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Rapid intermetallic growth under high strain rate deformation during high power ultrasonic spot welding of aluminium to steel

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ABSTRACT

High power ultrasonic spot welding is an alternative manufacturing process which recently has been developed for joining automotive bodies. This technique is a very low energy process, forming effective welds in less than a second particularly for difficult dissimilar material combinations such as aluminium to steel joint. However, in dissimilar joint the interdiffusion and thus intermetallic formation was accelerated due to high strain rate dynamic deformation in ultrasonic spot welding which deteriorates mechanical performance. The interfacial reaction between aluminium 6111-T4 and DC04 uncoated steel has been investigated as a function of welding time. For the optimum welding time of 1.5 s under a 1.4 kN axial pressure, the intermetallic layer thickness could have reached ~1.0 μm. Intermetallic islands were seen to nucleate across the microbonds at the interface within short welding times which spread and grow rapidly forming a continuous layer which mainly contains $FeAl_3$ and Fe_2Al_5 phases. The interfacial reaction occurred in solid state even for a long welding time. Modelling was carried out with the aim of showing that the rate of interfacial reaction was over 6 times greater than the rate observed in diffusion couple using rate constants achieved from the static heat treatment condition. This confirms that deformation-induced vacancies during the thermomechanical welding process accelerates formation of intermetallic layer at the interface.

1. Introduction

Multi-material design is nowadays considered to be an efficient way of balancing cost and increases environmental performance in future vehicle designs. This technique can involve joining various materials, such as advanced steels, light metals like aluminium and magnesium, and reinforced plastics [1]. Aluminium replacing steel is likely to have a major role in future car generations. The lower density and good mechanical properties of aluminium alloys open the way for new applications in car body structure. Car body structures contribute approximately 20% of the total vehicle weight and therefore, replacing steel with aluminium alloys is a promising weight saving solution. To date, limited range of aluminium alloys such as the Al–Mg non-heat treatable of 5xxx series and Al–Mg–Si heat treatable of 6xxx series have been used for different automobile structures [2].

The replacement of steel with aluminium in automotive applications is not straightforward. In conventional dissimilar welding such as resistance spot welding, problems associated with metallurgical incompatibility of materials including differences in melting point, and large residual stress result in low quality weld performances. In addition, occurrence of melting at the interface can result in accelerated formation of intermetallic layer and thus lower mechanical properties of the joints [3]. In comparison, Ultrasonic spot and friction stir spot welding are two promising new solid state processes that could potentially replace resistance spot welding, and use 10% of the energy [4]. They also reduce many of the issues like intermetallic formation associated with conventional welding, because no liquid phase is generated [5,6]. Nevertheless, the success of dissimilar joining is also dependent on maintaining issues such as operation costs, cycle time, reliability, and quality which are just a few of the many concerns that must be considered, in order to introduce a new industrial vehicle joining technique [7].

In ultrasonic spot welding high-frequency (15–40 kHz) linear oscillations are applied to the weld components by sonotrode tips which are connected to transducers (Fig. 1). Transducer converts electrical power into mechanical vibrational motion. The power setting generally controls the high frequency electrical power delivered to the transducer. The ultrasonic welding machine

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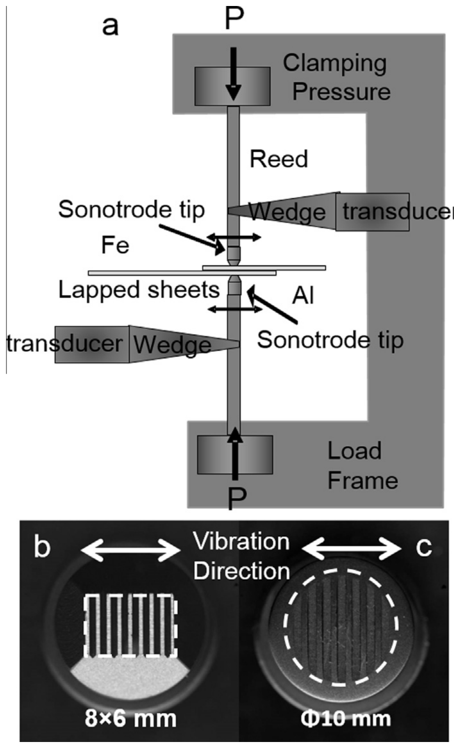

Fig. 1. (a) Schematic demonstration of ultrasonic spot welding, (b) flat serrated sonotrode tip touching aluminium and (c) domed shaped serrated bottom sonotrode tip touching steel.

requires minimal electrical power to initiate and maintain vibration in an unloaded condition. As the resistance of the work-piece increases, more power is required to maintain the vibration [8]. The maximum power required during a weld cycle is called "peak power". The range of power delivery and the frequency of vibration are different for various machines [9]. However, the parameters, such as welding time and axial pressure are adjustable. Full details of the welding performance has been brought in the previous works by the current author [9,10].

The formation of Fe_2Al_5 has been reported as the predominant Fe–Al intermetallic phase formed between aluminium and steel in both the solid and liquid state in most joining techniques, including friction and fusion welding [11–13]. According to thermodynamic calculations, the formation of the $FeAl_3$ phase is expected to be preferential as a result of having the largest negative free gibbs energy of formation [14]. However, the Fe_2Al_5 phase is thought to appear to form in most cases due to its higher kinetic growth rate [15] of 3.41×10^{-11} cm^2/S, compared to 0.01×10^{-11} cm^2/S for $FeAl_3$ at 600 °C [16,17]. Furthermore, there is a favoured crystallographic habit orientation between Fe_2Al_5 and ferrite, which facilitates nucleation of this intermetallic phase [18]. Reports on static diffusion couples of aluminium to steel show that, when undeformed, the reaction layer typically develops with two continuous sub-layers of $FeAl_3$ on aluminium side and Fe_2Al_5 on steel side [17]. It was also shown that the kinetic reaction of the intermetallic layer follows the parabolic behaviour [16]. However, in dissimilar thermomechanical joining such as friction stir spot welding the growth rate was seen to be abnormally rapid because of high rate diffusion rate because of deformation-induced vacancies produced severe plastic deformation [17].

Ultrasonic spot welding has also priority to friction stir spot welding due to undesirable aspects of the process including the keyhole left by the tool probe, and reduction of the top sheet thickness [4,19]. The majority of research on low power ultrasonic spot welding assumes bonding occurs at relatively low temperatures (300 °C) and is dominated by contact mechanics [20]. Despite ultrasonic spot welding has been used since the 1950 s to join thin foils, over the last years, high power ultrasonic welders have become more readily available and can be used to achieve high quality similar aluminium welds in panels up to 3 mm in thickness [21]. Recently, notable effort has been made in ultrasonic spot welding in car body structures, in order to understand the mechanism of joining [21–24]. The weld is formed as a consequence of the destruction and dispersion of oxides at the weld interface and involves the formation and spreading of microwelds accompanied with severe plastic deformation across the entire thermomechanical affected zones (TMAZs) [25]. With high power ultrasonic spot welding (<2–4 kW) it is possible to join the thicker gauge sheets required for car construction. For example, aluminium 1–2 mm gauge sheet can ultrasonically be welded with an energy input of 0.7–1.5 kJ to provide an optimum weld strength of ~3.5 kN exhibiting desirable nugget pullout fracture mode [24]. As a result of higher energy delivery to the work-piece, higher peak temperature have been detected at the interface of similar aluminium welds [26].

Ultrasonic welding is capable of producing plastic strain rates of around $\sim 10^3$ s^{-1} in the materials subjected to joining process [27]. Kulemin et al. have reported diffusion coefficient of 1.4×10^3 µm^2 s^{-1} in the solid state between copper and aluminium sheets in ultrasonic welding, which is 10^7 times higher than lattice diffusion at a 773 K of welding temperature [28]. In another work, results for aluminium to zinc dissimilar ultrasonic welds show that a significant melting point depression and enhanced inter-diffusion is occurred due to the presence of the large concentration of vacancies performed during deformation [27].

Currently, only a few works have been published on the effect of deformation on the interface reaction behaviour observed in dissimilar ultrasonic welding when high power system applied for thick gauge automotive sheets [29]. Previous reports by Prangnell et al. have tried to optimise the welding parameter for aluminium to steel using high power ultrasonic welding [10]. It was shown that the fracture mode changed from nugget pullout at the optimum condition to interface failure in very long welding time due to formation of thick brittle intermetallic later at the interface [10].

Here, we represent in details how the interface reaction layer (intermetallic) forms and affects the joint properties when performing bonding between 1.0 mm gauge aluminium and steel automotive sheets of AA6111 and DC04. The intermetallic reaction layer evolution and its growth rate have been investigated as a function of process parameters of welding time, clamping pressure and interface temperature. In order to determine the influence of the high strain rate of the dynamic deformation on intermetallic growth rate, the thickness of the reaction layer was compared to the growth under static condition.

2. Experimental details

In this study the welds were performed between aluminium 6111-T4 and steel DC04 sheets with ~1.0 mm thickness. In addition, the effect of high silicon and zinc aluminium alloys on intermetallic growth kinetics, has been studied, in order to attempt to inhibit the interfacial reaction during ultrasonic spot welding process (see the chemical compositions in Table 1). Sheets were cut into a rectangular shape of 100 mm length and 25 mm width to be welded at 25 mm over lapped position. For all experiments aluminium sheet was on the top touching flat serrated tip when the steel was touching the bottom domed shaped serrated tip as shown in Fig. 1b and c. Welds were performed by Sonobond dual-head spot system operating at a constant frequency of 20.5 kHz and a nominal power of 2.5 kW under 1.4–1.9 kN