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Feasibility Study of Short Cycle Time Friction Stir Spot Welding Thin Sheet Al to Ungalvanised and Galvanized Steel

^aYingchun Chen, ^bHaddadi Farid and ^cPhil Prangnell*

Materials Science Centre, School of Materials, The University of Manchester, Grosvenor Street, Manchester, M1 7HS, UK

^aYingchun.Chen@manchester.ac.uk, ^bFarid.Haddadi@postgrad.manchester.ac.uk

^cphilip.prangnell@manchester.ac.uk

Abstract: Dissimilar friction stir spot welds (FSSW) have been produced between 6111-T4 aluminium sheet and non-galvanised (DC04), hot dipped galvanized (DX54Z) or galv-annealed (DX53ZF) steel sheets, to investigate the feasibility of producing Al to steel welds with a industrially desired weld time of ~ 1 second and acceptable mechanical properties. Three approaches were explored, involving high and low friction FSSW tools, with and without a pin. The tensile strengths, fracture paths and microstructure of the joints were examined. Maximum failure loads, of 2.8 kN for Al-DC04, 3.2 kN for Al-DX54Z, and 2.4 kN for Al-DX53ZF, were obtained in lap shear tests and optimised joints were produced that failed by nugget pullout. The effects of plunge depth/rate, rotation speed and top-sheet material (Al or Steel) on the tensile strength, material flow, and fracture location of the FSSW joints, formed with a target time of 1 second, are discussed.

Keywords: Friction stir spot welding; 6111 aluminum alloy; steel; zinc galvanized; microstructure; mechanical properties.

Introduction

There is considerable interest in the manufacture of multi-material automotive body structures, combining aluminium and steel alloys, as a cost effective route to more mass efficient designs. Spot methods for joining aluminium alloys to steel sheet, therefore, have potential for major applications in the automobile industry, where high strength and low weight are desirable. Resistance spot welding (RSW) is currently the dominant joining technique employed in vehicle assembly because it is a fast and easily automated process. However, high energy consumption and the requirement for frequent electrode maintenance has been a major barrier to the adoption of RSW in aluminium welding [1]. Moreover, in aluminium to steel welds, any welding process where a liquid phase is formed is prone to the rapid formation of brittle intermetallic phases, which can seriously deteriorate the mechanical properties of the joint [2].

Friction stir spot welding (FSSW) is a relatively novel technology expected to rapidly expand as an alternative method for joining aluminium body structures in the automotive industry [3]. The process has significant advantages for joining light weight multi-material structures, involving aluminium to steel welds, as it requires far less energy than RSW (~3 kJ as opposed to ~ 50 kJ/weld [4]) and, more importantly, reduces intermetallic formation by avoiding liquid phase reactions. However, current literature shows that the long weld cycle time is a critical disadvantage that is inhibiting the widespread adoption of FSSW for joining dissimilar materials in car manufacturing [5-14]. Published optimum cycle times for dissimilar FSSWs are currently too long for many industrial applications, being at least 3-5 seconds, compared to less than 1

second for RSW. Shortening the weld cycle is thus necessary to allow wider scale implementation of FSSW in industry. A reduced weld time is also desirable to restrict the growth of intermetallic compounds at the interface between the two materials.

In this study, preliminary results are presented from an investigation into the feasibility of producing Al to steel welds in ~ 1 mm thick sheets with a target cycle time of around 1 second and acceptable mechanical properties. For dissimilar welding hard and soft material combinations, welding is normally carried out from the softer aluminium side and two main approaches that have been adopted; i) using a pin tool that penetrates the bottom steel sheet [15-17], or ii) using a short, or pinless, tool that only penetrates the softer aluminium top sheet [18]. Approach i) has been explored most successfully by North et al. [17] with thicker 1.8 mm sheet and benefits from the generation of a ‘bur’ on the steel, which creates a mechanical locking feature with the aluminium sheet, as well as exposing clean surface that can metallurgically bond with the aluminium. The second approach has been most widely studied by Fukumoto et al. [18] and probably involves creating a bond by rotating the deforming disc of aluminium, under pressure, below the tool, so that it is abraded against the stationary undeforming steel bottom sheet surface. However, to date the bonding mechanism has not been fully clarified with this technique. Here, we have also examined a third possibility - involving welding using a pinless tool from the steel side, which has the potential advantage of increasing the rate of heat generation and the pressure at the weld interface. For each approach the effects of plunge depth/rate and rotation speed, on the material flow and joint performance, with a target time of 1 sec, are discussed.

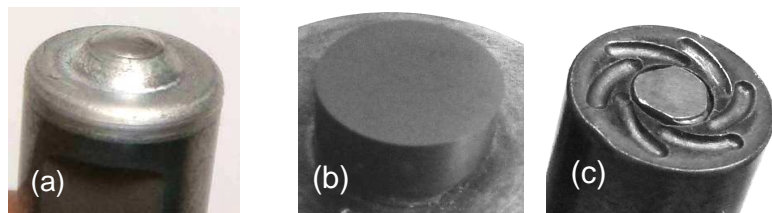
Experimental

The materials used in this study were a 0.93 mm thick 6111-T4 aluminum alloy sheet, which was welded to three different 1 mm thick steel sheets; (i) an uncoated formable steel, DC04, (ii) a hot dip galvanized steel, DX54Z, and (iii) a galv-annealed, DX53ZF, material. The materials were all supplied by Jaguar Land Rover and Corus UK. The standard compositions of the base materials employed in this study are summarized in Table 1. The welds were produced at the lap centre, on 25 mm by 100 mm strips with an overlap of 25 mm. Welds were produced with a simple WC pin tool and two kinds of pinless tool (shown in Fig.1), a low friction flat tool (made of WC) and a high friction wiper tool (made of tool steel), all with a 10 mm diameter shoulder. The flat tool had a CVD diamond coating to reduce sticking of aluminium to the surface of FSSW tool, which can cause pullout of the Al nugget during welding [18].

Alloys	Chemical compositions (wt %)												
	Al	C	Cu	Cr	Fe	Mg	Mn	Mo	Si	Ti	Zn	P	S
Al 6111	Bal.	<0.01	0.75	<0.01	0.25	0.75	0.2	<0.01	0.69	0.04	0.02	-	-
DC04	-	0.08	-	-	Bal.	-	0.4	-	-	-	-	0.03	0.03
DX54Z	0.01	0.01	-	-	Bal.	-	0.3	-	-	0.125	-	0.03	0.035
DX53ZF	0.01	0.03	-	-	Bal.	-	0.3	-	-	0.125	-	0.06	0.035

Table 1. Chemical Compositions of the sheet materials.

Fig.1 Images of the three tool designs investigated (a) a WC pin tool, (b) a WC CVD diamond coated pinless tool, (c) a tool steel wiper tool.



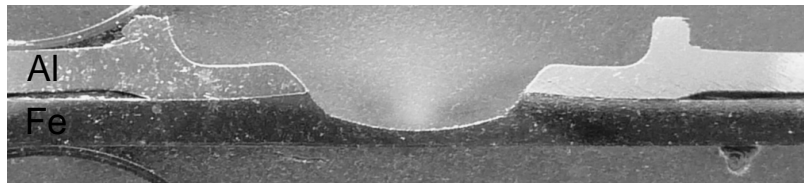
The wiper tool had six flutes to improve coupling with the sheet surface. In this study the relative short dwell time of one second was fixed and other parameters were varied to explore the process window for forming high quality defect free joints with an optimised failure load for this target time. After a series of feasibility tests, the following experimental parameter ranges were selected; rotation speed of 750 -2000 rpm, plunge rate of 10-100 mm/min, retraction rate of 5-50 mm/min and plunge depth of 0.3-0.8 mm. Position control mode was used in all the trials. The mechanical properties of the joints were measured by tensile shear tests carried out at a crosshead speed of 1 mm/min. The areas under the load-displacement curves were calculated to allow comparison of the relative failure energies. The weld interfaces were examined using a Philips XL30 FEGSEM scanning electron microscopy (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDS) analysis system. Fracture surfaces were analysed by X-ray diffraction (XRD) to identify any intermetallic phases formed. Metal flow was investigated by using a split aluminum top sheet consisting of two similar 6xxx alloys (6082 and 6111) of the same thickness, but with different copper contents to allow differential etching.

Results and Discussion

Pin tool

An example of a cross section through a typical weld produced with the DX54Z steel with the pin tool is shown in Fig. 2. Prior to this work it was anticipated that this approach could be exploited to produce very rapid welds, by abrading the bottom steel surface and creating a burr lock between the two sheets through deformation of the harder steel base material. Full results from this work are not presented here, due to a lack of space, but no real advantage was found relative to using the pinless tool design proposed by Fukumoto et al. [18] because of the thin gauge of the steel sheet. This meant that, even when virtually penetrating the bottom sheet, only a very small burr could be formed. In terms of a locking feature, any burrs generated were thus mechanically ineffective. Furthermore, the area abraded and consequently cleaned by the pin was only a small proportion of the tool footprint and good adhesion across this small area did not contribute greatly to the weld strength. Here, we will therefore focus on the other two flat approaches.

Fig. 2. Cross section through a typical weld produced with the WC pin tool.



Pinless tools – Soft Sheet Up

Al 6111 to uncoated Al-DC04 steel: When welding with the aluminium alloy as the top sheet, using the two pinless tool designs, the parameter range for producing defect free welds with the uncoated steel was quite wide. In this context, by “defect free” we mean welds not containing obvious cracks in the aluminium top sheet. Relatively high plunge and retraction rates of around 1.7 mm/s and 0.8 mm/s could, therefore, be selected in order to minimise the full welding cycle. This meant that with a fixed dwell time of one second the weld cycle was completed in less than ~ 2 seconds. Tensile shear test data in Fig.3 shows the effect of rotation speed and plunge depth, in the range of 800 to 2000 rpm and 0.5 to 0.8 mm, respectively, on the failure loads and failure energy, with a fixed one second weld dwell time. The typical failure modes of fractured samples are shown in Fig. 4, where it is evident that the rotation speed and plunge depth have a significant effect on the tensile shear failure load and energy absorption. The failure loads showed a sweet spot with peak values of ~ 2.8 kN, centred around the location of a rotation speed of 1600 rpm and plunged depth of 0.6 mm. This strength level compares favourably with 6111 Al to Al welds in the same gauge, using an identical tool diameter, which have a maximum

shear strength of ~ 3.4 kN [19]. Too low a rotation speed, or lack of a sufficient plunge depth, lead to a relatively low failure load because the heat generation and flow of the aluminium at the weld interface was not sufficient for bonding the two materials. On the other hand, over plunging, or too high a rotation speed, lead to a reduction in failure load because of either excessive thinning of the aluminium sheet, or reaction between Al and Fe due to too much heat generation (see below). Compared to the joints welded by the flat low friction WC tool, the joints welded with the wiper tool resulted in considerably higher failure loads. This resulted from better coupling between the tool and aluminium sheet, surface which lead to more rapid heat generation and greater material flow, within the one second dwell time. These results indicate that the tool material and surface geometry play an important role during rapid FSSW and better joint failure loads can be obtained in short weld times with a high friction tool when the processing window is in the optimum range.

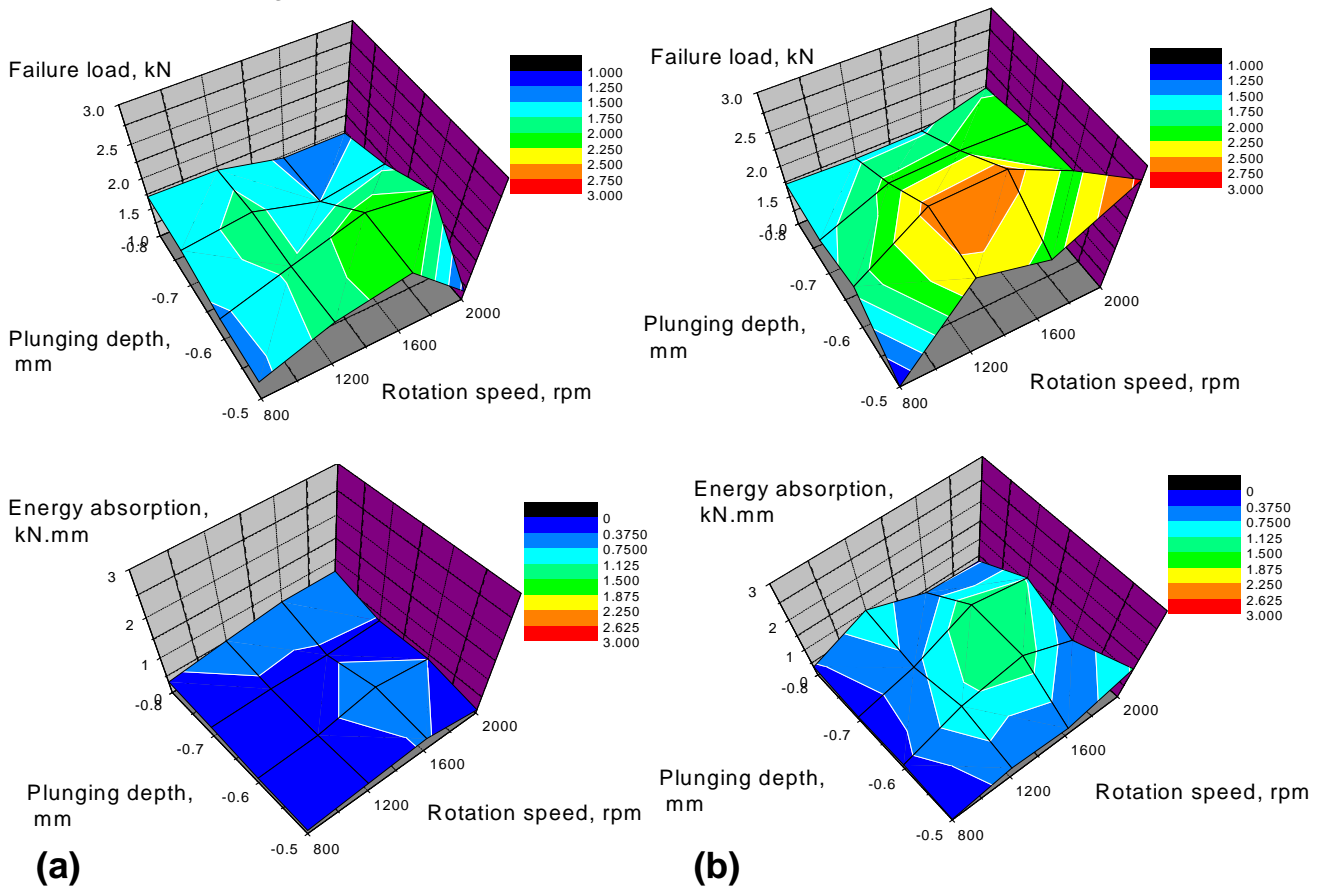


Fig.3. Failure load and failure energy, plotted against plunge depth and rotation speed, for the 6111-T4 Al-DC04 steel welds produced using; (a) a WC low friction tool and (b) a high friction wiper tool.

It can be seen from Fig. 3 that the variation in failure energy gave a similar trend to the shear strength results, with the optimum conditions corresponding to the same welding parameters. As expected (e.g. [20]) the failure energy was related to the failure mode of the joints (Fig. 4). Two typical failure modes were observed; a low energy interfacial fracture at the join-line, and a partial nugget pullout failure. The nugget pullout failure mode resulted in significantly higher energy absorption, due to a more progressive failure that results from tearing through the top sheet around the weld area. This manifests itself in a larger displacement prior to separation of the two sheets. While the welds produced with the optimised conditions, using

the high friction wiper tool, showed nearly a full nugget pullout fracture (Fig. 4b) the welds made with the low friction WC tool exhibited only the initiation of a pullout failure, with a correspondingly much lower failure energy (Fig. 4a).

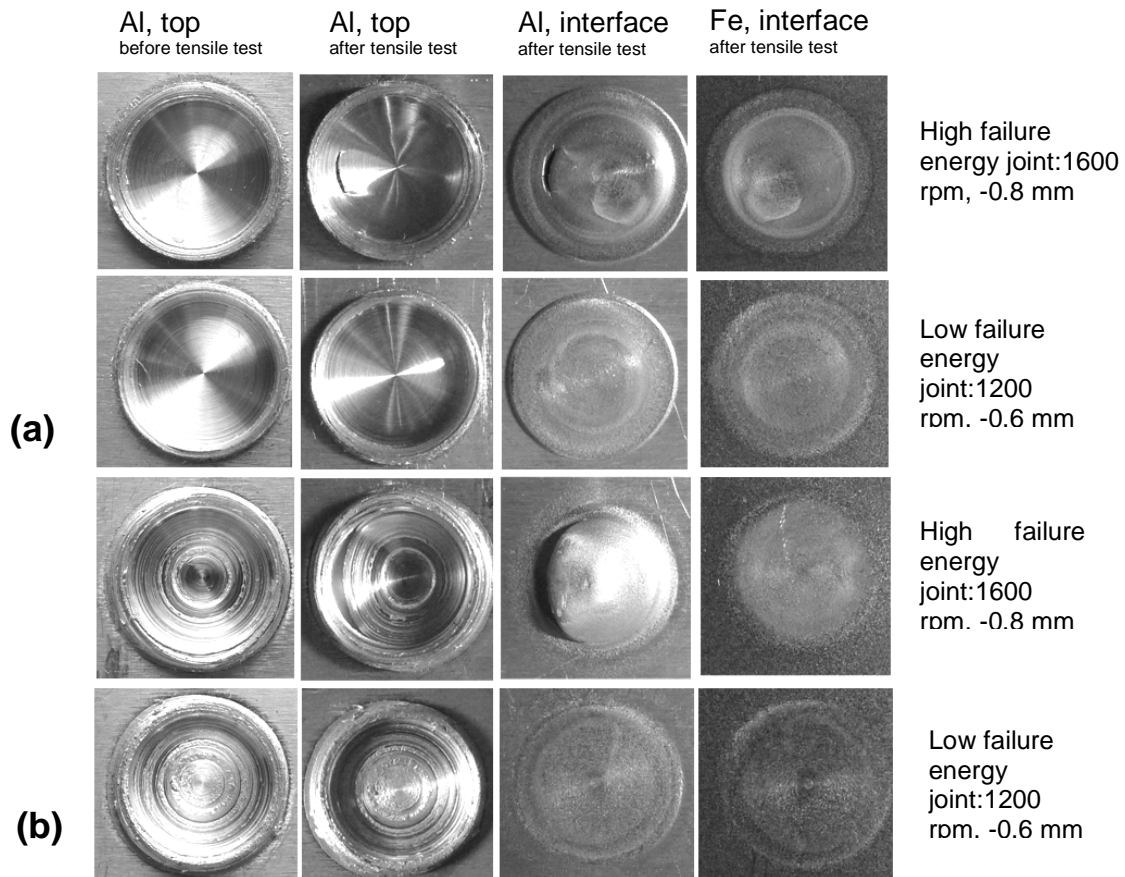


Fig.4. Appearances of the weld top surface and typical fracture surfaces of 6111-T4 to steel DC04 welds produced using: (a) a low friction WC tool and (b) a high friction wiper tool.

An SEM micrograph and EDX map of a weld interface, for the Al-uncoated steel joints, is shown in Fig. 5. The images show that only a very thin, less than $0.5 \mu\text{m}$, intermetallic compound (IMC) layer had formed at the interface because of the short weld time. For example, more typically $1-2 \mu\text{m}$ IMC layers have been reported in similar FSSW welds with cycle times of three seconds [9]. X-ray diffraction spectrums obtained from the fracture surfaces indicated that the IMC layer was mainly composed the FeAl_3 phase. The formation of FeAl_3 , prior to the formation of any other iron aluminide, is consistent with thermodynamic calculations, which show that among the compounds present in the Al-Fe binary system (e.g. FeAl_3 , Fe_2Al_5 , FeAl_2 , FeAl and Fe_3Al) FeAl_3 is the most stable and has the highest free energy change on formation [21].

Al 6111 to Zinc Hot Dipped Coated Steel: Compared to the DC04 un-coated steel welds, FSSW of 6111 Al to the zinc hot dipped steel DX54Z gave a very narrow process window for defect free joints. With the Zn coated steel the aluminium sheet tended to stick to the steel tool leading to tear out of the weld area during retraction (see Fig. 6). From Fig. 6 it can be seen that this was associated with a shear failure at the edge of the deformed aluminium disc under the tool and resulted because, with a Zn coating, there was not enough friction between the aluminium sheet and the steel substrate.

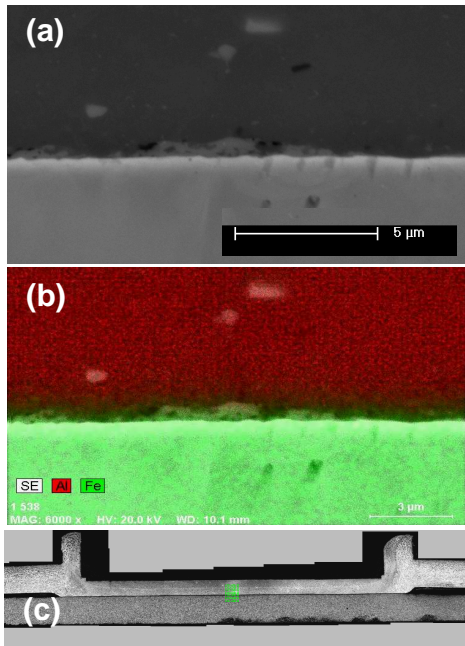


Fig.5. SEM images from the interface of a FSSW joint welded by the WC tool at 2000 RPM and a plunge depth of 0.7 mm; (a) SE (b) with an overlaid EDX Al and Fe elemental map and (c) a general cross section view of the weld.

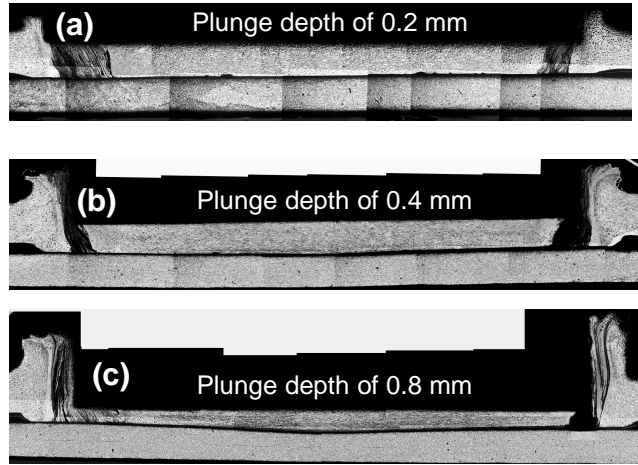


Fig.6. Examples of defect formation in the Al sheet with increasing plunge depth when welding Al to a Zn coated steel, using a rotation speed of 2000 rpm and too high a plunge rate of 150 mm/min; with the low friction WC tool.

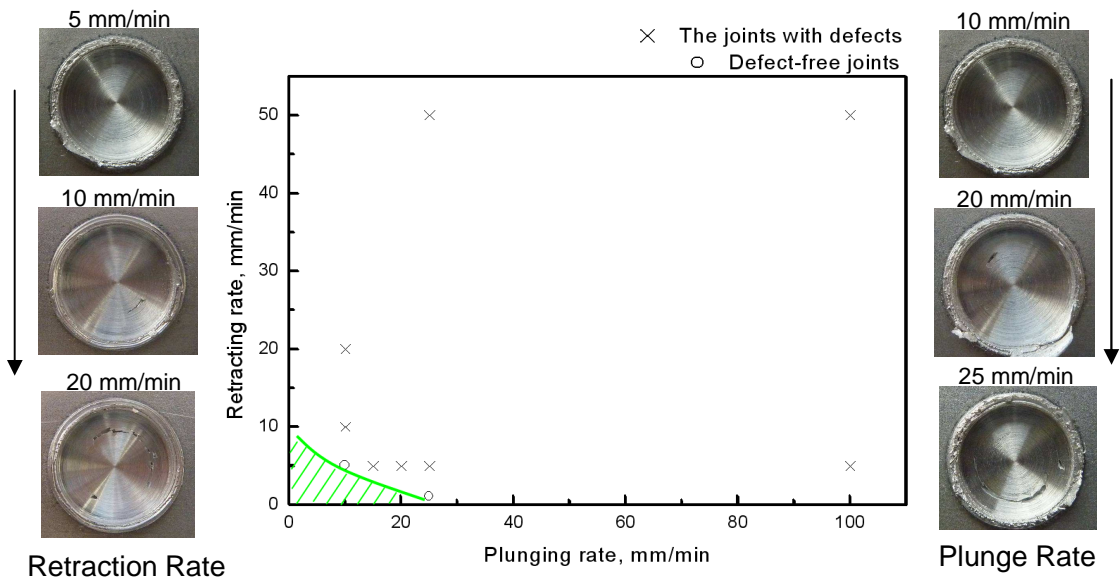


Fig.7. Effect of plunge and retraction rate on the process window of FSSW of Al-6111 to DX54Z steel using a low friction WC tool, flat tool, with a rotation speed of 2000 rpm and a plunge depth of 0.5 mm.

As a result the whole aluminium disc under the tool tended to rotate, leading to an extreme shear gradient and shear localisation between the disc and surrounding sheet. It was, therefore, not possible to use the high friction wiper tool for this material combination. After a serial of trials

defect free (crack free) welds could be produced with the low friction CVD diamond coated tool, once it was realised that that the plunge and retraction rate was a key factor in obtaining a defect free joints, as shown in Fig.7. Shear crack, defect-free, joints could be made with plunge and retraction rates of less than 0.17 and 0.08 mm/s, marked on the process map in Fig. 7. However, this significantly increased the weld cycle time. The following study of the effect of rotation speed and plunging depth on the failure load of spot welds produced with a dwell time of 1 sec was thus based on optimised maximum plunge and retraction rates of 10 mm/min and 5 mm/min, respectively, giving a weld time of ~ 10 seconds!

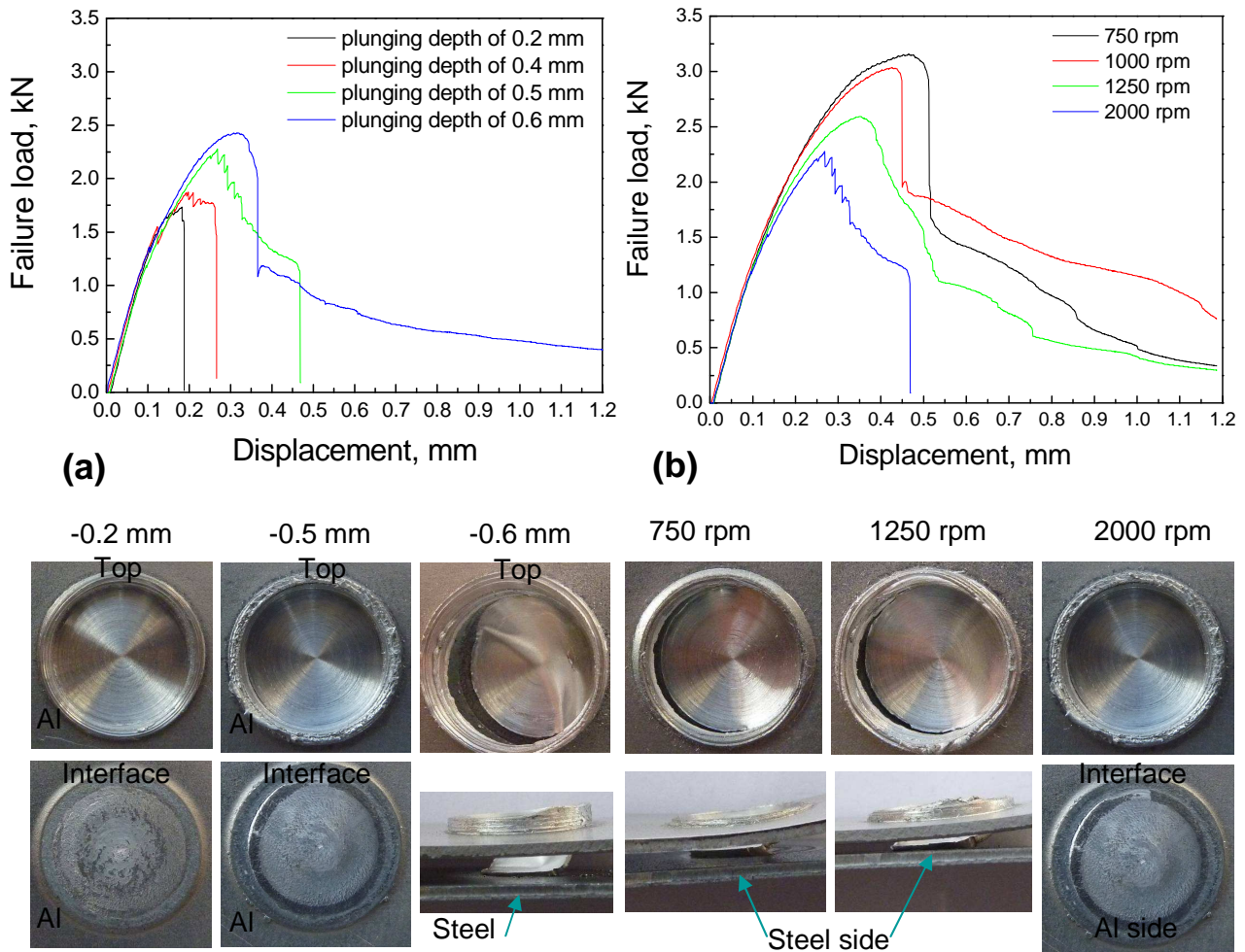


Fig. 8. Failure load plotted against plunge depth (a) and rotation speed (b) for the aluminium 6111 to DX54Z steel welds produced using WC low friction tool, including examples of the weld fracture surfaces after lap shear testing.

The tensile shear test results of joints welded with different plunge depths and rotation speeds are shown in Fig.8. When the optimum rotation speed or heat input was selected, a joint with considerable failure load and nugget pullout fracture mode can be obtained as shown in Fig.8, but the weld cycle time is now far too long.

As expected, the data shows that the plunge depth and rotation speed again have a significant effect on the tensile shear failure load and failure energy. The shear test results show that increasing the plunge depth caused a significant improvement in failure load and energy,

with a maximum of 2.5 kN, occurring at a depth of 0.6 mm and a rotation speed of 2000 rpm. For similar reasons to those discussed above, involving competition between an increase in temperature encouraging bonding and top sheet thinning, the fracture mode of the joints also changed from interfacial fracture to pullout with increasing plunge depth. However, an increase in rotation speed in the range studied was found to have a negative influence on the failure load. With decreasing rotation speed from 2000 to 750 rpm the failure load increased from 2.5 kN to a maximum of 3.2 kN, which is close to that typically seen for an Al-Al weld in 6111 with the same sheet thickness and tool diameter [19]. This probably occurs because at the low plunge and retraction rates, necessary to avoid shear defects, the heat input to the joint interface is too high, which may cause a thicker brittle intermetallic layer to develop at the weld interface. However, this behaviour, and in particular the role of Zn which melts in the welding process [5], needs further investigation.

Al 6111 to Galv-Annealed Coated Steel: With a one second target dwell time and the aluminium as the top sheet, no combination of welding parameters could be found with either pinless tool design that allowed the 6111 Al sheet to be successfully welded to the DX53-ZF galv-annealed steel. Within the range of parameters studied, the aluminium disc under the tool always either developed a shear crack, or attached to the tool and was pulled out when the tool was retracted.

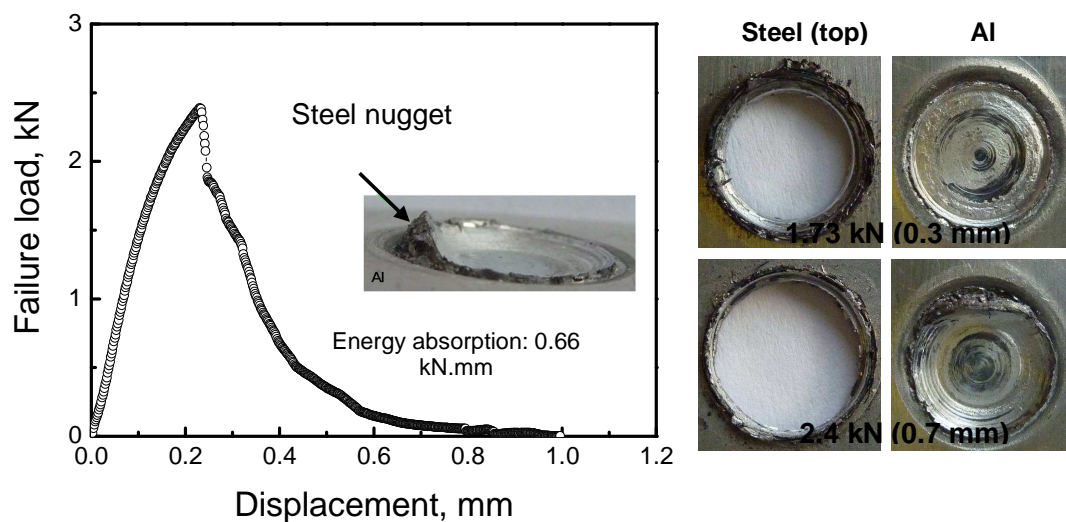


Fig.9. Typical loading curve and appearance of the fracture surfaces of FSSW joints between the DX53ZF steel and Al 6111 when welded from the steel side, showing pullout of a steel nugget.

Pinless tool – Hard Sheet Up

Al 6111 to Galv-Annealed Coated Steel: Owing to the poor results obtained above, when we attempted to weld the 6111 Al sheet to the DX53-ZF galv-annealed steel sheet, a further study was performed where welding was carried out with the higher melting point galv-annealed steel sheet placed on top of the aluminium. This necessitated the use of the simpler WC tool which was plunged into the steel top sheet. With this welding configuration surprisingly high strength joints were obtained with a failure load in the lap shear test of ~ 2.5 kN. Fig.9 illustrates a typical load-displacement curve and the fracture surface of a FSSW joint when the top sheet is steel, showing pullout of a steel nugget. When the welding tool is plunged in to the steel sheet surface more rapid heating and a higher temperature is generated, as this is normally limited by the rapid softening of aluminium, which has a much lower melting point as it approaches its liquidus temperature at the tool contact surface. In this configuration welds were possible with shorter

plunge and retraction times and this route clearly has potential for allowing a shorter welding cycle with more difficult material combinations. However, when the steel was used as the top sheet, two issues were encountered. One was a sticking problem between the steel top sheet and the surface of FSSW tool, and the other was the collapse of the softer bottom Al sheet, because of the higher pressure and temperatures reached during welding. However, these problems could be addressed by further optimisation of the welding parameters and the selection of a more suitable tool/coating material.

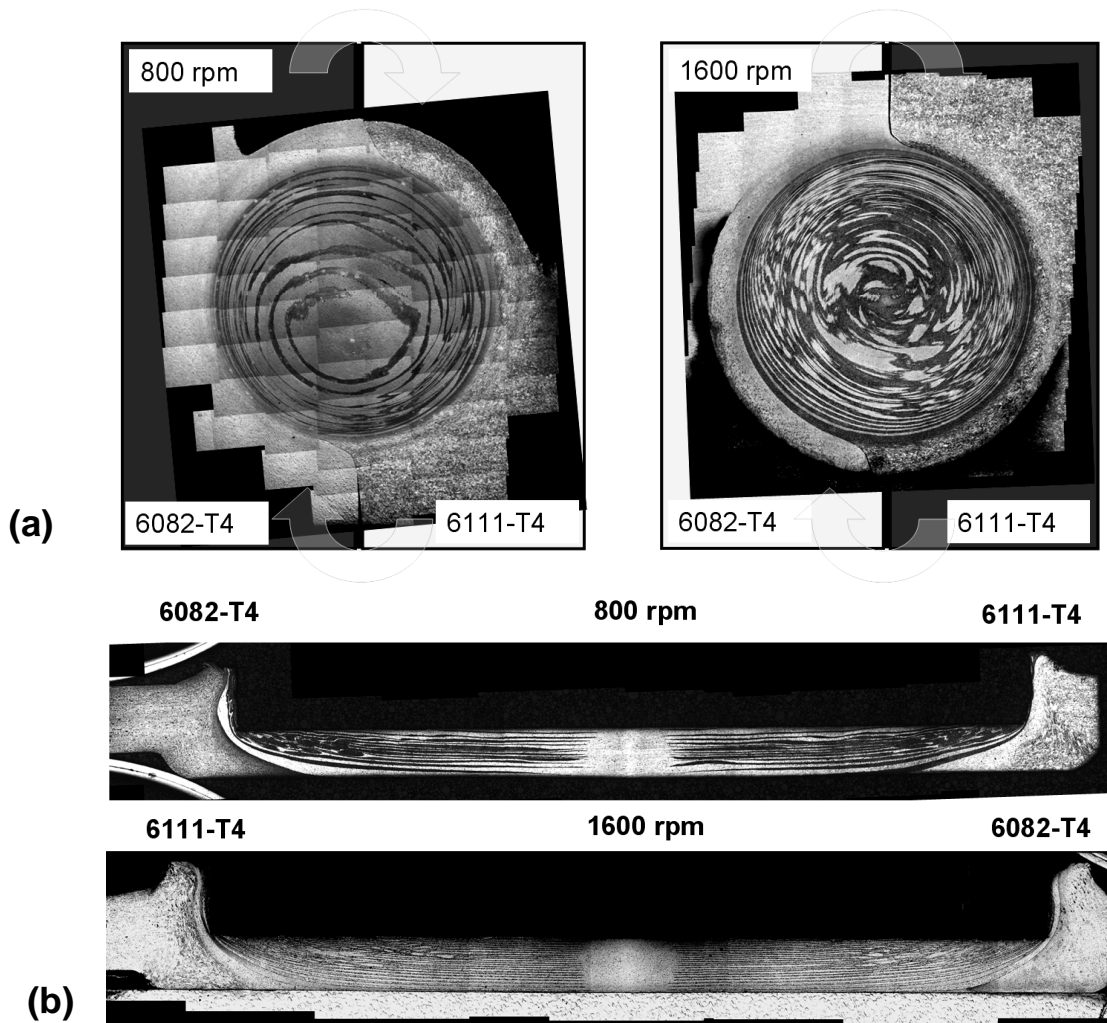


Fig.10. The flow behaviour observed using dissimilar Al-alloy welds; (a) the top plan view and (b) in cross section.

Material Flow in FSSW of Hard –Soft Materials

Because of the success of the simple pinless tool design in producing reasonable weld strengths within ~ two seconds, with uncoated steel, here we have attempted to study the flow behaviour of the aluminium top sheet in order to better understand the level of coupling that typically occurs with the tool and the welding process. This was investigated by welding with a split top sheet consisting of two Al-alloys (6111 and 6082) with similar mechanical properties, but different copper contents, to allow the flow of the materials in the weld to be identified by differential etching. Fig.10 shows the flow pattern close to the top surface in plan view and in the

weld cross section, with different rotation rates, using the low friction flat tool. The material flow shows evidence of a spiral like trace with intermixing of both adjoining sheets. A higher rotation speed leads to more rotations of the material below the tool, as expected. Moreover, the spacing of the intercalated materials is least near the boundary of tool, where the highest linear tool surface speed is reached. Indeed, in the cross section view it is clear that the centre of the weld is virtually static with a dead zone apparent where no mixing occurs. From the cross sections of the weld we can see that the materials from both sides were lapped layer by layer. The number of layers at rotation speed of 800 rpm is 13, which is almost exactly equal to the rotation cycles of tool for a one second dwell time (13.3 cycles). This result indicates that the material coupled well with the rotating FSSW tool and the bottom sheet steel surface, and the tool did not slide greatly along the top material during welding. With increasing the rotation speed, at 1600 rpm, the number of layers counted is 23, which is slightly less than the theoretical 26.7 cycle's rotation cycles of tool in this parameter). This suggests some sliding occurs between the tool and aluminium sheet at higher rotation speeds.

Conclusions

This work has demonstrated that reasonable Al-steel FSSW joints can be obtained with a weld dwell time of 1 sec, with careful selection of the parameters and tool design. However, because relatively slow plunge and retraction rates have to be used, this increases the weld cycle to two seconds, with uncoated steel, and to impractical lengths with zinc coated steels, when welding in the conventional configuration with a soft top sheet. Alternatively, it is possible that shorter welding cycles can be obtained when the tool interacts with the higher melting point steel material as the top sheet, giving a higher joining efficiency. It has been shown by material flow experiments that with a low friction tool the material couples surprisingly well with the tool surface. With Zn coated steel the disc of aluminium under the tool tends to rotate against the non-deforming harder steel substrate, causing weld defects. This process is probably encouraged because the Zn coating can melt reducing the friction between the aluminium and steel sheets.

The optimum strength levels obtained with a dwell time of one second, in lap shear tests, were 2.8 kN for Al to DC04, 3.2 kN for Al/DX54Z and 2.4 kN for DX53ZF/Al. This compares favourably with 6111 Al to Al welds in the same gauge, using an identical tool diameter, which have a maximum shear strength of ~ 3.4 kN [19]. Overall, it is clear that in FSSW the weldability of the two Zn coated materials, with aluminium, was far poorer than for uncoated steel and the harder ZF, or galv-annealed, coating made welding extremely difficult. The main issues in this case appear to be caused by pullout of the aluminium, which welds to the tool surface before sticking to the bottom sheet and circumferential cracking, due to the extremely high strain gradient that can occur at the edge of the stir zone with the stationary surrounding sheet. With slow plunge and retraction rates, welding occurs with more heat input and lower retraction forces, making it possible to produce defect free joints. However, this results in too long weld times. The weld strength is also limited by sheet thinning and reaction between the steel and aluminium producing an IMC layer at the interface.

Acknowledgements

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