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The effect of a paint bake treatment on joint performance in friction stir spot welding AA6111-T4 sheet using a pinless tool

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HIGHLIGHTS

- Strong joints with a nugget pull-out failure mode could be obtained within <1 s.
- Weld strength increased further after the paint bake treatment.
- Weld zone exhibiting more rapid ageing kinetics during the paint bake cycle.

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ABSTRACT

It has been previously shown that it is possible to produce friction stir spot welds (FSSW) in thin (1 mm thick) aluminium sheet, when using a tool without a probe, which has the significant advantage of not leaving a keyhole in the weld. The aim of this paper was to investigate the effect of a post-weld paint-bake thermal cycle on the performance and precipitation behaviour of FSSW joints produced using a pinless tool, in the heat-treatable Al automotive alloy AA6111-T4, with rapid, industrially relevant, weld cycle times. It has been demonstrated that strong joints could be obtained within <1 s, that exhibited a nugget pull-out failure mode, and the weld strength increased further after the paint bake treatment. After the paint-bake thermal cycle the weld zone was found to be considerably harder than the parent material and this behaviour has been attributed to the shorter delay time between welding and artificial ageing, relative to the longer pre-natural ageing time experienced by the parent sheet. With a rapid (<1 s) weld cycle, no hardness minima were observed in the heat affected zone (HAZ) after the paint-bake treatment.

1. Introduction

There is an accelerating trend in automotive manufacturing towards the greater use of light alloys, to reduce vehicle mass and achieve increasingly demanding fuel efficiency targets. Unfortunately, conventional welding processes, like resistance spot welding (RSW), are difficult to apply to aluminium (Al) alloys because of their high conductivity, low strength at elevated temperature, and tendency to degrade the electrodes [1,2]. Furthermore, other joining processes in production, such as self-piercing riveting (SPR) have high associated consumable costs [3–5].

Friction stir spot welding (FSSW) is a relatively new alternative joining method that has already been applied successfully to welding aluminium panels in automotive manufacturing by the Mazda Motor Corporation, who claim large energy (90%) and capital investment savings (40%), compared to RSW [6]. In a new development to this process it has recently been demonstrated, by the current authors, that it is possible to produce friction spot welds in thin (1 mm thick) 6xxx aluminium automotive sheet in a rapid cycle time of less than 1 s, when using a tool without a probe, and still achieve good joint properties [7]. A pinless tool approach to FSSW has the advantage of not leaving a keyhole in the weld centre, which causes cosmetic and corrosion issues, and is simpler and faster than the Refill™ welding method [8].

In automotive manufacturing Al alloy sheets, welded in an under-aged T4 temper (solution treatment + natural ageing), will normally undergo a paint-bake thermal cycle (PBC) where the car body is heated at temperatures of 150–180 °C to cure the paint applied in the final stage of the body assembly process. This treatment increases the yield strength of heat treatable alloys, like 6111, through artificial age hardening due to the creation of more solute clusters and by increasing the density of fine precipitates

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within the material [9,10]. However, most research on FSSW of 6xxx automotive sheet has only evaluated the properties of welds in the T4 temper condition, in which the material is originally supplied. It is thus important to understand the effect that this heat treatment operation will have on weld performance. To date, there have been few studies concerning the effect of a post-weld paint-bake thermal cycle (PBC) on the behaviour of friction stir spot welds. In one investigation, Blundell et al. [11] have reported that, even though the PBC increases the strength of the parent AA6111 sheet, it reduced joint performance. More work is, therefore, needed to understand the effect of the paint bake treatment, particularly in the case of rapid, pinless, FSSW, where a stronger material temper may affect the joint failure behaviour.

The main aim of this paper was thus to investigate the effect of a paint bake thermal cycle on the mechanical properties and fracture behaviour of FSSW joints produced in a typical heat-treatable AA6111-T4 automotive alloy, using a pinless tool and industrially realistic short welding times of less than 1 s. This was achieved by studying the joint's performance and post-weld ageing behaviour, using lap shear tests and careful hardness measurements, supported by electron microscopy of the joints' fracture paths and their weld zone precipitation behaviour.

2. Experimental

All the spot welds were produced in 0.93 mm thick AA6111-T4 Al-automotive sheet, with no surface preparation prior to joining, using a 10-mm diameter pinless tool with a fluted shoulder. A schematic diagram of the friction stir spot welding process with a pinless tool is shown in Fig. 1. Full details of the tool design and welding procedure can be found in Ref. [7]. The welding trials were performed with a friction stir welding machine. A standard 0.2 mm shoulder plunge depth was used in all cases, as this was previously found to be the minimum required to obtain a satisfactory weld [7]. The weld coupons were produced at the centre of a 25 mm overlap between two 25 by 100 mm strips. All welding was carried out under displacement control. The plunge and rotation rate were kept constant at 2.5 mm s^{-1} and 2000 rpm. Two dwell times of 0.5 and 1 s were studied. When combined with the plunge and retract, this gave total weld cycle times of ~0.7 and 1.2 s. A tight fitting clamping plate was used with a 12-mm diameter machined hole, to increase the hydrostatic pressure under the tool and prevent lifting of the top sheet. Dissimilar alloy welds were also produced between the AA6111 sheet and an AA6082 alloy, which is a 6xxx material with a lower Cu content but similar mechanical properties, to reveal the weld interface position by differential etching.

The temperatures reached in the samples were measured using thermal couples inserted vertically from the backing plate into the bottom surface of Al sheets. Measurements were made at a radial distance of 2.5 mm from the tool centre. The thermocouple tips were mounted ~0.1 mm proud of the anvil, ensuring good contact aided by the welding down force. Microhardness measurements (using a 1 kg load, 10 s dwell, and 3 s load application time) were made across the welds in the top sheet, at 0.5 mm below the top surface, immediately after welding (<1 h) and following post-weld heat treatment (PWHT). In order to simulate the paint-bake thermal cycle (PBC) that would be used in industry, the weld samples were artificially aged at 180 °C for 30 min immediately after welding. The welds were tested in a lap shear configuration using a constant displacement rate of 1 mm min^{-1} and the maximum strength and failure energy averaged over three repeated tests for each condition. The microstructures of the weld zones were characterised by a high resolution FEI Sirion FEG-SEM on samples prepared with a gentle finishing mechanical polish, using colloidal silica, followed by light electro-polishing in 30% nitric acid methanol solution at −25 °C. Fine-scale precipitation was studied by TEM using a Philips CM20 and an FEI Tecnai F30 with electro-polished samples prepared from the mid plane of the top sheet at the weld centre.

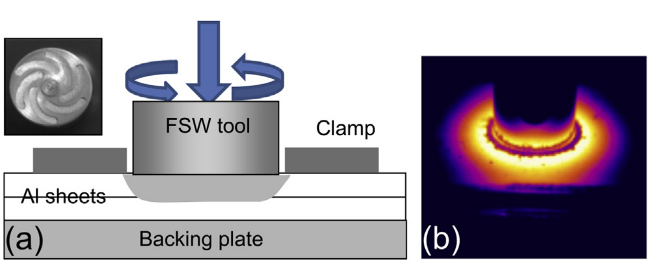

Fig. 1. (a) Schematic diagram of the friction stir spot welding process with a pinless tool and (b) thermal image obtained during welding with a 1 s dwell time. The design of the tool is shown in the inset.

3. Results and discussion

3.1. Welding behaviour

Optical images of cross-sections from the AA6111-T4 standard welds and AA6111-AA6082 interface marker experiment FSSWs, produced with dwell times of 0.5 and 1 s are shown in Fig. 2. For the experimental marker welds, a higher magnification view of the interface is also shown in Fig. 3. In Fig. 2 the conventional AA6111 weld sections show the extent of the deformation zones; however, the etching is sensitive to changes in the precipitation behaviour within the weld zones, whereas the dissimilar alloy weld cross sections give a clearer picture of the interface position between the two sheets. The weld formation process, in FSSW with a pinless tool, has already been described in detail in Ref. [7]. As discussed in this previous study, the deformation zone increases in depth with welding time, penetrating further into the bottom sheet. At the centre of the weld the join line is pushed down into the bottom sheet, and this starts to displace material from the bottom sheet sideways forming a hook. The hook formation is a relatively minor effect with short welding times (e.g. <1 s), but can become

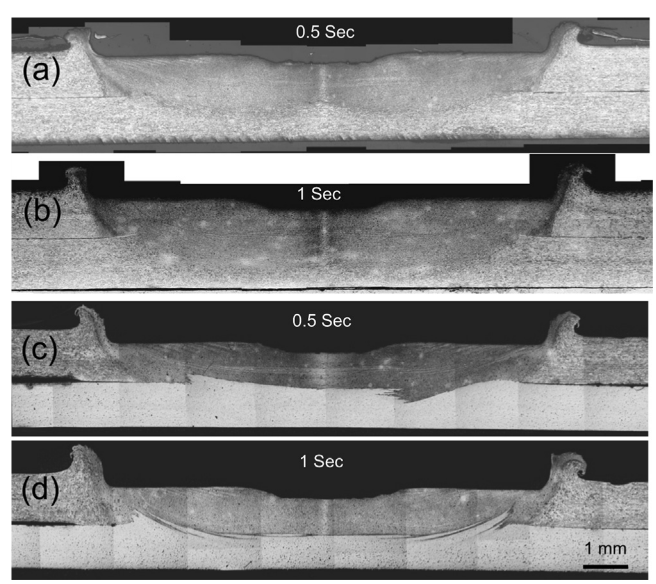

Fig. 2. Cross-sections of typical pinless AA6111-T4 FSSWs, produced with short dwell times of (a) 0.5 and (b) 1 s, compared to interface marker alloy welds between AA6111 and AA6082 made with the same welding times (c) and (d).