Influence of welding parameters on fatigue strength of spot-welded joint considering nugget size

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Abstract

Electrode force, welding current and time are welding parameters in determining the nugget size and the strength of spot-welded joint. The purpose of this study is, first, to evaluate the range of welding parameters under which the strength is robust and, second, to evaluate the relationship between welding parameters and the fatigue life. To achieve these purposes, two kinds of evaluations are made: (i) evaluation of the relationship between welding parameters and the nugget size using the heat transfer model; (ii) evaluation of the relationship between the nugget size and the fatigue strength considering the nominal stress at the nugget.

1 Introduction

A melting phenomenon does not occur or an expulsion phenomenon occurs at the spot-welded joint and the strength of welded joint changes remarkably under particular range of welding parameters. By this reason, it is necessary to predict the range of welding parameters under which the strength is robust. In addition to it, it takes lots of time to test the fatigue life under the acceptable nugget size. By this reason, the estimation of the fatigue life is necessary.

2 Test method

Aluminum sheets of 6T02P were spot welded under various combinations of welding parameters and tensile tests were carried out. After that, fracture surfaces
were observed with the microscope, and nugget diameters were measured. Fatigue tests were also carried out with various nugget sizes and the fatigue life was measured. Figure 1 shows the geometry of the test specimen. Fatigue tests were done under the stress ratio $R=0$, and the ends of the specimen are rigidly clamped.

3 Evaluation of the relationship between welding parameters and nugget size

3.1 Evaluation method

3.1.1 Radial temperature distribution on contact surface between sheets

Fig.2-1 shows the heat transfer model and parameters to be considered. During the weld, the temperature of the section (1) rises by the resistance heating, and its heat losses to surroundings, which affects the temperature distribution and the nugget size. By the way, melting phenomenon occurs because of the contact resistance $R_0$ between workpieces at first, and after melting, the resistance $R_1$ of workpiece itself generates heat. $R_0$ and $R_1$, are given as follows [1]:

$$R_0 = k\beta \sqrt{\frac{\sigma_S}{P}},$$  \hspace{1cm} (1)

$$R_1 = \beta \frac{l}{A_r},$$  \hspace{1cm} (2)

where $\beta$ is the specific resistance, $\sigma_S$ is the yield stress of workpiece and $k$ is constant determined by the kind of material. The temperature distribution can be determined by Fourier’s Law as follows, where heat losses to surroundings are considered. Heat losses are $Q_{out1}$ to the electrode tip contact surface and $Q_{out2}$ to the radial direction:

$$I^2R + \lambda \frac{\partial T}{\partial z^2} A_I + \lambda \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) \right] A_I = mc \frac{dT}{dt}.$$  \hspace{1cm} (3)

Eqn (3) shows that the temperature distribution is presented as the function of the directions $r$ and $z$. But this study considers the radial temperature distribution only, because the nugget size is defined on $Z=0$, which is contact surface between workpieces. Eqn (3) can be rewritten as follows:

$$I^2R - \lambda \frac{T - T_r}{l} A_I - \lambda \frac{T - T_l}{l} \cdot 2\pi l = mc \frac{dT}{dt}.$$  \hspace{1cm} (4)

The radial temperature distribution is given by integrating eqn (4) with respect to the time $t$. $C$ is the constant of integration:
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Figure 1: Geometry of the test specimen.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi$</td>
<td>Boundary of phase [m]</td>
</tr>
<tr>
<td>$A_t$</td>
<td>Tip contact area [$m^2$]</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass [kg]</td>
</tr>
<tr>
<td>$t$</td>
<td>Plate thickness [m]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density [kg/m$^3$]</td>
</tr>
<tr>
<td>$c$</td>
<td>Specific heat [J/kgK]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Thermal conductivity [W/mK]</td>
</tr>
<tr>
<td>$a$</td>
<td>Thermal diffusivity [m$^2$/s]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Specific resistance [$\Omega$m]</td>
</tr>
<tr>
<td>$L$</td>
<td>Latent heat [J/kg]</td>
</tr>
<tr>
<td>$\sigma_s$</td>
<td>Yield stress [MPa]</td>
</tr>
<tr>
<td>$T_r$</td>
<td>Melting point [K]</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Reference temperature [K]</td>
</tr>
<tr>
<td>$I$</td>
<td>Current [A]</td>
</tr>
<tr>
<td>$t$</td>
<td>Welding time [s]</td>
</tr>
</tbody>
</table>

Figure 2-1: Heat transfer model and parameters for spot-welded joint.

\[
(T - T_f) \lambda \left[ \frac{A_t}{l} + \frac{2\pi l}{\ln \frac{r_-}{r_+}} \right] = I^2 R C \exp(-\tau t),
\]

\[
(5)
\]

\[
\tau = \frac{1}{I} \left( \frac{1}{l^2} + \frac{2\pi}{A_t \ln \frac{r_-}{r_+}} \right)
\]

The radial temperature distribution before melting is determined as eqn (7) with the initial-condition of eqn (6). It is shown in Figure 2-2 (i):

\[
t = 0; \quad T = T_f.
\]

\[
(6)
\]
\[ T - T_f = \frac{l^2 R}{\lambda A_r} \left\{ 1 - \exp\left(-\tau t\right) \right\}, \]
\[
\tau = \frac{1}{l^2} + \frac{2\pi}{A_r \ln \frac{r_m}{r}}
\]

When the temperature reaches the melting point, phase change from solid to liquid occurred and the liquid phase is expanded during welding. Its temperature is maintained as the melting point, because the latent heat transfer occurred during this process. It is supposed that melting occurs at time, \( t=0 \) and the density \( \rho \) is equal with each phase. The radial temperature distribution after melting is determined as eqn (9) with the boundary-condition of eqn (8). It is shown in Figure 2-2 (ii):

\[ r = \xi; \quad T_1 = T_2 = T_d. \]

\[ T_i - T_f = \frac{l^2 R}{\lambda_i \left( \frac{A_r}{l} + \frac{2\pi l}{A_r \ln \frac{r_m}{r}} \right)} \left\{ 1 - \exp\left(-\tau_i a, t\right) \right\} + \left( T_d - T_f \right) \exp(-\tau_i a, t).
\]

\[ \tau_i = \left( \frac{1}{\ln \frac{r_m}{r}} - \frac{1}{\ln \frac{r_m}{\xi}} \right) \frac{2\pi}{A_r}.
\]

### 3.1.2 Evaluation of melting and expulsion phenomenon

Eqn (7) and Figure 2-2 (i) are the basis of the estimation formula under melting phenomenon. Because the temperature is the highest at \( r=0 \), melting phenomenon occurs when its temperature reaches the melting point. So the boundary-condition as follows can be applied:

\[ r = 0; \quad T = T_d. \]

\( R \) is expressed by eqn (1), and considering \( \ln(r,J) = \infty \), eqn (7) is rewritten as

\[ f(l,P,t) = C_0 \sqrt{P} \left( \frac{l^2}{1 - \exp\left(-\frac{at}{l^2}\right)} \right) = \text{const.}, \]

\[ C_0 = \frac{\sqrt{\sigma_s \beta}}{T_d \lambda}. \]

Eqn (9) and Figure 2-2 (ii) are the basis of estimation formula under expulsion phenomenon. First, the liquid phase is expanded during welding with its temperature being maintained as the melting point, and after that, the expulsion
occurs when the boundary of \( r=\xi \) reaches the tip contact radius \( r=r_e \). So the boundary-condition as follows can be applied:

\[
\begin{align*}
  r &= \xi = r_e; \quad T_1 = T_d. 
\end{align*}
\]  

(12)

In addition to it, the equation of continuity of the heat flow as follows is needed:

\[
\begin{align*}
  r &= \xi = r_e; \quad Lp \frac{d\xi}{dt} - \left( \lambda_1 \frac{\partial T_1}{\partial r} - \lambda_2 \frac{\partial T_2}{\partial r} \right) = \frac{I^2 R_e}{2nE l},
\end{align*}
\]  

(13)

where subscription 1 and 2 denote solid and liquid phase. The temperature \( T_2 \) is kept at the melting point \( T_d \), so \( \delta T_2/\delta T_1 = 0 \). Considering that the temperature is constant \( (T_1=T_2=T_d) \) at the boundary of \( r=\xi \), \( \exp(-\pi \alpha t) \) of eqn (5) is unrelated to the time \( t \). So the proportional constants \( k_1 \) and \( k_2 \) are introduced as follows:

\[
\begin{align*}
  \frac{1}{l^2} &= k_1, \\
  \phi &= \frac{2\pi}{A_e \ln\frac{r_e}{\xi}} = k_2, \\
  \frac{d\xi}{dt} &= \frac{d\phi}{dt} \left( \frac{1}{\frac{d\phi}{d\xi}} \right)
\end{align*}
\]  

(14)

\( R \) is expressed by eqn (2), and denoting \( \ln(r_e/\xi) = \ln(r_e/r_e) = \kappa \), eqn (13) is expressed as follows:

\[
\begin{align*}
  g(t) &= D_1 C_1 t^2 - C_2 (a_1 t + D_2) t^2 t = \text{const.,}
\end{align*}
\]  

\[
\begin{align*}
  D_1 &= \pi^2 \left( \frac{r_e^4}{l^2} + \frac{2r_e^2}{\kappa} \right), \\
  D_2 &= \frac{\kappa^2 r_e^4}{4l^2} + \frac{2\kappa r_e^2}{2}, \\
  C_1 &= \frac{T_d a_1}{Lp}, \\
  C_2 &= \frac{\beta}{Lp}
\end{align*}
\]  

(15)
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Figure 2-2: Radial temperature distribution on contact surface between sheets, before melting phenomenon occurs (i), after melting (ii).

Table 1: Material properties for calculating the values, $C_0$, $C_1$, $C_2$.

<table>
<thead>
<tr>
<th>$c$ [J/kgK]</th>
<th>917</th>
<th>$a$ [m$^2$/s]</th>
<th>9.09×10$^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ [kg/m$^3$]</td>
<td>2.7×10$^3$</td>
<td>$T_d$ [K]</td>
<td>933</td>
</tr>
<tr>
<td>$\lambda$ [W/mK]</td>
<td>238</td>
<td>$\beta$ [$\Omega$m]</td>
<td>2.40×10$^{-7}$</td>
</tr>
<tr>
<td>$L$ [J/kg]</td>
<td>-3.97×10$^3$</td>
<td>$\sigma_i$ [MPa]</td>
<td>2.45×10$^2$</td>
</tr>
</tbody>
</table>

3.2 Experiment for estimation of melting or expulsion phenomenon
The values, $f(I, P, t)$ and $g(I, t)$, can be estimated with the experiment. Under the experiment for evaluating the melting phenomenon, welding current $I$ is varied for fixed electrode force $P$ and time $t$. For evaluating the expulsion phenomenon, time $t$ is varied for fixed electrode force $P$ and current $I$. Material properties for the estimation are shown in Table 1.

3.3 Experimental data and estimated result
The comparison of the experimental results with the estimated results is made in Figure 3. The procedure for the estimation is shown in Figure 9.

4 Evaluation of the relationship between nugget size and fatigue strength

4.1 Evaluation method

4.1.1 Fracture mode
There are two patterns of fracture mode; that is, shear fracture and bending fracture according to Figure 4.
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Figure 3: Comparison of experimental result with estimated result.

Figure 4: Fracture mode, shear fracture (i), bending fracture (ii).

4.1.2 Definition of nominal stress
Nominal stress at the nugget edge is shown in Figure 5. Strain gages are attached to the nugget edge. The strength-relevant stress range for shear fracture is the shear stress range $\Delta \tau$ at the interface of the two plates in the nugget:

$$\Delta \tau = \frac{\Delta F}{A_N}. \quad (16)$$

The strength-relevant stress range for bending fracture is the normal stress range $\Delta \sigma_{\text{max}}$ on the inner side of the sheet at the nugget edge [2]. It is expressed as the sum
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of the tensile stress range $\Delta \sigma_F$ and the bending stress range $\Delta \sigma_M$. $\Delta \sigma_{\text{max}}$ is written as follows:

$$\Delta \sigma_{\text{max}} = \Delta \sigma_F + \Delta \sigma_M = D_F \frac{\Delta F}{d l} + D_M \frac{\Delta M}{Z} = \frac{W}{d} \left( D_F \Delta \sigma_{F_n} + D_M \Delta \sigma_{M_n} \right)$$

$$\Delta M = \frac{(7L + 3l)}{16L + 6l} \Delta F \approx \frac{(7L_0 + 3l)}{16L_0 + 6l} \Delta F$$

(17)

$D_F$ and $D_M$ are correction factors. Stress range, $\Delta \sigma_F$ and $\Delta \sigma_M$ can be determined by strain gages attached to the outer and inner surfaces of the sheet at the nugget edge:

$$\Delta \sigma_F, \Delta \sigma_M = E \frac{\Delta \epsilon_{\text{in}} \pm \Delta \epsilon_{\text{out}}}{2}.$$  (18)

![Strain gage diagram](image)

Figure 5: Nominal stress and the strain gages at the nugget edge.

4.2 Experiment for estimation of the relationship between nugget size and fatigue strength

4.2.1 Measurement of correction factors, $D_F$ and $D_M$

These studies suppose that $D_F$ and $D_M$ are determined by the ratio, $dl/W$. Figure 6 shows the relation between $\Delta \sigma_{F_n}$, $\Delta \sigma_{M_n}$ and $D_F$, $D_M$. The values of these factors increase with $dl/W$. But as for $D_M$, it changes with $\Delta \sigma_{M_n}$. This is because the offset of central axis, which generates bending moment $\Delta M$, decreases with loading. But this change can be regarded as small. This study evaluates fatigue life from $10^4$ to $10^6$ cycles and $D_F$, $D_M$ are calculated as the average values with this range of cycles. Figure 7 (i) shows the relationship between $\Delta \sigma_{F_n}$, $\Delta \sigma_{M_n}$ and fatigue life $N_f$ with the specimens; $d=4.3\text{mm}$, $W=30\text{mm}$. $\sigma_{F_n}$ changes from 14.3MPa to 24.2MPa and $\sigma_{M_n}$ changes from 37.6MPa to 67.3MPa. Figure 7 (ii) shows the relationship between average $D_F$, $D_M$ with this range of cycles and $dl/W$. 
Figure 6: Relation between stress ranges $\Delta \sigma_{Fm}$, $\Delta \sigma_{Mn}$ and factors $D_F$, $D_M$.

Figure 7: Relationship between stress range $\Delta \sigma_{Fm}$, $\Delta \sigma_{Mn}$ and the number of cycles to failure $N_f$ (i), relationship between average $D_F$, $D_M$ and $d/W$ (ii).

4.2.2 Relationship between $\Delta \sigma_{\text{max}}$ and number of cycles to failure $N_f$
Fatigue test, for estimating the relationship between $\Delta \sigma_{\text{max}}$ and $N_f$, was carried out using the specimens; $d =$ 4.3mm, $W =$ 30mm (Figure 7 (i)).

4.3 Experimental data and estimated result
The comparison of experimental results with estimated results are made in Figure 8. The procedure for the prediction is shown in Figure 9.
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Figure 8: Comparison of experimental result with estimated result.

Figure 9: Procedure for prediction of the relationship between these welding parameters and the fatigue life.
5 Conclusion

1. The temperature distribution on contact surface between workpieces was considered. It provided quantitative predictions on the range of welding parameters under which the strength is robust.
2. The relationship between the nugget size and the fatigue strength was estimated in considering the nominal stress at the nugget.

References