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Effect of the Pin Length and the Anvil Insulation on Friction Stir Spot welding Thin Gauge 6111 Automotive Sheet

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ABSTRACT
Friction stir spot welding (FSSW) is a relatively new solid state joining process, with potential applications in the automotive industry. It uses a rotating tool which is plunged and withdrawn without translation, to generate heat frictional, which softens the material and a solid state bond is made between the surfaces of the upper and lower sheets. The main aim of the work presented was to investigate the influence of tool pin length and the application of an insulating back face anvil, to improve the temperature distribution, on the lap shear strength of welds in thin (0.9 mm) 6111-T4 aluminium automotive sheet. It was found that the insulated anvil increased the peak temperature in the bottom sheet by ~ 30°C. Irrespective of the pin length, there was a general reduction in lap shear strength by ~ 15% and an associated change in failure mode when a ceramic anvil was used. It was noted that increasing the pin length from 1 to 1.4 mm also resulted in a similar change in failure mode and a reduction in shear strength from ~ 3.1 to 2.9 kN.

1.0 INTRODUCTION
There are clear drivers in the transport sector towards lower fuel consumption through the introduction of more weight efficient designs involving the substitution of Al and Mg alloys for steel. It is also desirable to reduce the energy requirements of manufacturing processes used in the automotive industry. Sheet steel body panels are conventionally joined by electrical resistance spot welding, which is a cheap and robust process with these materials. However, this welding method is far more difficult to apply to light alloys due to their high conductivity, low strength at high temperatures, and tendency to degrade the electrodes [1]. Alternative solutions under investigation by the automotive industry include self piercing rivets [jag], ultrasonic spot welding [ford], and Friction Stir Spot Welding (FSSW) [ref]. Of these processes ultrasonic spot welding shows some early promise while, although very effective, self piercing rivets have a high associated consumable cost.

Friction stir spot welding owes its origin to the linear friction stir welding (FSW) technique developed in 1991 by TWI [2]. As a joining process it has several advantages over other spot welding methods, including low consumable costs and very low energy consumption, relative to resistance spot welding, and has already been applied in industry by the Mazda Motor Corporation [3-4]. A schematic illustration of the friction stir spot welding process is shown in Figure.1. In FSSW a high speed rotating tool with a probe/ pin is plunged into the upper sheet of a lap joint while an anvil beneath the lower sheet supports the down force. The down force on the rotating tool is maintained for an appropriate time to generate sufficient frictional heat. The heated and softened material adjacent to the tool deforms plastically to very high strains and a solid-state bond between the surfaces of the upper and lower sheets is formed.

A number of groups have investigated optimisation of the FSSW technique by studying the effect of the process variables, including the role of the plunge, depth, rotation speed, hold time, and material, on the joint properties, level of bonding, and weld microstructure [5-15]. The process has also been modelled by the finite element method [11], in order to better understand the metal flow and heat distribution [11]. This work has demonstrated that for a given sheet thickness and material there is an optimum combination of weld time/tool RPM and plunge depth that maximises the degree of bonding.

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and gives the best lap shear strengths. Variants on the FSSW process have also been developed such as the ‘refill’ technique which give a better surface finish [3-4]. However, overall surprisingly little attention has been paid to the effect of the tool geometry and thermal management of the heat distribution during welding. For example, as nearly all the heat is generated by the material flow under the tool shoulder there will be a large thermal gradient between the top and bottom of the weld and insulation of the bottom anvil could potentially result in a more uniform through thickness heat distribution and deeper penetration of the deformation zone into the bottom sheet - possibly improving bonding. In one study Tozaki et. al.[5] have reported that increasing the pin length can improve weld shear strengths in 6061 2 mm thick sheet [5], which agrees with the proposition that the pin needs to penetrate the bottom sheet by ~ 30% to obtain maximum strength [16].

In this paper we have focused on the effect of two main variables in the FSSW process in significantly thinner 0.9 mm thick 6111-T4 automotive sheets, where the shoulder has a greater influence on the bond formed; namely the length of the pin relative to the shoulder plunge depth and the influence of reducing heat loss through the bottom face of the lower sheet by using an insulating material rather than a conventional steel anvil.

Figure 1. A schematic illustration of the friction stir spot welding process with a rotating tool and a stationary backing plate; (a) plunging, (b) welding, (c) retraction of the tool.

2.0 EXPERIMENTAL PROCEDURE

All the spot welds in this study were produced in a commercial aluminium 6111-T4 sheet (Solution heat treated and naturally aged) with a thickness of 0.91 ±0.05 mm - supplied by Jaguar cars. The sheets received no subsequent cleaning or surface preparation prior to joining. Table 1 gives the nominal composition of the 6111 aluminium alloy.

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Si</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt%</td>
<td>0.96</td>
<td>0.73</td>
<td>0.65</td>
<td>0.32</td>
<td>0.18</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 1. Nominal chemical composition in Wt% for the commercial 6111 alloy.

Welding trials were performed using a CS Powerstir friction stir welding machine, on 25 mm by 100 mm strips with an overlap of 25 mm. The weld was produced at the centre of the overlap. All spot welding was carried out under displacement control. The tool shoulder was manufactured from H13 tool steel with a hardness of 45-49 HRC. The tool had a removable 10° tapered triflat threaded pin with a diameter of 4 mm and was made from MP159 material. Four pin lengths were used in this investigation, 1.0, 1.2, 1.4 and 1.6 mm, with the 1.4 mm pin being comparable to tool designs most commonly reported in the literature [13, 7-8]. The tool shoulder was 10 mm in diameter, again selected to be consistent with the majority of previous studies [7-8]. The shoulder was flat, with a machined scroll to increase friction, but as these features were rapidly filled with metal during the first weld the shoulder could be considered featureless. In order to investigate the influence of the through thickness thermal profile generated during the welding cycle, two backing plates were used; a conventional mild steel anvil and an anvil laminated with an insulating 4 mm thick 25 x 20 x 4 mm Macor™ ceramic plate (thermal conductivity of 1.46 W m⁻¹K⁻¹, compared to 52 W m⁻¹K⁻¹ for steel).

The welding process was first optimised for a standard 1.4 mm pin tool with a conventional steel anvil at a rotational speed of 2000 RPM. Thereafter, for all the welds produced in this study, the following parameters were kept constant; plunge rate = 2.5mm/sec, rotational speed = 2000 rpm and dwell time at full plunge 2.5sec, giving a total weld time of ~ 3 sec, although this depended on the pin length as a longer pin slightly increased the plunge time (see table 2). The plunge depth was altered to obtain a constant target shoulder penetration depth of 0.2 mm, with the total tool penetration depth increasing
with pin length. A 0.2 mm shoulder plunge depth was found to give the best results, in terms of shear strength, with the conventional pin length, in agreement with the literature [13]. During welding the temperature at the base of the weld was recorded by embedding a 0.5 mm diameter K type thermocouple vertically in the backing plate. The thermocouple tip was mounted ~0.1 mm proud of the anvil at the centre of the welding spot, ensuring good contact under the welding down force, without distorting its shape. Temperature measurements were repeated at least three times for each welding condition with a maximum scatter of ~ ± 6°C.

For metallographic examination the welded joints were sectioned using a Struers Accutom-2 low speed saw, followed by grinding and finally polishing to an OPS finish. All test sections were etched using Keller’s reagent and analysed by optical microscopy to characterise the degree of bonding and general weld zone microstructure. Tensile lap shear testing was performed on each weld coupon using a constant displacement rate of 2 mm/min, in order to evaluate the mechanical strength of the joints produced. Results were averaged over three samples for each condition.

![Table 2. Summary of the spot welding parameters used in the trials, with and without anvil insulation.](image)

### 3.0 RESULTS AND DISCUSSION

Figure 2 shows the lap shear test results for the samples made with the three different pin lengths (1.0, 1.2, and 1.4 mm) produced with the two different backing plates; a mild steel and insulating ceramic anvil. It should be noted that welds produced with the 1.6 mm pin, and this plunge depth, penetrated through the bottom sheet and were thus excluded from the test matrix. The data for the two anvils shows similar trends as a function of pin length. For both experimental conditions a moderately higher joint shear strength was found using the shortest 1 mm pin. The lap shear strength continued to progressively reduce slightly for the longer pin lengths, but there was only a small difference between the results.

![Figure 2. The effect of pin length and anvil insulation on the FSSW lap weld tensile shear strength.](image)

Although the two data sets showed similar trends, with respect to pin length, the joints produced using a mild steel backing plate consistently exhibited considerably higher tensile shear strengths compared to the welds made using an insulating backing plate. For the strongest 1.0 mm pin length samples the maximum shear strength was 3.11 (±0.23) kN, using a mild steel anvil and 2.67 (±0.32) kN when a ceramic insulation layer was used. This translates to a ~15% reduction in joint shear strength. A Similar reduction in strength was observed when pin lengths of 1.2 and 1.4 mm were used with a ceramic anvil. Overall, the shear strength results compared very favourably with those published in the literature for welds produced in the same alloy with a similar sheet gauge and tool shoulder diameter. Lin et al. [8] report shear strengths of 1.94 kN with a flat shoulder, with higher values of 2.59 kN using concave shoulder and 1.54 mm penetration depth [7]. In comparison, Mitlin et al. [13] report very
similar values to those found here, with a pin insertion depth of 1.8 mm, giving shear strengths slightly over 3 kN, with a marginally larger tool (~11 mm shoulder and ~ 5 mm pin diameter; measured from their micrographs). However, the results in Figure 2 are interesting in that they contradict the findings of Tozaki et al. [5] who found that the weld shear strength increased with pin length in considerably thicker 2 mm sheet FSSW lap joints using a similar tool diameter.

The surprisingly large difference in shear strength seen between the welds produced with a conventional and ceramic anvil are related to higher temperatures being reached with the insulated backing plate, and the possible associated influence of thermal damage, due to overageing, and changes in material flow affecting the bond strength (see below). Figure 3(a) shows the thermal history recorded at the bottom surface of the lower sheet for each pin length using mild steel as the insulation material, whereas in Figure 3(b) a comparison is made between temperatures recorded using a normal and insulated anvil. The maximum temperatures reached were in the range of 360 - 380°C for the conventional anvil material and 390 - 410 °C with the insulated anvil. From the example thermal histories shown in Figure 3(b), for welds produced using a 1.4 mm pin, it can be seen that there is little effect of the ceramic layer on the initial heating rate, which is dominated by the rate of conduction of heat through the sheet thickness. However, there is significant increase in peak temperature reached during the weld dwell time, by ~ 25 °C to ~ 400 °C, and a notable reduction in cooling rate, after withdrawal of the tool, when an insulated anvil is employed.

The typical fracture modes of the different samples after lap shear testing are summarised in Figure 4, along with the average maximum failure loads and ‘failure energies’. In Figure 5 representative load displacement curves are shown for each type of pin and anvil used. The failure energy was estimated from the area under each curve. The appearance of the samples (Figure 4) was found to be consistent with repeated tests. It should be noted that when testing thin material in a lap shear test the sheets bend and the joint moves out of plane subjecting the spot weld to peel forces (or a sheet normal tensile component), resulting in a complex loading condition where the top sheet tears off in the bond area. The bond between the two overlaid sheets is known to involve regions of partial metallurgical bonding, where voids and interfacial oxide are still present, and near full metallurgical bonding, where the oxide is broken up due to the metal flow and few voids remain [13]. The metallurgically bonded area will also vary from weld to weld, depending on the conditions, with a kissing bond frequently being present near the edge of the shoulder contact area. In addition, penetration of the pin causes vertical flow of material from the base sheet close to the pin periphery, and this further deformation generally results in a better metallurgical bond by greater disruption of the interface close to the pin [13].

From comparison of the images in Figure 4 it can be seen that there are two distinctly different failure modes; (i) a failure associated with tearing open the original interface between the two sheets, which leaves the upper sheet largely intact, with the hole in the top sheet related to the pin diameter and the bottom sheet with a relatively clean appearance; or (ii) a failure, where the interface has not debonded, caused by tearing around the circumference of the bonded area, in which the hole diameter in the top sheet is related to the impression caused by the edge of the shoulder and a disc of material remains attached to the bottom sheet. Failure by mode (ii) is associated with a moderately higher maximum shear strength, but a far larger total fracture energy, compared to mode (i) (Figures 4 and 5).
<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Lap shear strength (kN)</th>
<th>Failure Energy (kN.mm)</th>
<th>Top of Bottom Sheet</th>
<th>Top of Upper Sheet</th>
<th>Underside of Upper Sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 mm Steel Anvil</td>
<td>3.27</td>
<td>5.98</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 mm Macor Anvil</td>
<td>2.6</td>
<td>2.84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 mm Steel Anvil</td>
<td>2.98</td>
<td>4.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 mm Macor Anvil</td>
<td>2.62</td>
<td>2.92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4 mm Steel Anvil</td>
<td>2.91</td>
<td>1.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4 mm Macor Anvil</td>
<td>2.48</td>
<td>1.63</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 4.** Examples of the effect of pin insertion depth on failure mode and average strength of the lap shear specimens.

**Figure 5.** Examples of the load displacement curves from lap shear tests on spot welds with different pin insertion depths and anvil materials.

For mode (i) the interface line moves up close to the pin due to vertical flow, to a degree depending on the pin insertion depth, which increases with its length. This leaves an increasing lip around the pin hole with greater pin length in the insulated samples. In some cases the failure can also locally tear through to the bottom sheet where there is better bonding near the pin, following the edge of the weld.
zone (e.g. Figure 4; 1.2 mm pin Macor Anvil). The lower strength Mode (i) failure has been far more commonly observed in other studies than mode (ii) and tends to dominate at thicker gauges [5-6].

As it does not involve debonding of the interface, the second failure mode is associated with a higher joint strength and energy. The debonding failure mode (i) can be seen to occur for both insulated and uninsulated welds produced with the longest 1.4 mm pin length. For all other pin lengths the insulated welds failed by mode (i), whereas the welds produced with the normal steel anvil failed by mode (ii). These two failure modes result from competition between the strength of the bond line between the top and bottom sheets and the reduction in strength of the top sheet due to thinning at the edge of the shoulder region, reducing the ligament width at the periphery of the weld, and from softening of the material due to HAZ damage from the weld thermal cycle - leading to the surprising conclusion that an insulated anvil appears to reduce the interface bond strength. For the non-insulated steel anvil tests it can be seen there is a consistent trend of change in fracture mode with pin length and shear strength/energy (Figure 4). The strongest weld with the short 1 mm pin fails by mode (ii) leaving a fully attached disc from the top sheet on the bottom and the interface clearly does not fail. With the longest 1.4 mm pin the sample fails by mode (i) due to interface debonding between the sheets with a lip remaining round the pin hole on the bottom sheet caused by greater vertical flow of the bottom sheet material with the longer pin. For the intermediate 1.4 mm pin length, it can be seen that the test coupon has failed in a mixed mode (i & ii) with the top sheet partially debonding before tearing around the periphery of the shoulder indent, leaving a bent partially attached disc on the bottom sheet pulled out from the top sheet.

Figure 6 shows low magnification optical micrographs of the cross sections of the FSSW samples for different pin lengths and the two different anvil insulation conditions. From comparison of these figures it can be seen that weld zones are quite similar in size and shape for all the welding conditions, although the plasticised zone does not extend as far down into the bottom sheet with a shorter pin length. There is also some indication that the base of the TMAZ is slightly wider in the case of the welds produced with back face insulation. Because the shoulder plunge depth was kept the same, there is not a great variation in the thickness of the top sheet ligament width at the edge of the shoulder contact area. For the two welds that failed by mode (ii) (1.0 and 1.2 mm pin length normal anvil Figure 5 (a) and (c)) it could be argued that the ligament width is slightly less for the weaker 1.2 mm pin weld. However, this might just be due to scatter in the local sectioning of a single weld out of several used for the shear test data. Indeed, the difference in strength for these two samples is more probably caused by the mixed mode failure in the 1.2 mm pin sample, discussed above, involving partial debonding of the interface, which leads to a higher stress on the remaining attached area.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Bond Length (mm)</th>
<th>Metallurgical bond length (%)</th>
<th>Partial metallurgical bond length (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 mm Steel Anvil</td>
<td>2.7</td>
<td>73</td>
<td>27</td>
</tr>
<tr>
<td>1.0 mm Macor Anvil</td>
<td>2.4</td>
<td>42</td>
<td>58</td>
</tr>
<tr>
<td>1.2 mm Steel Anvil</td>
<td>2.6</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>1.2 mm Macor Anvil</td>
<td>2.5</td>
<td>72</td>
<td>28</td>
</tr>
<tr>
<td>1.4 mm Steel Anvil</td>
<td>2.5</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>1.4 mm Macor Anvil</td>
<td>2.4</td>
<td>20</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 3. Estimated total bond length, radial distance, (full and partial metallurgical) along the sheet interface for the different tool pin lengths and anvil materials.

In Figure 7 higher magnification images are shown of the bond line for all the samples. When a steel anvil was used the sheet interface was found to consist of three types of bond; (i) a kissing bond in the non-contact area at the start of the joint interface of the two sheets, which has little mechanical strength and is ignored in Table 3, (ii) a partial metallurgical bond and (iii) a full metallurgical bond. The partial metallurgical bond was assumed to be where there are still continuous oxide patches along the bond line. A full metallurgical bond was considered to have formed where no continuous line of oxides could be seen along the bond line. The estimated lengths of each bond type are presented in Table 3 for all the welding conditions. In all cases where a ceramic anvil was used is the interface between the two sheets was dominated by a partial metallurgical bond, whereas without the insulation and with a shorter pin length a greater proportion of the join line had a full metallurgical bond.

Overall the variations in average shear strength seen are relatively small, making it difficult to determine subtle microstructural differences, and, given the scatter, care should be taken in over interpreting these results. However, of clear significance is the change in failure mode between the
samples, which implies a poorer interface bond is formed under the shoulder region for all the specimens that failed by mode (i). Closer investigation of the bond line (Figure 7) suggests this is associated with different levels of metallurgical bonding at the interface between the two sheets (Table 3). The weaker mode (i) failure occurred with the longest pin length studied (1.4 mm) and for all pin lengths when back face insulation was used. For the longest 1.4 mm pin this may be associated with the need to eject a greater volume from under the pin during the initial plunge, which causes more material to rise vertically near the pin and thus changes the flow behaviour, favouring a better bond near the pin at the expense of bonding along the more general and greater contact area further out under the shoulder. In the case of the insulated welds, the higher temperature was found to lead to a reduction in the weld down force during the dwell period by ~ 15%, which may be partially responsible for a poorer bond. In addition, a lower shear strain gradient would have been induced across the bond line because of the higher temperature in the material in the bottom sheet, which could influence the break up of oxide at the interface. Hardness measurements also showed a small difference, of ~6 HV at the top and ~8 HV at the bottom surfaces, between samples welded with the steel and the ceramic anvils. Therefore, a combination of poorer bonding and a slight reduction in yield strength due to over ageing maybe responsible for the reduction in shear strength seen for the ceramic anvil welds.

It is further interesting to compare the observation that a longer pin (within the range studied) reduces the shear strength to the results of Tozaki et al. [5], who found the opposite was true using a tool with same shoulder diameter. However, this work was carried out with greater pin lengths in considerably thicker 2 mm material. This results in a higher weld aspect ratio with the flow under the outer edge of the shoulder penetrating to a relatively shallower depth and having less influence on interfacial bonding of the sheets. In Tozaki et al’s [5] work the fracture path generally followed the interface between the two sheets, for all conditions, always causing interface debonding under the shoulder and was thus heavily influenced by the vertical flow of the bottom sheet induced by the pin. Under such conditions the material displaced by the pin is very important in controlling the bond strength and a longer pin is clearly beneficial.

4.0 CONCLUSIONS

The effect of pin length and anvil insulation on the lap shear strength of FSSW welds produce in thin (0.91 mm) 6111-T4 aluminium automotive sheet has been studied. For a constant shoulder plunge depth the, pin length was varied in the range 1.0 - 1.6 mm. For the welding conditions used. It was found that the temperature at the base of the bottom sheet increased through the application of an insulated anvil from ~370 to 400°C. Irrespective of the pin length, there was a general reduction in lap shear strength by ~15 % and a change in failure mode associated with a lower interface bond strength under the shoulder region when a ceramic anvil was used. It was noted that, with the constant shoulder plunge depth of 0.2 mm used, increasing the pin length from 1 to 1.4 mm lead to a small reduction in shear strength from ~3.15 to 2.9 kN with a normal steel anvil, which also resulted from a similar change in failure mode.

Acknowledgements

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Figure 6. Images of the FSSW joint cross sections in the 6111-T4 sheets for different pin lengths, with and without backing plate insulation; (a) 1.0 mm pin steel anvil, (b) 1.0 mm pin ceramic anvil, (c) 1.2 mm pin steel anvil, (d) 1.2 mm pin ceramic anvil, (e) 1.4 mm pin steel anvil, (f) 1.4 mm pin ceramic anvil.
Figure 7. Detailed images of the joint bond lines from the FSSW in the 6111-T4 sheet for different pin lengths, with and without backing plate insulation, (a) 1.0 mm pin steel anvil, (b) 1.0 mm pin ceramic anvil, (c) 1.2 mm pin steel anvil, (d) 1.2 mm pin ceramic anvil, (e) 1.4 mm pin steel anvil, (f) 1.4 mm pin ceramic anvil.
References