-worked method is controlled primarily by temperature. When a cold-worked material is heated to a certain temperature, the distorted and strained grains are consumed and replaced by a new set of unstrained grains. The temperature at which this change occurs is called the recrystallization temperature. The

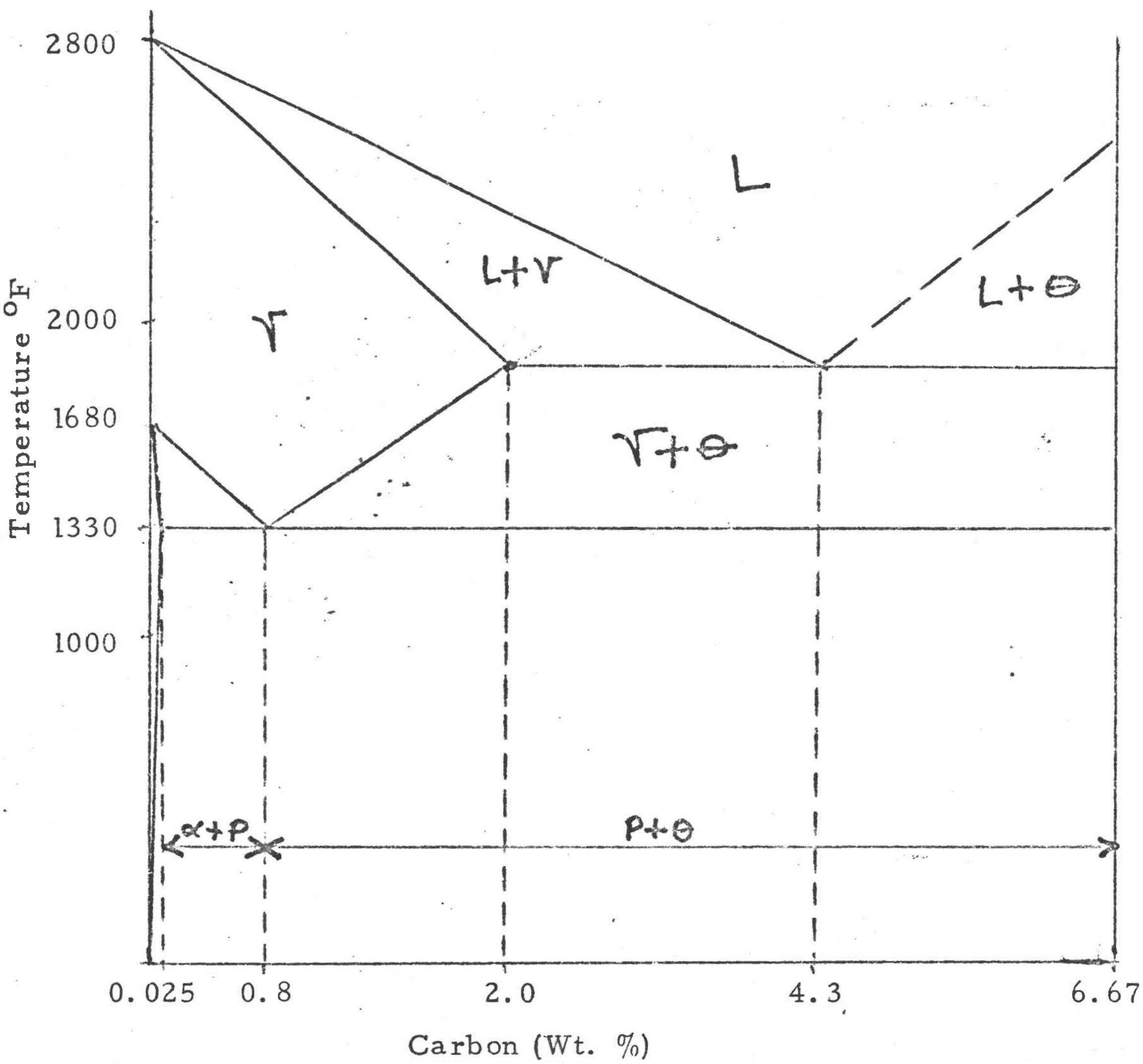

Fig. 1 A Simplified, Iron-Carbon Equilibrium Diagram(1)*

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*Numbers in the parentheses refer to references in the List of References.

recrystallization temperature depends upon the material and the amount of cold-work put into it.

During welding the temperatures in regions adjacent to the welding axis are always higher than the recrystallization temperature so that the cold-worked metal in this region is subjected to recrystallization. This reduces its hardness and strength.

Cold-worked as well as non-cold-worked metals are subjected to other changes during welding. The microstructure of the metal is altered by a heat treating effect. To understand this effect, knowledge of the iron-carbon equilibrium diagram is necessary. The diagram shown by Fig. 1 helps one understand the basic heat treating processes.

The main reason for heat treatment of steel is to strengthen it by causing more carbon to enter into solution and produce a supersaturated solution or to produce a fine structure of phases. If a steel is heated beyond 1333^{o}F, it can absorb more carbon in solution than it can at room temperature. The temperature 1330^{o}F is called the lower critical temperature. If a steel is heated further, beyond a certain temperature, it is fully austenitized. This term refers to face-centered-cubic structure of steel. The temperature above which a steel is fully austenitized is called the upper critical temperature. When a steel is in the astenite region, all the carbon is in solution.

Once a steel is austenitized (fully or partly), the hardness after cooling (i. e., after transformation) depends only upon the cooling rate.

The following table gives the transformation products for 0.8% carbon, plain carbon steel (eutectoid composition). The data applies to 5/8 inch diameter bars treated as indicated.

TABLE I

AUSTENITE TRANSFORMATION PRODUCTS[1]

Cooling Medium	Cooling Rate $^{o}F/sec$ at $1300^{o}F$	Transformation Product	Approximate Hardness
Water	300	Martensite	750 BHN
Oil	30	Fine Pearlite	380 BHN
Air	1	Medium Pearlite	280 BHN
Furnace	0.01	Coarse Pearlite	240 BHN

Martensite and pearlite refer to two types of microstructures in steels. The former is the supersaturated solid solution of carbon dissolved in either body-centered tetragonal or body-centered dubic iron and is very hard and brittle. Pearlite is the mechanical mixture (in a lamellar fashion) of ferrite and cementite. The fineness or coarseness of the pearlite refers to the thickness of this lamina.

During the welding of a steel, the temperatures in the vicinity of the welding axis become high enough to make the steel fully austenitized. Cooling is accomplished partially by radiation of heat from the joint, but mainly by conduction of heat into the surrounding regions of the metal. The cooling rate governs the final hardness in the austenitized zone. It is important to note that once a steel is austenitized the final hardness does not depend in any way upon the original hardness.

Temperatures during welding on a steel plate may vary from a few hundreds ^{o}F at the edge to over 2800^{o}F at the weld-axis. In the zone where temperatures did not exceed 1330^{o}F, the resulting hardnesses on the plate can be compared with those of the tempering curve. At the same time, the resulting hardnesses in the zone where temperatures exceeded the upper critical temperature, can be compared with jominy curve hardnesses. Knowing the cooling rates during welding, it is possible to compare the jominy curve hardnesses with weldment hardnesses for similar cooling rates.

The welding of a water quenched steel presents one principal difference from that of a cold-worked steel. The tempering effect results in recrystallization, while in a water-quenched steel, it results in carbon precipitating out of the supersaturated solution called martensite. Both of these processes are called tempering. Both of these processes result in a softening effect.

One might question the validity of hardness as a measure of physical properties of a metal. The fact is that hardness is proportional to the tensile strength for many metals. In the case of stress-relieved steels, hardness is related to tensile strength as Tensile Strength = 500 x B.H.N. Since engineers are frequently interested in tensile or ultimate strength, the use of hardness is well justified.

The change in hardness due to welding heat has always been of interest to researchers. Dr. W. G. Theisinger,[2] a metallurgical engineer, conducted experiments in the mid-thirties to study the effects of various variables encountered in welding which influence the hardness changes in the parent metals. His study covered both plain carbon steels and alloy steels. In the publications[2] that followed his study, he concluded that main variables were:

(1) Speed of welding

(2) Base metal compositions

(3) Base metal cross-section

(4) Welding current

(5) Type of electrode

W. D. Doty and E. S. Szekeres[3] in their publication in 1965 stressed the effect of pre-heating to get desired hardness in the parent metals. The curve below is taken from their publication, and it shows the effect of heat-input as well as of pre-heat on the cooling rate.

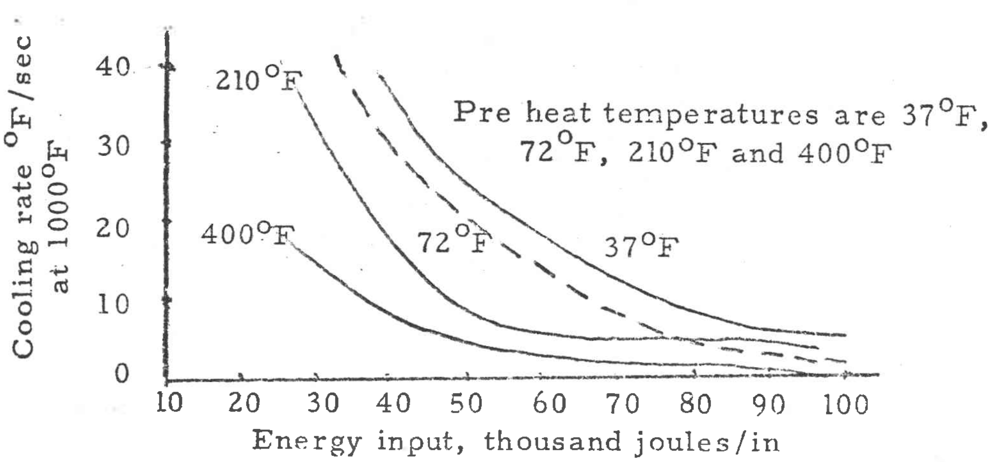

Fig. 2 Influencing Variables on Cooling Rates

It must be noted that this thesis does not treat the effects of all these variables. It deals with hardness prediction as a function of temperatures achieved and measured cooling rates. Maximum temperatures reached during welding at various points on a cross-section and the cooling rate at 1330^{o}F (wherever the maximum temperature exceeded the upper critical temperature) were measured. Tempering curves were also obtained for the metals under study. Jominy curves for these metals were likewise established experimentally. The hardnesses on the welded plates were measured at a few selected cross-sections. The hardnesses at points of interest were compared with those of the tempering or jominy curves.

This method can be useful to predict the hardness profile in the parent metal especially at a point where it is not possible to measure hardness, such as inside of a cylinder under repair. However, a heat transfer analysis on other means must supply the distribution of maximum temperatures and cooling rates.

It should be mentioned that this study was limited in certain respects. The chief limitation was that the welding speed was not quite constant for a particular weld. This, as we have seen, affects the cooling rate. It was assumed that the cooling rates on any longitudinal line along and parallel to the welding axis are similar. This mainly accounts for the inconsistency in the results obtained.

The results otherwise were found to be very consistent.

As discussed later on, the above developed method of predicting hardness appears to be applicable to designing welding techniques.

CHAPTER II

EXPERIMENTAL APPARATUS

The experimental apparatus consisted of steel plates, thermocouples, an amplifying unit, a recorder unit, a welding machine, electrodes, a furnace, a hardness tester and a Jominy test device. The description of each apparatus is discussed in this chapter.

Steel Plates

The metals used in the experiments were AISI 1020 cold-worked and AISI 4130 water-quenched steels in the form of plates. The size of the plates was 1/8" x 3" x 10". About seven plates of each metal were used. It was believed that a small thickness as 1/8" would give larger heat affected zone (HAZ). The 4130 steel plates were quenched in water after heating them to 1600^{o}F for 15 minutes. The hardness obtained in this way was 52 RC.

The reason for selection of AISI 1020 steel was that this type of steel is most widely used and is amply available in the cold-worked form. The selection of AISI 4130 was governed by the fact that it is very sensitive to cooling rates. This property renders good opportunities to study the variation of hardness as a function of cooling rate.

A comment about the selection of the plate size is appropriate. It was realized that if the thickness were increased to say 1/4", the same

HAZ might be obtained by increasing the heat input. But the thickness of 1/4" helps in providing faster cooling rates, and thus more pronounced variation of hardness. The width could better have been selected as 4 in. instead of 3 in. In case of the 4130 WQ (water-quenched) plates, the tempering effects were extended over the entire width of 3 in. If a 4 in. width were provided, it would have been possible to obtain a 4 in. wide HAZ.

Thermocouples

Chromel-Alumel thermocouples were used. Their range extends to about 2500^{o}F, and thus they are well suited to this application. The melting point of a steel is about 2800^{o}F. Shielded extension wires were used to connect the thermocouples to the amplifiers. The shielding protects the circuit from picking up external signals of the nearby electricity.

Amplifying Unit

A twelve-channel, D. C. amplifying unit Electro Instrument Company, Serial No. 200, Model FNO-6 was used. Four out of the twelve channels of the instrument were provided with model A-12, differential amplifiers. The wires from the four thermocouples were connected to these channels. The gains were set at 20 for the first two channels, and 50 for the other two. The gains were chosen to give maximum possible deflections of the recording pens during welding. The first channel was connected to the thermocouple which was at zero distance from the welding axis; the second was connected to the thermocouple at 1/4" distance, and so on in 1/4" increments.

The use of a differential amplifier was necessary to avoid any A. C. or D. C. offset caused by faulty grounding of the welding machine or ground loops.

Recorder Unit

A four-channel Sanborn Recorder (Model 154-100 B, Serial No. 1659) was used to record the amplified outputs from the thermocouples. Each of the channels consisted of amplifying, calibrating and recording elements. The recording system included a writing arm which was driven by a D Arsonval type galvanometer. The recording was done by the impression of a hot-wire ribbon stylus on Sanborn Permapaper, while the paper moved over a writing platen. The optimum paper speed was found to be 1 mm/sec., and this speed was used throughout the experiments. The attenuation was set at 5 for the first two channels and 10 for the other two. The channels of the recorder were in the same sequence as that in the amplifying units.

Welding Machine

A D. C., 200 amp., Lincoln Arc Welding Machine was used. The unit had a motor-driven, differentially compound wound D. C. generator.

Electrodes

The electrodes used were 3/16 in. dia., E 6011.

Furnace

A 6.5 KW electric furnace manufactured by Lucifer Furnace Company was used. It had the range 0-2300^{o}F (model no. HDL 7055. B, Serial No. 1441) for heating the various metal pieces that needed heat treatments.

Hardness Tester

A Wilson Rockwell Hardness Tester (Model 5TT BB, Serial No. 185) was used to measure the hardness of the plates. To measure hardness on the Jominy specimen, a special indexing head was used.

Jominy Test Device

The device was as per the sketch below.

1) Piping arrangement
2) Jominy specimen
3) Supporting plate
4) Galvanized can

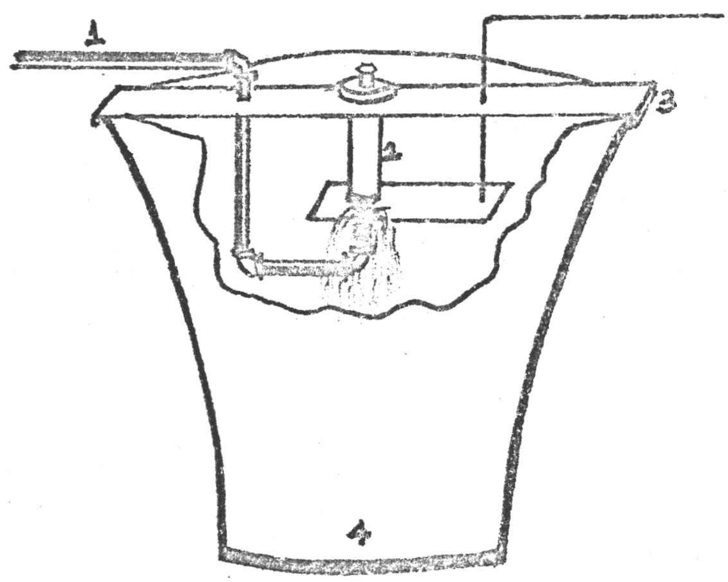

Fig. 3 Jominy Test Device

A galvanized 20-gallon can was used. The piping arrangement was supported on the open top by a steel plate.

The distance from the outlet end of the pipe to the bottom end of the Jominy specimen was 1/2". The outlet of the pipe was 1/2" inside diameter, consistent with SAE specifications. A plate, with a lever welded to it, was provided to expose the end of the test specimen quickly to the water-jet. A siphon tube was provided to empty the container during the test.

The jominy test specimens used were of standard size. The dimensions of the specimen were as shown in the following drawing.

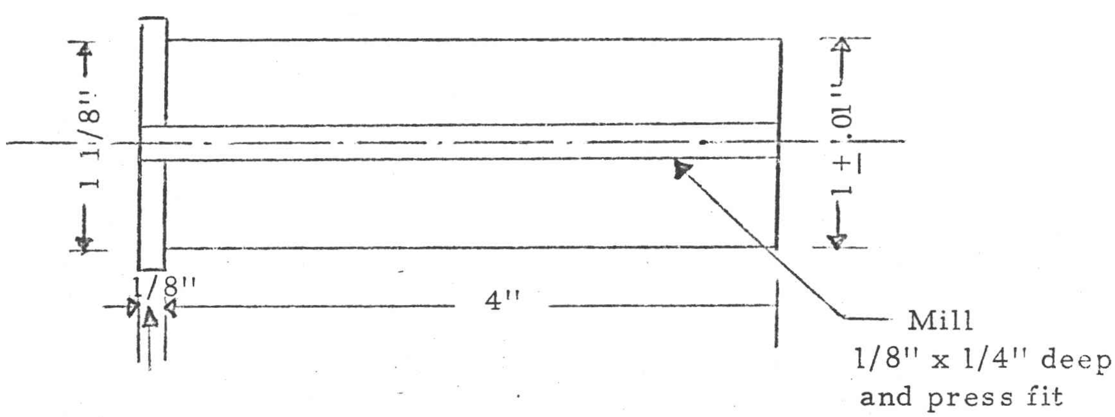

Figure 4 Jominy Specimen

After milling a 1/8" x 1/4" deep groove as shown in Fig. 4, a piece cut from the plate of corresponding material, was pressed in. Since there is always a possibility of variation in composition of two 4130 steels, insertion of a piece from the plate material was necessary.

It was important to see that the piece pressed in, made contact at all over its surface.

CHAPTER III

PROCEDURE

Thermocouples were used to find the time temperature history at different points of the cross-section of a steel plate. They were welded at distances of 0", 1/4", 1/2" and 3/4" from the weld-axis, on a side of the plate opposite to the one, upon which the weld bead was formed. By this arrangement the first two points gave the maximum temperatures (higher than the upper critical temperature), while the remaining two gave temperatures lower than the critical temperature.

To attach the thermocouples to the plate, a small, drop-size weld pool was melted on the plate surface, and the thermocouple joint was pushed into the pool. Care was taken to see to it that only the junction made contact with the weld pool.

The welding was done out of doors. Since the outside temperature ranged from 30^{o}F to 35^{o}F at the time of welding, the low temperature ends of the thermocouples were not kept in ice. Actually, temperature errors of as much as 20^{o}F in most cases would not be critical.

The thermocouple junctions and the amplifying units were connected by the shielded wires, about 7' long.

The photograph below shows the arrangement of the amplifier unit and recording equipment which were located just inside the building. The plates were welded just outside of the corrugated door shown in Fig. 5.

1) Steel plate
2) Amplifying uni
3) Recording unit

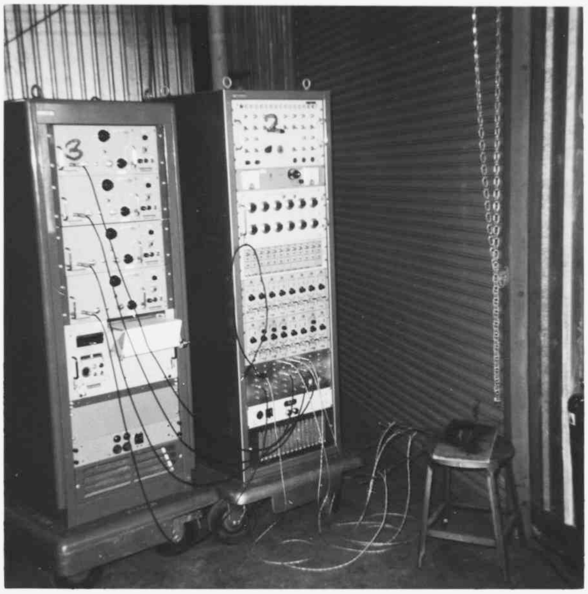

Fig. 5 Recording Arrangement

The welding machine was set at "normal welding" and the current was set at 50 amps. A 3/16", E-6011 electrode was used for welding. The warming up period for the amplifiers and the recorder was about 30 minutes. After proper calibration of both these units, the plates were welded.

The paper speed on the recorder was 1 mm/sec. The movement of the pen represented the input to the recorder in millivolts.

$$\begin{array}{c}\text{Input voltage to}\\ \text{recorder in millivolt}\end{array} = 0.05 \times \begin{array}{c}\text{attenuation}\\ \text{factor}\end{array} \times \begin{array}{c}\text{movement of pen}\\ \text{in cm.}\end{array} \times 1000$$

The above, when divided by the amplification factor, gave a reading in millivolts for the thermocouples. By the aid of standard conversion tables (such as one by Leed & Northrup Company), the millivolt recordings were converted into temperatures.

Knowing the maximum temperature at 0", 1/4", 1/2" and 3/4" from the welding axis, a plot of the distance from the welding axis versus the maximum temperature could be made. This way it was possible to know the maximum temperature at any point of the cross-section. It was assumed that the welding conditions at every cross-section were uniform. Cooling rates could be found by measuring the slope of the temperature traces on the chart (See Fig. 6, page 21).

After welding, the plates were allowed to cool off in the open atmosphere. The welded-side of the plate was ground flat to measure hardnesses. Hardnesses were measured at two selected cross-sections on each plate. Care was taken to avoid the areas surrounding the points where the thermocouples were welded, because these areas were already affected by heat before actual welding was performed. Graphs of hardness versus distance from the welding axis were obtained.

The above procedure was repeated for each of the plates. For a convention, the first of the two cold-worked 1020 steel plates was called as plate 1-CW, the second, as plate 2-CW. Similarly, the two plates of water-quenched 4130 steels were denoted as 1-WQ and 2-WQ.

To get the tempering curves for both steels, small pieces of dimensions 1/8" x 1 1/2" x 2 1/2" were put into the furnace at different temperatures, varying from 250°F to 1400°F. After heating for about 15 minutes and cooling in air, the hardnesses were measured. Curves of temperature versus hardness were plotted which constitute tempering curves.

Jominy end quenching tests were run according to SAE standard procedures. The test specimen was heated to 1600°F for 30 minutes. To reduce scaling of the specimen surface and to minimize carbon loss, the specimen was put into a graphite container while in the furnace. The column of water passing through the 1/2" dia. opening was adjusted to a free height of 2 1/2" above the opening. The specimen, after removal from the furnace, was placed in the jominy fixture (see Fig. 3). The plate which was inbetween the column of water and the specimen, was quickly removed by turning its lever. The specimen was kept in the fixture with the water running for ten minutes. The temperature of the incoming water was less than 85°F at all times.

The specimen was then ground off for 1/8" on the side where the sample piece was pressed in. An indexing fixture was used to hold the specimen and to move it 1/16" each time the hardness was measured. A graph was obtained of jominy distance versus hardness (which constituted a jominy curve).

CHAPTER IV

RESULTS AND DISCUSSION OF RESULTS

Proceeding as per the previous chapter, welding was performed on four plates, two of each metal. These plates, as stated before, were named as 1-CW, 2-CW, 1-WQ and 2-WQ. The results of hardnesses, maximum temperatures and cooling rates were obtained for each welded plate. These results and the other results are given and discussed in this chapter.

Fig. 6 shows the temperature versus time plot as recorded on the recorder during the welding of the 1-WQ plate. The recorded graphs for the other three plates were similar and are not included here for the sake of brevity.

The maximum temperatures at any cross-section are shown plotted in Figs. 7 and 8, separately for 1020 and 4130 steels.

With both the temperature and the hardness variations established, it is possible to check how closely these results agree with the jominy and tempering data.

Since the plates are either cold-worked or water-quenched, we expect the hardness to be minimum around 1330°F (due to tempering). Looking at the plot of maximum temperatures, it is seen that plate 1-CW achieved the 1330°F temperature at about 0.25 in. from the welding axis.

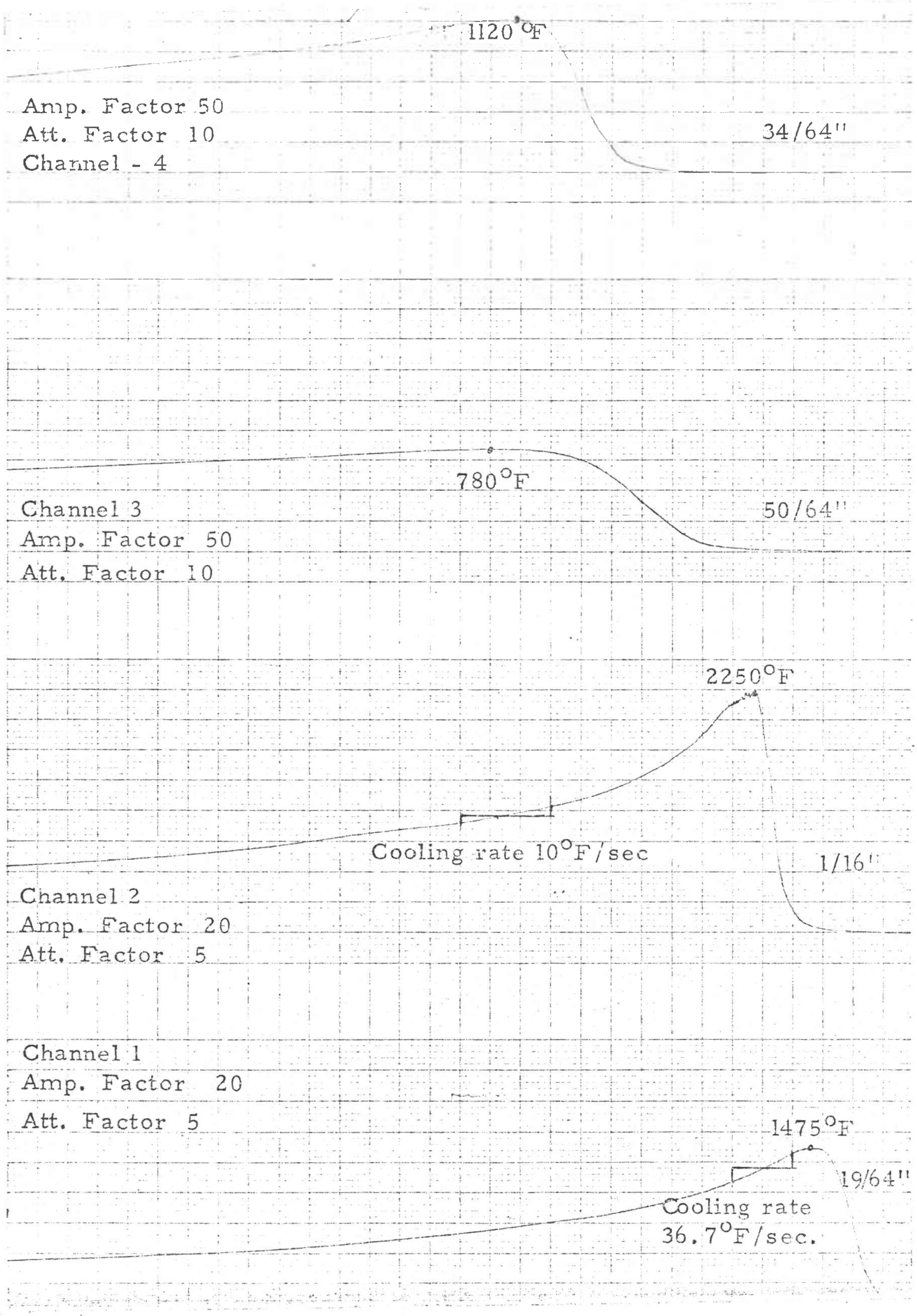

Fig. 6 Time-Temperature History (for 1-WQ)

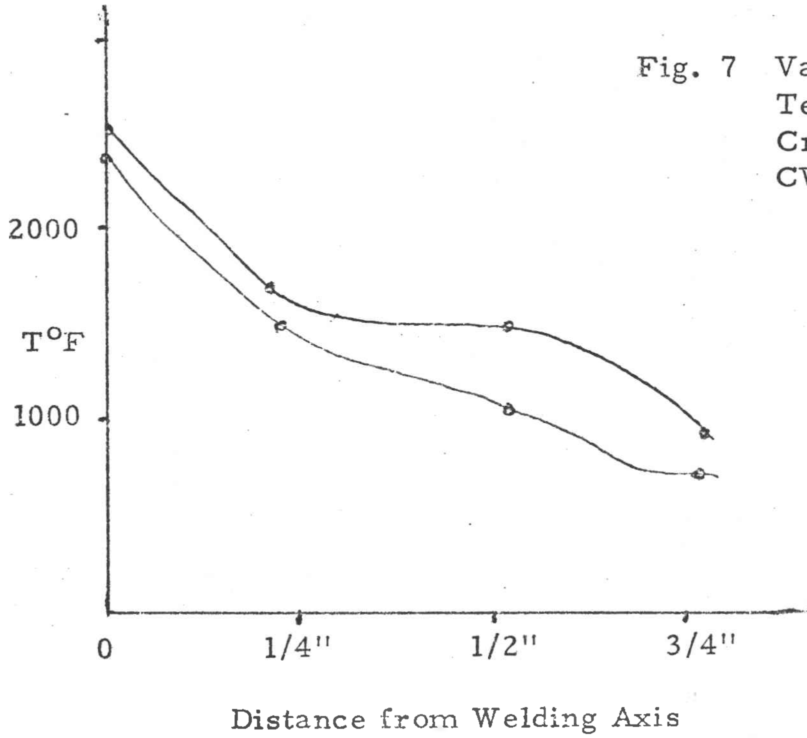

Fig. 7 Variation of Maximum Temperature Along a Cross-Section (for 1020 CW plate)

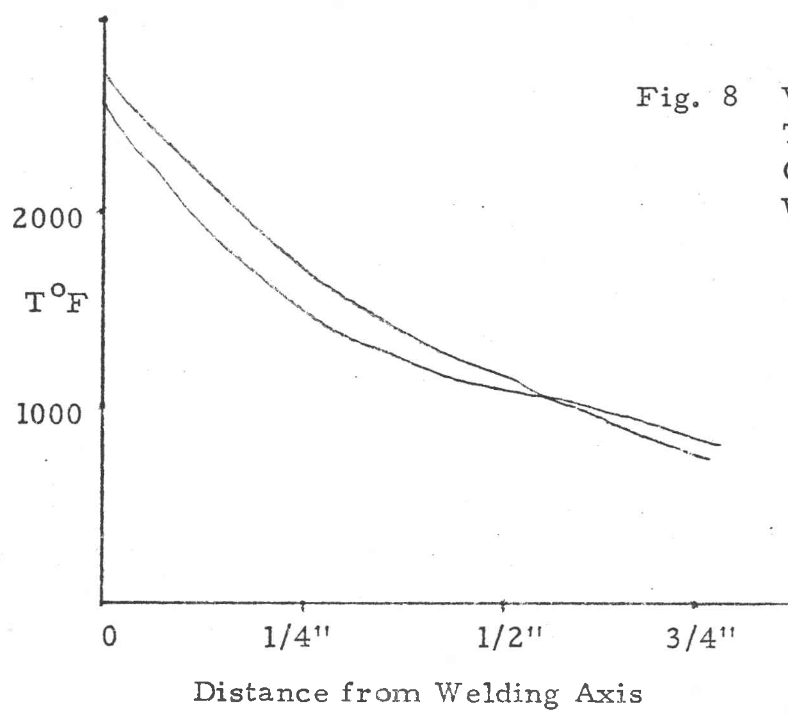

Fig. 8 Variation of Maximum Temperature Along a Cross-Section (for 4130 WQ plate)

The full line shows the profile at a cross-section 1 1/2" from the start of bead, while the broken line shows the same for a cross-section 4" away from the start.

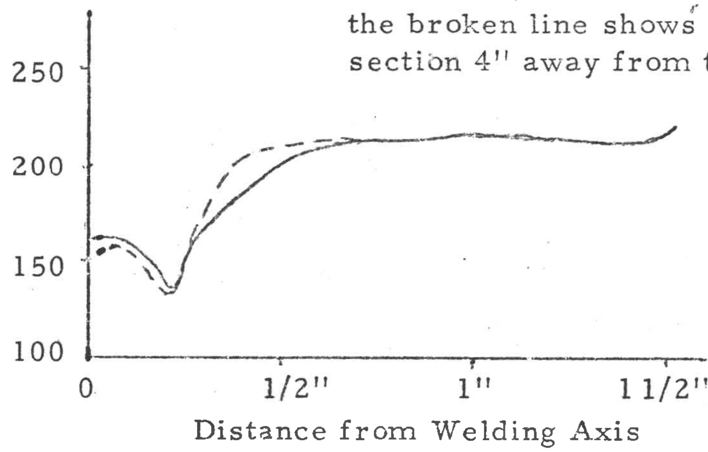

Fig. 9 Hardness Profile for 1-CW

Uniform hardness (before welding) in both the plates was 210 BHN

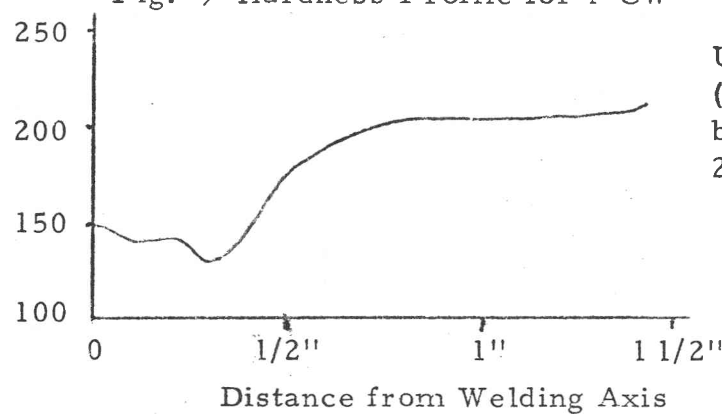

Fig. 10 Hardness Profile for 2-CW Plate

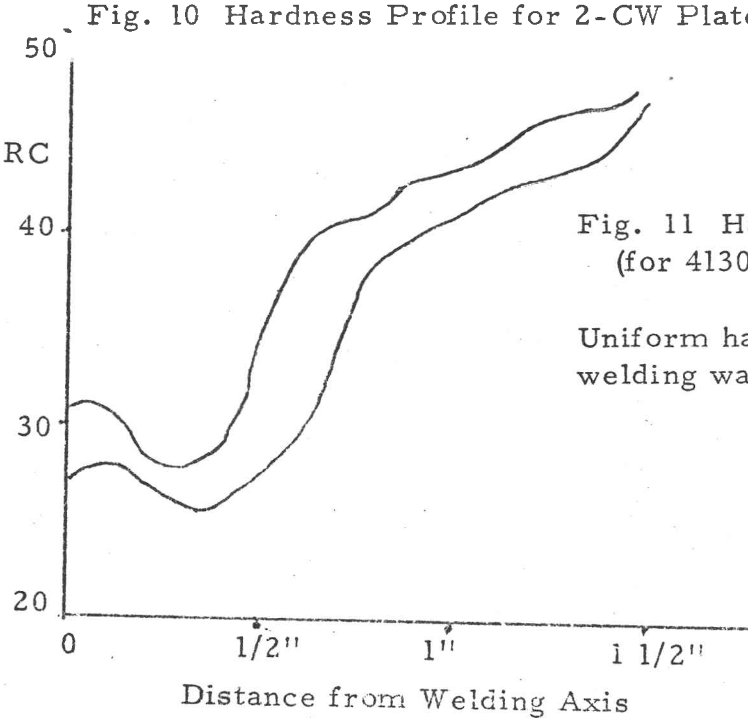

Fig. 11 Hardness Profile (for 4130-WQ Plates)

Uniform hardness before welding was 52 RC.

The hardness variation shows that the minimum hardness in plate 1-CW was at 0.22 in., which agrees reasonably well.

The data for plate 2-CW was not as consistent. The 1330°F temperature was obtained at about 0.6 in. from the axis, while the hardness profile shows the lowest hardness point to be at about 0.3 in. from the axis. This discrepancy was traced to the plate itself. The cross-section at which the thermocouple no. 3 was attached (1/2" from the axis), received an excess of heat input. The width of the bead at this cross-section was larger than at other places. Thus instead of producing the expected 1000°F temperature, it was about 1500°F at 1/2" away from the welding axis.

The 1330°F temperature point was found to be at 0.3" on 1-WQ plate. The same temperature appeared on the plate 2-WQ at 0.38", while the corresponding minimum hardness was seen at 0.35".

The final hardnesses on the plates were more or less uniform in the region where the temperature exceeded 1600°F. Looking into the iron-carbon equilibrium diagram, this region corresponds to the austenite region which is a single phase region.

Table II shows the cooling rates recorded at different points on the plates.

TABLE II

COOLING RATES

Plate	Distance from Axis in inch	Cooling rate at 1330°F in °F/sec.
1-CW	1/4 *	20
	0	17
2-CW	1/4	22
	0	22
1-WQ	19/64	38
	1/64	10
2-WQ	3/32 **	26
	3/32	10

From the cooling rates, it can be expected that the microstructure of 1020 steels may consist of about 25% fine pearlite and 75% ferrite (see iron-carbon equilibrium diagram Fig. 1), and the hardness of 0.25 x 380 + 0.75 x 80 - 155 BHN. (See Table I.) The actual hardness obtained is seen from the hardness profiles as just under 150 BHN.

The cooling rates near the starting point of the weld bead were found to be higher than those further along the bead. This is because the plate was heated after the start, and thus the cooling rate declined. Hardnesses measured along a line parallel to the axis shows this fact.

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*The point that faced the welding first is placed first in the second column of the table.

**The thermocouples were supposed to be 0" and 1/4" away from the axis. But the weld bead was not straight, so the distance represents actual distance after the welding was completed.

The graph below shows that hardness at the start of the bead is significantly higher than that near the end.

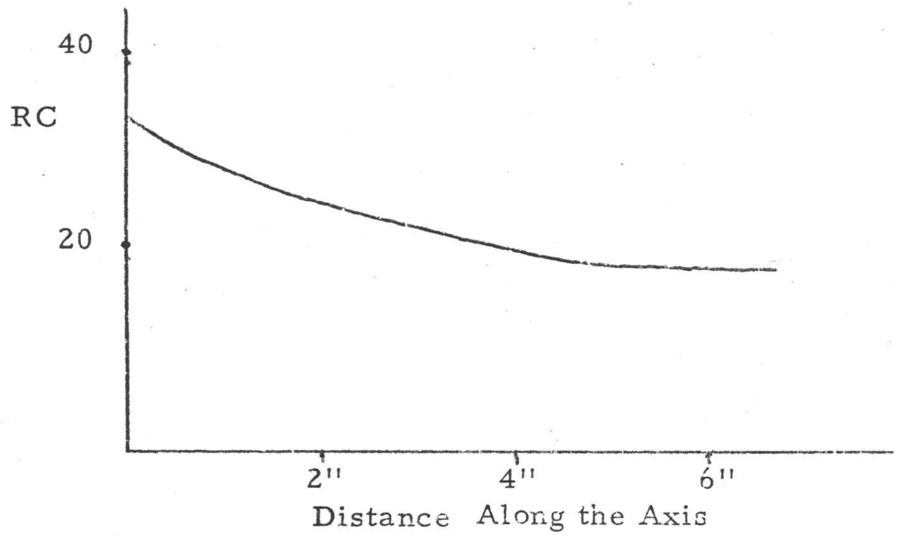

Fig. 12 Hardness Variation Along the Axis
(On a 4130 WQ Steel Plate)

This fact is also confirmed from Table II.

It is now possible to check whether or not the tempering effect on the plates follows the tempering curves.

Taking 1020 steel first, it can be seen on the plates 1-CW and 2-CW that wherever the temperature approaches 1300°F, the hardness measured was 130 BHN. The tempering curve for 1020 CW steel reveals this number as 133 BHN (Fig. 13).

The tempering effect on plate 1-CW extended to 0.7'' from the weld axis. The maximum temperature at this distance was 900°F. The tempering curve also agrees with this temperature-hardness combination. However, the data of plate 2-CW did not agree as well as mentioned before.

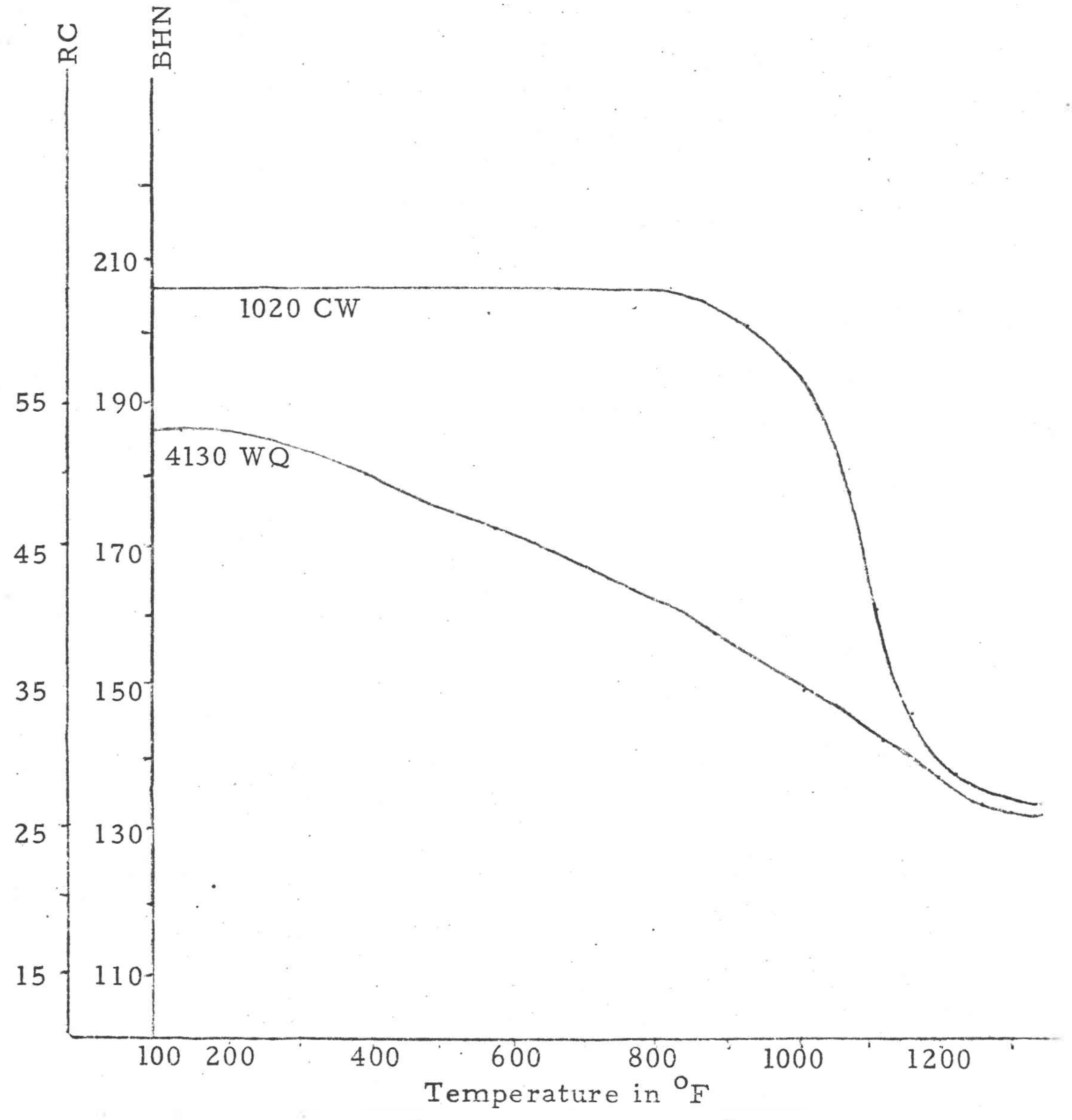

Fig. 13 Tempering Curves

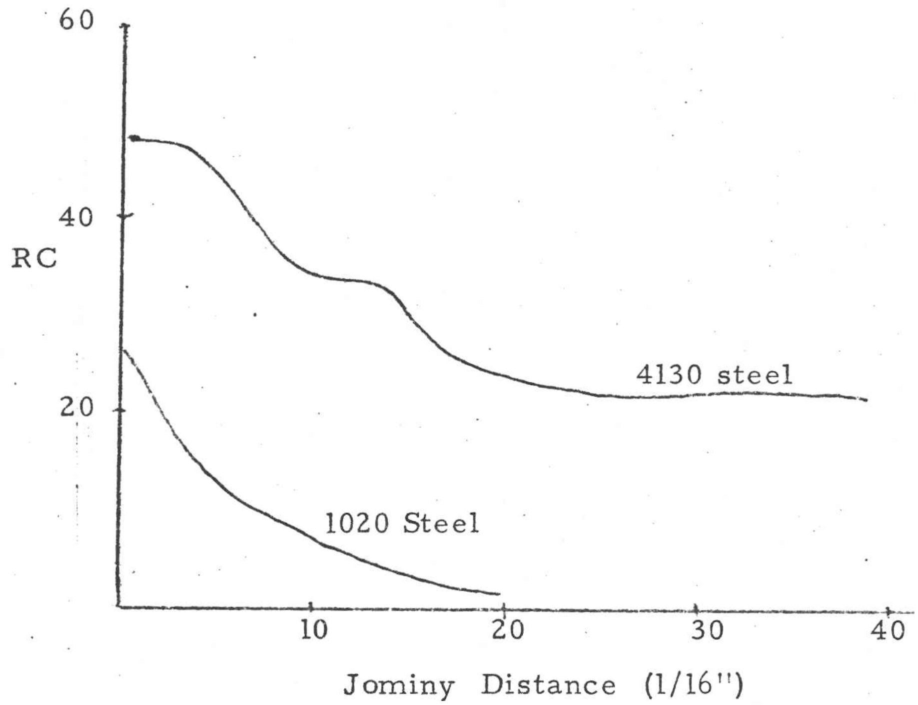

Fig. 14 · Jominy Curves

The following sketch illustrates the relation between jominy distance and cooling rate. It is approximately the same for the most steels.

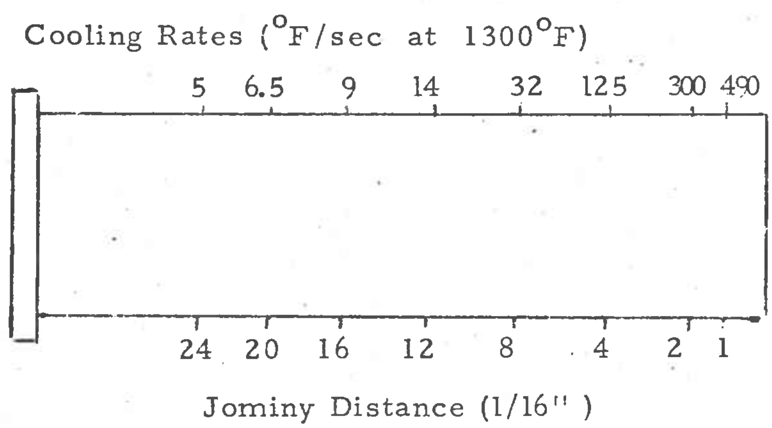

Fig. 15 Relation Between Jominy Distance and Cooling Rate[1]

In the case of 4130 WQ steel, good agreement was observed between the weldment hardness data and the tempering curves. The hardness profiles show that the hardnesses at 1300°F as 25.5 RC and 28 RC in the two plates. The tempering curve shows 25.5 RC for this temperature. The temperature profile shows that the temperatures at all points on a cross-section were higher than 250°F, the temperature below which the original hardness of 52 RC was not affected by tempering. The hardness profile curve again agrees with the tempering data, as the hardness at the extreme point, 1 1/2" away from the axis was 47 to 48 RC.

It is interesting to see that the hardness profiles under the effect of tempering are almost a reproduction of their respective tempering curves (compare Fig. 9, 10, and 11 with Fig. 13).

Now we proceed to check any possible correlation between the effects of cooling rates on the hardness, and the jominy end quench data.

The jominy curves obtained are shown in Fig. 14.

Upon examining the cooling rates on plate 1-WQ during welding, it can be seen from Table II (page 25) that the cooling rate recorded at a point 1/16" away from the axis is 10°F/sec (at 1330°F). The equivalent jominy distance (from Fig. 15) is 15. The corresponding hardness, seen from the jominy curve (Fig. 14) is 30.5. The measured hardness is seen in the hardness profile (Fig. 11) to be 30.5 RC at 1/16" away from the axis.

Hardness predictions from the jominy data for 1020 steels can be obtained in similar fashion. The cooling rates for this plate lie between

17 to 22^{o}F/sec (at 1330^{o}). The equivalent jominy distances are 9 to 11 (from Fig. 15), and the corresponding hardnesses seen in the jominy curve are 7 RC to 6 RC (about 160 BHN). The actual hardness in the austenitized region on the CW plates are about 150 to 155 BHN. Hence, the correlation is good.

CHAPTER V

CONCLUSIONS

The discussion of the results in the previous chapter clearly indicates the success of the method developed. From the same discussion the following conclusions can be derived.

(1) The experimental method developed in this thesis can predict the hardness profile after welding with a high degree of accuracy.

As discussed in the previous chapter, the predicted hardnesses fell in the range of $\pm$ 10%.

(2) A few inconsistencies in results can be avoided if the heat input is uniform throughout the length of the welding.

An automatic welding machine could provide greater consistency and hence provide less variation of data. However, the data obtained showed remarkable consistency.

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AN EXPERIMENTAL STUDY OF THE EFFECTS OF WELDING ON COLD-WORKED AND ON HEAT-TREATED STEELS AS THEY CORRELATE TO TEMPERING AND JOMINY DATA

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Kiran Patwari

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ABSTRACT

The basic object of this thesis was the developing of a method to predict the hardness profile on any cross-section resulting from the welding of 4130 water-quenched and of 1020 cold-worked steels.

The method developed in the thesis was found satisfactory. The hardness profile predicted from the tempering curves and the jominy curves for these steels followed closely the actual hardness profile measured after arc welding.

APPROVED: