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Modelling intermetallic phase growth during high-power ultrasonic welding of copper and aluminum

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ABSTRACT

An analytical model was developed to understand the rapid growth mechanism of intermetallic compounds (IMC) interlayer in high-power ultrasonic welding process. The analytic solution was derived for the relationships among welding time, interface temperature and vacancy concentration. The effectiveness of this model was tested by comparing the predicted thickness with the experimental value for high-power ultrasonic welding of copper and aluminium at various amplitudes. The consistency of the comparison demonstrates the accuracy of the model has been improved by considering the dynamic change process of vacancy concentration. Besides, the effects of vibration amplitude and resistance heat on the increasing of the intermetallic thickness have been investigated independently. The results show that the additional heat source could significantly promote the process of ultrasonic welding.

1. Introduction

Dissimilar metals joints have a great deal of potential applications in the automotive and electronics industries to achieve the goal of light weight and low cost [1]. Joints of aluminium alloys and copper are preferred in battery packs and electronics industry because of their high electrical and thermal conductivities. A major challenge in fusion welding of these dissimilar metals is the rapid development of the IMC layer. Ultrasonic welding (USW) may partially limit the increase of the intermetallic thickness due to the short bonding cycle and low heat input [2–4]. However, formation of the IMC layer at the faying surface is still inevitable in high power ultrasonic welding of dissimilar metal sheets, such as Cu–Al, Mg–Al and Fe–Al in automotive applications. It is well known that the IMC layer thickness is a key factor that affect the joint strength. A. Panteli suggested that the shear strength could reach the maximum as the IMC layer thickness was about 5 μm during USW of aluminium to magnesium [5]. Prangnell et al reported that a maximum strength could be achieved as the IMC layer thickness was about 1 μm during USW of aluminium to steel [6]. Liu et al pointed out that the Cu-Al joints could maintain mechanical strength if the IMC layer thickness was less than 1 μm in USW process [7]. Therefore, the proper IMC layer thickness is essential for obtaining a robust joint.

The IMC layer thickness at the welding interface during USW could be measured by a scanning electron microscope. In order to understand the growth law of the IMC interlayer, some researchers proposed models to estimate the intermetallic thickness. The predicted thickness was calculated with the parabolic growth model using the rate constants obtained under static test conditions. Significantly, these samples have been gently pre-welded with an ultrasonic welder before they suffer from the static heat treatments. A comparison between the experimental value and the predicted value have been conducted. A. Panteli showed that the reaction kinetics during ultrasonic welding of Mg and Al alloy were over twice than the rate obtained under static test conditions [5]. Farid Haddadi reported that the rate of interfacial reaction during ultrasonic welding of Fe and Al alloy was over 6 times greater than the rate observed in diffusion couple [8]. Liu showed that the growth rates of the intermetallic thickness during ultrasonic welding of Cu and Al alloy were still more than 14 times greater than the rate achieved from the static heat treatment condition [7]. Since the predicted models were built without considering the effects of lattice defects on the rapid growth of the intermetallic layers, their predicted thickness was significantly less than the measured value. Gunduz et al. [9] reported that the relationship between the diffusivity and vacancy concentrations during low-power ultrasonic welding of zinc foil and aluminium sheet. However, the growth of intermetallic compounds was not involved in his study. Besides, the vacancy concentration generated in USW was assumed as a static value.

As suggested above, the accurate mathematical model is still lacking

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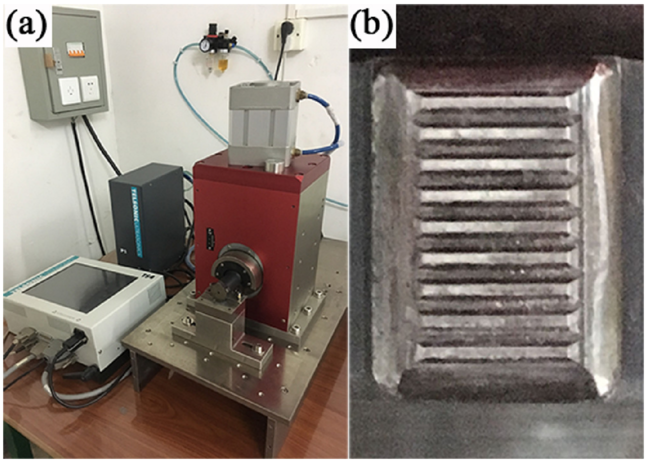

Fig. 1. (a) USW system used in this work and (b) knurl pattern of sonotrode.

for predicting the IMC layer thickness during high power USW. To accurately predicte the intermetallic thickness, the variation in the strain rate and the dynamic change process of vacancy concentration were considered in the study. The accuracy of the model were tested by comparing the predicted value with the measured IMC layer thickness during high power USW of copper and aluminium alloy. Furthermore, the effects of vibration amplitude and resistance heat on the increasing of the intermetallic thickness have been investigated independently.

2. Materials and methods

In this study, 0.8-mm-thick copper sheets and 0.8-mm-thick 5652 aluminium alloy sheets were lap-welded using a Telsonic M5000 system. The chemical composition of 5652 aluminium alloy is Al-2.02Mg-0.4(Si + Fe)-0.28Cr-0.04Mn-0.01Cu-0.01Zn(wt-%). The chemical composition of copper is 0.1O-0.01S-0.01As-0.01Pb(wt-%). The schematic of the system is shown in Fig. 1(a). The thickness growth of intermetallic compounds was controlled by adjusting welding time at a certain amplitude. Detailed experimental parameters are shown in Table 1. For all experiments, the copper samples were placed on the aluminium samples. The sheets were cut down to rectangular specimens of 25 mm width and 70 mm length. Additionally, the specimens were welded at the center of 25-mm overlapped area. The sonotrode has nine parallel ridges, as shown in Fig. 1(b). A K-type thermocouples of 0.25 mm diameter was used to measure the interface temperature at the weld center, as shown in Fig. 2. The hot end of thermocouple was first welded on the aluminium surface at the weld center by a resistance spot welder, and then the thermocouple wire was embedded along the machined groove between the copper and aluminium sheet. The temperature data were acquired with the sampling frequency of 100 kHz using the data acquisition system based on NI-6133. Interface temperature was measured repeatedly and the reliable results including the heating and cooling processes were retained. The welded samples were transversely sectioned across their center, parallel to the ultrasonic vibration direction. The intermetallic thickness was measured using a scanning electron microscope.

Table 1
Welding parameters.

Welding time T/s	Amplitude ξ_0/μm	Clamping force F/N	Frequency f/kHz
0.4-0.6	25	1975	20
0.6-1	22.5	1975	20
0.8-1.2	20	1975	20

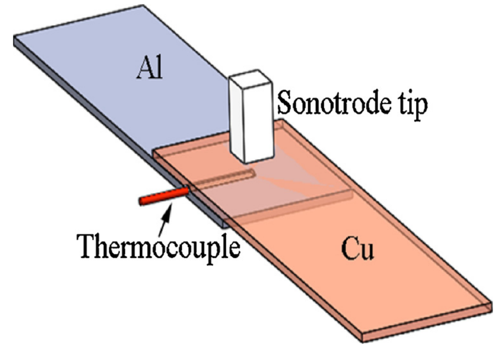

Fig. 2. A schematic for interface temperature measurement.

3. Analytical model

3.1. Hypothesis

In order to simplify the analytical model, the assumptions were made as follows:

(i) The material flow between the sonotrode and the anvil could be considered as a visco-plastic flow of an incompressible non-Newtonian material.
(ii) The plastic deformation is uniform under nine parallel ridges of the sonotrode. The temperature, stress and strain rate are symmetry about vertical section of the welding region center along the direction of ultrasonic vibration.
(iii) The vibration amplitude and clamping pressure are constant in USW process. The ultrasonic energy transmit from the ridge of sonotrode to welding interface in uniform manner.
(iv) The welded region between the sonotrode and welding interface is divided into two parts, as shown in Fig. 3. The thin compressible layer between nine parallel ridges and the welding interface is the plastic flow region. The plastic deformed region is distributed between parallel ridges, in which the deformation of the material occur, but does not flow along the direction of the ultrasonic vibration.
(v) Gunduz et al. [9] proposed that the diffusion in ultrasonic welding is dominated by the vacancy mechanism. It is assumed that the diffusion enhancement is solely due to the generation of excess vacancies.

3.2. Strain rate at the welding interface

The geometry of the welding samples is shown in Fig. 3. USW process could be simplified as a one-dimensional model to calculate the strain rate based on the uniformity and the symmetry stated by the first and second hypotheses. In the model coordinate, x axis is the normal direction of welding region and z axis is parallel to the ultrasonic vibration direction. The welding interface, the flow-deform interface and the convex surface of the welded materials respectively lie at x = 0, x = B and x = H for a certain moment, as shown in Fig. 4.

The continuity equation and momentum conservation equations for the visco-plastic flow of single-phase incompressible can be described as [10]

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\frac{\partial(u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}(\mu\frac{\partial u_j}{\partial x_i} + \mu\frac{\partial u_i}{\partial x_j}) - \rho\nu\frac{\partial u_j}{\partial x_1} \tag{2}$$

Where u is the velocity of plastic flow, the index notation for i, j = 1, 2 or 3 ($i \neq j$), representing the x, y and z directions in Fig. 4. ρ is the density, μ is the viscosity, and p is the pressure. During ultrasonic