ABSTRACT. It is impossible to make a complete list of welding schedules in resistance weld welding because of the large number of possibilities of sheet combinations. Therefore, the welding parameters chosen for a particular welding operation are largely dependent on the experience of the operator, although some guidelines are available. The difficulty in schedule selection arises from the number of independent parameter involved, such as different sheet thickness combinations, different material properties of the sheets, welding current and welding time, electrode face diameter, electrode force, etc. There are a number of efforts attempting to develop systematic procedures for welding schedule selection, such as the law of thermal similarity, yet none of them has been widely accepted, primarily due to the fact that the schedules produced by these procedures are often proven inadequate.

In this study, a new method is proposed for selecting welding schedules based on the heat balance in welding. A theoretical derivation of welding parameters is conducted using a “characteristic” thickness, instead of the physical thickness of sheets. This thickness consists of the effects and contributions of electrode indentation, heat-affected zone, and fusion zone. The theory has been verified by welding low-carbon steel sheets of uneven thickness.

Introduction

Resistance spot welding (RSW) is a major sheet metal joining process in many industries, such as the automotive, appliance, and aerospace industries. Resistance welding was invented by Elihu Thomson in 1877 (Ref. 1) and has grown enormously since the first steel welded automobile was introduced in 1933 (Ref. 1). Resistance spot welding has become the predominant means for auto body assembly, with an average of two to five thousand spots on each passenger car produced (Ref. 1).

In resistance spot welding, a primary concern for a practitioner is to select correct welding schedules. A welding schedule is a set of welding parameters, such as welding current, weld time, electrode force, and electrode face diameter, which would produce a weld with desired features, such as certain geometric dimensions, weld strength, etc. The Resistance Welder Manufacturers' Association (RWMA) (Ref. 2) offers weld schedules and many other recommended practices are available for this purpose. Most of the welded schedules are empirically developed. Although they are very useful in finding good weld schedules for even-thickness welding, schedules for welding uneven-thickness sheets are generally developed by and practiced within individual manufacturers. Because even-thickness combinations are rarely used in practice, there is clearly a practical need of systems and procedures used to derive schedules for uneven-thickness combinations. Both theoretical and combined theoretical-empirical methods have been employed for systematically determining welding schedules. The common techniques used in this respect are summarized below.

The Law of Thermal Similarity

The law of thermal similarity (LOTS) has been commonly used in the automotive industry in Japan to develop resistance welding schedules (Ref. 3). It is based on a heat flow analysis, which attempts to make the temperature distributions in various weld thicknesses similar. The LOTS has been used to develop schedules to obtain desirable temperature profiles based on the known data, i.e., to extrapolate the results obtained from known standard specimens for predicting the temperature profile for a different combination of sheet stack up (Ref. 4). It gives a relationship between the distance and time that makes the temperature distributions similar for different thickness stack ups. It has been mostly used as a guideline for choosing welding schedules for thin sheets based on those verified for thick sheets.

The law of thermal similarity states that similar temperature profiles will be produced if the weld time is proportional to the square of the sheet thickness (Ref. 4), or

\[
t = h^2 \quad (1)
\]

i.e., if the welding time is \( t_f \) for a sheet of thickness \( h_f \), then \( n^2 t_f \) is the time needed to weld a sheet of thickness \( n \times h_f \). The total weld time is determined by the total thickness of the stack up and the thinnest outer sheet determines the maximum duration of any weld pulse. Other welding parameters can be derived similarly.

In general, when the plate thickness and diameter of the electrodes are magnified by \( n \) times, the welding time should be increased to \( n^2 \) times and the current density decreased to \( n \) times in order to have the new temperature distribution similar to the original one (Refs. 3, 5).

Let \( h_f, d_{ef}, (d_{ef}^2), \delta_f, (\delta_f^2), \) and \( t_f \) (t_f) be the thickness, electrode diameter, current density, and welding time, respectively, of the original sheet stack up (the new sheet stack up). Then, the temperature distributions for the two stack ups are similar if (Ref. 3)

\[
h_2 = n \times h_1 \quad (2)
\]

\[
d_{ef2} = n \times d_{ef1} \quad (3)
\]

\[
\delta_f = (1/n) \times \delta_f \quad (4)
\]

\[
t_2 = n^2 \times t_f \quad (5)
\]

KEYWORDS
Resistance Welding
Weld Schedule
Heat Balance
Spot Welding
Uneven Thickness
Sheet Metal
### Table 1 — Welds Made with Different Schedules

<table>
<thead>
<tr>
<th>Sheet Thickness (mm)</th>
<th>Source of Weld Schedule</th>
<th>LOTS Schedule</th>
<th>Welding Electrode Diameter (mm)</th>
<th>Welding Electrode Force (kg/lb)</th>
<th>Welding Electrode Schedule</th>
<th>Weld Time (ms/cycles)</th>
<th>Weld Diameter (mm)</th>
<th>Expulsion Occurrence</th>
<th>Surface Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>Handbook (Ref. 6)</td>
<td>LOTS from 1.21</td>
<td>0.62</td>
<td>6.35</td>
<td></td>
<td>10500</td>
<td>150/9</td>
<td>227/500</td>
<td>6.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LOTS from 1.89</td>
<td>0.40</td>
<td>4.41</td>
<td></td>
<td>8367</td>
<td>77/4.6</td>
<td>136/299</td>
<td>3.2</td>
</tr>
<tr>
<td>1.21</td>
<td>Handbook (Ref. 6)</td>
<td>LOTS from 0.75</td>
<td>1.61</td>
<td>10.24</td>
<td></td>
<td>16940</td>
<td>390/23.43</td>
<td>590/1301</td>
<td>7.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LOTS from 1.89</td>
<td>0.64</td>
<td>5.08</td>
<td></td>
<td>10853</td>
<td>116/6.97</td>
<td>242/532</td>
<td>3.4</td>
</tr>
<tr>
<td>1.89</td>
<td>Handbook (Ref. 6)</td>
<td>LOTS from 0.75</td>
<td>2.52</td>
<td>16.00</td>
<td></td>
<td>26460</td>
<td>953/57.15</td>
<td>1440/3175</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LOTS from 1.21</td>
<td>1.56</td>
<td>11.11</td>
<td></td>
<td>21086</td>
<td>488/29.28</td>
<td>863/1903</td>
<td>10.8</td>
</tr>
</tbody>
</table>

![Fig. 1 — Partition of zones in a weldment for heat calculation. q = heat (Joules), h = thickness (mm).](image)

**Indentation: q1**

**HAZ: q2**

**Nugget: q3**

**Nugget: q4**

**HAZ: q5**

**Indentation: q6**

### Limitations of the Law of Thermal Similarity

Although the law of thermal similarity may theoretically yield similar temperature profiles for different stack ups, many of the welds obtained by the authors using the LOTS schedules were either undersized or with heavy expulsion. As the purpose of the LOTS is mainly for obtaining an understanding of the RSW process, its use for predicting schedules for actual welding practice is limited. The law does not hold well in welding sheets of dissimilar thicknesses as it only considers the total thickness of the stack up and does not account for the individual thicknesses of the sheets. The LOTS does not consider the effect of the actual heat input to make a weld. A welding experiment carried out by the authors on coated mild carbon steel highlights the differences between handbook-suggested schedules and those predicted by the LOTS, as seen in Table 1.

In Table 1, three materials of different thickness were welded using schedules obtained from the *Welding Handbook* (Ref. 6) and from the LOTS. The schedules based on LOTS for welding a particular thickness are derived from the schedules for welding the other two materials (selected using the schedules from the *Welding Handbook* (Ref. 6). For instance, a schedule for welding 0.75-mm steel can be obtained directly from the *Welding Handbook* (Ref. 6) (first row of Table 1), or it can be derived using LOTS based on proven schedules (provided by the *Welding Handbook* (Ref. 6) on 1.21-mm steel and 1.89-mm steel (second and third rows of Table 1). A good welding schedule is defined as the one that yields a large weld without expulsion. It can be clearly seen that there is a large difference between the weld schedules suggested by the *Welding Handbook* (Ref. 6) and those predicted by the LOTS; and the former are usually more realistic and yield significantly better welds than the latter. Due to the limitations mentioned above, the LOTS cannot be directly used for practical welding as it was not intended for such a purpose in the first place.

A new theory is proposed in this work to overcome some of these limitations. The weld schedules predicted as per the new theory are based on heat balance equations and are, therefore, closer than the LOTS to the actual physical welding conditions. Besides providing more accurate welding schedules, the theory can accommodate different sheet thicknesses in a single stack up, and is thus closer to the practical welding scenario.

### Heat Balance

In RSW, heat balance can be defined as a condition in which the fusion zones on both pieces being joined undergo approximately the same degree of heating and pressure application (Ref. 7). It describes the ideal situation when a symmetric weld (with equal depth of nugget penetration) is made. Heat balance is influenced by the relative thermal and electrical conductivities of the materials to be joined, the geometry of the weldment, the thermal and electrical conductivities, and the geometry of the electrodes.

A heat balance can be achieved if two identical sheets are welded together with electrodes of equal mass and contour and heat is generated in both the pieces uniformly, with an oval-shaped weld cross section. However, if one of the pieces has higher electric resistivity than the other, heat will be generated more rapidly in this piece, resulting in a less-than-perfect weld depending upon the amount of heat imbalance. In the case of dissimilar metals,
Proposed Theory

The basic idea of the theory proposed in this work is that the total heat needed to create a weldment can be partitioned into those needed for the fusion zone, the heat-affected zone (HAZ), and the indented area, where significant amount of heat is required. Instead of considering the thickness of the entire stack up (as by the LOTS), the heat input into each of the zones of the stack up is accounted for. Therefore, rather than treating it as an entity, the weldment is split into different zones for heat calculation. Such a division is necessary when the sheets have different thicknesses, material properties, etc.

For a two-sheet stack up, there are two nugget zones at the center, surrounded on either side by a heat-affected zone and an outer indentation zone, as shown in Fig. 1.

The basic equation for heat calculation during heating a solid or a liquid is

\[ Q = m \times C_p \times \Delta T \]  

(6)

where \( m \) is the mass, \( C_p \) is the specific heat of the material, and \( \Delta T \) is the change in temperature due to heating. Each zone is idealized as a short cylinder for simplicity. For instance, assuming the HAZ has the same diameter as the electrode face, the mass of the HAZ can be expressed as

\[ m = \frac{\pi \times d_e^2 \times h \times \rho}{4} \]  

(7)

where \( d_e \) is the electrode diameter, \( h \) is the height of the HAZ, and \( \rho \) is the density of the sheet. Then the heat in the HAZ can be calculated using Equation 6.

The heat components can be calculated once the mass, thermal properties, and the possible maximum temperature increases are known. The volumes of various zones in a weldment are generally different. However, an assumption that the zones are (short) cylinders of the same diameter but different heights is made in this study for simplicity. Actually, their diameters are not much different for a well-controlled grown weld. The electrode diameter \( d_e \) can be used as the diameter of the fusion zone in each sheet. The HAZ has the liquid densities at melting temperature, and \( p'_1 \) and \( p'_2 \) are the average densities, \( C_p'1 \) and \( C_p'2 \) are the specific heats of the liquid between \( T_{max} \) and \( T_{melt} \) and \( L_{f1} \) and \( L_{f2} \) are the latent heats of fusion.

The total heat used to make the weldment is

\[ q = q_1 + q_2 + q_3 + q_4 + q_5 + q_6 \]

Based on the heat components calculated, a characteristic dimension \( H \) is defined as

\[ H = h_1 \frac{q_1}{q} + h_2 \frac{q_2}{q} + h_3 \frac{q_3}{q} + h_4 \frac{q_4}{q} + h_5 \frac{q_5}{q} + h_6 \frac{q_6}{q} \]  

(15)

This characteristic dimension is used instead of the actual thickness of the entire stack up (as used in the LOTS) as it differentiates the contributions of various regions in an actual heating process. Although they are closely related in the physical process, the various thicknesses are independently defined, and they can be altered independently to obtain the desired features of a weldment.

This theory was verified in the case of developing welding schedules for uneven-thickness sheet stack ups. The first step is to develop good schedules for welding even-thickness sheet stack ups. One can then be developed using those for welding even-thickness sheets and this theory.

For even thickness stack up, the weld time, welding current, electrode force, and electrode diameters were chosen from the Welding Handbook (Ref. 6), as shown in Table 2. For a sheet stack up, the heat input needed for making a weldment is propor-
The temperature in the weldment is assumed proportional to the heat generated, and inversely proportional to the characteristic thickness and the square of the electrode diameter (Ref. 9) when the welds formed are similar.

\[ T = \frac{q}{H \times d_e^2} \]  

As the zones in a weldment are assumed similar to their counterparts in the individual welds, Equation 24 can be used to approximate the temperature of a weldment. Let \( q_1 \) and \( q_2 \) be the total heat content of the two stacks, then the combination stack up, the heat content \( q_3 \) is given by

\[ q_3 = \frac{q_1 + q_2}{H_3 \times d_e^2} \]  

**Experiment**

Experiments were carried out to verify the theory and prove it suitable for use as a guideline for selecting welding schedules not listed in the Welding Handbook. The experiments were conducted on a resistance spot welding machine equipped with a programmable weld control unit. A 35-KVA transformer was used along with a "C" type gun. The raw material used was bare mild carbon steel sheets of 14- (0.75-mm), 18- (1.21-mm), and 22- (1.89-mm) gauge of ASTM A569 and ASTM A366 grade.

Ambient temperature = 27°C, melting point for mild steel = 1535°C, maximum temperature reached was assumed to be 1735°C (with 200°C overheating), specific heat of mild steel = 2529 J/kg°C, latent heat of fusion = 241585.5 J/kg, the average density of mild steel between room temperature (27°C) and melting temperature (1535°C) is 7470 kg/m³, (liquid) density at 1535°C = 7190 kg/m³, density at 1735°C = 6915 kg/m³ (Refs. 10-12). Several sets of welds were made with the calculated schedules based on the schedules for even-thickness sheet welding listed in the Welding Handbook (Ref. 6). The welds were peel tested and the weld diameter was measured. Samples were prepared for metallographic examination and measuring various dimensions. With the help of these measured dimensions, the welding parameters for other sheets were predicted using the equations of the proposed theory. Then using these predicted weld parameters, new sets of welds were made.

**Table 2 — Welding Handbook Schedules for Uncoated Low-Carbon Steel Sheets (Refs. 6, 7)**

<table>
<thead>
<tr>
<th>Sheet Thickness (mm)</th>
<th>Welding Current (A)</th>
<th>Weld Time (ms/eye)</th>
<th>Electrode Force (kg/lb)</th>
<th>Electrode Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.508</td>
<td>8500</td>
<td>117/7</td>
<td>181/400</td>
<td>4.78</td>
</tr>
<tr>
<td>0.635</td>
<td>9500</td>
<td>133/8</td>
<td>204/450</td>
<td>6.35</td>
</tr>
<tr>
<td>0.762</td>
<td>10500</td>
<td>150/9</td>
<td>227/500</td>
<td>6.35</td>
</tr>
<tr>
<td>0.889</td>
<td>11500</td>
<td>175/9</td>
<td>272/600</td>
<td>6.35</td>
</tr>
<tr>
<td>1.016</td>
<td>12500</td>
<td>197/8</td>
<td>317/650</td>
<td>4.78</td>
</tr>
<tr>
<td>1.143</td>
<td>13500</td>
<td>250/10</td>
<td>349/750</td>
<td>4.78</td>
</tr>
<tr>
<td>1.270</td>
<td>14000</td>
<td>317/13</td>
<td>409/900</td>
<td>4.78</td>
</tr>
<tr>
<td>1.524</td>
<td>15000</td>
<td>467/20</td>
<td>654/1200</td>
<td>9.53</td>
</tr>
<tr>
<td>1.778</td>
<td>16000</td>
<td>544/16</td>
<td>776/1600</td>
<td>9.53</td>
</tr>
<tr>
<td>2.032</td>
<td>17000</td>
<td>635/14</td>
<td>876/1800</td>
<td>9.53</td>
</tr>
<tr>
<td>2.286</td>
<td>18000</td>
<td>726/18</td>
<td>952/2100</td>
<td>9.53</td>
</tr>
<tr>
<td>2.667</td>
<td>19500</td>
<td>816/18</td>
<td>952/2100</td>
<td>9.53</td>
</tr>
<tr>
<td>3.048</td>
<td>21000</td>
<td>952/21</td>
<td>952/2100</td>
<td>9.53</td>
</tr>
</tbody>
</table>
and the procedure was repeated. Finally, the weld parameters obtained from welding schedules predicted by the proposed theory were compared with those obtained in actual welding.

Results and Discussion

First, even-thickness sheets of 0.75 and 1.21 mm thicknesses were welded, with schedules very close to the ones given in the Welding Handbook (Ref. 6). The weld diameter was measured, and microscopic observations revealed the thicknesses of various zones for calculating the characteristic dimensions. From this data, weld schedules for a stack of 0.75 + 1.21-mm sheets were predicted using the equations of the proposed theory. Welding using these schedules yielded the expected weld sizes without expulsion. The results are tabulated in Table 3.

In Table 3, the current in the experiment (No. 3) was searched, based on the predicted value, to obtain a similar characteristic height as the predicted. This practice was to show that a characteristic height (and, therefore, a weldment) can be created in welding using schedules derived by the theory. The table reveals the experimental results obtained for the uneven-thickness combination in good agreement with those predicted by the theory. The welding schedules predicted by the proposed theory yielded a good weld in terms of size and surface quality. Several additional tests were carried out to further verify the results of the proposed theory and build a confidence interval on its ability to predict correct weld schedules.

Using the same welding schedule, several welds were made and the weld size was measured to establish a variance on the weld diameter. The variance on the mean diameter of the welds was found to be very small ($\mu_0 = 4.93, \sigma^2 = 0.0514$).

With all other weld parameters kept constant, the weld time was varied over a range. It was confirmed the weld by the selected schedule had the largest size without expulsion. Weld times below the selected one resulted in undersize welds, while weld times above the chosen one led to expulsion.

With all other weld parameters kept constant, the weld current was varied over a range. It also proved that the weld current at the schedule selected gave the largest nugget size without expulsion. Again, lower than selected currents gave a smaller weld button while expulsion occurred for higher currents.

Experiments have shown the predicted welding parameters used are optimized to have the largest weld diameter without expulsion. The parameters can be predicted with 98% confidence. Thus the theory helps to predict welding schedules for uneven-thickness sheets with good accuracy and ease for practical use.

Summary

A new theory based on heat balance was proposed for developing schedules in welding uneven-thickness sheet combinations. It takes into account the heat input into the fusion zone, the HAZ, and the electrode indentation and uses basic proportionality equations to reflect their contributions in welding to predict the welding parameters. The proposed theory was verified experimentally, and it provides a simple guideline for selecting weld schedules for uneven-thickness two-sheet metal welding, based on those of even-thickness schedules. The theory and the procedure can be implemented in a production environment and can serve as a ready reference for choosing welding parameters on the shop floor.

Acknowledgment

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References