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Mechanisms of joint and microstructure formation in high power ultrasonic spot welding 6111 aluminium automotive sheet

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ABSTRACT

Resistance spot welding (RSW) is difficult to apply to aluminium automotive alloys. High power ultrasonic spot welding (HP-USW) is a new alternative method which is extremely efficient, using ~2% of the energy of RSW. However, to date there have been few studies of the mechanisms of bond formation and the material interactions that take place with this process. Here, we report on a detailed investigation where we have used X-ray tomography, high resolution SEM, and EBSD, and dissimilar alloy welds, to track the interface position and characterise the stages of weld formation, and microstructure evolution, as a function of welding energy. Under optimum conditions high quality welds are produced, showing few defects. Welding proceeds by the development and spread of microwelds, until extensive plastic deformation occurs within the weld zone, where the temperature reaches ~380 °C. The origin of the weld interface 'flow features' characteristic of HP-USW are discussed.

1. Introduction

The pressures of climate change are driving the automotive industry towards more fuel efficient products and lower energy consumption manufacturing processes. In the future this will require the greater use of lightweight body structures fabricated from aluminium and magnesium alloys, as well as multi-material designs [1]. This 'road map' for the industry has highlighted the need for more efficient joining methods. Because it is a cheap and robust process, steel car bodies are conventionally joined by electrical resistance spot welding (RSW). Unfortunately, RSW is difficult and expensive to apply to aluminium alloys, owing to their high conductivity, low strength at temperature, and tendency to degrade the electrodes [2,3]. Of particular concern is the high energy cost of resistance spot welding aluminium (see Table 1) with 50–100 kJ required per weld [4,5]. Alternative solutions are self-piercing rivets, clinching, friction stir spot welding (FSSW), adhesive bonding, laser welding and GTAW, or GMAW [6–8]. However, fusion processes are limited by the poor weldability and high levels of distortion that are characteristic of aluminium alloys [6]; further, riveting and bonding have additional consumable and surface treatment costs, respectively [7]. FSSW is an interesting more efficient (~3–6 kJ per weld) solid-state process which shows considerable potential for joining aluminium and dissimilar materials [8–11]. Under optimum conditions the joint's mechanical performance are comparable to RSW, but the weld cycle can be quite long (e.g. 2–5 s [7–10,12,13]).

A further spot joining process that has received less attention is ultrasonic welding (USW) [4,5,14–17]. Although ultrasonic welding has been used since the 1950s to join thin foils [18], it has only comparatively recently become economic to apply this technique to thicker gauges, due to the wider availability of higher power systems. USW is an attractive point joining technique for light alloys, as it is far more efficient than RSW, using only 0.6–1.5 kJ per weld. It is also more efficient than FSSW, because the energy is predominantly generated at the weld-line [19,20] rather than at the top surface [8,9]. Furthermore, USW has the same advantages as FSSW, in that it is a solid-state friction joining process, but has a shorter weld cycle (typically<0.5 s), and has been reported to form joints with good mechanical performance and no HAZ damage [4,14,15]. Recently the Ford Motor Company have investigated the feasibility of applying ultrasonic welding (USW) to spot welding aluminium body structures with promising results [4,5,17].

An ultrasonic metal spot welder typically consists of five main elements (Fig. 1): (i) The power supply, which provides electrical energy at a high frequency (typically 20 kHz), (ii) a piezoelectric transducer, which converts electrical energy into linear mechanical vibrations of the same frequency, (iii) a wedge that amplifies the mechanical amplitude, (iv) a reed, which transmits vibratory

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Table 1
Comparison of the approximate energy requirements and weld cycle times for different spot joining processes in 1 mm aluminium sheet.

Process	Energy per weld (kJ)	Weld time (s)
RSW	50–100	0.15–0.3
FSSW	3–6	1–5
USW	0.6–1.5	0.25–0.6

energy to the work piece and, finally, (v) a pneumatic cylinder, that provides a clamping pressure during welding. The operating power of sheet metal spot welders, under consideration for automotive applications, is of the order of 2–3 kW [4]. In a dual reed welder two sonotrode tips couple with both outside surfaces of the lapped sheets, and oscillate out of phase, which introduces a small (~20–40 μm [21]) high frequency linear displacement across the weld interface under a normal load resulting from the clamping force.

While much research has been carried out on ultrasonic welding of thin foils and wires within the electronics industry (e.g. [18,21–24]), there has been surprisingly few in depth investigations into the weld evolution and material interactions with this technique. Most research on conventional low energy USW assumes bonding occurs at relatively low temperatures ($<300\,^{\circ}$C) and is dominated by contact mechanics, with any deformation highly localised to the weld faying surfaces [18,21,24–26]. It is thought that sliding across the interface breaks the oxide between the two surfaces at contacting asperities resulting in adhesion, forming microwelds, which then increase in density and spread over the area affected by the vibration of the sonotroded tips. The weld strength is thus primarily related to the effective net area of microbonds [26]. Heat is generated initially from sliding friction, and the anelastic response of the material, but as galling and microbonds form the majority of energy is dissipated by plastic deformation [19,24–27].

With the exception of the notable work of Jahn et al. [4,5,17] and a few other authors [16,28] there has been even less research published on the weld formation and microstructure evolution during the application of high power USW (HP-USW) systems to spot welding the thicker sheet material of interest to the automotive industry. However, it is clear that in this case extensive plastic deformation occurs within the weld zone, that is not just localised at the interface, and the process of weld formation is difficult to interpret [5,16,17]. In HP-USW the welding process results in the displacement of the join-line in a complex wave-like pattern [5,16]. A range of 'flow' or 'wake' features have been noted [5,16], including vortices, or swirls and spirals, as well as bifurcation of the join-line, but the origin of these effects is poorly understood. Further, the welds have been reported to contain defects including, retained oxide, porosity, and micro-cracks [5]. Heterogeneous deformation structures, commensurate with severe deformation and containing ultrafine grains and high dislocation densities, have also been observed at the weld-line [16,17], but no evidence of a heat affected zone has been reported.

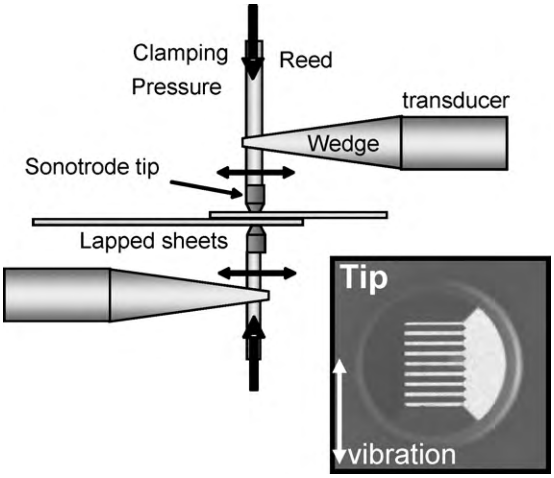

Fig. 1. Schematic diagram of the dual-reed ultrasonic welding machine, with an image of the 8 mm × 6 mm sonotrode tip used as an insert.

The overall objective of the work, that will be discussed here, was to improve our current understanding of the mechanisms of weld formation, when HP-USW is applied to aluminium automotive sheet and the material interactions that occur in the process. To this end, we report on the results of a detailed investigation, where we have studied the material flow using dissimilar alloy combinations, combined with, X-ray tomography, and high resolution FEG–SEM and EBSD, to characterise the weld defects, stages of weld formation, and microstructure evolution, as a function of welding energy, focusing on a standard automotive material AA6111-T4 in 0.92 mm thick sheet.

2. Experimental

All the data presented is for welds produced in 0.92 mm thick, 6111-T4, aluminium sheet supplied by Novelis, with no cleaning or surface preparation prior to joining. The HP-USW system employed was a dual wedge-reed 2.5 kW, Sonobond-MH2016 machine, operating at 20.5 kHz. The flat 8 mm × 6 mm sonotrode tips used had serrated surfaces comprised of nine parallel ridges (or teeth) to improve gripping of the lapped sheets (see insert Fig. 1). The tips were oriented with their long dimension parallel, and the ridges perpendicular, to the vibration direction. Weld test coupons were produced using standard size 25 mm × 100 mm strips, with the weld located at the centre of a 25 mm overlap, under a constant pressure of 31, 40 or 50 MPa (defined as force over the whole tip area). The pressure was calibrated against a load cell. The sheets were gently clamped to avoid vibrational damping. The welding direction was perpendicular to the coupon. Different weld energies of up to 1.5 kJ were obtained by varying the weld time with a constant target power (P) of 2.5 kW, controlled by the USW machine. It should be noted that weld energy (U) and time (t) are approximately interchangeable; i.e. as $U = P \times t$. For example, 1 kJ at 2.5 kW is equivalent to ~0.4 s. In order to evaluate the mechanical strength of the joints, and establish the optimum welding conditions, tensile lap shear tests were performed on the weld coupons. Results were averaged over three tests with the peak load measured, as well as the total failure energy, from the area under the load displacement curves. Weld temperatures were measured using 0.5 mm diameter k-type thermocouples placed as close as possible to the sonotrode tip contact area (the position is indicated in Fig. 4) either just below the top sheet surface or imbedded, using a precision drilled hole, to contact the bottom sheet top surface (weld interface position).

X-ray tomography was used to characterise the weld quality, in terms of the interface defect areas, as a function of weld time, using a Metris HMX225 X-ray radiography set. This system had a conical X-ray beam with a maximum energy of 225 keV, and a focal spot size of 5 μm, giving a resolution of ~6 μm in aluminium. 800 radiographs were recorded on a 1024 × 1024 CCD. The whole weld area was scanned by cutting out the weld and fixing it to a rotating cylinder. Volume reconstruction was performed with a three-dimensional FBP (Filtered Back Projection) algorithm [29]. The welded joints were sectioned across their centre, parallel to the direction of vibration and the weld zone microstructures were characterised using a high resolution FEI Sirion FEG–SEM equipped with an HKL EBSD system. Images were obtained on unetched mechani-