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Energy and bond strength development during ultrasonic consolidation

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ABSTRACT

A process model was developed that couples the effects of the three adjustable ultrasonic consolidation (UC) process parameters (amplitude, force and speed) into a single term – thermal weld energy due to frictional and volumetric heat generation. Infrared thermography was used to evaluate weld energy during UC and a relationship was established between weld energy and the peel strength of ultrasonically consolidated aluminum. An optimum processing widow was identified for bonding Al 1100-0 and Al 3003-H14 based on UC processing temperature and weld time. Bonding occurred well below the material melting temperatures, confirming that thermal softening in the bulk of the material or melting are not the bonding mechanisms and that bonding takes place in the solid-state.

1. Introduction

Ultrasonic consolidation (UC) is a low temperature solid state bonding process which can bond multiple metal foils or a foil to a substrate under the influence of pressure and ultrasonic vibrations. Bond quality is controlled through three adjustable process parameters (Fig. 1): sonotrode clamping force (F_c), sonotrode oscillation amplitude (λ) at a given frequency (f), and sonotrode speed (S). The material type and geometric parameters (e.g. foil thickness, width and surface roughness) also influence the bond properties.

UC bonding mechanisms should be separated into two categories as suggested by Kong et al. (2005): (i) volumetric bonding effects and (ii) surface bonding effects. Volumetric bonding effects include elastic and plastic deformation enhanced through reduced yield stress due to acoustic and thermal softening. Bakavos and Prangnell (2010) investigated the bond interface of UC welds through microscopy and proved that significant amounts of plastic deformation occur during the UC process. Yang et al. (2009) investigated the microstructure of UC bonds using a scanning electron microscope and concluded that volume effects are important in flattening out rough surfaces and bringing the base metal into intimate contact. Kelly et al. (2013) have shown that plastic deformation in aluminum bonded with UC is significantly increased due to acoustic softening and to a lesser extent by bulk thermal softening. This increased plastic deformation facilitates the onset of bonding by bringing additional material into intimate contact.

Surface bonding effects include interfacial friction and shearing that break up the oxide layers and bring more metal from both surfaces into intimate contact. Using a scanning electron microscope, Bakavos and Prangnell (2010) identified evidence of oxide "flakes" near the bond interface that were dispersed during UC processing. Fujii et al. (2011) investigated the bulk and interface microstructures of ultrasonic welds through an electron backscattered technique and found a significant microstructural change near the bond interface. Mueller et al. (2013) used a scanning electron microscope and X-ray energy dispersive spectroscopy to develop a method to estimate the interdiffusion coefficient of copper–aluminum UC bonds as a function of accelerating voltage and apparent diffusion distance. de Vries (2004) used a force sensor to measure the interface forces during UC and found that the coefficient of friction and shear force at the bond interface play an important role in bond formation. Yang et al. (2009) concluded that surface effects as well as volume effects are important to UC bonding: plastic deformation and progressive shearing facilitate bonding through the dispersal of surface contaminants and oxides and allow for intimate contact between the pure metal of each part. Zhang and Li (2008) used a thermo-mechanical FEA to investigate temperature distribution and shear stresses during UC.

A thermocouple or infrared (IR) camera are used to measure UC processing temperatures. Yang et al. (2009) and Sriraman et al. (2011) have measured UC temperatures by sandwiching a

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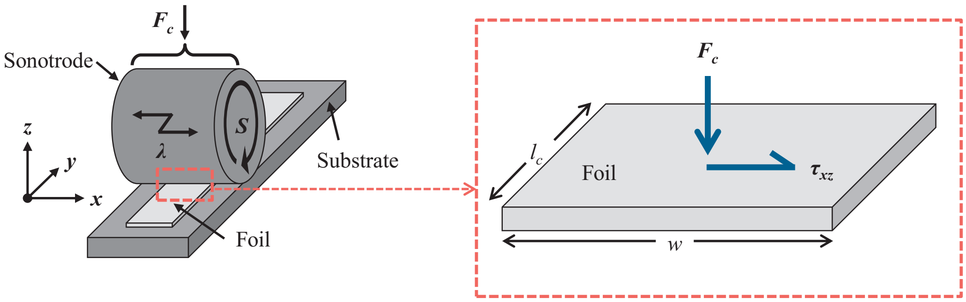

Fig. 1. Diagram of ultrasonic consolidation and forces acting on the foil.

thermocouple between two layers of foil. Thermocouple measurements during UC have two disadvantages when compared to IR camera measurements: (i) the thermocouple is between the two foil layers and can interfere with bonding and (ii) thermal measurements can only be taken at one location per thermocouple. de Vries (2004) showed that an IR camera is a useful method to measure UC temperatures because the entire transient temperature distribution can be easily measured. Koellhoffer et al. (2011) used an IR camera to record UC temperatures and calculated friction at the bond interface using thermal FEA.

Previous studies on UC bond quality can be broken into two categories: (i) microscopy to identify bonded area and (ii) mechanical bond strength measurements. Kong et al. (2005) used "linear weld density" (LWD) to evaluate the percent of the foil width that is bonded during UC. LWD was defined as the percentage of contact points across the width of the foil that show evidence of diffusion. Friel et al. (2010) found that linear weld density generally increased with increasing amplitude and force. Obielodan et al. (2010) used optical microscopy to identify gaps between adjacently bonded foils and optimized the foil spacing during processing to minimize these defects.

Several methods have previously been used to test the strength of UC bonds. Obielodan et al. (2011) used lap-shear to test the strength of aluminum–titanium UC bonds. A drawback in using a lap-shear test to evaluate the strength of UC bonds is that tensile failure happens in the base material before failure at the bond interface unless the bond is very weak. Zhang et al. (2009) developed a "push-pin" test to measure the strength of UC bonds and also found that strength increases with increasing amplitude and deceasing speed. Kong et al. (2005) used a floating roller peel test to evaluate the strength of UC bonds. Friel et al. (2010) also used a peel test to evaluate UC bonds and relate the peel strength to the LWD. Peel testing is useful in investigating the change in bond quality throughout the length of a UC seam weld.

During UC, weak bonds are created with relatively low values of UC process parameters because there is insufficient energy for bonding to occur. High UC process parameters can also result in poor bond quality due to excessive damage to the parts as bonds are formed and subsequently broken. A window of optimum UC process parameters was identified by Kong et al. (2003) for Al 6061 through peel testing. A similar study was also done by Kong et al. (2004) for Al 3003. Janaki Ram et al. (2006) investigated the effect of UC process parameters on linear weld density (LWD) and found that the highest quality bonds generally occur at high λ, high F_c and low S. Hopkins et al. (2012) tested the lap-shear and transverse tensile strength of UC bonds and confirmed that bond strength follows the same trends in LWD found by Janaki Ram et al. (2006). Despite the fact that trends between individual UC process parameters and bond strength have been established, there is a lack of literature on a comprehensive method to relate λ, F_c and S to bond strength for a given material.

Due to the complex relationship between the UC process parameters and bond quality, several previous researchers have suggested relating energy to UC bond strength. Bakavos and Prangnell (2010) investigated the relationship between electrical energy and tensile shear strength using an ultrasonic spot welder and found that strength increases as energy increases; however, this work assumes that all electrical energy is converted to mechanical vibrations at the bond interface. As discussed by de Vries (2004), electrical energy input into the UC system is the upper limit of energy available for bonding as there will be system losses and suggested that measurements taken at the bond interface would be a better indicator. A method to calculate weld energy based on IR camera thermal measurements is presented and the relationship between weld energy and bond strength is investigated in this work.

2. Model development

Ultrasonic vibrations during UC are responsible for heat generation and for stick-slip motion at the bond interface. The temperature increase during UC reflects the total thermal weld energy (E) due to friction heat generation (E_{fr}) and volumetric heat generation (E_v) due to plastic deformation.

$$E = E_{fr} + E_v \tag{1}$$

E is an indirect indication of shear stress and acoustic softening in the material. At low levels of shear stress, displacement across the foil thickness is near zero and there is maximum displacement for frictional heating. At high levels of shear stress, friction and volumetric heating occur along with increased strain energy and acoustic softening in the material. E is developed during the weld time (t_w): time that the sonotrode is in contact with a given area of the foil. t_w is related l_c and S according to Eq. (2).

$$t_w = \frac{l_c}{S} \tag{2}$$

Throughout t_w the mechanics of the process transition from frictional sliding motion before bonding to stick-type motion after bonding. Frictional heat generation (q_{fr}) is related to the shear stress (τ_{xz}) due to sonotrode oscillations, the average speed of the foil–substrate interface during a given oscillation (s_{fr}) and the contact area (A_c) between the foil and the substrate according to Eq. (3).

$$q_{fr}(t) = A_c \tau_{xz}(t) s_{fr}(t) \tag{3}$$

τ_{xz} and s_{fr} vary throughout t_w as the process transitions from slip to stick dominated motion. A_c is equal to the product of the foil width (w) and the contact length (l_c) between the sonotrode and the foil in the y-direction (shown in Fig. 1) according to Eq. (4).

$$A_c = w l_c \tag{4}$$