An FE computer model to investigate the effects of varying A.C. frequency and strip speed during high speed resistance seam welding of tinplate

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Abstract

High Speed Resistance Welding (HSRW) is a high-volume manufacturing route for the production of welded steel cans. Full optimisation of such a process requires a scientific understanding of the relationships between process variables and thermal effects occurring in the weld zone and heat affected zone. This paper follows on from previous work undertaken as part of an ongoing project to develop a predictive FE computer model of the HSRW process. Presently, the model has been used to investigate the thermal effects of welding speed and A.C. frequency on the macro scale evolution of the nuggets developed during welding. The model formulation and results generated using the model are described. The effects of varying strip speed and A.C. frequency on temperature distributions, current density fields and predicted nugget lengths are highlighted.

Keywords: high speed resistance seam welding, weld nugget, thermal behaviour, current density.

1 Introduction

Welded steel cans represent the most predominant form of metallic packaging for human and pet food products, worldwide [1]. Although high-speed resistance welding lines with linear speeds of over 1ms⁻¹ have been developed, extra demand is being imposed on process capability and product performance. To utilise this process to its optimum capability and to increase the welding latitude
(the breadth of possible process parameters to still give a satisfactory weld), a predictive model of the thermal behaviour during the welding procedure itself would be advantageous.

Seam welding can be thought of effectively, as many overlapped spot-welds. In the HSRW process, two copper electrodes pass an A.C. current through a small area of overlapped tinplate. If the electrical current density is heavy enough, then the tinplate is heated to a plastic or even molten state and through electrode roll pressure, fusion can take place and a welded seam is produced at very high speeds [2, 3]. When a voltage $V$ is applied to a resistance $R$ in a circuit, a current flow $I$ will result. Any change in voltage or resistance will result in a change in current. The combination of current and resistance will give rise to heat due to collisions between the moving electrons and the lattice structure of the steel. Therefore, a drop in the measured amount of current, will result in less generated heat if there is a constant resistance – the opposite is also true whereby more measured current results in more heat. The same effect will ensue if measured current is constant and resistance changes, i.e. more resistance results in more heat. Allowing current to flow through a resistor – in this case the overlapped tinplate, for a period of time $t$ – in this case the half-cycle of current, gives rise to an increase in temperature. Thus temperature is a product of $R$, $t$ and $I$.

Some of the main factors that can affect weld integrity in tinplate welds are described below.

1. Magnitude of welding current – This controls heating and in practice is controlled by a potentiometer. Incorrect settings may result in hot or cold welds [4], both of which are of poor quality and therefore undesirable.
2. Resistance of the overlap which is affected by: -
   (i) Width of overlap
   (ii) Length of time that current is applied – this is controlled by the frequency of supply to the welding transformer [5].
   (iii) Thickness of tin coating
   (iv) Quality or thickness of tinplate
   (v) Contamination in welding area – particularly lacquer flooding [2]
   (vi) Force applied to the overlap to help deform the heated zone into a single structure – the pressure is applied through a spring acting on the upper electrode roll. The direct relationship between welding pressure and welding current means that an increased pressure can result in a cold weld due to a lower electrical resistance.
3. Weld Speed – Since A.C. current forms a weld nugget for every half cycle [6].
4. Contact Resistance – Electrical contact resistance of the material surface can adversely affect the weldability of the steel can body. The total resistance path between the welding electrodes influences this parameter[7, 8].
5. Steel Thickness – Higher levels of weld current are required for thicker steel if one wishes to maintain weld quality [6].
6. Carbon Content – generally the electrical resistivity of steel is increased with higher carbon content and so a higher current is necessary to maintain a
weld of sound quality because higher resistivity results in lower current density [2, 6, 9, 10].

The thermal effects of some of the process variables mentioned above are amenable to simulation using computer-modelling methods. In this paper a prototype model is described that attempts to illuminate the consequences of varying different process parameters on the predicted thermal behaviour during welding – in this case the frequency and velocity. In particular, regions in the weld zone where very high temperatures can develop are of special interest [11] if their location matches that of predicted and microstructurally observed isotherms.

2 Model formulation

An Eulerian approach is used in this model such that the material to be welded is assumed to flow through a static finite element (FE) mesh. The FE code is a specially developed in-house FORTRAN 90 code. Each node in the mesh possesses several dependent variables consisting of electrical potential (V), the x, y and z components of Current Density (Am⁻²), the x, y and z components of Velocity (ms⁻¹), temperature (°C) and fraction solid (dimensionless: 0 to 1).

The first step of the model involves generating a finite element mesh. Parameters such as the diameter and width of the welding electrode rolls, thickness of the tinplate, amount of deformation and welding frequency can be set-up individually as well as quantifying the number and distribution of nodes. The contact lengths and contact areas of electrode to workpiece are then calculated automatically by the model. Once the chosen parameters are input and the mesh is generated, eqn (1), namely the Laplace equation, is solved to determine two potential fields, \( \phi_e \) and \( \phi_f \), the electrical potential field and the flow potential field respectively, and Dirichlet type boundary conditions are used.

\[
\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0
\]  

As shown in fig.1, for \( \phi_e \), fixed electrical potential boundary conditions are used at the location on the mesh of where the electrode rolls would be and initially a constant electrical conductivity is assumed. For \( \phi_f \), fixed flow potentials are used at the inlet and outlet planes of the mesh. Checks are made to make sure that material is conserved by keeping the cross-sectional areas of the planes the same, even though it changes geometrically.

Current density vectors are obtained by numerically differentiating the electrical potential field \( \phi_e \). Velocity vectors are obtained by numerically differentiating the flow potential field \( \phi_f \). The heat conduction & source terms as shown in eqn (2) are first calculated by use of an FE solver called Pre-Conjugate Gradients (PCG):
Figure 1: Schematic diagrams showing fixed electrical boundary conditions on the mesh at theoretical electrode roll contact and fixed flow boundary conditions on ends of mesh.

\[
\frac{k(T)}{\rho c(T)} \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] + S \left( \frac{i^2 \beta}{\rho c(T)} \right) + \frac{H}{c(T)} \frac{\partial f_s}{\partial t} \quad (2)
\]

The convection field as shown in eqn (3) would then be applied for one iteration, after 1 build of the FE matrix.

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \quad (3)
\]

Following this, a new value for current density would be worked out to recalculate values for heat conduction and source terms. The convection field would be applied again for one iteration after 1 build of the matrix. This forms the modelling procedure of the transient convection/diffusion model which is a combination of eqns (2) and (3). Source terms for the generation of heat via the Joule heating effect and latent heat release/absorption are included. Of most importance is the Joule heating term. The A.C. current is simulated by the use of a sine wave with an appropriate frequency. At each time increment and subsequent build of the matrix, the Joule heating source term is multiplied by the absolute value of the sine wave (S) providing a time dependent oscillating heat source. During this phase of the simulation, typical temperature dependent electrical resistivity values are used for a low carbon steel as are values...
accounting for specific heat at ambience and melting point. The resistivity values vary from $12 \times 10^{-05}$ to $116 \times 10^{-05} \mu \Omega \text{cm}$ over the temperature range 25 to 1000 °C.

T is temperature (°C), t is time (s), u/v/w are velocity (ms$^{-1}$), k is thermal conductivity (20 Wm$^{-1}$°C$^{-1}$), $\rho$ is density (7200 kgm$^{-3}$), c is specific heat capacity (712 Jkg$^{-1}$°C$^{-1}$), S is the A.C. sine wave multiplier, $i$ is current density (Am$^{-2}$), $\beta$ is electrical resistivity ($\Omega$m), H is the latent heat of fusion (277 000 Jkg$^{-1}$) and $f_s$ is the fraction solid (dimensionless). The mesh used in this work contains 16560 linear hexahedral elements with 20300 nodes.

It must be emphasized that the model uses a fixed mesh generated purely by geometric considerations. At this stage a full-blown stress analysis has not been attempted and the movement of the material through the rolls is governed wholly by the flow potential equation [12]. Work by the authors with this approach to the modelling has been reported previously [13].

As a further point, if one looks at the surface of a typical HSRW seam, a ridged topography can be seen indicating a periodic loading. This happens because the spring loaded upper electrode roll naturally oscillates with applied electrical sine wave [14]. As the overlapped workpiece passes through the electrodes, the material heats and softens and the electrode roll pushes into the overlapped material and an indent in the material is observed - this indent reaches its maximum depth when the current is at its maximum value. The next piece of material coming in is cooler because the current is decreasing as the sine wave moves away from its maximum value and therefore not as soft and the spring loaded electrode roll is pushed up resulting in a ridge. This “indent/ridge/indent/ridge” along the longitudinal length of the weld seam therefore has an effect on the current density since the varying contact time of the electrode roll on the workpiece has an effect on the contact length. This invariably affects the current path area as the lower electrode roll is smaller than the upper electrode roll. This phenomena is approximated in the program numerically with the current density following the pattern of the applied sine wave as opposed to geometrically due to the nature of the static mesh.

3 Results

The simulations have all been run on the same grid geometry with an overlap width of 0.6mm and a strip thickness of 0.2mm with typical in-practice radii for the electrode rolls of 31mm for the lower electrode roll and 42.5mm for the upper electrode roll. Table 1 summarizes the parameter changes with respect to frequency and nugget size and the corresponding velocity required to maintain the required nugget size.

All of the results are presented as 3D representations of the maximum temperatures experienced at any time during the simulation once it has reached a “cyclic” steady state typically after 20 cycles.

Fig. 2 shows the images for frequency 558Hz on a scale of 25°C to 1500°C. In order to change the nugget sizes whilst maintaining the frequency, the velocity has been increased from 0.558 ms$^{-1}$ to 1.115 ms$^{-1}$, so in effect the strip is moving...
almost twice as fast for the same number of A.C. cycles. In (i), the definition of individual weld nuggets is difficult to see but it is much more apparent in (ii) and (iii) where the nuggets get progressively larger as the weld speed increases with the highest temperatures concentrated at the cut edge of the mesh. At this point the current density is highest at the sharp edges as indicated by the cross-section representation on fig. 2 and so the temperatures are highest.

Table 1: Process parameters used in the simulations.

<table>
<thead>
<tr>
<th>Nugget Size</th>
<th>Frequency 558Hz</th>
<th>Frequency 710Hz</th>
<th>Frequency 858Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50mm</td>
<td>0.558 ms(^{-1})</td>
<td>0.710 ms(^{-1})</td>
<td>0.858 ms(^{-1})</td>
</tr>
<tr>
<td>0.75mm</td>
<td>0.837 ms(^{-1})</td>
<td>1.065 ms(^{-1})</td>
<td>1.303 ms(^{-1})</td>
</tr>
<tr>
<td>1.00mm</td>
<td>1.115 ms(^{-1})</td>
<td>1.420 ms(^{-1})</td>
<td>1.737 ms(^{-1})</td>
</tr>
</tbody>
</table>

It is interesting to note however, that as this happens, the maximum temperatures decrease as velocity increases due to the reduced contact time for heat generation. Fig. 3 shows longitudinal sections taken for (ii) with the effect of the higher current densities at the cut edges resulting in higher temperatures.

Fig. 4 shows the images for frequency 710Hz on a scale of 25°C to 1500°C. In order to change the nugget sizes whilst maintaining the frequency, the velocity has been increased from 0.710 ms\(^{-1}\) to 1.420 ms\(^{-1}\), so again the strip is moving twice as fast for the same number of A.C. cycles. In (i), the definition of individual weld nuggets is clear to see but it is much less apparent in (ii) and (iii) where the nuggets get progressively larger as the weld speed increases. Again,
the maximum temperatures decrease as velocity increases due to the reduced contact time for heat generation.

Figure 3: Longitudinal Sections exhibiting the nugget shape and the higher temperature isotherms at the cut edges.

Figure 4: Frequency 710Hz with varying velocity to result in nuggets sizes of (i) 0.5mm, (ii) 0.75mm and (iii) 1.0mm.

In Fig. 5 the images for frequency 868Hz on a scale of 25°C to 1500°C show how the maximum temperatures are lower due to the overall higher frequency in this simulation condition. Velocity has been increased from 0.858 ms\(^{-1}\) to
1.737 ms\(^{-1}\). In (i), the definition of individual weld nuggets is clear to see but it is much less apparent in (ii) and (iii) where the nuggets get progressively larger as the weld speed increases.

![Figure 5: Frequency 868Hz with varying velocity to result in nuggets sizes of (i) 0.5mm, (ii) 0.75mm and (iii) 1.0mm.](image)

4 Conclusions

In all cases, the maximum temperatures decrease with increasing velocity as there is less contact time for heat generation so for example, whilst comparing all of the nugget sizes of 0.5mm, it can be seen how the temperature decreases as frequency and velocity increase so the definition of weld nuggets becomes clearer. Further to this, the higher temperatures favour the sharp edges where the current density is highest.

At present, the model matches expected scenarios as exhibited in practice and is currently being developed and improved. At this stage, it is possible to model and visualize thermal behaviour phenomena that are otherwise impossible to directly observe in practice due to the nature of the process.

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References


