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HAZ development and accelerated post-weld natural ageing in ultrasonic spot welding aluminium 6111-T4 automotive sheet

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Abstract

By careful hardness measurements, supported by electron microscopy, it has been shown that there is a clearly observable heat-affected zone (HAZ) when ultrasonic spot welding (USW) aluminium automotive alloys like AA6111-T4, the severity of which depends on the welding energy. In contrast, it has been previously reported that because of the low-energy input with USW no HAZ can be detected. Immediately after welding, softening is seen in the weld zone relative to the normal T4 starting condition. However, this is rapidly recovered by natural ageing, which masks the presence of a HAZ, and the weld strength over long natural ageing times significantly exceeds that of the parent T4 material. This behaviour is caused by dissolution of the solute clusters and Guinier–Preston zones present in the T4 sheet due to the high weld temperatures, which were recorded to reach over 400 °C at the weld interface, followed by accelerated post-weld natural ageing. Interestingly, the weld zone was found to naturally age faster, and to a more advanced state, than the parent material. Modelling has been used to demonstrate that a large excess vacancy concentration can potentially be generated by the high-strain-rate dynamic deformation in USW, which can accelerate the natural ageing response seen in the weld.

Keywords: Ultrasonic welding; AA6111; Aluminium; Heat-affected zone; Natural ageing

1. Introduction

In the future, the reduction of emissions in the automotive sector will require the greater use of lightweight structures fabricated from aluminium [1]. Unfortunately, it is difficult to apply conventional resistance spot welding (RSW) to aluminium alloys because of their tendency to degrade the electrodes [2] and the large energy cost (50–100 kJ per weld) that results from their high electrical conductivity [3,4]. This has highlighted the need for more efficient joining methods. There are several alternative solutions available, such as self-piercing riveting (SPR), friction stir spot welding (FSSW), adhesive bonding and laser welding, which have already found applications in more specialized aluminium automotive products [5–7]. A further process that has lately received some attention is high-power ultrasonic spot welding (USW) [3,4,8–12]. USW has been used since the 1950s to join thin metal foils [13]. However, due to technological advances in the welding systems available, it has only been applied to thicker automotive sheet comparatively recently. In principle, USW is an attractive method for joining aluminium car body panels because it is a solid state process, has a short weld cycle (typically <0.5 s) and is far more efficient than RSW, using only 0.6–1.3 kJ per weld. Research by the Ford Motor Company has demonstrated the feasibility of USW aluminium body structures with promising results, at least in laboratory trials [3,4].

Most high-power USW metal spot welders under consideration for structural automotive applications are linear systems with a power of 2–3 kW and operate at ∼20 kHz [3,4,10,11]. In USW, the parts are normally clamped with a constant pressure between either, a sonotrode tip and anvil or, in a dual reed welder, between two sonotrode tips, which grip the surfaces of the sheets. The sonotrode tips

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oscillate in the plane of the lapped sheets to produce a small (∼10–20 μm) high-frequency linear displacement across the weld interface [14,15]. Research on low-energy USW reports that bonding occurs at relatively low temperatures (<300 °C) and is dominated by contact mechanics, with any deformation localized to the weld faying surfaces [13–17]. To date, there have been comparatively few investigations into the weld development and microstructure evolution with thicker automotive sheet materials (e.g. [9,11]). In recent studies in 1 mm gauge 6111-T4 sheet by Jahn et al. [4] and Bakavos and Prangnell [18] the mechanisms of weld formation, material flow behaviour and defects seen in high-energy ultrasonic spot welds have been investigated. Similar to in low-power welding, weld formation initially occurs by the ultrasonic vibration breaking down the surface oxide layer between contacting asperities at the faying surfaces, resulting in local adhesion and the formation of microwelds [15,18]. In the early stages of welding the joint strength is thus primarily related to the net area of microbonds, and failure in lap shear tests is by fracture along the joint interface. With increasing welding energy, the microbonds spread and coalesce until little unbonded interface remains. The failure then changes to a nugget pull-out mode, allowing good joint properties to be obtained [18,19]. In high-power USW it has been shown that optimum weld strengths are obtained when extensive plastic deformation takes place throughout the entire sheet thickness between the sonotrode tips [5,18,19]. This is associated with a considerable rise in temperature in the weld zone, which softens the material and allows the sonotrode tips to sink into the sheet surfaces. In the process, the weld interface is displaced into complex wave-like flow patterns [4,11,18,19].

The fact that in high-power USW the sonotrode tips sink into the sheet under relatively low clamping pressures (∼40 MPa) [18,19] suggests that high temperatures are reached in the weld zone. For example, Bakavos and Prangnell [18] measured peak temperatures in the range of 300–400 °C close to the sonotrode tip contact area and the temperature reached at the weld interface would be expected to be at least 50–100 °C higher than this level [20]. When welding thermally sensitive heat-treatable aluminium alloys it is thus surprising that it is commonly claimed in the literature that USW results in no observable heat-affected zone, or HAZ (e.g. [4]). Although it is possible that this is because of the short nature of the weld cycle [18], at the very least, in this temperature range, microstructural changes, such as the dissolution of Guinier–Preston zones (GPZs) and solute clusters, would be expected to occur in automotive alloys like 6111, which are welded in a T4 temper [21,22].

The main objective of this paper was to investigate more thoroughly than previously the effect of high-energy input ultrasonic spot welding on the hardness distribution in the weld zone and the associated impact on second-phase precipitation, when joining heat-treatable aluminium automotive alloys. This was accomplished by the use of careful hardness measurements, both immediately after welding and following prolonged post-weld natural ageing, supported by electron microscopy. The temperatures within the weld zone were also accurately measured at the weld interface. In addition, modelling was explored to evaluate the potential for the high-strain-rate cyclic deformation during USW to generate an excess vacancy concentration and thus influence the post-weld natural ageing response.

2. Experimental

USW welds were produced in 0.93 mm thick 6111-T4 aluminium sheet supplied by Novelis UK, with no cleaning or surface preparation prior to joining, using a dual wedge-reed 2.5 kW Sonobond-MH2016 machine, operating at 20.5 kHz. The nominal composition of the 6111 alloy is given in Table 1. Welding was carried out with 8 by 6 mm flat serrated sonotrode tips, comprising nine parallel ridges (or teeth), to ensure good gripping of the lapped sheets. The tips were oriented with their long dimension parallel, and the serrated ridges perpendicular, to the vibration direction. Full details and diagrams of the welding system and tip design can be found in Ref. [18]. The lap weld test coupons were produced using 25 mm × 100 mm strips, with the weld located at the centre of a 25 mm overlap, under a constant pressure of 40 MPa. Different welding energies of up to 1.5 kJ were applied with a constant power of 2.5 kW. The temperatures reached in the weld samples were measured outside of the tip contact area using a calibrated thermal imaging camera and as close as possible to the hottest location in the weld, which is at the join line at the weld centre [18–20], using embedded sacrificial 0.5 mm diameter K-type thermocouples. The thermocouple temperature measurements were repeated several times and only the results that gave “sensible” heating and cooling curves were retained (i.e. time–temperature histories with a similar profile to that expected from modelling with no inflections and sharp peaks; see Fig. 2b).

The welded joints were sectioned across their centre, parallel to the direction of vibration. Hardness measurements were made on metallographically polished surfaces across the welds at a depth of 0.5 mm below the top surface (i.e. across the mid-plane of the top sheet) using a Vickers microhardness testing machine with a load of 1 kg. Hardness measurements, averaged over five data points, were performed as soon as possible after welding (within 1 h), and following time intervals of 2 weeks and 8 months. The post-weld natural ageing response of the weld zone was also compared to that of re-solution-treated parent sheet samples by obtaining average values from the centre

Table 1
The nominal composition of the 6111 alloy used in this investigation (in wt.%).

Alloy	Mg	Si	Cu	Fe	Mn	Cr	Fe	Al
Al 6111	0.8	0.9	0.7	0.25	0.3	0.1	0.3	Bal.