Thermal Modeling of Friction Welding

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Modeling of the friction welding process depends entirely on the accurate frictional heat generation term. In the present work it is demonstrated that the inverse heat conduction approach best represents the actual heat flow. Unlike other existing thermal models, this proposed model does not require the friction coefficient, the shear yield stress, nor the interface temperature data.

KEY WORDS: friction welding; heat flow; modeling; inverse analysis.

1. Introduction

Friction welding, as a solid-state joining process, is now well established as a means of joining many different types of materials because it has proved to be a reliable and economical way of producing high quality welds. The joint has a narrow heat affected zone and shows plastically deformed material which is subject to severe plastic deformation due to the high local temperature and internal pressures. Rotary friction welding is the oldest and most popular method used commercially since the 1940s. Orbital friction welding (since the 1970s) and linear friction welding (since the 1980s) are the next variants of friction welding process invented to extend the existing applications for rotary friction welding to non-circular and asymmetric components.

It is important to comprehend the concept of the process and to know how the change in process parameters can influence the joint properties. Such an understanding will help to improve the weld quality, to eliminate weld defects, and to transfer a knowledge of welding procedure to new conditions (e.g. for new geometry or new material). Therefore, modeling of the process with the aim of predicting the weld properties as a function of process parameters has been a central part of the investigation of friction welding processes for several decades. Since the late 1950s, the process has been widely studied both analytically and numerically. Empirical and analytical studies as well as computer-based models of the friction welding (FW) process have been developed to examine heat flow, material deformation, microstructure evolution and solid-state phase changes. Inasmuch as many properties of the final weld are directly related to the thermal history of the workpiece, the process itself is greatly influenced by the heat generation term. Although the investigations have been very useful to understand the different physical, metallurgical and mechanical aspects in friction welding, most of the models are insufficient due to the lack of an accurate expression for the heat generation term. Several phenomena associated with the process, such as severe plastic deformation, steep temperature gradients, very high rubbing velocity and strain rate and their influences on the frictional behavior of the material, and solid-state phase transformations make analyses of the FW very difficult. Another difficulty is understanding the dependency of the friction coefficient with temperature, pressure and velocity.

Thus, in the present work, the difficulties associated with the existing thermal analysis of FW are discussed. An approach based on the inverse heat transfer method for modeling the heat source in FW is presented. Unlike most analytical approaches, this method is not based on a high degree of knowledge regarding the frictional and plastic deformation behavior of the material at a wide temperature range (from low temperature to the solidus temperature).

2. Thermal Analysis

In all thermal models of FW the main task is to calculate the temperature profile in the specimen by solving the heat transfer equation. Based on the principle of conservation of energy, the following equation of heat conduction is undertaken with an appropriate set of initial and boundary conditions:

$$\rho C_p \frac{dT}{dt} = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} \right) + \rho C_p \nu \frac{dT}{dt} + \dot{S} \tag{1}$$

where $\rho$ is the material density, $C_p$ is the specific heat, $k$ is the thermal conductivity, $T$ is the temperature, $t$ is the time and $x_i$ with index notation of $i=1, 2$ and $3$ represents the $x$, $y$ and $z$ directions, respectively (see Fig. 1). The convective term on the right hand side of the equation accounts for the axial shortening of the specimen during FW, which is given by the product of the temperature gradient and the shortening velocity $\nu$. The volumetric heat source term $\dot{S}$ (W m$^{-3}$) is arising from plastic work in the workpiece next to the faying surface. In the present work for the benefit of simplicity, the heat generation from plastic dissipation ($\dot{S}$) is ignored due to its low value compared to the frictional heat.
The friction stress along the interface of the two bodies as a function of the normal pressure and the shear yield stress of the material and magnitude of the rubbing velocity at the weld interface is

\[ q(t) = \tau_{fr} \cdot v \] (2)

The major unknown term in the thermal analysis of friction welding is the shear stress due to the friction \( \tau_{fr} \). It is usually assumed that the resistance to sliding along the interface between the workpieces is uniform along the entire contact surface. The most common simplifying assumption made with regard to friction stress \( \tau_{fr} \) between the workpieces involves Coulomb friction. For Coulomb friction, it is assumed that the contact shear stress \( \tau_{fr} \) is proportional to the contact (normal) pressure \( P \) with the proportionality factor \( \mu \) called the Coulomb coefficient of friction \( i.e. \tau_{fr} = \mu P \).

Many factors such as temperature, surface roughness, material properties and magnitude of the sliding velocity affect frictional behavior \( \mu \) and the forces \( \tau_{fr} \) that resist sliding between the two surfaces. In the literature, many different friction coefficient values are reported even for the same sliding materials, which is attributed to the large number of potential friction-affecting factors. Consequently, due to the change in surface conditions \( e.g. \) temperature, strength and roughness\) at every moment of friction welding, a different friction coefficient should be chosen in order to adopt an appropriate shear stress on the welding interface \( \text{Fig. 2} \). Moreover, because the Coulomb friction law is based on rigid contact surfaces, when severe plastic deformation is involved, as in friction welding, the Coulomb friction is not sufficiently representative for the frictional heat generation. Therefore, it is reasonable to take the friction stress along the interface of the two bodies as a

\[ q(t) = (1 - \delta)\tau_{fr} \cdot v + 0 < \delta \ll 1 \]

where \( \tau_{fr} \) is the Coulomb friction \( \text{Fig. 2} \), \( \tau_{fr} \) is the shear yield stress of the material and \( \delta \) is the contact state variable, which denotes the extent of plastic deformation \( \text{sticking condition} \) at the weld interface. When \( \delta = 1 \), the shear yield stress at the friction surface is achieved whereas the friction surface is Coulombic when \( \delta = 0 \) \( \text{see Fig. 3} \).

During FW, the interface temperature rises rapidly and, consequently, the material is softened and the shear yield
stress at the faying surface is reduced. For the calculation of $q(t)$, as shown in Fig. 3, three stages may be defined according to the variation of shear yield stress and friction condition (sliding or sticking) with interface temperature.\textsuperscript{(18)} When the temperature is low, the heat generation is described by the Coulomb friction law (i.e. $\delta = 0$). At high temperatures, when the shear yield stress is low, the full plasticity condition is assumed and pure sticking condition (i.e. $\delta = 1$) is adapted. Beginning of full plasticity can be assumed at the temperature of 0.6 $T_m$ ($T_m$ is the melting temperature of the material in Kelvin), where the yield stress is low and, usually, dynamic recrystallization occurs.\textsuperscript{(18)} For the third situation at medium temperature range, which is the transition from Coulomb friction to full plasticity at the interface, the heat is generated by both Coulomb friction and plastic work at the rubbing surface (i.e. $0 < \delta < 1$). The transition temperature range is defined according to the variation of shear yield stress as a function of temperature (Fig. 3).

From the procedure explained above for the determination of $q(t)$, it can be seen that the criteria to describe different stages of heat generation and surface/material conditions is not straightforward. On the one hand, an appropriate Coulomb friction coefficient should be chosen, which, however, varies during the FW process and is not known. On the other hand, the transition from Coulomb (slip) friction to full plastic condition (stick) is fully dependent on the interface temperature as well as friction coefficient, which are also unknown. As a result, it is not straightforward to determine accurately the frictional heat generation term, because the required parameters shown in Fig. 2 and Fig. 3 are very dependent on the unknown surface temperature. Therefore, the predictive capability of the thermal model based on the friction theory and shear yield stress is very limited.

This dilemma can be overcome by an ‘inverse’ heat conduction (IHC) approach which is a convenient method for the analysis of heat generation at inaccessible locations such as friction surface.\textsuperscript{(16,18,19)} Therefore, due to the practical difficulty involved in the exact measurement of surface temperature or surface temperature gradient, the surface conditions can be estimated from temperature measurements made at some convenient positions inside the solid, see Fig. 4. Such a problem is termed as the ‘inverse’ problem of heat conduction, wherein the temperature history at an interior point is prescribed and the surface conditions are calculated from the solution of the transient heat conduction equation satisfying the prescribed interior conditions.\textsuperscript{(16,18,19)}

The boundary and initial conditions when solving Eq. (1) are:

$$-k \frac{\partial T}{\partial x} \bigg|_{x=0} = q(t) = 0, \quad \text{for} \ t > 0 \quad .................(4)$$

$$T(x, 0) = T_0, \quad \text{for} \ t = 0 \quad .................(5)$$

where $T_0$ is the initial temperature of the specimen. The objective is to calculate the surface heat flux, $q(t)$, based on the temperature measurements during the welding experiment at position ($x = x_0$), see Fig. 4. The inverse problem is solved by minimizing the objective function, $R$, which is the least squares norm defined as

$$R = \sum_{j=1}^{j} \sum_{i=1}^{I} (Y_{ij} - Y_{ij})^2 \quad .................(6)$$

where $Y_{ij}$ and $T_{ij}$ are the vectors containing the measured and predicted temperatures and the superscripts $i$ and $j$ indicate distance and time increments, respectively. The details of the inverse approach can be found elsewhere.\textsuperscript{(16,18,19)}

For the thermal modeling of FW, unlike the approach based on friction theory and shear work (i.e. Eq. (3), Fig. 2 and Fig. 3), the inverse heat conduction approach does not require as much information such as surface temperature, shear yield stress and friction coefficient. The main requirement for the inverse approach is the temperature data measured at a location near to the friction heated region.

3. Results and Discussion

The calculated heat generations at the friction interface using the two methods for an orbital friction welding of eutectoid steel bars are shown in Fig. 5. The welding conditions and the thermo-physical properties are given in Refs. 17, 18). For the Coulomb friction, a value of 0.2 is taken which provides the best possible agreement between computed and experimental temperatures. An appropriate temperature range for the transition condition defined in Ref. 18) is utilized. For the inverse analysis, experimentally measured axial shortening and temperature data are used. The calculated heat flux with friction theory shows a con-
stant heat generation value in the Coulomb friction zone. The heat generation increases to a peak value in the transition zone from Coulomb friction to the full plasticity condition. Due to the thermal softening and reduction of shear yield stress, the heat generation rate drops after the transition zone. The heat generation estimated with the IHC method increases continuously to a peak value and then decreases. The peak values of the two approaches are comparable, which supports the presumed transition zone from Coulomb friction to a full plasticity condition. The calculated heat input with \( \mu = 0.1 \), shown in Fig. 5, is given to evaluate the effect of a change in Coulomb friction value on the thermal analysis as follows.

A measure of how well the proposed models represent the actual heat generation rate can be deduced by comparing the predicted and measured temperature data. Therefore, for the two proposed models, the thermal profiles will now be compared. The computed temperature profiles at the position of \( x_0 = 2.5 \text{ mm} \) (the initial distance from the interface) are shown in Fig. 6 and compared to the actual data. The heat generation obtained from the IHC method predicts the temperature profile accurately, whereas prediction of friction theory is generally not promising (for \( \mu = 0.1 \) the result is worse). The disagreement between the friction model and experiment is expected, because it is based on a constant high heat input rate from the beginning of the process, which is not realistic. In fact, the heat generation rate in friction welding usually does not start from high values, which remains constant up or close to the end of the friction stage. However, friction theory model is fairly successful to represent the data at the end of the friction welding cycle.

The poor correlation between the temperature profiles predicted by the friction theory and the experimental data reveals that the friction coefficient varies significantly during the FW process and using a constant value would lead to inaccurate results. The proposed model based on the shear work could be improved by using variable Coulomb friction values. However, due to the influence of many factors including unknown interface temperature on frictional behavior and thus \( \mu \), it is virtually impossible to provide an appropriate function for the friction coefficient. The only way to propose proper values for the friction coefficient as a function of temperature or process time is the IHC analysis, because the inverse approach provides accurate heat generation values in the FW process. With the computed heat flux and resulting interface temperature profile, and using Eq. (2) with the assumption of uniform pressure distribution in the friction surface, the apparent friction coefficient can be calculated. The basis for the analysis of the friction coefficient is that with performing a number of FW experiments and using the IHC analysis, it would be possible to provide an interrelationship between the estimated coefficient of friction, welding parameters and temperature. This will eventually eliminate the need for performing a weld in order to provide input data for modeling and the predictive capability of the model would be increased. The two approaches (friction theory and inverse method) presented for the analysis of frictional heat generation are compared systematically in Table 1.

### 4. Summary

It is demonstrated that the heat generation is the key term in the analysis and thermal modeling of the FW process. The modeling of the heat generation is crucial and very important for the thermal, mechanical and metallurgical analyses of FW. In the past several decades, the FW community has been presented with many kinds models aimed at describing different aspects of FW. One of the most important aspects of FW modeling is to predict the effects of the FW process parameters on quality of the weld. Although the proposed approaches are helpful to understand the process in more detail, however, the question is whether they can be rapidly used to survey and predict the effect of process parameters in FW. The models are also hampered by the lack of availability of thermo-physical and especially thermo-mechanical data at the pertinent temperatures and strain rates required for accurate modeling.

The present IHC model is an improvement over thermal models, in the sense that it captures the exact temperature profile by providing accurate heat generation values. The model itself is simple, and more interesting is that the crucial data such as friction coefficient and shear yield stress as a function of temperature and other parameters are not required as input data for the model. Compared to the existing thermal models, the IHC model requires less input data and shows results with better accuracy. The model is, however, based on the measured temperature data. Thus, its predictive capability is limited to the experimental data. Nevertheless, the applicability of the proposed thermal model can be extended by performing a few FW experiments with different welding parameters and calculating the heat generation for each experiment. Eventually, a relationship between the welding parameters and the heat generation term can be established. This, in turn, can be used for further prediction
of the effect of the welding parameters on the joint quality.

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