An Experimental Investigation of the Relation Between the Cooling Rate and Welding Variables in Fusion Welding

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AN EXPERIMENTAL INVESTIGATION OF THE RELATION
BETWEEN THE COOLING RATE AND WELDING
VARIABLES IN FUSION WELDING

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

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

by
Sujit Biswas
August 1972
This thesis by Sujit Biswas is accepted in its present form
by the Department of Mechanical Engineering Science of Brigham Young
University as satisfying the thesis requirement for the degree of Master
of Science.

Date
DEDICATED

To my parents
ACKNOWLEDGEMENTS

The author of this thesis is indebted for the guidance and help rendered by Dr. Milton G. Wille and Mr. William Hayes, both of the Department of Mechanical Engineering and takes this opportunity to forward many thanks for the same.
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CHAPTER I

INTRODUCTION

In the field of welding metallurgy, much attention is given to the effects which the welding arc or flame will have on the structure and properties of the metals being joined. The engineer is interested in the intensity and extent of physical changes brought about by the unavoidable "heat treatment" which accompanies the execution of a weld.

In some alloys, particularly hardenable steels, the effects of welding heat on structure are as dependent upon the rate with which the material cools through a certain temperature range as upon the peak temperatures. In general, with steel, the higher the peak temperatures (above the critical) and the faster the cooling rate, the greater is the likelihood that martensite will form in the heat-affected zone.

Hence, a relation between cooling rate and welding variables and pre-heat temperature of material is very desirable in predetermining the cooling rate that will follow.

For example, in steel, it is usually of interest to ascertain the cooling rate prevailing in the critical temperature range. Having determined the prevailing cooling rate, it then becomes a question of whether or not this exceeds the critical cooling rate at the temperature characteristic of the heat affected zone. If so, the pre-heat temperature may be elevated to the point where the weld cooling rate becomes less than the critical cooling rate, and martensite
formation is avoided.

The first step in investigating a relation between cooling rate and welding variables and material property was to determine the variables which affected cooling rate. Cooling rate was determined at 1300°F since it is usually of interest to ascertain the cooling rate prevailing at the critical temperature. It was concluded after investigation that the cooling rate depends upon the variables which are included in the function as follows:

\[ CR = f(VI, s, t, w, \theta p, k, \rho, c) \]

where

- \( VI = \) heat input (voltage, \( V \), times current, \( I \)),
- \( s = \) welding speed,
- \( t = \) thickness of plate,
- \( w = \) width of plate,
- \( \theta p = \) pre-heat temperature,
- \( k = \) thermal conductivity of the plate metal,
- \( \rho = \) mass density of the plate metal,
- \( c = \) specific heat of the plate metal.

To reduce the number of variables dimensionless products were investigated by dimensioned analysis which is discussed in Appendix A.

There were many different independent sets of dimensionless products that could be formed from the given set of variables.

The criterion for arranging the variables was to obtain the maximum amount of convenience in utilizing the dimensionless variables. This was accomplished by having the significant variables each occur in only one dimensionless term.
In the dimensionless matrix, the first variable is the dependent variable, the second variable is that which is easiest to regulate experimentally, the third variable is that which is next easier to regulate experimentally, and so on.

The dimensionless products obtained were, as shown in Appendix A, as follows:

\[
\frac{CRt \cdot c}{\alpha^3} = \phi \left( \frac{VIw}{\rho a^3} \cdot \frac{st}{a} \cdot \frac{t}{w} \cdot \frac{s^2}{\theta pc} \right)
\]

To determine the relationship between the dimensionless products, the procedure adopted was as follows:

Let,

\[
\frac{CRt \cdot c}{\alpha^3} = \pi_1
\]

\[
\frac{VIw}{\rho a^3} = \pi_2
\]

\[
\frac{st}{a} = \pi_3
\]

\[
\frac{t}{w} = \pi_4
\]

and

\[
\frac{s^2}{\theta pc} = \pi_5
\]

Let the relation between the dimensionless products be

\[
\pi_1 = k \pi_2 \pi_3 \pi_4 \pi_5
\]

Now, if five experiments are conducted changing the variables in such a way as to change at least one dimensionless product, we will get
a set of five equations.

\[
\begin{align*}
\pi_1(1) &= K \pi_2(1)^a \pi_3(1)^b \pi_4(1)^c \pi_5(1)^d \\
\pi_1(2) &= K \pi_2(2)^a \pi_3(2)^b \pi_4(2)^c \pi_5(2)^d \\
\pi_1(3) &= K \pi_2(3)^a \pi_3(3)^b \pi_4(3)^c \pi_5(3)^d \\
\pi_1(4) &= K \pi_2(4)^a \pi_3(4)^b \pi_4(4)^c \pi_5(4)^d \\
\pi_1(5) &= K \pi_2(5)^a \pi_3(5)^b \pi_4(5)^c \pi_5(5)^d
\end{align*}
\]

Taking Logarithm,

\[
\begin{align*}
\log \pi_1(1) &= \log K + a \log \pi_2(1) + b \log \pi_3(1) + c \log \pi_4(1) + d \log \pi_5(1) \\
\log \pi_1(2) &= \log K + a \log \pi_2(2) + b \log \pi_3(2) + c \log \pi_4(2) + d \log \pi_5(2) \\
\log \pi_1(3) &= \log K + a \log \pi_2(3) + b \log \pi_3(3) + c \log \pi_4(3) + d \log \pi_5(3) \\
\log \pi_1(4) &= \log K + a \log \pi_2(4) + b \log \pi_3(4) + c \log \pi_4(4) + d \log \pi_5(4)
\end{align*}
\]
\[
\log \pi_1(5) = \log K + a \log \pi_2(5) + b \log \pi_3(5) + c \log \pi_4(5) + d \log \pi_5(5)
\]

The unknowns \(a, b, c, d,\) and \(K\) can be solved by Gaussian's Elimination method. The actual testing involved seven sets of data. To average the values of \(a, b, c, d,\) and \(K\) a computer program was written which could solve all the possible combinations of \(5 \times 5\) matrices from a set of seven equations and a subroutine which could solve the matrices by Gaussian Elimination method which is discussed in Appendix B.

As discussed later on, the above developed method for investigating a relationship between cooling rate and welding variables appears to be applicable to predict the cooling rate.
CHAPTER II

EXPERIMENTAL APPARATUS

The experimental apparatus consisted of steel plates, thermocouples, strip chart recorders and a welding machine.

Steel Plates

The plates used in the experiments were AlSi 1020, commercially known as mild steel. The sizes used were: 1/8" x 2" x 12", 1/2" x 4" x 12", 1/8" x 10" x 12", 1/4" x 2" x 12", 1/4" x 4" x 12", 1/4" x 10" x 12", 3/8" x 2" x 12", 3/8" x 4" x 12" and 3/8" x 10" x 12". Twelve plates were used choosing at least one plate of all the above mentioned sizes. The width of the plates were drastically changed so as to study the effect of width on the cooling rate, minimum width being at least the width of the heat affected zone (HAZ). Maximum thickness of the plate was limited by the capacity of the welding generator.

Thermocouple

Chromel-Alumel thermocouples were used as their range extends to about 2500°F, and thus they are appropriate to this application. The ends which were imbedded into the plate were shielded by porcelain tubes.

Brush Recorder

Two two-channel, Brush Mask 220 Recorders, Gould, model 0902, were
used. The wires from the four thermocouples were connected to these four channels. The paper speed was set at 1 mm/sec, and gain set at 1 mV/div. The gain was chosen to give maximum possible deflections of the recording pens during welding. The first channel was connected to the thermocouple which was at 1/4" distance from the welding axis, the second was connected to the thermocouple at 1/2" distance, and so on in 1/4" increments.

Welding Machine

A D.C. amp, Lincoln Arc Welding Machine, Serial No. A2170826, was used. The unit had a motor-driven, differentially compound wound D.C. generator.

Automatic Arc-Welder

An automatically controlled arc-welding research apparatus was used for controlling the rod feed and welding speed. The apparatus was built to automatically arc weld specimens for research work by controlling weld velocity and weld current. Weld velocity was controlled by a reversible variable speed series motor driving a moving table carriage which was mounted with roller brushings on two supporting guide bars, through a screw drive. A weld specimen placed on this table could then be moved at a constant, pre-selected velocity underneath the arc of a vertically or inclined positioned electrode. By monitoring the welding current a servo-control system automatically produced the proper rod feed rate or rod position such as to maintain the current constant. An error signal between a reference voltage and a current-monitoring shunt voltage drove the system to adjust the electrode's arc length to maintain a constant current.
CHAPTER III

PROCEDURE

Thermocouples were imbedded at distances of $\frac{1}{4}$", $\frac{1}{2}$", $\frac{3}{4}$" and 1" from the weld axis, on one side of the plate. Imbedding was done by drilling slightly over-sized holes to about half the thickness of the plate depth, and squeezing the metal around the thermocouple after inserting it in the hole.

By this arrangement only the first point gave the maximum temperature (higher than the upper critical temperature), while the remaining three gave temperatures lower than the critical temperature.

Welding was done in the heat-treatment laboratory. The low temperature ends of the thermocouples were kept in ice. The hot junction of the thermocouples was shielded with porcelain tubes.

The welding generator was set at 40 amps to start with and was subsequently varied between 40 amps and 150 amps for different sets of experiments.

The welding apparatus was set at AUTO and the direction of the table was set on either LEFT or RIGHT. The speed of the table was varied, by changing the position of the knob of the silicon-controlled rectifier (SCR). The sensitivity of the amplifier was pre-adjusted such as to maintain a constant arc-length when the START button was pushed.

The paper speed and the sensitivity on the Brush Recorder was
set at 1 mm/sec and 1 mv/div respectively.

The welding generator was turned on and the START button of the welding apparatus was pushed to start welding.

After welding, the plates were allowed to cool off at the room temperature and the time-temperature history was obtained on the Chart of the Brush-Recorder. Cooling rates were found by measuring the slope of the temperature traces on the chart (see Figure 1) at 1300°F.

The above procedure was repeated for each of the plates with different welding speeds and currents.

Twelve experiments were conducted for different values of the welding variables. Only seven experiments gave maximum temperatures higher than the upper critical temperature.

The experimental data obtained are tabulated in Table I.

**TABLE I**

**EXPERIMENTAL DATA**

<table>
<thead>
<tr>
<th>No</th>
<th>Voltage V Volts</th>
<th>Current I Amps</th>
<th>Length of Weld L Inches</th>
<th>Thickness t Inches</th>
<th>Width w Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>120</td>
<td>8</td>
<td>1/4</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
<td>130</td>
<td>7.75</td>
<td>3/8</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>135</td>
<td>7</td>
<td>3/8</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>31</td>
<td>125</td>
<td>7.25</td>
<td>1/4</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>125</td>
<td>7.5</td>
<td>1/8</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>31</td>
<td>150</td>
<td>6</td>
<td>1/4</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>28</td>
<td>85</td>
<td>5.6</td>
<td>1/8</td>
<td>4</td>
</tr>
</tbody>
</table>

Values of thermal conductivity and specific heat were averaged out over the temperature range of each experiment.
A computer program was written, to read in the different values of specific heat and thermal conductivity, which is described later.
CHAPTER IV

RESULTS AND DISCUSSION OF RESULTS

Seven experiments which gave maximum temperature higher than the upper critical temperature were chosen for analysis. Tangents were drawn at 1300°F and the slope measured to find out cooling rate at 1300°F.

Conversion factors for all the dimensionless groups were calculated. The sample calculation for the dependent dimensionless group is as follows:

\[ \pi_1 = \frac{cR}{a^3} \]

\[ = \frac{68 \left( \frac{^0F}{\text{sec}} \right) \times (\text{sec}^3)(\text{ft}^4) \times c(\text{BTU})}{a^3(\text{ft}^6) \times 4 \times 12 (\text{lbm} \cdot ^0\text{F})} \]

Converting lb\text{m} into lb\text{f} we have:

\[ = \left( \frac{^0\text{F}}{\text{sec}} \right) \left( \text{sec}^3 \right)(\text{ft}^4)(\text{BTU})(\text{ft}) \]

\[ \times \frac{(\text{sec})(\text{ft}^6)(1\text{lb} - ^0\text{F})}{(\text{sec}^2)} \]

Converting BTU into lb\text{f} - ft we have:
which is dimensionless.

Hence, the conversion factor is

\[ \frac{778.17 \text{ lb} \cdot \text{ft}}{\text{lb} \cdot \text{ft}} \]

\[ = J \times g \]

\[ = 778.17 \times 32.2 \]

\[ = 25500.64 \]

Seven equations were obtained each having five unknowns. The unknowns, which were the exponents of the dimensionless group and a constant quantity, were obtained by solving twenty-one (the maximum number of 5 x 5 different matrices formed from seven equations of five unknowns) by the Gaussian Elimination method. The value of the constant coefficient and experiments were evaluated by averaging out the twenty-one values obtained by twenty-one 5 x 5 matrices.

A computer program was written in Fortran IV programming language to calculate all the dimensionless groups. It solved all twenty-one matrices averaging out the values of the constant coefficient and exponents and calculated the cooling rates for all the seven experiments using relation obtained between the cooling rate and welding variables. It also compared the experimental cooling rates with the cooling rate obtained by the relation obtained, calculating the deviation, percentage deviation and average percentage deviation.

The deviations were found to be within five percent. Hence, the relationship obtained fit the data well.

The final relationship with the exponents and constant
coefficient calculated by the computer program, which is discussed in Appendix B, is as follows:

\[
\frac{CR}{t^4c} = 0.178 \times 10^{-15} \left( \frac{VT}{pa} \right)^2 \left( \frac{st}{\alpha} \right)^{0.126} \left( \frac{t}{w} \right)^{0.469} \left( \frac{s^2}{\beta pc} \right)^{0.73}
\]

The experimental cooling rates and the cooling rates obtained by the relationship obtained compared as follows:

**TABLE II**

**COMPARISON BETWEEN EXPERIMENTAL AND CALCULATED DATA**

<table>
<thead>
<tr>
<th></th>
<th>Cooling Rate</th>
<th>Percentage Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>Calculated</td>
</tr>
<tr>
<td>68</td>
<td>62</td>
<td>8.7</td>
</tr>
<tr>
<td>73</td>
<td>74.4</td>
<td>-1.9</td>
</tr>
<tr>
<td>112</td>
<td>109.1</td>
<td>2.5</td>
</tr>
<tr>
<td>84</td>
<td>78.4</td>
<td>6.6</td>
</tr>
<tr>
<td>34</td>
<td>33</td>
<td>2.8</td>
</tr>
<tr>
<td>68</td>
<td>70.7</td>
<td>-4.0</td>
</tr>
<tr>
<td>18</td>
<td>15.9</td>
<td>11.8</td>
</tr>
</tbody>
</table>

The accuracy for the seven sets of data was 5 percent.
CHAPTER V

CONCLUSIONS

The amount of deviation clearly indicates the success of the relation developed. From the deviation obtained, the following conclusions can be derived.

1. The experimental relation developed in this thesis can predict cooling rate with ± 5 percent accuracy.

2. A few inconsistencies in results can be avoided if the heat input is uniform throughout the length of the weld for seven experiments.

3. Better accuracy would be obtained if the arc length of each experiment was measured and the heat input was multiplied by the arc efficiency which varies between about 65 percent for an arc length of 1/4" to 80 percent for an arc length of 1/8".


APPENDIX A

DIMENSIONAL ANALYSIS

The cooling rate depends upon the following nine variables: heat input, speed, thickness, width, pre-heat temperature, thermal conductivity, mass density and specific heat of the specimen.

The basis of dimensional analysis as a formal procedure is the Buckingham $\pi$-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 $\pi$ terms, each $\pi$ 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

$$\pi_1 = \phi(\pi_2, \pi_3, \ldots \pi_{n-k})$$

where each $\pi = Q_1^a Q_2^b \ldots Q_n^x$ with the resulting product being 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 ($\theta$).

$n =$ number of variables 9

$k =$ number of primary dimensions 4
(n - k) = 5, \pi \text{ terms are the greatest number of independent } \pi \text{'s which will represent the physical equation.}

The arrangement of the variables with their dimensions, as discussed earlier, is given dimensional matrix form as follows:

\[
\begin{bmatrix}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
C & R & V & I & s & t & 6 & p & w & k & p & c
\end{bmatrix}
\]

\[
\begin{array}{cccccccccc}
M & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
L & 0 & 2 & 1 & 1 & 0 & 1 & 1 & -3 & 2 \\
T & -1 & -3 & -1 & 0 & 0 & 0 & -3 & 0 & -2 \\
\theta & 1 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & -1 \\
\end{array}
\]

A set of homogeneous linear algebraic equations whose coefficients were the number in the rows of the matrix was written

\[
\begin{align*}
R_2 + R_7 + R_8 &= 0 \\
2R_1 + R_3 + R_4 + R_6 + R_7 - 3R_8 + 2R_9 &= 0 \\
-R_1 - 3R_2 - R_3 - 3R_7 - 2R_9 &= 0 \\
R_1 + R_5 - R_7 - R_9 &= 0 \\
\end{align*}
\]

Any values could be assigned to \( R_1, R_2, R_3, R_4 \) and \( R_5 \) and Equation (a) could be solved for \( R_6, R_7, R_8 \) and \( R_9 \). The solution was accomplished readily by the elementary elimination procedure. The result is

\[
\begin{align*}
R_6 &= 4R_1 + R_2 + R_3 - R_4 + 2R_5 \\
R_7 &= -3R_1 - 3R_2 - R_3 - 2R_5 \\
\end{align*}
\]
\[ R_8 = 3R_1 + 2R_2 + R_3 + 2R_5 \]

(b)

\[ R_9 = 4R_1 + 3R_2 + R_3 + 3R_5 \]

Values assigned were \( R_1 = 1, R_2 = R_3 = R_4 = R_5 = 0 \) and Equation (b) yielded \( R_6 = 4, R_7 = -3, R_8 = 3, R_9 = 4 \). Similarly, for \( R_2 = 1, R_1 = R_3 = R_4 = R_5 = 0 \), Equation (b) yielded \( R_6 = 1 \), \( R_7 = -3, R_8 = 2, R_9 = 3 \), for \( R_3 = 1, R_1 = R_2 = R_4 = R_5 = 0 \), \( R_6 = 1 \), \( R_7 = -1, R_8 = 1, R_9 = 1 \), for \( R_4 = 1, R_1 = R_2 = R_3 = R_5 = 0 \), \( R_6 = -1 \), \( R_7 = 0, R_8 = 0, R_9 = 0 \) and for \( R_5 = 0, R_1 = R_2 = R_3 = R_4 = 0 \), \( R_6 = 2 \), \( R_7 = -2, R_8 = 2 \) and \( R_9 = 3 \).

The solution could be neatly arranged in the matrix form shown below:

<table>
<thead>
<tr>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( R_3 )</th>
<th>( R_4 )</th>
<th>( R_5 )</th>
<th>( R_6 )</th>
<th>( R_7 )</th>
<th>( R_8 )</th>
<th>( R_9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi_1 )</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>-3</td>
<td>3</td>
</tr>
<tr>
<td>( \pi_2 )</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-3</td>
<td>2</td>
</tr>
<tr>
<td>( \pi_3 )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>( \pi_4 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \pi_5 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>-2</td>
<td>2</td>
</tr>
</tbody>
</table>

Accordingly, the following complete set of dimensionless products were obtained:

\[ \pi_1 = CR w^4 k^{-3} \rho^3 c^4 \]
\[ \pi_2 = VI w^4 k^{-3} \rho^2 c^3 \]
\[ \pi_3 = s w k^{-1} \rho c \]
\[ \pi_4 = tw^{-1} \]
\[ \pi_5 = \theta p w^2 k^{-2} \rho^2 c^3 \]

Substituting \( a = \frac{k}{\rho c} \) we get:

\[ \pi_1 = \frac{CR w c}{a^3} \]

\[ \pi_2 = \frac{VIw}{\rho a^3} \]

\[ \pi_3 = \frac{sw}{a} \]

\[ \pi_4 = \frac{t}{w} \]

\[ \pi_5 = \frac{\theta p w^2 c}{a^2} \]

Now

\[ \pi_6 = \frac{\pi_2^2}{\pi_5} = \frac{s^2 w^2}{a^2} \times \frac{a^2}{\theta p w^2 c} = \frac{s^2}{\theta pc} \]

\( \pi_6 \) clearly involved less variables than \( \pi_5 \) and hence was replaced for \( \pi_5 \).

The final dimensionless products could be represented as:

\[ \frac{CRt^4 c}{a^3} = \phi \left( \frac{VIw}{a^3}, \frac{st}{a}, \frac{t}{w}, \frac{s^2}{\theta pc} \right) \]
A computer program which will evaluate all possible 5 x 5 matrices from a set of seven equations and solve them by a subroutine. The subroutine solves all the 5 x 5 matrices by Gaussian Elimination method.

INPUT DETAILS

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<td>31-40</td>
<td>Cooling Rate, Exp. #5</td>
<td>F10.5</td>
<td>34</td>
</tr>
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<td>Cooling Rate, Exp. #6</td>
<td>F10.5</td>
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</tr>
<tr>
<td>51-60</td>
<td>Cooling Rate, Exp. #7</td>
<td>F10.5</td>
<td>18</td>
</tr>
<tr>
<td>61-70</td>
<td>Thickness of plate, Exp. #1</td>
<td>F10.5</td>
<td>.25 inch</td>
</tr>
<tr>
<td>71-80</td>
<td>Thickness of plate, Exp. #2</td>
<td>F10.5</td>
<td>.375 inch</td>
</tr>
<tr>
<td></td>
<td>Thickness of plate, Exp. #3</td>
<td>F10.5</td>
<td>.375</td>
</tr>
<tr>
<td></td>
<td>Thickness of plate, Exp. #4</td>
<td>F10.5</td>
<td>.25</td>
</tr>
<tr>
<td></td>
<td>Thickness of plate, Exp. #5</td>
<td>F10.5</td>
<td>.125</td>
</tr>
<tr>
<td></td>
<td>Thickness of plate, Exp. #6</td>
<td>F10.5</td>
<td>.25</td>
</tr>
<tr>
<td></td>
<td>Thickness of plate, Exp. #7</td>
<td>F10.5</td>
<td>.125</td>
</tr>
<tr>
<td></td>
<td>Sp. heat of the plate metal</td>
<td>F10.5</td>
<td>0.15 BTU/lb°F</td>
</tr>
<tr>
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<td>F10.5</td>
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<td>Information</td>
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<tr>
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<td>1-10</td>
<td>Sp. heat of the plate metal</td>
<td>F10.5</td>
<td>0.15</td>
</tr>
<tr>
<td>11-20</td>
<td>Sp. heat of the plate metal</td>
<td>F10.5</td>
<td>0.15</td>
</tr>
<tr>
<td>21-30</td>
<td>Sp. heat of the plate metal</td>
<td>F10.5</td>
<td>0.17</td>
</tr>
<tr>
<td>31-40</td>
<td>Sp. heat of the plate metal</td>
<td>F10.5</td>
<td>0.14</td>
</tr>
<tr>
<td>41-50</td>
<td>Sp. heat of the plate metal</td>
<td>F10.5</td>
<td>0.14</td>
</tr>
<tr>
<td>51-60</td>
<td>Sp. heat of the plate metal</td>
<td>F10.5</td>
<td>0.327 ft^2/hr</td>
</tr>
<tr>
<td>61-70</td>
<td>Diffusivity of the plate metal</td>
<td>F10.5</td>
<td>0.28 ft^2/hr</td>
</tr>
<tr>
<td>71-80</td>
<td>Diffusivity of the plate metal</td>
<td>F10.5</td>
<td>0.327</td>
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<th>Information</th>
<th>Format</th>
<th>Value</th>
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<td>Diffusivity of the plate metal</td>
<td>F10.5</td>
<td>0.313</td>
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<td>Diffusivity of the plate metal</td>
<td>F10.5</td>
<td>0.252</td>
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<tr>
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<td>Diffusivity of the plate metal</td>
<td>F10.5</td>
<td>0.35</td>
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<td>Diffusivity of the plate metal</td>
<td>F10.5</td>
<td>0.364</td>
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<tr>
<td>41-50</td>
<td>Heat input, Exp. #1</td>
<td>F10.5</td>
<td>3600. Watt</td>
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<td>Heat input, Exp. #2</td>
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<td>Heat input, Exp. #3</td>
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<td>Heat input, Exp. #4</td>
<td>F10.5</td>
<td>3875.</td>
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<td>Heat input, Exp. #5</td>
<td>F10.5</td>
<td>3750.</td>
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<td>Heat input, Exp. #6</td>
<td>F10.5</td>
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<td>Heat input, Exp. #7</td>
<td>F10.5</td>
<td>2380.</td>
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<td>Mass density of the plate metal</td>
<td>F10.5</td>
<td>490 lb/ft^3</td>
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<td>490</td>
<td></td>
</tr>
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<td>Mass density of the plate metal</td>
<td>F10.5</td>
<td>490</td>
<td></td>
</tr>
<tr>
<td>61-70</td>
<td>Mass density of the plate metal</td>
<td>F10.5</td>
<td>490</td>
<td></td>
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<td>Mass density of the plate metal</td>
<td>F10.5</td>
<td>490</td>
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<td>Value</td>
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<td>1-10</td>
<td>Mass density of the plate metal</td>
<td>F10.5</td>
<td>490</td>
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<td>Mass density of the plate metal</td>
<td>F10.5</td>
<td>490</td>
<td></td>
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<td>21-30</td>
<td>Welding speed</td>
<td>F10.5</td>
<td>47.14 ft/hr</td>
<td></td>
</tr>
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<td>Welding speed</td>
<td>F10.5</td>
<td>62.83</td>
<td></td>
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<td>41-50</td>
<td>Welding speed</td>
<td>F10.5</td>
<td>72.41</td>
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<td>F10.5</td>
<td>72.50</td>
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<td>Welding speed</td>
<td>F10.5</td>
<td>56.25</td>
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<td>71-80</td>
<td>Welding speed</td>
<td>F10.5</td>
<td>54.54</td>
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<td>1-10</td>
<td>Welding speed</td>
<td>F10.5</td>
<td>50.90</td>
</tr>
<tr>
<td>11-20</td>
<td>Width of plate, Exp. #1</td>
<td>F10.5</td>
<td>2 inches</td>
</tr>
<tr>
<td>21-30</td>
<td>Width of plate, Exp. #2</td>
<td>F10.5</td>
<td>2 inches</td>
</tr>
<tr>
<td>31-40</td>
<td>Width of plate, Exp. #3</td>
<td>F10.5</td>
<td>2 inches</td>
</tr>
<tr>
<td>41-50</td>
<td>Width of plate, Exp. #4</td>
<td>F10.5</td>
<td>4 inches</td>
</tr>
<tr>
<td>51-60</td>
<td>Width of plate, Exp. #5</td>
<td>F10.5</td>
<td>10 inches</td>
</tr>
<tr>
<td>61-70</td>
<td>Width of plate, Exp. #6</td>
<td>F10.5</td>
<td>10 inches</td>
</tr>
<tr>
<td>71-80</td>
<td>Width of plate, Exp. #7</td>
<td>F10.5</td>
<td>10 inches</td>
</tr>
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</table>

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<th>Value</th>
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<tbody>
<tr>
<td>1-10</td>
<td>Pre heat temperature</td>
<td>F10.5</td>
<td>75°F</td>
</tr>
<tr>
<td>11-20</td>
<td>Pre heat temperature</td>
<td>F10.5</td>
<td>75°F</td>
</tr>
<tr>
<td>21-30</td>
<td>Pre heat temperature</td>
<td>F10.5</td>
<td>75°F</td>
</tr>
<tr>
<td>31-40</td>
<td>Pre heat temperature</td>
<td>F10.5</td>
<td>75°F</td>
</tr>
<tr>
<td>41-50</td>
<td>Pre heat temperature</td>
<td>F10.5</td>
<td>75°F</td>
</tr>
<tr>
<td>51-60</td>
<td>Pre heat temperature</td>
<td>F10.5</td>
<td>75°F</td>
</tr>
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<td>61-70</td>
<td>Pre heat temperature</td>
<td>F10.5</td>
<td>75°F</td>
</tr>
</tbody>
</table>
Output

Exponents: \( a = 2.7, b = 0.126, c = 0.469, d = 0.73 \)

Constant, \( k = 0.178 \times 10^{-15} \)

Average deviation = 4.9 percent
APPENDIX

THESIS

DIMENSION CR(7), T(7), C(7), AL(7), VI(7), RHO(7), S(7), W(7), THP(7), B(9)
* P(9,9), Tx(9), S5(9), BB(9), A(9,9), X(9), AB(9,9), AC(9,9), D(9,9), E(9,9)
* F(9,9), H(9,9), Q(9,9), R(9,9), SUM(9), R1(9,9), R2(9,9), R3(9,9)
* R4(9,9), R5(9,9), R6(9,9), R7(9,9), R8(9,9), R9(9,9), R10(9,9), R11(9,9)
* AVE(9), V(9,9), CRF(9), DIF(9), PDI(F(9), AK1(9), AK2(9), AK5(9)

READ(5,1) R, T, C, AL, VI, RHO, S, W, THP

N=5

1 FORMAT(8F10.5)
   DO15I=1,7
150 AK1(I)=(C(I)*5.4378416500.)/(AL(I)**3)
   DO2I=1,7
2 B(I)=ALOG3(CR(I)*(T(I)**4)*AK1(I))
   DO15II=1,7
151 AK2(I)=18.444898./(AL(I)**3)
   DO3II=1,7
3 P(I,1)=1.
   DO4I=1,7
4 P(I,2)=ALnG10(VI(I)*T(I)*AK2(I))
   DO5I=1,7
T3(I)=T(I)/12.
5 P(I,3)=ALnG10((S(I)*T3(I))/AL(I))
   DO6I=1,7
P(I,4)=ALnG10(T(I)/W(I))
6 AK5(I)=1./75.*(C(I)*778.17*32.2)
   DO8I=1,7
S5(I)=S(I)/3600.
8 P(I,5)=ALnG10(S5(I)*S5(I)*AK5(I))
   DO10I=1,N
BB(I)=B(I)
DO1O=1,N
10 A(I, J)=P(I, J)
   CALL ELIMIN(A, N, RR, X)
   DO11 J=1,N
10 SUM(I)=X(I)
   DO11 I=1,N
   K=I+1
   RR(I)=R(K)
   DO11 J=1,N
11 A(K, J)=P(K, J)
   CALL ELIMIN(A, N, RR, X)
   DO11 I=1,N
101 SUM(I)=SUM(I)+X(I)
   DO12 I=1,N
   K=I+2
   RR(I)=R(K)
   DO12 J=1,N
12 A(I, J)=P(K, J)
   CALL ELIMIN(A, N, RR, X)
   DO12 I=1,N
102 SUM(I)=SUM(I)+X(I)
   DO13 I=1,N
   K=I+3
   IF(K-7)14,14,15
15 K=K-7
14 RR(I)=R(K)
   DO13 J=1,N
13 A(I, J)=P(K, J)
   CALL ELIMIN(A, N, RR, X)
   DO13 I=1,N
103 SUM(I)=SUM(I)+X(I)
   DO16 I=1,N

#FIC

029
K = I + 4
IF (K = 7) 17, 17, 18
18 K = K - 7
17 BR(I) = B(K)
D016 J = 1, N
16 E(I, J) = P(K, J)
CALL ELIMN (E, N, RB, X)
D010 I = 1, N
104 SUM(I) = SUM(I) + x(I)
D019 I = 1, N
K = I + 5
IF (K = 7) 20, 20, 21
21 K = K - 7
20 BR(I) = B(K)
D019 J = 1, N
19 F(I, J) = P(K, J)
CALL ELIMN (F, N, RB, X)
D0125 I = 1, N
105 SUM(I) = SUM(I) + x(I)
D022 I = 1, N
K = I + 6
IF (K = 7) 23, 23, 24
24 K = K - 7
23 BR(I) = B(K)
D022 J = 1, N
22 G(I, J) = P(K, J)
CALL ELIMN (G, N, RB, X)
D0196 I = 1, N
106 SUM(I) = SUM(I) + x(I)
D025 I = 1, N
K = I
IF (I = 4) 26, 26, 27
27  K=I+1
26  BR(I)=R(K)
    DO 25 I=1,N
25  H(I,J)=P(K,J)
    CALL ELIMIN(H,N,AB,X)
    DO 127 I=1,N
127  SUM(I)=SUM(I)+X(I)
    DO 28 I=1,N
    K=I+1
    IF (I-4).EQ.29,29,39
      K=K+1
29  BR(I)=R(K)
    DO 28 J=1,N
28  Q(I,J)=P(K,J)
    CALL ELIMIN(Q,N,AB,X)
    DO 128 I=1,N
128  SUM(I)=SUM(I)+X(I)
    DO 31 I=1,N
    K=I+2
    IF (I-4).EQ.32,32,39
      K=K-6
32  BR(I)=R(K)
    DO 31 J=1,N
31  R(I,J)=P(K,J)
    CALL ELIMIN(R,N,AB,X)
    DO 129 I=1,N
129  SUM(I)=SUM(I)+X(I)
    DO 34 I=1,N
    K=I+3
    IF (I-4).EQ.35,35,36
      K=K-6
35  BR(I)=R(K)
DO34J=1,N
34 R1(I,J)=P(K,J)
   CALL ELIMIN(R1,N,BB,X)
  DO11CI=1,N
110 SUM(I)=SUM(I)+X(I)
  DO37I=1,N
   K=I+4
   IF(I<4)38.39.40
  40 K=K+1
  39 K=K-7
   BR(I)=B(K)
  38 R2(I,J)=P(K,J)
   CALL ELIMIN(R2,N,BB,X)
  DO111I=1,N
111 SUM(I)=SUM(I)+X(I)
  DO41I=1,N
   K=I
   IF(I<4)42.43.44
  44 K=K+1
  43 K=K+1
   BR(I)=B(K)
  42 R3(I,J)=P(K,J)
   CALL ELIMIN(R3,N,BB,X)
  DO112I=1,N
112 SUM(I)=SUM(I)+X(I)
  DO45I=1,N
   K=I+2
   IF(I<4)46.47.48
  48 K=K+5
  47 K=K-5
46 \text{BR}(I) = B(K)
\text{DO} 45 \text{J} = 1, N
45 \text{R11}(I, J) = \alpha(K, J)
\text{CALL ELIMN(R11, N, BB, X)}
\text{DO} 113 \text{I} = 1, N
113 \text{SUM}(I) = \text{SUM}(I) + x(I)
\text{DO} 49 \text{I} = 1, N
K = I + 3
\text{IF}(I - 4)51, 52, 53
53 K = K - 2
52 K = K - 5
51 \text{BR}(I) = \beta(K)
\text{DO} 49 \text{J} = 1, N
49 \text{R4}(I, J) = P(K, J)
\text{CALL ELIMN(R4, N, BB, X)}
\text{DO} 114 \text{I} = 1, N
114 \text{SUM}(I) = \text{SUM}(I) + y(I)
\text{DO} 54 \text{I} = 1, N
K = I + 4
\text{IF}(I - 4)55, 56, 57
57 K = K - 2
56 K = K - 5
55 \text{BR}(I) = R(K)
\text{DO} 54 \text{J} = 1, N
54 \text{R5}(I, J) = P(K, J)
\text{CALL ELIMN(R5, N, BB, X)}
\text{DO} 115 \text{I} = 1, N
115 \text{SUM}(I) = \text{SUM}(I) + y(I)
\text{DO} 58 \text{I} = 1, N
K = I + 1
\text{IF}(I - 4)59, 60
60 K = K + 1
59 BR(I) = B(K)
   DO58 J = 1, N
58 R6(I, J) = P(K, J)
   CALL ELI(MN(R6, N,BB,X))
   DO116 I = 1, N
116 SUM(I) = SUM(I) + X(I)
   DO117 I = 1, N
117 SUM(I) = SUM(I) + X(I)
   DO61 I = 1, N
   K = I
   IF(I - 4) 62, 63, 63
63 K = K + 1
62 BR(I) = B(K)
   DO61 J = 1, N
61 R7(I, J) = P(K, J)
   CALL ELI(MN(R7, N,BB,X))
   DO64 I = 1, N
   K = I
   IF(I - 3) 65, 66, 67
67 K = K + 1
66 K = K + 1
65 BR(I) = B(K)
   DO64 J = 1, N
64 R8(I, J) = P(K, J)
   CALL ELI(MN(R8, N,BB,X))
   DO118 I = 1, N
118 SUM(I) = SUM(I) + X(I)
   DO69 I = 1, N
   K = I + 5
   IF(I - 3) 70, 71, 72
72 K = K + 1
71 K = K - 7
70  \textbf{REM} = \text{R} (K) = \phi (K)
D069J = 1, N
69  R9(I, J) = P(K, J)
   \textbf{CALL} \text{ \texttt{ELIMIN}(R9, N, BB, X)}
D0119I = 1, N
119 \text{SUM(I)} = \text{SUM(I)} + \text{X(I)}
D073I = 1, N
K = I + 3
   \textbf{IF} (I - 3) 74 = 75, 76
74  K = K - 7
75  K = K + 1
74  \text{RR(I)} = \text{R} (K)
D073J = 1, N
73  R12(I, J) = P(K, J)
   \textbf{CALL} \text{ \texttt{ELIMIN}(R12, N, BB, X)}
D0122I = 1, N
122 \text{SUM(I)} = \text{SUM(I)} + \text{X(I)}
D0122I = 1, N
121 \text{AVE(I)} = \text{SUM(I)} / 211
   \text{AVE(I)} = 11 \times \text{AVE(I)}
   \textbf{WRITE} (6, 500) (\text{AVE(I)}), I = 1, 5
52 \text{FORMAT}(1H1, 5E15.7)
D0233I = 1, 7
2:0 \text{Y(I, 2)} = (V(I) \times T(I) \times A(2)(I))
D0219I = 1, 7
2:1 \text{Y(I, 3)} = ((S(I) \times T3(I)) / A(1)(I))
D0219I = 1, 7
2:2 \text{Y(I, 4)} = (T(I) / W(I))
D0219I = 1, 7
2:3 \text{Y(I, 5)} = ((S5(I) \times S5(I) \times A(5)(I))
D0219I = 1, 7
2:10 \text{Y(I, 1)} = \text{AVE(I)} \times \text{Y(I, 2)} \times \text{AVE(2)} \times \text{Y(I, 3)} \times \text{AVE(3)} \times \text{Y(I, 4)} \times \text{AVE(4)} \times (}
Y(I,5) = AVE(5)

DO204I=1,7

204 CRE(I) = Y(I,1) * (AL(I)**3) / ((T(I)**4) * C(I) * AK1(I))
WRITE(6,205)(CR(I), I=1,7)
WRITE(6,205)(CRE(I), I=1,7)

205 FORMAT(1H3, 7E15.7)
DO206I=1,7
DIF(I) = CR(I) - CRE(I)

206 PnIF(I) = (PIF(I) / CR(I)) * 100.
WRITE(6,207)(DIF(I), I=1,7)
WRITE(6,207)(PnIF(I), I=1,7)

207 FORMAT(1H3, 7E15.7)
SUMP = 0.
DO208I=1,7

208 SUMP = SUMP + PnIF(I)
SUMP = SUMP / 7
WRITE(6,209)(SUMP)

209 FORMAT(1H3, E15.7)
STOP
END
*Y(I,5)*=AVE(5)
DO204 I=1,7  
204 CRE(I)=Y(I,1)*(AL(I)**3)/((T(I)**4)*C(I)*AK1(I))
WRITE(6,205)(CRE(I),I=1,7)
WRITE(6,205)(CRE(I),I=1,7)
205 FORMAT(1Ha,7E15.7)
DO206 I=1,7  
DIF(I)=CR(I)-CRE(I)
206 PINF(I)=(PINF(I)/CR(I))*100.
WRITE(6,207)(DIF(I),I=1,7)
WRITE(6,207)(PINF(I),I=1,7)
207 FORMAT(1Ha,7E15.7)
SUMP=0.
DO208 I=1,7  
208 SUMP=SUMP+PINF(I)
SUMP=SUMP/7.
WRITE(6,209)SUMP
209 FORMAT(1Ha,E15.7)
STOP
END
SUBROUTINE FELIMIN(AA,N,RR,X)
DIMENSION AA(9,9),BB(9),A(9,9),Y(9),X(9),T(9)

NN=N+1
DO220 I=1,N
A(I,NN)=BR(I)
DO220 J=1,N
220 A(I,J)=AA(I,J)

K=1
1 CONTINUE
DO21 I=1,N
21 IN(I)=I
2 CONTINUE
4K=K+1
IS=K
IT=K
R=ARS(A(K,K))
DO3 I=K,N
DO3 J=K,N
IF(ARS(A(I,J))<8)3,31
31 IS=I
IT=J
R=ARS(A(I,J))
3 CONTINUE
IF(IS-K)4,4,41
41 DO42 J=K,NN
C=A(IS,J)
A(IS,J)=A(K,J)
42 A(K,J)=C
4 CONTINUE
IF(IT-K)5,5,51
51 IC=ID(K)
ID(K) = ID(I)
ID(IT) = IC
DO52 I = 1, N
C = A(I, IT)
A(I, IT) = A(I, K)
52 A(I, K) = C
5 CONTINUE
IF(A(K, K) < 0.0001*ABS(W), 71, 7)
6 A(I, J) = A(I, J)*W
7 CONTINUE
K = KK
IF(K - N > 1.02, 81, 102)
8 A(N, N) = A(N, NN)/A(N, N)
NM = N - 1
DO9 I = 1, NM
K = N - 1
KK = K + 1
Y(K) = A(K, NN)
DO9 J = KK, N
Y(K) = Y(K) - A(K, J)*Y(J)
9 CONTINUE
DO10 I = 1, N
DO10 J = 1, N
IF(IP(J)-1)10,101,10
101 X(I)=Y(J)
13 CONTINUE
RETURN
102 WRITE(6,12)
RETURN
12 FORMAT(1H6,'NO UNIQUE SOLUTION')
END
AN EXPERIMENTAL INVESTIGATION OF THE RELATION
BETWEEN THE COOLING RATE AND WELDING
VARIABLES IN FUSION WELDING

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ABSTRACT

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

The cooling rate of a specimen whose temperature rises above the upper critical temperature can be predicted from the relationship arrived at.

COMMITTEE APPROVAL: