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Mechanical analysis of ultrasonic welding considering knurl pattern of sonotrode tip

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ABSTRACT

Ultrasonic welding is attracting increasing attention in dissimilar material joining. The knurl pattern of sonotrode tip strongly affects the contact status and friction coefficient at the sonotrode/workpiece interface and thus plays a significant role on joint formation. Finite element models, with/without consideration of geometrical feature of sonotrode tip, were constructed to reveal the role of sonotrode geometry during ultrasonic welding process of copper to aluminum. The coupled thermal–mechanical fields and high-strain-rate deformation of metallic materials were incorporated in the models. The simulated results showed that the serrated knurl pattern of sonotrode tip greatly influenced the in-process variables (including stress, strain and displacement) at the contact surfaces of specimens. The localized concentration of plastic strain caused by the specific design of serrated tip knurl pattern, turned out to be the major cause for joint formation. Based on the evolution of average state variables in the bond area, ultrasonic welding process could be divided into three periods. Specimen deformation and material flow mainly occurred in the initial period of welding process. The simulated results were further verified by comparing specimen deformation and temperature evolution with experimental results.

1. Introduction

In the manufacturing process of battery electric vehicles (BEVs), a large number of battery cells are assembled to form a lithium-ion battery pack in order to meet the desired power and capacity. Copper and aluminum are commonly used in the fields of BEVs because of their high electrical and thermal conductivity [1]. Joining of Al–Cu is a critical issue in battery assembly. Traditional fusion welding technologies, such as laser welding and resistance spot welding are faced with great challenges in Al–Cu welding because of their remarkable differences in electrical and thermal properties [2]. As a solid state welding process, ultrasonic welding (USW) [3–6] can avoid the defects caused by fusion welding, such as brittle phases and porosities in the fusion zone [7–9]. Meanwhile, it can reduce the formation of intermetallic compounds (IMCs) between dissimilar materials [10]. Therefore, USW is considered as a potential joining technique for joining Al–Cu.

Ultrasonic welding is a rapid joining process during which high frequency ultrasonic energy is used to produce a solid-state bond between two pieces of metals [11–14]. A typical USW process is shown in Fig. 1. It consists of two main steps, clamping step and welding step. Specimens were placed between sonotrode and anvil. A certain force is applied by the sonotrode and the specimens get into intimate contact under the exertion of clamping force, as shown in Fig. 1(a). During the welding step, the sonotrode vibrates parallel to the contact area in ultrasonic frequency. Bond comes into formation at the faying interfaces of specimens. Micro bonds gradually initiate at the faying interfaces and ally together to form a sound joint, as illustrated in Fig. 1(b).

The bonding mechanism of USW has been studied by numerous researchers for more than 50 years. Nevertheless, the process is still not fully understood [15]. Researches have put forward various mechanisms for the joining process, for example, mechanical interlocking [16], interdiffusion and recrystallization [17], generation of heat by friction and plastic deformation [18] and even melting [19]. Among all the proposed theories, plastic deformation and structure deformation at the faying interface has generally been considered playing significant role for the joint formation process [20]. During ultrasonic welding process, workpieces make relative motion to each other at ultrasonic frequency. Under the combined effect of normal stress and vibratory shear stress caused by ultrasonic vibration of sonotrode, large areas of materials come into plastic deformation phase [21]. Experimental results [22–26] showed that localized frictional heating and plastic deformation at the contact area are critical factors for the initial formation of ultrasonic weld joints. A great deal of plastic deformation and material flow occurs across the faying interfaces of workpieces. Weld formation initially develops at specific regions under the tool, with plastic deformation highly localized at the interface between the two specimens. Therefore, USW can be concluded as a coupled thermal–mechanical

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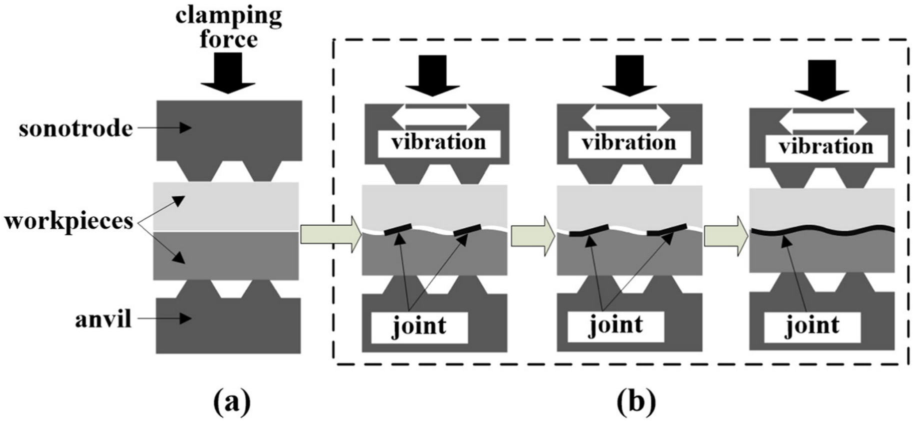

Fig. 1. An illustration of USW process: (a) clamping step and (b) welding step.

process, during which mechanical behavior of materials should be considered as a significant issue.

From the experimental work mentioned above, it can be found that the joint at the contact interface does not come into formation simultaneously and uniformly, but as a wavelike shape and in sequence because of the specific geometry of sonotrode tip. The sonotrode tip is not flat but with certain ridges that oriented with an angel to the vibration direction as can be seen in Fig. 1. The serrated geometry of sonotrode tip and transient nature of welding process leads to some special characteristics of ultrasonic welding, such as severe stress concentration and plastic deformation, instant temperature increase, complicated contact status and material interaction under high-frequency vibration of sonotrode [27]. Therefore, it's difficult to obtain the real-time data (plastic flow, complicated stress concentration and instant temperature increase) from experimental measurements so as to get comprehensive understanding of the coupled thermal–mechanical process [15]. On the other hand, the numerical simulation method, such as finite element method (FEM) can overcome these obstacles to some extent and has been employed by researchers in recent years.

The work by Siddiq and Ghassemieh [28] incorporated the materials' thermal and acoustic softening effects during ultrasonic welding process into finite element model particularly. They adopted the material property of combined isotropic-kinematic hardening model with extension for temperature dependence. The temperature and plastic deformation distribution at the interfaces could be obtained. Zhang and Li [15] constructed a dynamic thermal–mechanical coupled finite element model of ultrasonic welding of aluminum foils on aluminum substrate. Their model was a small part of the whole ultrasonic welding process, namely up to 50 cycles, a period of 2.5 ms. It correlated to Von-Mises plastic strain with the bonded area of ultrasonic joints. In-process variables, such as normal stress, shear stress, slide distance and plastic deformation on the contact interface were discussed to propose a possible mechanism for ultrasonic bond formation. De Vries [27] and Elangovan et al. [29] analytically computed the heat generation by friction and plastic deformation separately. The presented model was capable of predicting temperature and stress distribution and their influences on the workpieces, sonotrode and anvil. Gao and Doumanidis [30] and Doumanidis and Gao [31] characterized the interface friction conditions via a simple analytical model of elastic stress field, which was used to correct a full 2-D, quasi-static/dynamic, elasto-plastic numerical model. The calibrated model was capable of studying the material plastic deformation initiation and propagation, the slippage at the interface surface and the dynamic effects of ultrasonic loading on the bonding process. The relationship between propagation of plastic deformation and the bond development was constructed. Lee et al. [32] used the combined standard/explicit algorithm, incorporating with commercial software Abaqus to simulate ultrasonic dissimilar metal welding. They made a lot of assumptions by using the implicit algorithm to simulate the dynamic process for the goal of calculation time reduction. The verified procedure was capable of predicting welding energy and stress distribution of the workpieces.

Much work has been done by predecessors and some valuable conclusions have been obtained through finite element analysis of ultrasonic welding process. Most of the time, the purpose of the finite element analysis is to find out the average temperature distribution and plastic deformation at the contact interface. The specific geometry of sonotrode tip is ignored in consideration of calculation cost reduction and convergence of numerical analysis. Thus the plastic deformation and flow under the sonotrode tip, which are critical for the bonding process, cannot be predicted to some extent. In fact, the design of gripping surface of sonotrode tip has great influence on plastic deformation and heat generation of workpieces, so as to affect the performance of USW joint [27]. Therefore, there are some defects to understand the joint formation process by the mentioned numerical analysis.

In the present study, finite element (FE) models, with/without consideration of sonotrode geometry have been constructed to analyze the ultrasonic welding process of Cu to Al plates. Both models are three dimensional (3D) thermal–mechanical coupled. The evolution of in-process variables (stress, strain and deformation) are obtained and discussed in detail to find out the effect of sonotrode tip on the joint formation process. Specimen deformation and temperature evolution on the surface of specimens is compared with experimental results to validate the proposed model.

2. Finite element analysis model

2.1. Material properties

Johnson–Cook plasticity model is suitable for modeling high-strain-rate deformation of metals. This constitutive model has been applied by researchers in simulation of friction stir welding process [33–35]. USW has the same kind of material deformation characteristics as friction stir welding [36]. Both processes are over a wide range of strain, strain rate and temperature. The hardening rule of Johnson–Cook is a particular type of isotropic hardening where the effective stress, σ, is assumed to be of the following form

$$\sigma = \left[A + B\left(\bar{\varepsilon}^{pl}\right)^{n}\right]\left[1 + C\ln\left(1 + \dot{\varepsilon}_0\right)\right]\left(1 - \hat{\theta}^{m}\right) \tag{1}$$