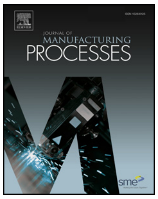
Journal of Manufacturing Processes 35 (2018) 580–594

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro



Ultrasonic spot welding of aluminum alloys: A review

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ARTICLE INFO

Keywords:
Ultrasonic spot welding
Aluminum alloy
Mechanical properties
Macrostructure and microstructure
Weld interface

ABSTRACT

As a solid joining technique, ultrasonic spot welding is a promising spot welding process to fabricate the aluminum alloy joints. This paper summarizes the current state of joining aluminum alloy by ultrasonic spot welding with numerous critical issues, such as general process parameters, materials flow, interfacial temperature, interfacial shear force, stress distribution, relative motion, strengthening mechanism, macrostructure, microstructure and mechanical properties. Meanwhile future trends in the field are pointed out.

1. Introduction

Aluminum (Al) alloys have been widely used in the domains of power devices modules packing, electronic technologies, automobile body structure and wind and solar power controlling, due to their advantages of high specific strength, superior processability, predominant anti-erosion, high conductivity, environmental friendly character and recoverability [1–4]. Unfortunately, fusion welding processes employed in aluminum alloys are conductive to the generation of hot cracking, high levels of welding distortion and the poor weldability [5–8]. Resistance spot welding is difficult to join aluminum alloys due to their high conductivity, low strength at elevated temperature and tendency to degrade the electrodes [9]. Friction stir spot welding has disadvantage of long weld cycle (e. g. 2–5 s) [10,11]. However, ultrasonic spot welding (USW) has advantages of pollution-free, high efficiency, short weld time (typically < 0.5 s), insensitivity to material conductivity and heterogeneity [12,13], which is a promising spot welding process to fabricate the aluminum alloy joints.

There are numerous studies about aluminum alloy fabricated by USW. However, to the best of the authors' knowledge, no review papers about USWed aluminum alloy joints exist. This paper reviews the USW process, macrostructure, microstructure, parameter optimization and mechanical properties of aluminum alloy joints, and then future trends and conclusions are given. The aim of this paper is offer a good basis for follow-on study.

2. USW process

Since the 1950s USW, a solid phase joining technique, was first introduced for thin foils joining, wire bonding and tube sealing [14]. Due to the advancements in the welding system technology [15], it is feasibly used to join thicker metal sheets, but generally the thickness of sheet is less than 3.0 mm. Because when the thickness of metal sheet is over 3 mm, the heat generation and relative motion at the weld interface is poor. Thus increasing the power of USW machine is urgent in the future. USW utilizes high shear frequency mechanical vibration to generate a friction-like shear relative motion between two faces of the sheets, resulting in plastic deformation and shearing of surface micro-asperities that transmit contaminants and oxides, to promote the generation of effective metal-to-metal contact areas and joining at the faying surfaces. Therefore, a solid state joint is achieved. In general, only the lapped joint can be successfully achieved by USW. Schematic of illustration of USW is shown in Fig. 1.

2.1. General process parameters

Macrostructure, microstructure evolution and mechanical properties of the USWed joint are mainly determined by the employed process parameters. The process parameters during USW involve ultrasonic frequency, vibration amplitude, clamping force, power (P) and energy (U) or time (t). Ultrasonic frequency, generated by transducer that is designed to operate at a specific frequency, is 20, 30 or 40 kHz in the metal welding machine. In fact, welding frequency is determined by a basic metallurgical physics characteristic as welding power requirements, which is determined by the component dimensions and materials of base metal, and the overall design of transducers and coupling components. Vibration amplitude of the sonotrode tip is a critical parameter affecting the joint quality, which can transmit mechanical

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https://doi.org/10.1016/j.jmapro.2018.09.009
Received 4 July 2018; Received in revised form 24 August 2018; Accepted 7 September 2018

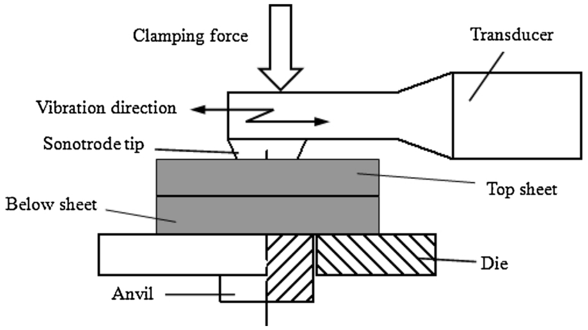

Fig. 1. Schematic of illustration of USW.

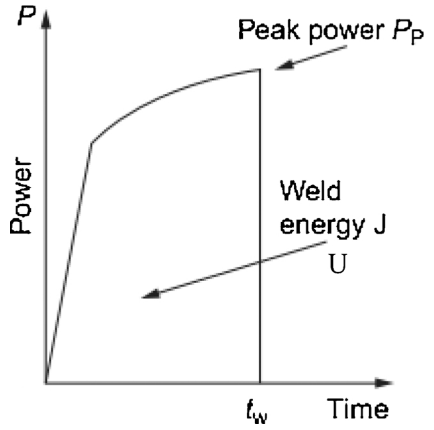

Fig. 2. Relationship among peak power, weld energy and weld time [16].

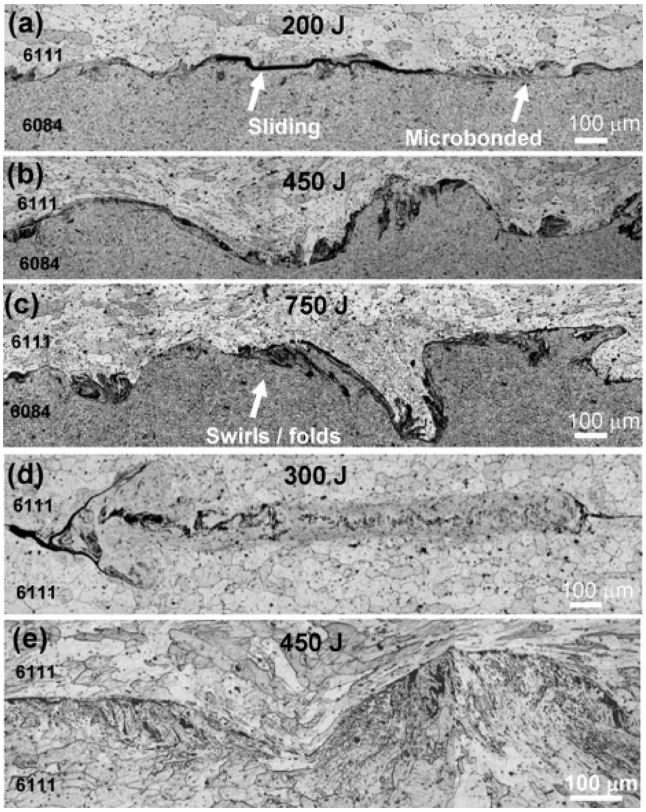

Fig. 3. SEM of weld cross-sections for the USWed joint [12].

energy to the weld interface. It is noted that vibration amplitude is generally in the range of 10–100 μm. In some welding machine, vibration amplitude is a dependent variable that has a relationship with the welding time or energy applied to the machine. In other machines, vibration amplitude is an independent variable; impedance is being set up and regulated by the supply of power due to the added characteristics of the feedback control system. The selection of welding vibration amplitude hinges on the welding conditions as determined by materials. Clamping force is a crucial parameter during USW, which is exerted on the metal sheets by the anvil and sonotrode tip, thus the metal sheets being welded can be pressed firmly together. The selection of clamping force depends on the materials being welded. The optimum clamping force can be achieved by adjusting welding parameters, below which joints will be weak to nonexistent, and above which the phenomena of welding zone thinning and sonotrode sticking may take place. It is noted that USW machine can be set up to operate in time or energy control mode, thus energy and time are approximately interchangeable; i.e. as $U = P \times t$. For instance, 1 kJ at 4 kW is equal to 0.25 s. Fig. 2 shows the relationship among peak power, weld energy and weld time. The area under the power curve is weld energy. It can be seen that power, energy and time are not independent. Once the power is set, as the weld process progresses, the given level of power can be reached, meanwhile weld energy and time will reach a specific value. Or, time can be set, and the weld will progress until such energy as the given level is obtained. In fact, the power-time curve can present various forms that are dependent on material categories, dimensions, surface conditions, welding parameters (amplitude and clamping force), tooling, and specific characteristic of a fixed welding machine.

2.2. Materials flow

Once the welding parameters are optimized, underlying material flow under the combined action of the sonotrode tip and anvil throughout the weld interface occurs, leading to a wave-like displacement at the weld interface combined with complex plastic deformation that has been demonstrated as the formation of wave characteristics near the weld interface. The wave characteristics contain vortices, ripples, and spiral like patterns, as shown in Fig. 3. In addition, Jahn et al. [17], Allameh et al. [18] and Haddadi et al. [19] also gave the detailed descriptions about wave characteristics for understanding the material flow. It is noted that when the base metal sheets are similar or have few differences, the wave characteristics can occur. If the base metal sheets have big differences in melt point, yield strength and hardness, the wave characteristics can not be presented, thus the material flow will be not obvious, as reported in the previous studies [8,20–27]. Material flow is extremely complex. Not only welding parameters play a key part, material types and dimensions bring about another challenge in governing the migration of the materials at the weld interface.

2.3. Interfacial temperature

Temperature of weld interface is a key factor to the weld formation. Because appropriate weld interface temperature is conductive to improve the weldability via lowering the material yield strength and controlling the intermetallic compounds [4,28]. During USW, the heat generation, leading to the increase of weld interface temperature, are achieved from plastic deformation heating, frictional heating at the weld interface and possible acoustic heating from the ultrasonic wave [29,30]. The frictional heat generation is due to the large vibration amplitude between the faying interfaces. The vibration frequency is set at 20 kHz by the spot welder, increasing amplitude leads to the increase of velocity, which can have a positive effect on the decrease of yield strength of Al alloy sheet, the local Al alloy sheets become softer, and then severe plastic deformations take place under the action of shear force and clamping pressure. In addition, as the welding process progresses, the yield strength of the Al alloy is continuously lowered due to