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Microstructural and mechanical performance of aluminium to steel high power ultrasonic spot welding

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ABSTRACT

Welding of Aluminium 6111-T4 to bare and two different zinc coated steels was successfully carried out using high power ultrasonic spot welding. The thermal behaviour and non-uniform heat distribution at the local weld area were investigated. The effect of heat generation on precipitates dissolution and natural aging of Al6111-T4 was studied. The maximum hardness in TMAZ was 10-15Hv higher than natural aging which is because of higher rate of precipitation due to reduction in grain/subgrain size. The performance of soft hot-dipped DX56-Z and hard galvannealed DX53-ZF zinc coated steels was discussed in terms of mechanical properties and joinability, in comparison with uncoated steel. The highest peak load (3.25 kN) and fracture energy (∼5 kN mm) was reached in the case of aluminium to hot dipped DX56-Z zinc coated steel joints owing to the maximum ductility. In contrast, in aluminium to galvannealed DX53-ZF zinc coated steel joints failure was promoted earlier with low mechanical properties of 2.6 kN shear strength and 1.25 kN mm fracture energy as a result of damage to the zinc layer. Formation of brittle Al–Fe intermetallic layer at the interface of aluminium to bare steel was the main effect of reduction in ∼3.0 kN lap shear strength at the maxima. Surface damage due to sonotrode welding tip penetration was seen to be more severe in aluminium to bare DC04 steel compared to other weld combinations that resulted strength loss when the thickness of the weld nugget is reduced at the optimum condition.

1. Introduction

Prangnell and Bakavos (2010) stated that dissimilar material joining is an important target for the automotive sector in order to reduce the weight of car body structures for greater fuel efficiency. However, Haddadi (2012) and Nishihara et al. (2010) reported that the reaction at the interface and material incompatibilities are the most challenging barriers in joining dissimilar materials. It was shown by Zhang et al. (2014) that thermomechanical joining processes are most likely found to be successful with overcoming issues associated with the differences in melting points and thus limiting the formation of intermetallics at the interface.

Dissimilar aluminium to steel ultrasonic spot welding has been previously investigated by Watanabe et al. (2009). Investigation on other material combinations such as magnesium to fibre reinforced polymer composites was also reported by Amancio-Filho et al. (2011). Recently, aluminium and magnesium were successfully joined together by Panteli et al. (2012) using high power ultrasonic spot welding. Chen et al. (2012) have tried the same high power welding frame for joining similar AA6111, investigating the effect of intensive cyclic plastic deformation on strengthening precipitates. Haddadi and Prangnell (2013) confirmed that formation of liquid zinc delays dynamic recyrtallization under severe plastic deformation. In another work, Robson et al. (2012) predicted that intermetallic formation at the interface of aluminium and magnesium is accelerated due to deformation-induced vacancies using high power ultrasonic spot welding. It was shown by Patel et al. (2014) that weld formation between magnesium and galvanized steel is facilitated when the zinc coating melts, causing Mg–Zn eutectic reactions.

So far, Bakavos and Prangnell (2010) have reported the highest lap shear strength of 3.5 kN within a short welding time of 0.25 s for similar aluminium ultrasonic joint, owing to an extended continuous bond at the interface. On the other hand, Haddadi (2012) showed that formation of thick Fe_2Al_5 and $FeAl_3$ phases at the aluminium/steel interface deteriorates the lap shear strength from a maximum of 3.1 kN to a minimum of 1.7 kN with increasing welding temperature (time). A work by Panteli et al. (2012) demonstrated that joining aluminium to magnesium results in a relatively low weld strength (∼2.1 kN) due to rapid formation of $Al_{12}Mg_{17}$ and Al_3Mg_2 within 0.4 s of welding time, which is significantly shorter

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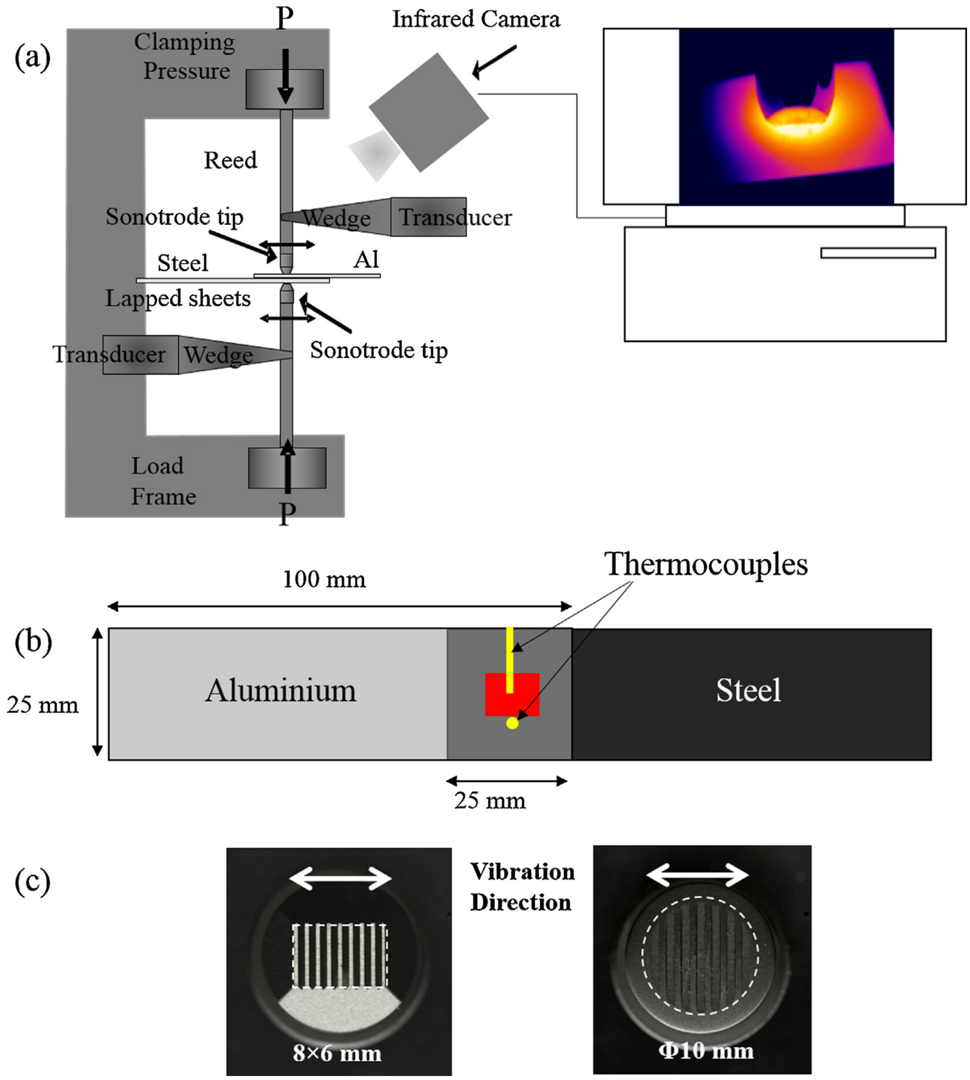

Fig. 1. (a) A schematic illustration ofthe welding setup showing the components of the MH2016 dual head ultrasonic spot welder and the integrated thermal camera, (b) the weld sample geometry showing the positions of the two thermocouples for temperature measurements close to the sonotrode tip edge and weld centre, (c) image of the flat (left) and dome-shaped(right) sonotrode welding tips.

than the optimum conditions for aluminium to steel joints reported by Haddadi (2014). In another effort by Balasundaram et al. (2014), 3.4 kN strength was achieved by joining aluminium to copper; however, insertion of a zinc layer was required to avoid the formation of Al_2Cu intermetallic compound.

Although Barnes and Pashby (2000) claimed that friction based joining processes are not supposed to involve melting, Panteli et al. (2012) showed the formation of liquid phases during aluminium to magnesium ultrasonic welding. In addition, Al–Zn eutectic reaction was reported by Haddadi et al. (2012) at the interface of aluminium to galvanized steel joints reaching ~380 °C with increasing welding cycle to ~0.5 s. In other efforts by Balasundaram et al. (2014) and Cheng and Li (2007), it was evident that the use of zinc interlayer between aluminium and copper causes liquation through eutectic reaction, promoted by the increase in temperature due to frictional heat generation and plastic deformation between the weld components as a result of the high frequency vibration.

In this work, high power ultrasonic spot welding of AA6111-T4 to steels with different coatings is investigated, focusing on the details of heat generation during welding and its effects on the microstructural properties at the interface and the mechanical performance of the joint. The evolution of the mechanical properties is correlated to the microstructural changes under various process parameters.

2. Experiments

Several automotive materials were used in this work, all in the form of thin sheets with similar thickness of approximately 1 mm. The work was performed with a single heat treatable aluminium alloy, AA6111-T4, welded to steels with three different surface conditions: (i) un-coated, (ii) coated with a soft hot-dipped zinc coating or (iii) coated with hard galvannealed zinc coating. The nominal composition and the thickness of each as received materials are given in Table 1.

A Sonobond™ MH2016 Dual Head Spot Welder, which is schematically shown in Fig. 1a, was used in this work. Different weld energies of up to 4.3 kJ were obtained by increasing the welding cycle from 0.18 to 3.0 s at a constant target power of 2.5 kW. The welding processes were carried out under a range of clamping forces (1.4 to 2.3 kN). Metal sheets were cut into 100 mm × 25 mm to be welded in a 25 mm overlapped position, as demonstrated in Fig. 1b. In all experiments, aluminium sheet sample was placed on the top touching the flat serrated tip; the steel was placed at the