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The effect of interface reaction on vibration evolution and performance of aluminium to steel high power ultrasonic spot joints

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High power ultrasonic spot welding is an energy efficient technique with great potentials for joining dissimilar metals in automotive applications. Efforts were carried out to find out the effect of interface reaction on ultrasonic vibration behaviour during the welding process. Rapid coarse scale drift was observed as the tips settled on the work-piece when the power was initially applied. A small periodic displacement (0.1 μm) took place at the earliest stage of welding which built up to 2.5 μm in a short time. It gradually approached a steady state of ~4–6.5 μm for the majority of the weld, adopting a bimodal amplitude when the peak height alternated every second cycle. Finally, the vibration rapidly decayed when the power was turned off. The vibration amplitude was measured as the highest point during joining bare steel to aluminium and decreased with zinc coated steels as a result of the coating hardness behaviour. This took place when zinc was melting at the interface due to Al–Zn eutectic reaction, thus causing the vibration to be in sliding condition with low power delivery. The sliding condition accompanied by less deformation was found to delay heat generation and therefore, dynamic recrystallization.

1. Introduction

There is a significant interest in reducing the mass of vehicles to improve their fuel efficiency. This can be carried out by the introduction of multi-material designs, involving lightweight alloys such as aluminium and magnesium joined to steel as a less expensive material [1–7]. High Power Ultrasonic Spot Welding is an energy efficient technique for joining dissimilar materials, minimizing many problems caused by comparable fusion welding processes, such as intermetallic phase formation at the interface [3,4,8,9]. However, to date this technique is more applied to the welding of thin gauge foils in electronics and battery applications [10–14] than in automotive body structure applications [15–18]. A considerable advantage of this welding method is that various dissimilar material combinations, such as metals to ceramics, glasses and composites, as well as dissimilar metals including aluminium sheets to steel, can be produced [19–21].

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. The high frequency vibration is generated by a piezoelectric component system which is transmitted to a booster/horn stack setup with specific characteristics of amplitude. In order to maintain the vibration at a consistent amplitude level, electric power delivery is controlled during the welding process, which can be varied by axial force on the weld components [22]. As the resistance of the work-piece increases, more power is required to maintain the vibration [23]. 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 [24]. The power can be defined as:

$$\text{Power} = F.\frac{dS(t)}{dt} = \mu Fn\frac{dS(t)}{dt}$$

where F is the force applied on the sonotrode welding tip, which is a function of the friction coefficient (μ) and clamping force (F_n), and dS(t)/dt is the cyclic vibrational speed of the welding tip. As the clamping force and the velocity of weld tips are controlled at a fixed level, the power delivery is determined by of friction coefficient of the weld interface, which is related to the surface condition of the weld components when coupled together [22]. For the ideal clean weld interface, the power can reach the maximum level within less than 0.05 s. approaching a steady state condition leading to the maximum amplitude of vibration until the end of welding when vibration collapses. However, the power can reduce by 30–50% over a period of time when the weld interface is contaminated, resulting in low frictional resistance to the relative displacement of the welding components [22]. The power can ramp-up with increasing welding time as the interface contamination can be removed and scattered around the weld periphery by cyclic shearing forces from the welding sonotrode [3,24].

In high power ultrasonic spot welding, three possible scenarios of phase-shift, pause and amplitude stepping can be considered for defective vibration [12]. In the 180°-phase shift, the direction of sonotrode vibration is changed in the middle of the welding process. This results in

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the phase shift to appear as $\sin(\omega t + \ + \pi)$, whereas $\sin(\omega t + \ )$ is the original wave and π shift deviation. A pause will happen by not providing an energy source input to transducers for a few moments and therefore, system response is expected to be attenuated. Amplitude stepping takes place when the amplitude of the vibration is modulated [12].

Tool penetration was seen to occur in different stages of; (i) forging when it is initially engaged to the weld components and (ii) further penetration due to metal softening by plastic deformation when the temperature increased at the weld nugget [25]. In contrast to contaminant weld interface, a greater tip penetration was demonstrated for clean interface because of higher friction rate when weld components are less in sliding condition, leading to superior softening and deformation [1,22,25]. High frequency cyclic deformation accompanied by high rate heat generation was seen to cause dynamic recovery and therefore recrystallization for clean weld interface which was less effective for weld components with an interlayer or contaminants [24].

To perform a weld, materials are held between the sonotrode tip and anvil using the clamping force [1]. Energy is initially dissipated by sliding friction, but in soft metals such as aluminium, galling and microbonding rapidly occur when the oxide layer breaks down at these early contact points [15]. As a result, more energy is dissipated by increasing the level of plastic deformation, and microwelds, that spread in density and size, form across the interface as a function of welding time [19]. In the case of dissimilar ultrasonic welding, a lack of deformation in the harder metal is expected at the interface, due to its higher yield stress, which delays weld formation [26]. Melting of interlayers, such as the zinc coating in aluminium to galvanized steel welding, can hinder vibration since the melting zinc reduces friction between the weldment components [24].

Previous efforts by the authors have sought to optimize the welding parameters required for aluminium to steel ultrasonic welds in automotive gauge sheets [1,3,24,27,28]. In the present investigation, the vibration behaviour was studied during the welding process carried out between a typical aluminium automotive alloy (AA6111-T4) and uncoated steel (DC04), in addition to two different zinc coated steel sheets with soft (hot dipped DX56-Z) and hard (galvannealed DX53-ZF) coatings, using a 2.5 kW dual reed ultrasonic welder. The target of this work was to obtain a better understanding of the main factors affecting the vibration behaviour, with a particular emphasis on the role of the surface condition of weldment materials.

2. Experimental

Ultrasonic spot welding was carried out by joining AA6111-T4 alloy sheets to un-coated (DC04), soft (DX56-Z) and hard zinc coated (DX53-ZF) steel sheets. The average thickness of the zinc coated steels was measured to be within the range of ~10–15 μm. However, full details about the materials and their compositions can be found in a previous work [1]. Welding was performed using a Sonobond dual-reed system operating at 20.5 kHz, under a constant force of 1.4 kN [3]. The welds were performed on 25 mm by 100 mm strips at the centre of a 25 mm overlap, following the standard sample geometry [1,3,24,27,28]. The power was kept constant at 2.5 kW and the welding time was varied up to 3.0 s. No surface treatment such as grinding was carried out prior to welding. Further details on the welding procedure are available in previous efforts [1,3].

Lap shear tensile testing was performed at 1 mm/min. The average tip penetration into the aluminium side of the welds was investigated using a 3D NanoFoucus μscan SC200MT profilometer operating with a laser source. The use of this technique resulted in measuring the depth of tip penetration into the work-piece as a function of welding time. In order to perform accurate measurement of tip penetration, the laser beam size was chose for 1 μm.

The interface temperatures were recorded using 0.5 mm diameter k-type thermocouples positioned through a channel accessing the weld interface. To investigate the microstructure, sample were cross sectioned. After mounting the samples in brass holders, they were then ground progressively on standard silicon carbide (SiC) paper from #600 to #1200 grades. In each stage, larger surface scratches are replaced progressively by smaller ones when using a finer grinding paper. Then, the samples were polished on 6 μm and 3 μm diamond cloths for 3–5 min to remove all scratches from the grinding process. Finally, the samples were polished with an OPS colloidal silica suspension for 3–5 min to give a mirror finish. For EBSD sample preparation, the final OPS stage was increased to 60 min. Microstructure and grain structure studies were performed using Philips Sirion, Philips XL-30 (FEGSEM) and Zeiss EVO60 VPSEM Electron Microscopes fitted with hkl EBSD detector.

In order to obtain a better understanding of the power delivery, the amplitude of vibration during the welding process was measured using a Laser Interferometer (SIOS SP-S LSV Series). The vibrometer is set up and the laser beam is focussed on a reflective surface of the moving part, and angled so that the reflected beam returns to the receptor. Fig. 1 shows the real vibrometer setup on the ultrasonic spot welding machine. The vibrometer was fixed on a separate desk avoiding displacement due to vibration of welding machine during the process. The beam was focussed on the top reed in its original position before welding. Data recording was started before clamping the work-piece and ended as it was unclamped. The sampling rate was fixed at ~100 kHz. This allowed the full wave to be captured during welding which led to measurement of the vibration amplitude frequency drifting of the welding head.

3. Results and discussion

Fig. 2 shows the peak temperatures detected from the weld interface with increasing welding time. It was shown that increasing the welding time resulted in an increase in temperature in the joints of aluminium to both zinc coated steels; in addition, a temperature equivalent to the Al–Zn eutectic reaction temperature (382 °C) was reached within less than 0.5 a second [1]. However, significantly higher peak temperature was recorded when aluminium was welded to un-coated steel. This is due to a greater rate of power dissipation when the zinc layer is absent at the interface [24], which arises from better coupling and higher friction rate with the bare steel sheet. Basically, Coupling is vibrational response of weld components to cyclic movement of sonotrode tips [1,24]. In welding aluminium to either zinc coated steel, the temperature was shown to be above that of the Al-Zn eutectic melting point at longer times (>0.5 s), and in the early stages of welding, the weaker zinc coating encourages a sliding contact condition at the faying surfaces, leading to a lower early rate of heat generation [1,24].

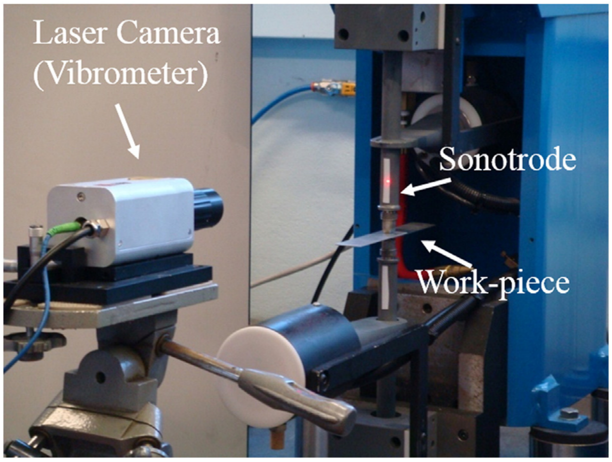

Fig. 1. Vibrometer setup on the ultrasonic spot welding machine.