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Interface structure and bonding in abrasion circle friction stir spot welding: A novel approach for rapid welding aluminium alloy to steel automotive sheet

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ABSTRACT

Aluminium alloy 6111-T4 and steel DC04 1 mm sheets have been successfully welded with a cycle time <1 s by "Abrasion circle friction spot welding", a novel approach to joining dissimilar materials. This was achieved by using a probe tool translated through a circular path to abrade the steel sheet. It is shown that successful welds can be produced between these two weld members with a cycle time of less than one second, that exhibit very high failure loads and a nugget pullout fracture mode desired by industry. Transmission electron microscopy investigation of the joint interface revealed no intermetallic reaction layer. The weld formation mechanisms are discussed.

1. Introduction

Multi-material designs, involving high performance Al and steel alloys, are now considered to be one of the best ways forward for reducing the weight of automotive body structures [1,2]. The development of reliable techniques for joining Al to steel sheet has thus become the subject of considerable interest (e.g. [1]). Resistance spot welding (RSW) is currently the dominant method used for joining steel car bodies, because it is fast, versatile, and easily automated [2]. Unfortunately, when using RSW to weld Al to steel, a thick intermetallic compound (IMC) reaction layer is formed which can badly affect the joint performance [3]. Friction stir spot welding (FSSW) is a relatively new alternative technology that has potential for joining multi-material structures [4–7], because it requires far less energy than RSW and, more importantly, reduces IMC formation by avoiding liquid phase reactions. However, currently the cycle time for Al–steel FSSW is quite slow (typically 3–5 s) and there is a tendency for the welds to fail at the joint interface with low fracture energies [1,2,4,5].

To date, three main approaches have been reported for friction spot welding Al to steel [5,8–15]: (i) FSSW with a conventional pin tool that penetrates the bottom steel sheet [8,9,12,13], (ii) FSSW with a tool that only penetrates the softer Al top sheet [5,10,12–15], or (iii) friction bit joining (FBJ), which uses a sacrificial steel bit [11].

The first approach has been explored most successfully by North et al. [9] in thicker (1.8 mm) sheet combinations where it benefits from the generation of a 'bur' on the steel sheet that creates a mechanical locking feature. However, with this method in thin sheet the locking effect is minimal and the bonded area is not very large, because of the exit hole and small area of clean steel surface exposed by the pin penetration, unless long weld times are used to allow diffusion bonding to occur under the tool shoulder [12,13]. The second approach was originally thought to create a bond by generating flow in the aluminium so that it is abraded against the stationary un-deforming steel sheet surface, while maximizing the joint area by eliminating the exit hole [5]. However, recent studies by Prangnell et al. [12,13] have demonstrated that a sticking condition occurs across the top and bottom sheet interface and the weld is largely produced by static diffusion bonding. It is thus difficult to obtain a strong bond between two dissimilar materials, within a short dwell time, as there is no cleaning effect on the non-deforming steel sheet. Because long weld times are required, a relatively thick IMC layer is commonly produced by this process that typically consists of Fe_2Al_5 and $FeAl_3$ aluminide phases [13–15].

The third approach is similar to friction stud welding, and uses a consumable steel bit to penetrate the Al top sheet, which is welded to the steel surface [11]. However, in terms of weight saving, this is probably not the best solution.

From experience of applying these methods [5,8–15], it is clear that to produce a high quality joint in a short weld time it is essential to develop a self cleaning process where, as well as exploiting frictional heating and pressure, oxide free surfaces are exposed between the two weld bodies at the join interface. Here, a new

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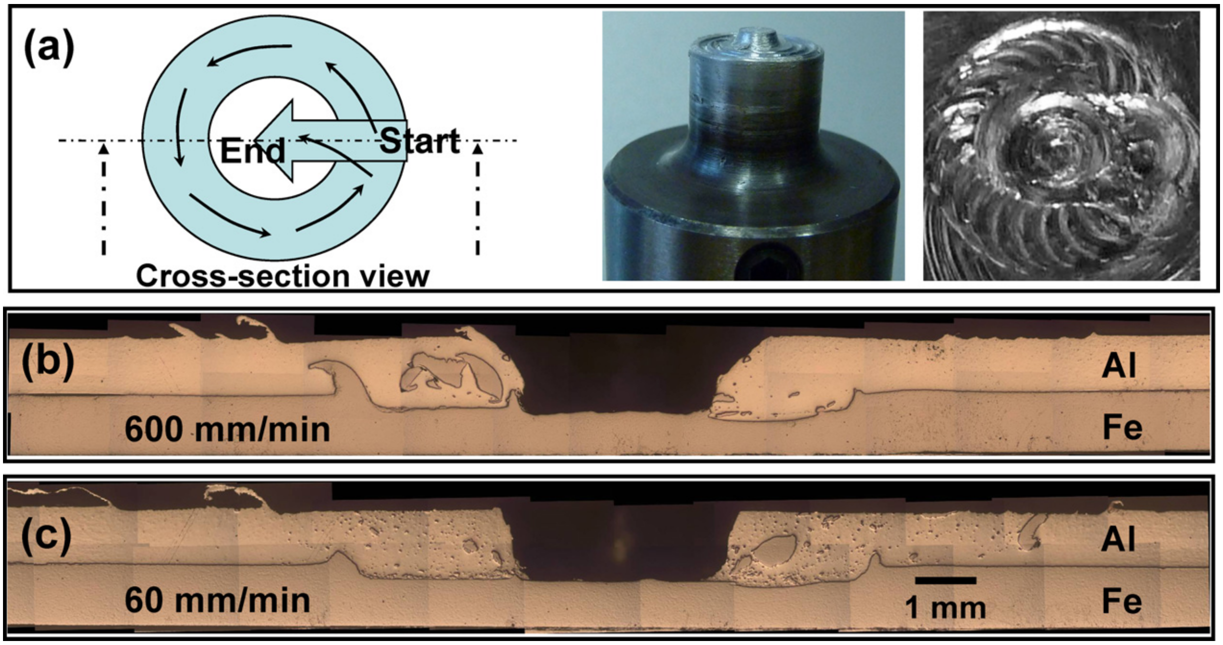

Fig. 1. (a) Schematic diagram of the orbital translation path used in abrasion circle friction spot welding, with an insert showing the tool and weld surface; (b) and (c) typical cross sections of welds for translation speeds of 60 and 600 mm min^{-1}.

approach has been examined to achieve this aim (shown in Fig. 1), which has been termed Abrasion Circle FSSW (or ABC-FSSW). In this process a tool designed with a probe, that slightly penetrates the bottom steel sheet, is plunged into the softer Al sheet and then travels along a circular path, with a radius equivalent to the probe diameter, to obtain a continuous joining area. Finally, the tool is moved to the centre of the circle and extracted to make an axisymmetric weld.

The objective of this paper is to report on the joint performance that can be achieved with this novel process and characterise the interface structure and joining mechanisms involved.

2. Experimental

The materials welded were 1 mm thick 6111-T4 Al (Al–0.75 Cu–0.69 Si–0.75 Mg–0.25 Fe–0.2 Mn; wt%) with roughness average (Ra) of 1.12 μm and DC04 low carbon steel sheet (0.08 C–0.4 Mn–0.03 P–0.03 S; wt%) with roughness average (Ra) of 1.6 μm. The sheets were cut into 100 mm by 25 mm rectangular samples and lap-welded using a FSW machine. The weld was located at the centre of a 25 mm overlap with the Al sheet placed on top. The tool had an 11 mm diameter steel shoulder, with a scroll profile to improve the flow of material, and a tapered 3 mm diameter WC 1 mm long probe. The radius of the probes orbital path was 2.5 mm, which produced a swept area of 8 mm diameter on the steel surface. In the results presented here, the translation speed was changed in the range of 60–2000 mm min^{-1}, giving weld times from 0.5–18 s. After a series of feasibility tests, the following parameters were fixed in these experiments, a low rotation rate of 800 rpm (to reduce the heat input), shoulder plunge depth of 0.1 mm (displacement control mode); and zero tilt angle.

The welded joints were sectioned across their centre, for metallographic analysis. Hardness measurements were performed as soon as possible after welding (within 1 h), to avoid natural ageing, across the mid plane of the top Al sheet using a 1 kg load. The mechanical properties of the joints were measured at room temperature by lap-shear tensile testing, with a crosshead speed of 1 mm min^{-1}. Each data point is the average of three tensile tests. The integrated area under each load-displacement curve was used to give a relative comparison of the fracture energy.

Thermal history recording during ABC-FSSW was performed with embedded sacrificial 0.5 mm diameter K-type thermocouples inserted to the edge of the swept area at the joint interface in the bottom steel sheet. Samples for transmission electron microscopy (TEM) were removed from the joint interface using a dual beam FEI Nova NanoLab focused ion beam (FIB) milling system and examined in an FEI Tecnai F30 microscope, equipped with energy-dispersive X-ray spectroscopy (EDS).

3. Results and discussion

Typical cross sections through the Abrasion Circle FSSW welds produced at different travelling speeds are shown in Fig. 1(b) and (c). Three advantages were found relative to the conventional FSSW approaches outlined above: (i) after welding the thickness of the Al was almost equal to that of the parent sheet because a plunge depth of only 0.1 mm needed to be used. As a result, ABC-FSSW joints can bear more load in service compared to welds produced with a pinless tool, where plunge depths > 0.5 mm are required [5,12]; (ii) the effective steel surface abraded by the probe and cleaned of oxide is significantly greater in area than that exposed with a stationary probe; (iii) because of the larger swept area, a bigger bur lock was created between the two sheets than is normally possible in FSSW with a thick gauge. In addition, the process window was very wide. Surprisingly, sound welds with high strengths (Fig. 2) could be produced even at translation speeds as great as 2 m min^{-1}, giving a weld time of only 0.5 s.

Lap-shear test data in Fig. 2(a) shows the effect of travel speed on the failure load and fracture energy. The results are compared to typical FSSW data obtained from welding identical materials with a standard 10 mm diameter pin, or pinless, welding tool (Fig. 2(c) and (d)). From Fig. 2 it can be seen that ABC-FSSW process gives superior joint strengths at short weld times and, more importantly, is a very robust producing high fracture energies with a nugget pullout failure mode over the entire range of travel speeds investigated (Fig. 2(b)). In comparison, except for longer welding times the static FSSWs tended to fail by interface cleavage and exhibit

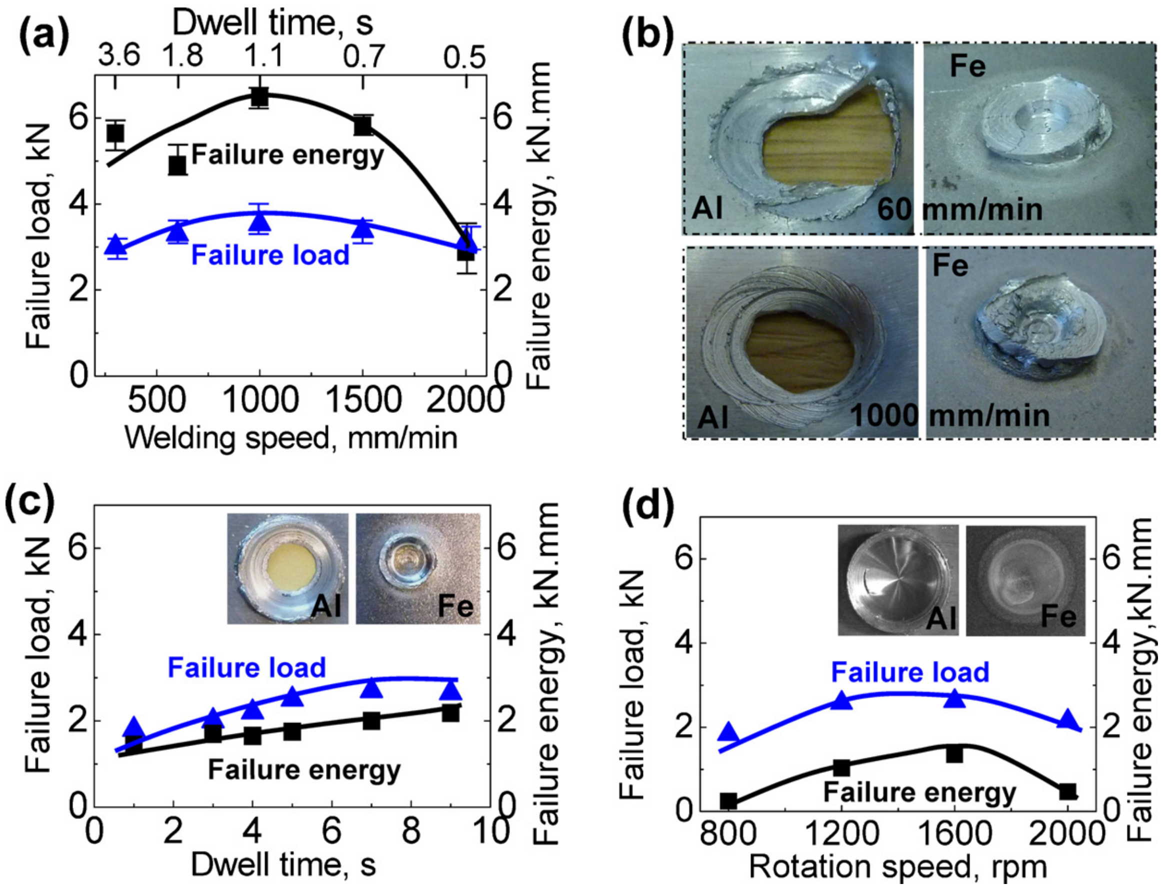

Fig. 2. (a) Lap shear strength and failure energies, plotted against translation speed and dwell time; and (b) typical fractured joints produced by the ABC-FSSW process, compared to similar data for static FSSW with a standard 10 mm diameter tools, (c) 1.4 mm pin, (d) pinless [12,13].

lower fracture energies [12,13]. A maximum failure load of 3.5 kN and fracture energy of 6.5 kN.mm was obtained with a translation speed of 1 m min^{-1}, which gave a weld time of only 1.1 s. Similar failure loads and fracture energies can not be approached in static FSSW welds even with dwell times of over 5 s [12,13].

Because in the ABC-FSSWs failure occurred by nugget pullout, it tended to be dominated by the strength of the Al top sheet in the weld zone. Thus, at too low translation speeds, there was a reduction in failure load as a result of more thermal damage to the Al alloy. In comparison, with too high translation speeds the weld properties started to reduce because the heat input became too low and this resulted in a reduction in the net metallurgically bonded weld area.

In Fig. 3 hardness profiles are shown through the weld centres, immediately after welding, from the mid plane of the Al top sheet. A softened region, relative to the original T4 sheet temper (~80–82 Hv), can clearly be seen. In the case of the high translation speed weld, softening only extends slightly outside of the stir zone giving rise to a heat affected zone (HAZ) ~3 mm in width. In comparison, with a lower welding speed, the HAZ extends further, to a width of about 5 mm, and the minimum hardness level is slightly reduced. The scatter in hardness in the weld zone is caused by steel debris generated by abrasion of the steel sheet (see below).

To understand the nature of the interface formed during welding, between the Al and steel surfaces, the microstructure across the weld join line was characterised by TEM. Compared to the parent materials, the grain structures near the join line were greatly refined from the severe deformation generated by the tool probe. In Fig. 4 fine ~3 μm equiaxed, Al grains and heavily deformed elongated (~15 nm by ~200 nm) ferrite grains and subgrains can be seen either side of the interface. The ferrite grains increased in width to ~100–200 nm at about 0.5 μm from the join line. The Al grains/subgrains exhibited a high level of recovery owning to the weld temperatures exceeding 400 °C (see Fig. 5). In Fig. 5 thermal measurements show that for weld speeds of 600 and 60 mm min^{-1}, the maximum temperatures reached in the weld zone were 420 °C and 450 °C, respectively. However, the material experiences a twin peak in the thermal cycle owing to the circular path of the tool.

Interestingly, a continuous IMC reaction layer could not be seen by TEM and hardly any IMC particles were found attached to the steel-Al interface. This 'clean' interface is clearly responsible for

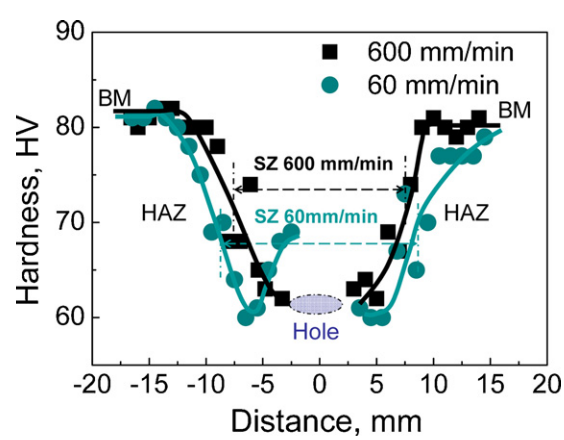

Fig. 3. Micro-hardness profiles in the Al sheet cross-sections of the ABC-FSSW joints at low and high translation speeds.

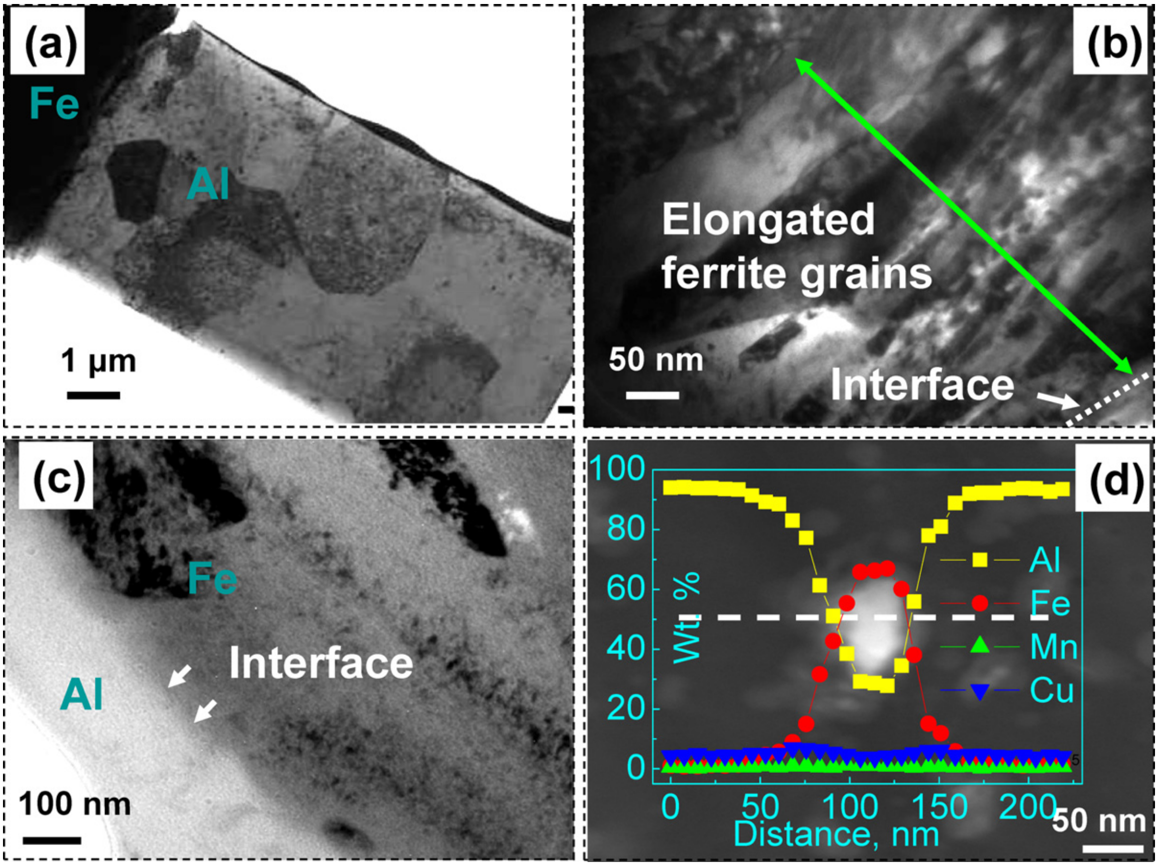

Fig. 4. TEM images from the weld interface (600 mm min^{-1} weld): (a) fine Al grain structures near the join line and (b) fine elongated ferrite grains; (c) high magnification view of the interface showing no evidence of a continuous IMC layer (d) HAADF image of wear debris present in the Al with an EDS line scan across a typical wear-particle (white dashed line).

the excellent weld failure energies, noted above, which have been achieved by avoiding the formation of a brittle IMC reaction layer. However, a considerable volume fraction of wear debris was found within the weld zone in the Al sheet (Fig. 4(a)). The HAADF image (Fig. 4(d)) and EDS line scan suggests that the steel wear particles had partially reacted and consisted of a ferrite core with an intermetallic skin, although the exact IMC phase formed has not yet been identified.

To form a successful friction weld, between dissimilar metals, it is necessary to disrupt the oxide contaminated surfaces of both weld bodies without growing a thick IMC reaction layer [5,8,12,13]. For metallurgical bonding to take place it is also important to ensure the materials are exposed to sufficient temperatures and pressures to achieve intimate contact between the two surfaces [13,16]. When, using a pinless tool, successful welding becomes problematic because the joining interfaces are not cleaned by a third body, or abraded sufficiently by the deforming aluminium under the tool, to remove the contamination layer on the steel surface [5,10]. In pinless FSSW high pressures, temperatures, and long weld times give rise to the spread of bonding from asperities, where the oxide surface is locally damaged on the steel sheet. This allows significant inter-diffusion to occur which leads to the nucleation of

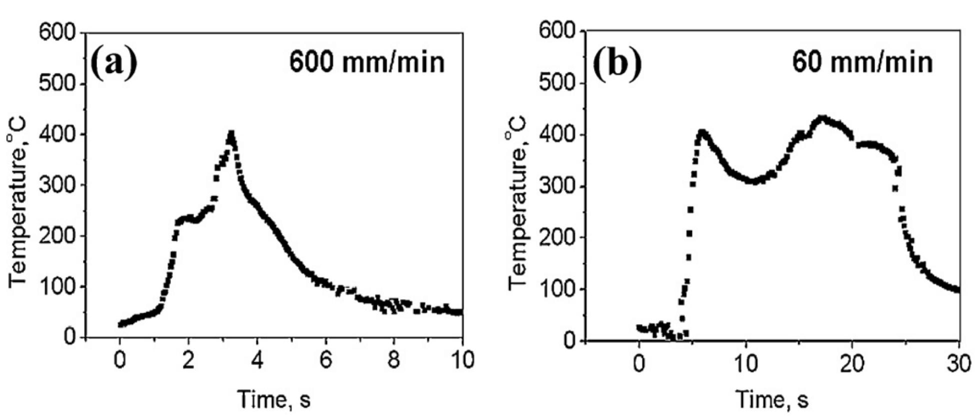

Fig. 5. Thermal history recorded during ABC-FSSW with a high (a) and low (b) travel speed, from a thermocouple inserted to the edge of the swept area at the joint interface in the bottom steel sheet.

intermetallic compounds at the interface. These local reaction centres then spread sideways across the interface until a continuous IMC layer is formed [5,12,13]. With a traditional pin tool a similar situation develops under the shoulder and the aluminium contacting the area directly abraded by the pin is very small. Additional new surface is exposed by the 'burr' generated when the pin penetrates into the bottom steel sheet but, when welding thin gauges, the pin cannot plunge very deeply and the amount of material that is displaced is small [5,12,13].

In contrast, in ABC-FSSW the orbital path of the probe allows the pin to abrade the steel sheet surface removing the oxide layer, while the flow of severely deformed aluminium around the probe, under the hydrostatic pressure generated by the shoulder, refills the pin cavity as it moves. This allows atomically clean metal surfaces, from both weld members, to come into intimate contact and form a metallic bond without the requirement for long contact times at high temperatures. The weld temperature and pressure, needed to form a weld by ABC-FSSW are, hence, mainly determined by the flow requirements of the aluminium alloy necessary to produce defect-free joints and achieve intimate contact with the steel surface over a large net weld area. Thus, a weld can be formed much more rapidly, and at lower temperatures, avoiding intermetallic reaction at the weld interface. In addition, it is worth noting that the severe deformation and fine grain structure that occurs across the interface may also accelerate inter-diffusion between the two materials and allow more effective bond formation at lower temperatures.

4. Conclusions

Abrasion circle friction spot welding – a novel approach to joining dissimilar materials has been examined to produce a high quality joint in a short weld time. The main findings of this study are summarised as follows:

a) High quality friction spot welds were successfully produced between thin Al and steel automotive sheet within a weld time of one second – target time desired by industry.
b) This process provides an effective strategy to create a larger metallurgically bonded weld area, which is achieved by translating the tool through an orbital path so that the probe can be used to clean the steel sheet over a swept area, exposing fresh clean surface during welding.
c) Transmission electron microscopy investigation of the joint interface revealed no intermetallic reaction layer, which is due to the solid state nature of the process and rapid weld cycle. The strong metallurgical bond and IMC free interface contribute to the feasibility of obtaining high weld strengths and failure energies.
d) The dominant factor limiting the joint performance in the welds is the strength of the Al top sheet, which can be reduced by the formation of HAZ damage during welding.

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