Integrated Thermal-Microstructure Model to Predict the Property Gradients in Resistance Spot Steel Welds.

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Abstract

An integrated model approach was proposed for relating resistance welding parameters to weldment properties. An existing microstructure model was used to determine the microstructural and property gradients in resistance spot welds of plain carbon steel. The effect of these gradients on the weld integrity was evaluated with finite element analysis. Further modifications to this integrated thermal-microstructure model are discussed.

Introduction

To make consistently good resistance spot welds, two conditions must be met. First, an optimum set of welding parameters must be defined to produce the properties desired of the weld. Second, controls must be implemented to maintain process variables within the necessary ranges so that optimized welds can reproducibly be made. These two conditions are applicable to any welding process.

Standard procedures for optimizing resistance spot welds rely on evaluation of some physical attributes of the welds [1]. For instance, process variables are adjusted to produce a desired weld indentation depth or nugget size. For carbon steels, process variables such as welding current, welding time and squeeze pressure are selected based on material thickness rather than composition. Consequently, the same optimization procedure used for low strength steels would also be applied to high strength steels. Weldment properties, however, depend on microstructure, and the welding parameters that produce optimized properties for one kind of steel may not be optimized for a different one. This means that relying on physical attributes to specify resistance spot welding parameters is inherently unreliable in terms of optimizing weldment properties.

The work presented here on microstructure development is part of a comprehensive effort to optimize resistance welding by more accurately describing and integrating the physics, mechanics, and metallurgy of the process. The overall approach is outlined in Fig. 1. For any welding process and alloy a process model can be constructed to determine how the thermal history of the fusion zone and surrounding base material depends on welding parameters. Knowing the thermal history and the relevant metallurgical information about the alloy being welded, the microstructure throughout the entire weldment can be predicted. This step is embodied in the microstructure model. The microstructure gradient in the weldment will result in a mechanical property gradient that can be defined if the necessary microstructure-property relationships are known or determined experimentally. Once the gradient of properties is established, then the response of the weldment to external loading can be predicted. This can be done, for instance, by using finite element analysis to create a structural model of the entire welded component.

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Microstructure Modeling

Microstructure models for resistance spot welds must be capable of describing the phase transformations during heating, cooling and tempering processes. This includes the phase transformations of austenite to ferrite and ferrite to austenite, the precipitation of carbides in martensite, and the dissolution of carbides and nitrides.

In the past, there have been many efforts to model microstructure development in the fusion zones and heat-affected-zones (HAZ) of welds [2-6]. In general, these models describe austenite formation and precipitate dissolution during heating and austenite decomposition during cooling [3,6]. In the model by Ion et al., the carbon equivalence (Cₐₚ) value and the time to cool from 800°C to 500°C (Δₜ₈₀₀₋₅₀₀) determine the volume fractions of bainite, martensite and ferrite-pearlite mixtures (see Fig. 2). This model is widely used. However, its predictions of microstructure are not accurate at low cooling rates for low carbon steels [4].

Another model by Watt et al. is generally valid only for high carbon steels [5]. This is because the transformation rate equations were developed using high carbon steel time-temperature-transformation (TTT) diagram data. Bhadeshia et al. also developed a phenomenological model for sequential decomposition of austenite to various ferrite morphologies [6]. The Bhadeshia model is applicable for a wide range of weld cooling rates and for low carbon steels [4]. For example, the TTT and continuous-cooling-transformation (CCT) diagrams predictions based on this method are quite applicable even to low carbon steels [8]. However, this model is incapable of describing simultaneous transformation of austenite to different ferrite phases. Recently, Jones and Bhadeshia developed a more refined model for describing the simultaneous formation of idiomorphic and allotriomorphic ferrite based on overall transformation kinetic equation [7]. The possibility of extending this work to consider other ferrite morphologies and also reverse transformation appears feasible.
Our long-term objective is to incorporate microstructure modeling of the type developed by Jones and Bhadeshia into our effort. The work presented here, however, represents an effort to establish the feasibility of our overall approach, and to demonstrate the key role played by microstructure modeling. Consequently, for the sake of expediency, these results for microstructure prediction in resistance spot welds were obtained with the model of Ion et al. In addition, some of the transformation temperatures were calculated using ThermoCalc [9] to estimate the austenite formation during heating. A generalized approach that is more rigorously based on alloy thermochemistry and phase transformation kinetics is still under development.

![Fig. 2. Typical variation of phase fractions with time to cool from 800°C to 500°C for a plain carbon steel [Fe-0.048 C - 0.1 Si - 0.18 Mn (wt.%)], calculated by Ion et al. model [3].](image)

**Experimental**

The alloy used for this study was an uncoated plain carbon steel (supplied by Inland Steel Co.). Its analyzed composition and designation is given in Table 1. It was supplied as a 0.81-mm-thick sheet.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ti</th>
<th>Nb</th>
<th>Balance.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQSK</td>
<td>0.048</td>
<td>0.01</td>
<td>0.18</td>
<td>0.001</td>
<td>0.003</td>
<td>Fe</td>
</tr>
</tbody>
</table>

The resistance spot welds were made with a bench-mounted, single phase, direct energy machine. Its stacked core transformer was rated at 100 kVA. The machine was also fitted with a PC-based process control and data acquisition system. Male cap taper electrodes (ME25 CMW, T. J. Snow Co., Inc.) were used corresponding to RWMA Class 2, RWMA alloy no. 2.18200 (Wrought Cu-Cr alloy). The truncated cone electrodes were dressed to a 5-mm-nominal face diameter. Conditioning of the electrodes and determination of welding parameters was done
using industry guidelines for welding automotive sheet steels [1]. The parameters finally used to make the spot welds were 2224 N (500 lb) welding force at a current of 7800 A for 12 cycles. Standard techniques were used for both optical and electron metallography. All finite element analyses were done using ABAQUS software running on a stand-alone UNIX workstation. Microstructure modeling was done on a PC.

Results and Discussions

Weld Microstructure

![Weld Microstructure Image](image)

Fig. 3. Typical microstructures in DQSK resistance spot welds: (a) Weld zone after 12 cycles; (b) Weld metal region exhibiting a mixed martensite-bainite microstructure; and (c) transmission electron micrograph showing bainitic sheaves made up of ferrite sub-units. Other areas showed the presence of lath martensite.

Figure 3(a) shows the overall weld nugget appearance with fusion zone, and regions of fully austenitized, partially austenitized, and unaffected based metal. Optical microscopy at high-magnification showed both martensitic and bainitic constituents in the weld nuggets [see Fig.3(b)]. Transmission electron microscopy confirmed the presence of both martensite and bainite in the weld metal [see Fig.3(c)]. The carbon content of DQSK steel (0.048 wt%) is low, which means that the weld metal regions must have cooled at rapid rates to form bainitic and martensitic microstructures. Using the relation between microstructure and $\Delta t_{800-500}$ (see Fig. 2) the cooling rates are expected to be greater than 3000°C/s. The above analysis was confirmed with the TTT and CCT diagram analysis (see Fig. 4).
Fig. 4. Calculated CCT and TTT diagram for DQSK steel using the method outlined in the reference 8. The CCT diagram shows that the weld cooling rates need to be higher than ~3000°C/s to induce martensitic microstructure. [The above method can presently (September 1998) be used on-line at the Internet address: http://engm01.ms.ornl.gov.]

The presence of martensite and bainite will lead to a very high hardness in the weld metal region and this was confirmed by experimental measurements, Fig. 5. A large hardness gradient was found in the HAZ. A smaller hardness gradient was also observed within the weld nugget, which could be related to variations in the cooling rates within this region. The hardness gradients across the weldment are expected to influence the final properties of these resistance spot welds. Preliminary cross-tension tests have supported this speculation [10].

Fig. 5. Hardness variation across the DQSK resistance spot weld. Large hardness gradients are observed at the boundary between fusion zone and HAZ.
Microstructure Modeling

To be a useful tool, the integrated weld model (Fig. 1) must be capable of describing the effects of process variables on weldment properties. As previously discussed, a critical element of an integrated process model is a microstructure model. Existing process [11-13] and microstructure models [3] were used to evaluate the feasibility of our ability to construct an integrated model, and to establish its importance in determining structural integrity.

The microstructure modeling presented here is based on the thermal history of a resistance spot weld predicted with the relatively simple process model developed by Cho and Cho [11]. For this thermal simulation, the welding parameters used were those established experimentally on DQSK with the electrodes removed at the end of 12 cycles. The thermal conditions at the end of 12 welding cycles are shown in Fig. 6(a). The left and bottom edges of Fig. 6(a) are symmetry axes so only one quadrant of the weld nugget (at lower left corner of the image) is shown. The thermal histories experienced by representative locations along the steel-steel interface corresponding to weld metal (Node 1), fully austenitized (Node 14), and partially austenitized (Node 270) regions are given in Fig. 6(b). This thermal information was subsequently used to calculate the fractions of ferrite, bainite, and martensite present at various locations throughout the weldment. Example results are given in Table 2. The calculations showed a large gradient in hardness and were generally in agreement with experimentally measured values.

![Fig. 6. (a) Calculated distribution of maximum temperature based on the Cho and Cho [10] model (the image colors range from 1494°C to 200°C). (b) Weld thermal cycles experienced at representative locations along the weld interface.](image-url)
Table 2. Calculated microstructure and hardness for DQSK

<table>
<thead>
<tr>
<th>Region</th>
<th>Martensite</th>
<th>Bainite</th>
<th>Ferrite</th>
<th>VPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node1</td>
<td>0.97</td>
<td>0.02</td>
<td>0.01</td>
<td>245</td>
</tr>
<tr>
<td>Node14</td>
<td>0.99</td>
<td>0.01</td>
<td>0.00</td>
<td>258</td>
</tr>
<tr>
<td>Node270</td>
<td>0.50</td>
<td>0.00</td>
<td>0.50</td>
<td>182</td>
</tr>
</tbody>
</table>

Structure-Property Relationships
Theoretically, the microstructure at various locations in the weld should be related to its local yielding behavior through stress-strain relations given by:

\[ \sigma = \sigma_{YS} + K \varepsilon^n, \]  

(1)

where \( \sigma \) is the true stress, \( \sigma_{YS} \) is the yield stress, \( \varepsilon \) is the true strain, \( K \) and \( n \) are constants. However, there is no comprehensive structure-property correlation to estimate the above equation from the different constituent fractions of microstructure. Therefore, in this work, we estimated hardness using the published relation given in Ion et al.[3]. Example hardness values are also given in Table 2. Subsequently, the hardness values were used to estimate yield strength values from the expression [14]:

\[ \sigma_{YS} = \left( \frac{H}{3} \right) (0.1)^{m-2}; m = 2.15, \]  

(2)

After the microstructure calculations and tensile property estimations, structural model calculations were performed to evaluate the response of a single resistance spot weld to an externally applied shear load. The test geometry used in the calculation is shown schematically in Fig. 7. To simplify the analysis, the weldment was arbitrarily assigned 4 individual property zones based on the thermal history information provided by process modeling (Fig. 6(a)). These 4 zones corresponded to weld metal, base metal, and two localized intermediate regions of HAZ. The properties of the HAZ regions were derived from those of Nodes 14 & 270 in Table 2. The sensitivity of the calculations to property gradients was evaluated by additional calculations where uniform properties (those of the DQSK base metal) were assumed throughout the joint.

Fig. 7. Schematic of shear test geometry.

Predictions of the response of the weldments to shear loading are shown in Fig. 8. The macroscopic deformation associated with shear loading is shown in Fig. 8(a). Shear loading produced a strain concentration in the HAZ regions of the weldments. The load-displacement behaviors for the two weldments are given in Fig. 8(b). The presence of the weld including property gradients reduced the overall load-carrying capacity for this geometry and loading condition by about 50%. These results suggest that gradients of microstructure and properties
like those produced in resistance spot welds may have a significant effect on the mechanical behavior of a welded component.

Fig. 8. Results of shear test simulation for a spot welded joint. (a) Strain distribution throughout the joint with large strains observed near the HAZ. (b) Load-displacement curves for the joint with either four property zones or homogeneous properties.

It is anticipated that, when fully developed, the integrated model approach will provide a reliable means for systematically examining the influence that welding parameters and process conditions have on the mechanical behavior of welded components. It follows then that optimization of the resistance welding process should be possible based on the particular alloy and component being welded.

On-going Research
The process model used in the above example has ignored mechanical effects that can be classified into two categories. First, the apparent contact areas between the electrode and steel sheet, as well as between the contacting steel sheets, continuously change due to deformation. These contact area changes lead to changes in current density. Secondly, the mechanical deformation also changes the contact pressure distribution and this in turn affects the contact resistance at the electrode-steel and steel-steel interfaces. These changes lead to non-uniform Joule heating at the interfaces. Deformation effects are being incorporated into the process model by using an incrementally coupled electrical-thermal-mechanical finite element analysis [15]. To facilitate this approach, a phenomenological model [15, 16] was developed using the
Greenwood equation [17]. This model relates the contact resistance, bulk resistivity, temperature and pressure (see Fig 9). The calculations show that the contact resistance initially increases with temperature for a given pressure. However, further temperature increases cause the contact resistance to decrease. The competing effects of increasing bulk resistance and decreasing strength with temperature cause this behavior. At low temperatures, the increase in bulk resistance increases the contact resistance. Above a critical temperature range, however, the steel deforms thereby increasing the contact area and decreasing the contact resistance.

Fig. 9. Steel-steel contact resistance-temperature-pressure diagram for a circular contact area of 7.49 mm radius.

The incrementally coupled electrical-thermal-mechanical model was applied to simulate weld nugget formation in DQSK steel sheets with a flat electrode and a curved electrode (radius = 156 mm) for similar welding parameters (Fig. 10). During the simulations, the molten zone formed at the end of the 6th cycle with flat electrodes and melting initiated at the edges of contact region [see Fig. 10(b)]. For curved electrodes, the molten zone formed at the end of the 4th cycle at the center of the contact region [see Fig. 10(a)]. In addition, the temperature distributions were completely different in both the cases. This difference in predicted heating behavior is mainly due to local variations of pressure across the contact area and the resulting variations in contact resistance and current density. This finding is consistent with industrial guidelines for electrode conditioning, as new electrodes often produce different weld nugget growth behavior than that of "conditioned" electrodes. It is noteworthy that previous work [11,12] with pressure independent contact resistance did not capture this effect.
For microstructure predictions, the Ion et al. model was sufficient for the present simulations. However, its capabilities are limited. For instance, it cannot describe the kinetics of austenite formation during heating or tempering reactions during post-weld heat treatment cycles. Therefore, research is also underway to couple thermodynamic [9] and kinetic [18] analyses to develop a simultaneous transformation kinetics model similar to that of Jones and Bhadeshia [7]. In addition, experiments are being conducted to better define the relationship between microstructure gradients and local tensile properties, and how this influences weldment properties.

Fig. 10. Predicted temperature profile at the onset of molten zone (darker region) formation. The image colors range from 300 to 1780 K. (a) For curved electrodes at the end of the 4th cycle and (b) for flat electrodes at the end of the 6th cycle.

Summary and Conclusions
1. The feasibility of an integrated process-microstructure-property-structural model for relating resistance-welding parameters to weldment properties was demonstrated.
2. A coupled process-microstructure model was used to describe large microstructure and hardness gradients in the resistance spot welds. The predicted microstructure and hardness gradients were in general agreement with the experimental observations.

3. Finite element analysis on the effect of these hardness gradients in weldments predicted that they may reduce load carrying capacity.

4. On-going modifications to the integrated process model include a phenomenological model for contact resistance, an incrementally coupled electrical-thermal-mechanical process model, and a microstructure model capable of describing phase changes during heating, cooling and tempering cycles.

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References


