Correlation of Weldment Hardness Profiles in Steels with Jominy End-Quench Data

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CORRELATION OF WELDMENT HARDNESS PROFILES
IN STEELS WITH JOMINY END-QUENCH DATA

A Thesis
Presented to the
Department of Mechanical Engineering
Brigham Young University

In Partial Fulfillment
of the Requirement for the Degree of
Master of Science

by
Deepak Panjabi
May 1967
This thesis by Deepak C. Panjabi is accepted in its present form by the Department of Mechanical Engineering of Brigham Young University as satisfying the thesis requirement for the degree of Master of Science.

November 21, 1966
Date
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CHAPTER I

INTRODUCTION

Welding occupies an important place as a major metal fabricating process and steel is the backbone of many an industry. Therefore it is of paramount importance to know the effect of welding on steel.

The primary object of this research was to be able to predict the hardness profile of a given steel specimen when it is arc welded. Experimental results were used in conjunction with standard data to predict the hardness profile.

Welding is the manufacturing process of joining two or more pieces of material together by utilizing only the fundamental attraction forces that hold the atoms of a solid into their fixed positions. If arc welding is used, a lot of heat is evolved. Consequently in arc welding, the material is subjected to heating followed by cooling.

Metals are good heat conductors. The atoms in the metal pass heat along rapidly to their neighbors. Therefore it is obvious that if one edge of a plate is welded, heat will flow from that edge towards the opposite edge of the plate; hence there will be an increase in the temperature drop as the distance is increased from the weldment. This effect is easily seen as a zone of varying shades of color grading from black to light gray on the surface of the material. (See Figure 1) This zone is called the heat-affected zone. This grading in color shade is due to the iron oxides. The color of the oxide is an indication of the maximum temperature reached.

The critical temperature of eutectoid steel, AISI 1080, is 1333°F. If this steel is heated above this temperature it is austenitized. That
Fig. 1. Sketch of Arc Welded Steel Plates Showing Positions of Color Isotherms. (From Datsko)
is steel is in the austenite region of the phase diagram (see Figure 2). At this high temperature the eutectoid steel consists of a single phase \( \gamma \) or austenite. Austenite is a solid solution of carbon dissolved interstitially in face-centered cubic iron. Austenite is very soft at this high temperature. The austenizing of steel serves to homogenize it. During welding, temperatures of 1333\(^{\circ}\)F and above are obtained. Therefore steel undergoes the above microstructural change during welding. A part of the heat-affected zone does not attain the critical temperature. Therefore that region does not experience this change in microstructure.

Each ferrous alloy has lower and upper critical temperatures. Below these temperatures austenite transforms into any combination of ferrite, pearlite, cementite and martensite, depending on the rate at which the part cools from the welding temperature.

If an austenized AISI 1080 specimen is allowed to cool in the furnace, the cooling rate will be about 0.01\(^{\circ}\)F/sec at 1300\(^{\circ}\)F and the resulting microstructure would be coarse pearlite. If the cooling rate is increased to 30\(^{\circ}\)F/sec at 1300\(^{\circ}\)F as in oil quenching the microstructure obtained is called fine pearlite. If the specimen is water quenched the cooling rate would be about 300\(^{\circ}\)F/sec at 1300\(^{\circ}\)F. At this cooling rate the austenite transforms into martensite. Martensite is a supersaturated solid solution of carbon dissolved interstitially in either body-centered tetragonal iron or body-centered cubic iron.

A second phase precipitates out of martensite (which is a supersaturated solid solution), if it is heated to between 350\(^{\circ}\)F and 1333\(^{\circ}\)F. This is called tempering. The primary martensite which is a body-centered tetragonal transforms to body-centered cubic secondary
Fig. 2. A Simplified, Iron-Carbon Micro-constituent Diagram. (From Datsko³)
martensite. For tempering temperatures between 250°F and 400°F some carbon precipitates out of the solution in the form of transition carbides. The decrease in hardness is very slight. As the tempering temperature is raised, the decrease in hardness is further decreased.

A change in the microstructure of steel will cause a change in the hardness. The cooling rate of the austenized steel determines its microstructure. The End-Quench Hardenability curve correlates the cooling rate and the hardness.

The End-Quench Hardenability curve, also known as the Jominy, is a curve of Jominy distance against hardness. Each Jominy distance is equivalent to a cooling rate, hence the correlation.

The Jominy sample is a cylinder of steel 1" round and 3 7/8" long with a flange on one end 1½" diameter and 1/8" thick. The sample is first normalized, machined to size and then heated to the proper quenching temperature for the steel being treated. It is then inserted in a hole in a fixture (see Figure 3) so that it hangs vertically on the flange over a ½" round orifice which is ½" below the bottom end of the sample. The hole in the fixture will pass the bar but not the flange. Water comes through the ½" orifice with sufficient pressure to rise to a height of 2½" when the sample is not in place, this being controlled by a gate valve. The water, when making the test, is allowed to continue to flow until the sample is cold. Smooth, flat surfaces are then ground 0.015" deep lengthwise on opposite sides of the sample. Rockwell hardness readings are then made at 1/16" intervals from the quenched end along the length of the ground surface as shown in Figure 4. The rate of quenching is very fast at the bottom end, and because the heat must pass through the sample by conduction, the top portion is cooled very
Fig. 3. Cutaway view showing fixture for making Jominy hardenability tests. The test specimen is shown hanging in the flange. (From 5)

Fig. 4. Diagram of Rockwell C readings on a standard Jominy end quench hardenability test sample of NE 9440 steel. (From 6)
slowly. This means that the same piece of steel has been cooled at different rates starting with a very rapid quench at the bottom to a very slow cooling at the top. By running Rockwell hardness tests along the side of the sample from the bottom to the top, it is possible to find out what hardnesses were developed by different rates of cooling.

The purpose of this experimental analysis was to correlate the cooling rate with the welding conditions. Once this was done, it was just one more step to predict the hardness from the cooling rate by means of a Jominy curve. This procedure can only be followed for temperatures attained during welding that are above the upper critical temperature.

For temperatures attained below the lower critical temperature use is made of the tempering curve. A tempering curve is a graph of tempering temperature against hardness. Therefore, given the welding conditions or the tempering temperature, it is possible to predict the hardness.
LITERATURE SURVEY

Little research has been done in correlating hardness with the varying welding conditions. The principal concern has been with welding from a metallurgical point of view. Dr. W. G. Theisinger in "Heat Effect in Welding" \[1\] discusses the heat treatment of the steel plate due to welding. He found out that there is drastic quenching of the heated metal in the welding process as brought about by the mass cooling effect of the surrounding plate metal. Steels can be made to assume the microscopic constituents from pearlite to martensite with the corresponding hardness of each class. He also obtained the variation in hardness as the welding speed was changed. This is shown in Figure 5.

A. C. Ward in "How Heat and Time Affect Welding" \[2\] discussed the change in the microstructure of the workpiece due to welding heat and also the use of Time Temperature Transformation Diagram (TTT). The TTT diagram correlates time, temperature and transformation products. The diagram indicates the amount of time required for austenite to transform into another phase when it is held at a constant temperature below the upper critical temperature. Although the TTT diagram depicts constant temperature transformation, one can approximate the critical cooling rate which is the slowest cooling rate that will produce all martensite. This critical cooling rate can be approximated by plotting a cooling curve on the TTT diagram that is tangent to the "nose" or "knee" of the S-shaped TTT curve.

The TTT diagram tells what to expect of metal adjacent to the weld zone. It warns the welder of the formation of brittle martensite. It

*Numbers in brackets refer to references in Bibliography.
Fig. 5. S.A.E. 4130 (0.33 per cent carbon, Cr-Mo). Maximum allowable welding speed based on 100 points Brinell = 13 in. per min. (From Theisinger)
calls attention to the need for post-weld heat treatment to avoid failure in service through stress cracking. If one knows how long the workpiece takes to cool down to room temperature then it is relatively easy to determine whether martensite will be present by considering the TTT diagram.
CHAPTER II

EXPERIMENTAL EQUIPMENT

Steel plates were welded by means of a D.C. arc welding machine with 1/8" diameter 6011 electrodes. The time-temperature history of the welded region was recorded by a strip recorder system used in conjunction with an amplifier system and four thermocouples. An integrating digital voltmeter was used to obtain slow cooling rates. A Rockwell hardness tester was used to obtain the hardness of the specimen plates.

Steel Plate

AISI 4130 steel was selected on the basis of its Jominy curve and availability. AISI 4130 steel has a gradual change in hardness as the Jominy distance is increased. (See Figure 6) The size of the specimen plates for welding was 1/8" x 2" x 5½". The region of the heat-affected zone was the criterion for the selection of plate width. One-eighth inch thickness was selected because it produced a large heat-affected zone. This in turn facilitated the recording of temperatures above the critical temperature. The length was determined on the basis of convenience of welding.

The specimen plates were flame cut from a larger plate. This introduced heat effects. The plates were then austenitized and quenched to remove these effects.

As discussed earlier, a part of the heat-affected zone is heated below the critical temperature. Therefore it will not be austenitized in that region. But if the steel is tempered there will be a change in the microstructure. For tempering, steel has to be austenitized,
Fig. 6. Hardenability Band 4130 H. (From S.A.E. Handbook 1965.)
quenched and reheated to a tempering temperature. Hence the plate can be tempered by welding heat if it has been first austenitized and water quenched. Therefore, the AISI 4130 specimen plates were water quenched after heating them into the austenite region. If the plate was welded after water quenching, it could warp and crack. Therefore, in order to remove the quenching stresses and increase ductility, the plates were reheated to 350°F. They were heated up to 350°F and not above in order to maintain the original hardness of the plates.

D.C. Arc Welding Machine

A 200 ampere Lincoln Welding Machine, serial no. A2170826 was used for obtaining the power for welding. The arc welding unit is an electric-motor-driven D.C. generator. The welding generator is a differentially-compound-wound, self-excited D.C. generator.

Recorder System

The Sanborn recorder, model 154-100 B, serial no. 1659, was used for obtaining the time-temperature history of the heat-affected zone. This recorder is a direct writing unit instrument which uses a bank of D'Ar Sonval galvanometers to record a number of variables simultaneously. Each galvanometer movement drives a writing arm which wipes a hot wire ribbon stylus across Sanborn Permapaper while the paper is moving over a knife edge writing platen. The final recording is permanent, instantaneous and in true rectangular coordinates. It has paper speeds of 0.25, 0.5, 1.0, 2.5, 5.0, 10, 25, 50 and 100 mm/sec. Sensitivity is one millimeter on the chart per milli ampere of current.
Amplifier System

A model A-14 D.C. Amplifier of Electro Instrument Company was used to amplify the voltages obtained at the hot junction of the thermocouples. Model A-14 is a completely self-contained, totally transistorized, wide-band D.C. amplifier featuring low noise, high stability and accurate gain control. The high D.C. input impedance of 100 megaohms shunted by 0.002 mfd prevents circuit loading when measuring voltages from high impedance sources. Gain is controlled by a rotary selector switch in the front panel. The function of the D.C. amplifier is to amplify low-level A.C. and D.C. voltages and to provide proper impedance matching between voltage source and subsequent equipment.

Thermocouple

Chromel-Alumel thermocouples were used because of the high temperatures involved. The thermocouples leads were about a foot long so as to maintain the extension lead wires at the room temperature.

Copper extension lead wires were used. They became part of the thermoelectric circuit and the thermocouple actually consisted of the extension lead wires plus the thermocouple itself. Since the copper lead wires and junctions remained at room temperature, negligible voltage error was introduced.

Electric Furnace

The electric furnace of Lucifer Furnace Company, serial no. 1441, was used for heating the specimen plates.

Rockwell Hardness Tester

The Wilson Rockwell hardness tester, model 3JR, serial no. 3759,
was used to obtain the hardnnesses of the specimen plates. Brale penetrator was used; "C" scale was used.

**Voltmeter**

A 50 volts voltmeter of Simpson Electric Company, model no. 260, inventory no. 0425, was used to measure the arc voltage while the plates were welded.

**Microammeter**

A D.C. microammeter of Hewlett Packard, model no. 425A, serial no. 002-01838 was used for obtaining the shunt voltage to measure the current passing through the welding circuit.

**Ammeter Shunt**

A 50 mv 300 amp ammeter shunt was used for the measurement of the current in the welding circuit.
CHAPTER III

EXPERIMENTATION

The experiments that were conducted can be classified into three parts:

1. Obtaining the cooling rates and tempering temperatures during welding.
2. Obtaining Jominy End-Quench data for AISI 4130.
3. Obtaining tempering curve for AISI 4130.

Welding Experiments

The edge of the steel plate was welded. Temperatures at four different points in the heat-affected zone were recorded. Temperature readings above the upper critical temperature were used to obtain the cooling rate while those below the lower critical temperature were used for obtaining the tempering temperatures due to welding heat.

One end of the chromel thermocouple wire was spot welded to one end of the alumel thermocouple wire thereby forming a chromel-alumel thermocouple. Before the thermocouples were spot welded to the plate, the surface was ground to remove the scale. There was direct contact between the metal and the thermocouples. Four thermocouples were used to obtain the readings. They were placed at distances of 5/8", 11/16", 1½" and 1¾" respectively from the edge of the plate. The reason for this placement of thermocouples was that two readings should be obtained above the critical temperature and two below. But as it turned out, only one reading was obtained above the critical while three were obtained below the critical.
Thermocouples were protected by porcelain insulators. The free ends of the thermocouples were coated with silver solder. The copper extension lead wires were then soldered to these free ends.

The extension lead wires were attached into the amplifier system. The outlet of the amplifier system was connected to the recorder system. From the standard tables it was found out that 1600°F corresponds to 36.19 mv, 1400°F to 31.65 mv, 1100°F to 24.63 mv and 500°F to 10.5 mv. These values were obtained from "Conversion Tables for Thermocouples" of Leeds & Northrup Company. The gain of the amplifier was adjusted so as to obtain full-scale deflection of the writing pens of the recorder for the above-mentioned voltages.

The amplifier system and the recorder system were switched on half an hour before the experiments were conducted. The block diagram of the experimental set-up is shown in Figure 7.

Two voltmeters and an ammeter shunt were introduced into the welding circuit to obtain the voltage and the current during welding. Since the voltmeter pointer fluctuated a lot during welding, the average value was noted.

The edge of the plate was welded and the recorder recorded the time-temperature history of the four selected points. The speed of the welding operator was measured by means of a stop watch.

The experiment was repeated for different voltages and currents. It was observed that there was not much variation in the voltage and the current as their respective selectors on the welding machine were turned from one extreme to the normal setting.

During the experiments, the plastic covered copper extension lead wires would pick up a lot of outside electrical interference.
This was increased many fold when the plate was being welded. Consequently no legible readings were obtainable. To eliminate this interference, shielded copper extension lead wires were used. Interference was also picked up when the shielded extension lead wire made contact with the ground cable of the welding machine. Care was taken to prevent this contact.

From the time-temperature history, the cooling rate of the point nearest to the weld was found while the maximum temperatures at the other three points were noted. The hardness of these three points was found by means of a Rockwell hardness tester.

By means of dimensional analysis (refer to the appendix) a graph of dimensionless power against dimensionless cooling rate is obtained. A D.C. arc welding machine was used for the experiments. Therefore, the power is given by the product of voltage and current. Power is plotted against cooling rate. Welding speeds corresponding to the points obtained on the graph are noted. In this way, it was anticipated that constant speed lines might be found. (See Figure 8)

For the other three points of the heat-affected zone, maximum temperature was plotted against hardness on the graph of the tempering curve. In this way it was possible to compare the hardness due to welding heat and the hardness obtained due to the actual tempering process.

Tempering Curve

To obtain the tempering curve for AISI 4130 steel, four specimen plates were used. The size was arbitrarily selected as $\frac{1}{4}'' \times 2'' \times 5\frac{1}{2}''$. First the specimen plates were heated to 1525°F. They were
Fig. 8. Graph of Power Versus Cooling Rate
held at this austenizing temperature for half an hour. Then they were water quenched. Then thermocouples were attached to them, one on each specimen as in the welding experiments. These pieces were then tempered to 357°F, 637°F and 817°F respectively. They were held at the tempering temperatures for five minutes before being cooled to room temperature. Then their hardness was measured. The temperature was plotted against the hardness to obtain the tempering curve for AISI 4130 steel. (See Figure 9)

**Hardenability Curve**

To obtain the Jominy curve for AISI 4130 steel, four specimen plates were used. The sizes were arbitrarily selected as 1/8" x 1" x 1 1/2", 1/8" x 2" x 2", 1/8" x 1" x 2 1/2" and 1/8" x 2" x 1 1/2". Each plate had a thermocouple attached to it. Specimen one was connected to the integrating digital voltmeter. Specimens two, three and four were connected to the temperature recorder system. All four specimens were austenitized. They were held at the austenizing temperature of 1525°F for half an hour. Then specimen one was air cooled. Its cooling rate at 1300°F was obtained from the readings of the digital voltmeter. Specimen two was water quenched and specimen three was oil quenched. Their cooling rates were obtained from a time-temperature plot. Specimen four was furnace cooled. It was difficult to obtain its cooling rate. To obtain its cooling rate the drop in temperature from 1340°F was timed. This gave the average cooling rate. Hardness of all the four specimens was measured by the Rockwell hardness tester. The equivalent Jominy distances for the cooling rates was found. From the data so obtained, three points were
Fig. 9. Tempering Curve

Points obtained from welding experiments
plotted on the standard hardenability curve of AISI 4130 steel. (See Figure 10)

RESULTS OF WELDING EXPERIMENTS

<table>
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<tr>
<th>Expt No</th>
<th>Voltage in volts</th>
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<th>Speed in in/min</th>
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<td>1</td>
<td>23</td>
<td>60</td>
<td>5.59</td>
<td>73</td>
</tr>
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<td>2</td>
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<td>74</td>
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<td>3</td>
<td>25</td>
<td>60</td>
<td>5.88</td>
<td>74</td>
</tr>
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<td>4</td>
<td>24</td>
<td>60</td>
<td>8.25</td>
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<td>5</td>
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<td>9.48</td>
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<th>Power in Watts</th>
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<td>1500</td>
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<td>2.</td>
<td>1/25</td>
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<tr>
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<td>1/25</td>
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<tr>
<td>4.</td>
<td>1/10</td>
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DATA FOR TEMPERING CURVE

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<th>Temperature</th>
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<tr>
<td>1. 357°F</td>
<td>490</td>
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<td>2. 637°F</td>
<td>432</td>
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<td>3. 817°F</td>
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TEMPERERING RESULTS OF WELDED PLATE

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<td>1. 424°F</td>
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<tr>
<td>2. 636°F</td>
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<tr>
<td>3. 1278°F</td>
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DATA FOR HARDENABILITY CURVE

Water quenched
  Cooling Rate 1148°F/sec at 1300°F
  Hardness 51Rc
  Jominy Distance 1 approximately

Furnace cooled
  Cooling Rate 0.07°F/sec at 1300°F
  Hardness 10Rc
  Jominy Distance asymptotic

Air cooled
  Cooling Rate 21°F/sec at 1300°F
  Hardness 28Rc
  Jominy Distance 10

Oil quenched
  Cooling Rate 694°F/sec at 1300°F
  Hardness 49Rc
  Jominy Distance 1 approximately
Fig. 10. Hardenability Curve
EVALUATION OF EXPERIMENTAL RESULTS

Welding Experiments

We shall be concerned with only four of the eight variables, namely cooling rate, power, welding speed, and distance from the edge of the weld. The other four variables, namely thermal conductivity, specific heat, density and thickness of plate are fixed as soon as the steel is selected.

Points one and two on the graph (see Figure 8) have the same cooling rate and power, but there is a one second difference in time taken to weld. This difference could be attributed as experimental error. The maximum temperature at point one was 1372°F which was constant for 1/25th of a second. At point two it was 1488°F which was constant for 1/25th of a second.

Point three had the same cooling rate as points one and two while the power has increased with a decrease in speed. Maximum temperature was 1654°F for 1/5th of a second. The higher temperature indicates that the thermocouple was placed nearer the weld than in the previous two cases. Cooling rates become slower the farther we move from the weld. Other things being equal the higher the maximum temperature reached by a point in welding the higher the instantaneous cooling rate will be after cooling has begun. Consequently the cooling rate of point three should be higher than points one and two. But the cooling rate obtained is the same. This must be due to the decrease in speed. Therefore placing a thermocouple nearer the weld and increasing the power is compensated by a decrease in welding speed.
This brings to light a means of reducing two variables, welding speed and current, to a single factor. Figure 5 shows the effect of increasing the speed of welding while holding the amperage and voltage constant. The hardness of the affected zone increases as the welding speed is increased. The same variation in hardness could be obtained if the welding speed was held constant and the amperage reduced through a definite range. The relationship between amperage, voltage and welding speed in inches per minutes may be expressed as:

\[
\frac{\text{amperes} \times \text{volts} \times 60}{\text{welding speed in/min} \times 9486 \times 10^{-7}} = \text{B.T.U./in}
\]

The heat input of point one is:

\[
\frac{60 \times 23 \times 60}{5.59 \times 9486 \times 10^{-7}} = 14.05 \text{ B.T.U./in}
\]

The heat input of point two is:

\[
\frac{60 \times 23 \times 60}{5.5 \times 9486 \times 10^{-7}} = 14.229 \text{ B.T.U./in}
\]

The heat input of point three is:

\[
\frac{60 \times 25 \times 60}{5.88 \times 9486 \times 10^{-7}} = 14.479 \text{ B.T.U./in}
\]

In general as long as these variables are balanced either by higher amperage and higher speed or lower amperage and lower speed, the heat energy expressed in B.T.U./in will remain constant and the effect on the welded member will be approximately the same. It is to be noted that the hardness of the heat-affected zone increases as the number of B.T.U. per inch is decreased.
The effect of increasing welding speeds or decreased heat energy input causes increased hardness in the metal adjacent to the weld.

The heat input of point four is:

\[
\frac{60 \times 24 \times 60}{8.25 \times 9486 \times 10^{-7}} = 9.826 \text{ B.T.U./in}
\]

The heat input of point five is:

\[
\frac{90 \times 23 \times 60}{9.48 \times 9486 \times 10^{-7}} = 11.426 \text{ B.T.U./in}
\]

Hence we see that the heat energy input of points four and five is less than that of points one, two and three. Therefore the hardness of four and five should be more than that of points one, two and three from which we deduce the cooling rates of four and five to be higher than that of points one, two and three. Moreover cooling rate of point four will be more than that of point five. The maximum temperature at point four was 1603°F for 1/10th of a second while at point five it was 1506°F for 1/25th of a second.

Hence we conclude that for the cooling rate to be maintained and consequently the hardness, the power should be increased while the welding speed is decreased. For the same power the speed should be decreased to increase the cooling rate. We can also conclude that the distance from the weld does not play a very important part for the region above the critical temperature.

Some data from "Heat Effect on Welding" by W. G. Theisinger was incorporated in the results in order to get a clearer idea of the results.
From the graph of Brinell Hardness against welding speed (see Figure 5), the hardness for speeds of 5.5 in/min and 8.25 in/min were obtained. The Jominy distances for the two speeds were obtained by referring to the hardenability curve. The cooling rates were obtained from the Jominy distances. These results were plotted on the graph of cooling rate versus power. (See Figure 11) The two points on this graph corresponding to the same speed were joined to give constant speed line.

From this we conclude that the cooling rate is limited with fixed speed. The cooling rate decreases as the power is increased, keeping the speed constant.

Tempering Curve

The points on the tempering graph, due to welding heat, were below the tempering curve of AISI 4130 steel. This may be due to the fact that the hardness at the points of insertion of thermocouples could not be accurately determined. Another factor that could have contributed to the lowering of the curve could be that the plate was not heated long enough at the maximum temperature.

Hardenability Curve

The standard hardenability curve of AISI 4130 steel gives the maximum and minimum values. (See Figure 6) Some points on this curve were obtained by the experiments conducted. This gave an indication of the hardness values for this particular sample of 4130 steel.

The points obtained on this curve due to water quenching and oil quenching were very close. This is because the thickness of the
Fig. 11. Modified Graph of Power Versus Cooling Rate
specimen plates was very small. The air-cooled specimen had a hardness of 28 Rc and a cooling rate of 21°F/sec at 1300°F. The furnace-cooled specimen had a hardness of 10 Rc and cooling rate of 0.07°F/sec at 1300°F. The point, due to furnace cooling, lies outside the range of the graph.
CONCLUSION

It is now possible to predict the hardness profile of AISI 4130 steel under varying welding conditions. Consider an experimental point whose temperature is 1603°F (above the critical temperature). The power for this point is 1440 watts and welding speed is 8.25 in/min. Now by referring to Figure 11 the cooling rate for this point is 40°F/sec at 1300°F. In Figure 10 the hardness corresponding to this cooling rate is 30 Rockwell C. The hardness of the sample point, by actual measurement, was found to be 34 Rockwell C. Therefore, the results obtained are within 13.3%. 

Now consider a point which attained a temperature below the critical temperature. The maximum temperature of this point was 637°F. The hardness obtained by referring to Figure 9 is 400 GHN. While the hardness obtained, due to tempering, is 437 BHN. This is within 9.2%.

In this way it is possible to obtain the hardness profile of the heat-affected zone. The results obtained could be used for plate of any thickness since dimensionless groups were used for obtaining the relationships.

The thermal conductivities of all the structural steels are sufficiently close to being identical so that they all have about the same cooling rate when cooled under the same condition. By the use of this property of steels it is possible to predict the hardness profile of heat-affected zones for any steel.


DIMENSIONAL ANALYSIS

The heat-affected zone and the terms for its formation are inherent in any process which produces a weld. Its depth and hardness depend upon the following eight variables: thermal conductivity, specific heat, density, velocity, thickness of the plate, distance from the weld, power and the cooling rate.

The purpose of the dimensional analysis is to reduce the number of variables. This is accomplished by grouping the variables in such a way as to obtain dimensionless groups. This facilitates the experimental determination of the relationship between the variables.

The basis of dimensional analysis as a formal procedure is the $H$ Theorem, which states that a complete physical equation such as

$$Q_1 = f(Q_2, Q_3, \ldots, Q_n)$$

may be expressed in the form of a number of $H$ terms, each $H$ term representing a product of powers of some of the $Q$'s, which in terms of the primary dimensions, form a dimensionless group. Thus the above equation may be expressed as

$$H_1 = \phi (H_2, H_3, \ldots, H_{n-k})$$

where each $H = Q_1^a Q_2^b \ldots Q_n^x$ with the resulting product being a dimensionless when each $Q$ is expressed in terms of the primary dimensions. The primary dimensions in this case are mass ($M$), time ($T$), length ($L$) and temperature ($\Theta$).

$$n = \text{number of variables} \quad 8$$

$$k = \text{number of primary dimensions} \quad 4$$
\((n-k) n\) terms are the greatest number of independent \(n\)'s which will represent the physical equation. This means that there will be \(8-4 = 4\) independent \(n\) terms. Four variables are arbitrarily selected. These in turn are combined with each of the remaining four variables to give four \(n\) terms. The four variables that were arbitrarily selected are thermal conductivity, specific heat, density and thickness of the plate.

**Definition of the Variables**

Thermal Conductivity (\(K\)) - heat transmitted through a cube of unit dimensions per sec per degree of temperature

\[
\frac{\text{(BTU) (ft)}}{(\text{OF}) (\text{sec})(\text{ft}^2)} = \frac{\text{(lb ft)} (\text{ft})}{M \theta T}
\]

Specific Heat (\(S\)) - heat capacity of the material

\[
\frac{\text{(BTU)}}{(\text{lb}) (\text{OF})} = \frac{L}{\theta}
\]

Density (\(\rho\)) - mass per unit volume

\[
\frac{(\text{lb})}{(\text{ft}^3)} = \frac{M}{L^3}
\]

Velocity (\(V\)) - distance traversed in unit time

\[
\frac{(\text{ft})}{(\text{sec})} = \frac{L}{T}
\]

Thickness of the plate (\(X\)) - distance

\[
(\text{ft}) = L
\]

Distance from the weld (\(y\)) - distance

\[
(\text{ft}) = L
\]
Power (P) - product of voltage and current for D.C.

\[ \text{VXI watts} = \frac{ML}{T} \]

Cooling Rate (CR) - change in temperature in unit time

\[ \frac{(\circ C)}{(\text{sec})} = \frac{\Theta}{T} \]

To obtain the \( \Pi \) terms

\[ \Pi_1 = K^a S^b P^c X^d V \]

\[ \Pi_1 = (\frac{M}{\Theta T})^a (\frac{L}{T})^b (\frac{M}{L^3})^c (L)^d (\frac{\Theta}{T}) = M^a L^b T^c \Theta^d \]

From which we get the following equations:

\[ a = c = 0 \]
\[ -a = b = 0 \]
\[ -a - 1 = 0 \]
\[ b - 3c + d + 1 = 0 \]

Solving we get

\[ a = -1, b = 1, c = 1, d = 1 \]

\[ \Pi_1 = (\frac{M}{\Theta T})^{\frac{1}{2}} (\frac{L}{T})^1 (\frac{M}{L^3})^1 (L)^0 (\frac{\Theta}{T}) \]

\[ \Pi_1 = (\frac{1}{K}) (S) (P) (X) (V) \]

\[ \Pi_2 = K^a S^b P^c X^d C R \]

\[ \Pi_2 = (\frac{M}{\Theta T})^a (\frac{L}{T})^b (\frac{M}{L^3})^c (L)^d (\frac{\Theta}{T}) = M^a L^b T^c \Theta^d \]

\[ a + c = 0 \]
\[ b - 3c + d = 0 \]
\[ -a - 1 = 0 \]
\[ -a - b + 1 = 0 \]

Solving we get

\[ a = -1, b = 2, c = 1, d = 1 \]
\[ \Pi_2 = \left( \frac{M}{G_T} \right)^{-1} \left( \frac{T}{\theta} \right)^2 \left( \frac{M}{L^3} \right)^1 (L)^1 \left( \frac{\theta}{T} \right) \]

\[ \Pi_2 = \left( \frac{1}{K} \right) \left( S^2 \right) (P) (X) (C R) \]

\[ \left( \frac{M}{G_T} \right)^a \left( \frac{T}{\theta} \right)^b \left( \frac{M}{L^3} \right)^c (L)^d \left( \frac{\theta}{T} \right)^e = \theta^o\theta^o \]

\[ a + c + 1 = 0 \]
\[ b - 3c + d + 1 = 0 \]
\[ -a - 1 = 0 \]
\[ -a - b = 0 \]

Solving

\[ a = -1, \ b = 1, \ c = 0, \ d = 2 \]

\[ \Pi_3 = \left( \frac{M}{G_T} \right)^{-1} \left( \frac{T}{\theta} \right)^1 \left( \frac{M}{L^3} \right)^0 (L)^2 \left( \frac{\theta}{T} \right)^{2e} \]

\[ \Pi_3 = \left( \frac{1}{K} \right) \left( S \right) (X^2) (P) \]

\[ \Pi_4 = k^a s^b p^c x^d y \]

\[ \left( \frac{M}{G_T} \right)^a \left( \frac{T}{\theta} \right)^b \left( \frac{M}{L^3} \right)^c (L)^d (L) = \theta^o\theta^o \theta^o \]

\[ a + c = 0 \]
\[ b - 3c + d + 1 = 0 \]
\[ -a = 0 \]
\[ -a - b = 0 \]

Solving

\[ a = 0, \ b = 0, \ c = 0, \ d = -1 \]

\[ \Pi_4 = \left( \frac{M}{G_T} \right)^0 \left( \frac{T}{\theta} \right)^0 \left( \frac{M}{L^3} \right)^0 (L)^{-1} (L) \]
\[ \Pi_4 = \frac{y}{x} \]

These four \( \Pi \) terms give us a graph of \( \Pi_3 \) against \( \Pi_2 \) keeping \( \Pi_1 \) and \( \Pi_4 \) constant.
CORRELATION OF WELDMENT HARDNESS PROFILES
IN STEELS WITH JOMINY END-QUENCH DATA

An Abstract of
A Thesis
Presented to the
Department of Mechanical Engineering
Brigham Young University

In Partial Fulfillment
of the Requirement for the Degree of
Master of Science

by
Deepak Panjabi
May, 1967
ABSTRACT

The primary object of this research was to be able to predict the hardness profile of a given steel specimen when it is arc welded.

The hardness of a point whose temperature rises above the upper critical temperature can be predicted from the graph of power versus cooling rate used in conjunction with a hardenability curve. The hardness of the point whose temperature remains below the lower critical temperature can be predicted from a tempering curve. In this way the hardness profile of the heat-affected zone can be predicted.

Approved: