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Process robustness of single lap ultrasonic welding of thin, dissimilar materials

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ABSTRACT

Fusion welding processes, such as resistance welding and laser welding, face difficulties in welding thin layers of dissimilar materials. Ultrasonic welding overcomes many of these difficulties by using high frequency vibration and pressure to input energy into the affected area to create a solid state weld. This paper presents a process robustness study of ultrasonic welding of thin metal sheets. Quality of the welded joints is evaluated based on mechanical tests and the quality criterion is then applied to evaluate the weldability. These results were used to determine both the optimal weld parameters and the robust operating range.

1. Introduction

Conductive materials such as copper, aluminium, and nickel are widely used in the electronics industry. In recent years, those materials have also been adopted as electrodes, current collectors, and bus bars in manufacturing automotive lithium-ion batteries. Battery joints need large weld areas and excellent joint strength to support high power applications. Due to the high conductivity of aluminium, copper and nickel, resistance welding techniques cannot be applied effectively to joining such materials. Joining of these materials is faced several additional challenges: dissimilar material properties, multilayer sheet joints, and varying material thickness combinations [1]. To overcome those obstacles using conventional welding methods, higher energy and shorter welding time with more precise control are required. Govekar et al. [2] proposed a new droplet joining method based on laser welding for thin and dissimilar materials. Other techniques, such as duo-thermal soldering process [3], high-energy droplet deposition technique [4], and control of melting ratio of dissimilar metals in laser welding [5], were also proposed to deal with these challenges.

Ultrasonic welding is an alternative method that can be applied for battery joining. Even though it has been commonly applied to joining plastics, the mechanism of the ultrasonic welding for metal joining is different from that of welding plastics and is less understood. Several researches showed different mechanisms [6]: (a) localized melting or heating arising from friction, elastic hysteresis and plastic deformation [7,8], (b) mechanical interlocking [9], (c) interfacial nascent bonding [9–11], and (d) chemical bond involving diffusion [12]. Nevertheless, the principle of ultrasonic metal joining is not yet fully established. Fundamental studies about the process mechanisms and researches on the definition of weld quality, optimization of input parameters, and robust process design are necessary for successful application of the ultrasonic metal welding. Zhou et al. [13] analyzed the interfacial and circumferential failures at the ultrasonic spot weld and showed cohesive-zone analyses for joint fracture. Kong et al. [14] developed a theoretical weld strength model in ultrasonic consolidation process. Elangovan et al. [15] optimized welding input parameters to maximize tensile shear strength. Even though several studies have been conducted on the quality of the ultrasonic metal welds, there exists a lack of quality guidelines for implementing the ultrasonic metal welding in volume production. Moreover, to optimize input parameters and identify the robust process window, the sensitivity of weld quality to these parameters must be established. Process robustness studies have been carried out for resistance welding of steels and aluminium [16,17], but such studies do not exist for ultrasonic metal welding. Therefore, this paper aims to classify the weld quality in ultrasonic metal spot welding using information obtained through maximum loads and failure types in T-peel tests.

To establish the weld quality and process robustness range, this paper presents an experimental study for ultrasonic welding of copper and nickel plated copper sheets. Welding pressure and welding time are selected as the variables in a full factorial experiment. The T-peel test is used to extract a maximum load and define the failure mode. With both failure modes and the maximum load after T-peel test, the weld quality classification results in five distinctive classes. The estimated response surface of the maximum peel load based on experimental data explains weld quality distribution and sensitivity of the response. Finally, a weldability lobe is identified for the first time for ultrasonic welding of copper and nickel plated copper sheets.

2. Ultrasonic metal welding

Ultrasonic metal welding is a process in which a high frequency ultrasonic energy, usually 20 kHz or above, is used to produce oscillating shears to create solid-state bonds between two sheets clamped under pressure as shown in Fig. 1. Unlike the ultrasonic plastics welding, the direction of the ultrasonic oscillation in metal welding is parallel to the weld contact area. Compared to

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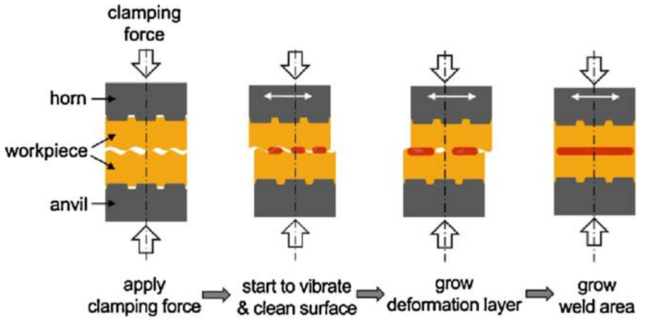

Fig. 1. An illustration of ultrasonic welding process.

traditional fusion welding processes, ultrasonic welding has several inherent advantages derived from its solid-state process characteristics. The main advantage is that it works for dissimilar, conductive materials such copper and aluminium. Other advantages include absence of liquid–solid transformations which results in clean welds, low energy consumption, no atmosphere control required, environmentally friendliness and very fast process.

A typical ultrasonic metal welding system consists of five subsystems: (1) a controller, (2) an ultrasonic transducer (or converter), (3) a booster, (4) a pneumatic cylinder, (5) a horn (or sonotrode) and an anvil. During welding, a clamping force is applied to the workpieces; the high frequency of electrical energy is converted into the mechanical energy by the transducer; ultrasound waves are transmitted to the horn; the lateral forces at high frequency break down contamination to expose bare metals area between sheets interfaces; metals are heated by the ultrasonic energy and material deformation; the bond area is increased at elevated temperature [1].

3. Experiment

3.1. Experimental design

A 0.2 mm thick copper sheet and a 0.2 mm thick nickel plated copper sheet were welded. The thickness of the nickel coating layer on the copper sheets is about 3 μm. The sheet dimension is 45 mm in length and 25 mm in width. As shown in Fig. 2, the copper sheet is placed on top of the nickel plated copper sheet.

Based on the screening tests conducted prior to this study, welding pressure and welding time were selected as the design variables. The output variable selected to represent weld quality is the maximum load obtained through the T-peel test, described in Section 3.2. The experimental design to investigate various types of weld quality requires wide input variable ranges. In case of welding pressure, the welding machine can generate pressure ranged from 10 to 80 psi. Table 1 lists all input factors and their levels. Welding pressure was varied between 10 and 70 psi at 15 psi intervals and five levels of welding time were chosen from 0.2 to 0.8 s with increments of 0.15 s. The experiment was conducted using a full factorial design and the number of experimental conditions was 25 with 10 replicates for each test condition. A total of 250 samples were prepared for the T-peel test.

3.2. T-peel test

To evaluate weld quality, the T-peel method as shown in Fig. 3 is used. After welding, sheets on the weld specimen were bent 90° in two directions to allow the specimen to be clamped. A load is then applied to peel the weld sample with a speed of 10 mm/min.

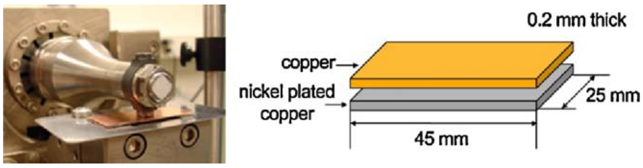

Fig. 2. Welding machine and specimen size.

Table 1
Factors and levels for experimental design.

Factor	Factor name	Levels
P	Welding pressure (psi)	10, 25, 40, 55, 70
T	Welding time (s)	0.2, 0.35, 0.5, 0.65, 0.8

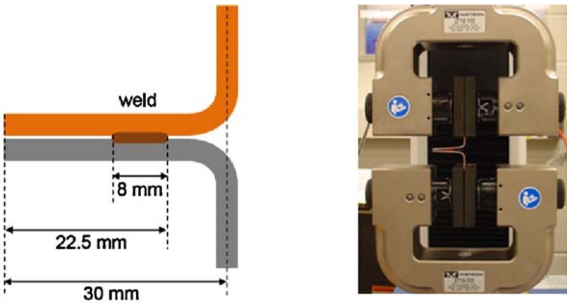

Fig. 3. T-peel test configuration and tester machine.

Fig. 4 represents the failure modes and load–displacement graphs at two different welding conditions and explains the relationship between the failure mode and the load–displacement history. Fig. 4(a) represents a good weld condition where the load–displacement curve first reaches the peak, and then levels off to plateau before the two pieces were completely separated. This indicates that a strong bond between the sheets results in a higher load than what the base material, copper, can carry. Fig. 4(b) represents an over weld condition where no such plateau was observed because cracks were developed around the weld and the material tore along with the crack. Hence, the maximum T-peel load from the load–displacement curve and the failure mode can be used to form the ultrasonic weld quality criterion.

4. Results

4.1. Weld quality classification

Even though the maximum peel loads are a good indicator to define good and bad welds, it does not classify the type of faulty welds such as cold and over (cracked) welds. Therefore, the failure modes are needed to help the weld quality classification. Five distinctive quality classes are defined in Table 2 based on the failure modes and load–displacement curves. Classes I and II are interfacial separation within a weld according to failure images, which has no crack around the weld. The amount of remaining bonds differentiates these classes in terms of peel load based on the load–displacement curve. Class III shows large areas of material bonding, having more than 50% remaining after peel. Class IV is similar to class III, but tear begins at the weld boundary resulting in lower peel load since excessive energy transfer creates stronger bonding, but cracks have initiated around the weld. Class V represents full button fracture due to cracks all around the weld.

Using the defined weld quality classification, weldability criterion can be designed. For instance, only class III can be considered as good weld when the process requires the strict quality criterion. Class I and II are considered the cold welds and classes IV and V represent the over weld, all bad qualities. Fig. 5 shows the weldability lobe under the strict quality criterion using data from this study where zones of parameters for good weld quality are identified.

4.2. Response surface for the maximum peel load

Response surface is a technique to visualize the relationship between input variables and output responses. The response