

Friction Stir Blind Riveting: A Novel Joining Process for Automotive Light Alloys

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ABSTRACT

Friction stir blind riveting (FSBR) is a new process for joining automotive light alloys based on aluminium and magnesium. During FSBR, a blind rivet, rotating at high speed (typically 2000-12000 rpm), is brought in contact with the upper sheet or workpiece of a lap joint. The frictional heat generated between the rivet and the workpieces softens the material and this, in turn, reduces the force required to drive the rivet into the workpieces. Once fully inserted, the blind rivet is upset using the internal mandrel and an appropriate tool, as in conventional blind riveting. The FSBR process thus retains the one-sided accessibility of conventional blind riveting, but eliminates the extra predrilling and any subsequent cleaning steps required for the latter process.

In this paper we investigate the effects of the main process parameters, rotational speed and feed rate, and the rivet design, on rivet insertion force and torque as well as the static tensile shear strength of lap joints produced using various wrought aluminium alloys (AA 5005-H34, AA 6013-T6, AA 6260-T6 and AA 6005A-T5), die cast aluminium alloys (A380 and Aural-2 cast) as well as a twin roll cast magnesium alloy (AZ31B-O), with sheet thicknesses in the range 1.6-3.0 mm. Commercial breakstem steel rivets with hollow mandrel head design resulted in significantly lower rivet insertion force and torque values compared to those with solid mandrel heads. In addition, the hollow mandrel head rivets minimised flash formation and provided a means to accommodate the workpiece material displaced by the plunging rivet within the hollow mandrel head cavity. Tensile

shear strengths of lap joints (stack-ups in the range 3.2-6 mm) of the various aluminium alloys and the magnesium alloy were in the range 4-6.5 kN. We also present results on the capability of FSBR for dissimilar materials joining, for example, wrought aluminium alloys to die cast ones and aluminium alloys to magnesium alloys.

INTRODUCTION

Lightweight aluminium and magnesium alloys are being increasingly used in automobiles in recognition of their role in reducing vehicle mass and hence fuel consumption and green house emissions. Their wider adoption in mainstream vehicles has been impeded by the lack of appropriate joining technologies. Resistance spot welding (RSW) is the principal joining process in the automotive industry as it is rapid, reliable, cost-effective and delivers high quality, durable joints for various steel grades and sheet metal thicknesses currently used. However, aluminium spot welding presents some unique problems because of the high thermal and electrical conductivity of its alloys. The problems associated include weld porosity, weld expulsion, fast electrode wear and inconsistent weld quality [1,2]. This has led to the application of solid state joining processes such as friction stir spot welding (FSSW), also known as friction spot joining (FSJ) [3,4], shown schematically in Figure 1(a), and mechanical fastening methods including self piercing riveting (SPR) and blind riveting, illustrated in Figure 1(b) [5]. Both FSSW and SPR require access to both sides of the joint being made. Blind riveting, as the name indicates, does enable one-sided joining, but requires a predrilled hole which may need to be deburred, reamed, honed or furnished in order to

increase the joint fatigue life. These operations add to the process time, thus making the process less suitable for large volume production.

Friction stir blind riveting (FSBR), proposed by Wang and Stevenson, is a new process for the one-sided joining of aluminium alloys that addresses some of these deficiencies [6,7]. As the name indicates, the process combines features of FSSW and blind riveting. During FSBR, shown schematically in [Figure 1\(c\)](#), a blind rivet, rotating at high speed, is brought in contact with the upper sheet or workpiece. As in FSSW, the frictional heat generated between the rivet and the workpieces softens the material and this, in turn, reduces the force required to drive the rivet into the workpieces. Once fully inserted, the blind rivet is upset using the mandrel and an appropriate tool, as in conventional blind riveting. The FSBR process thus retains the one-sided accessibility of conventional blind riveting, but eliminates the extra predrilling step required for the latter process. Gao et al. showed that FSBR is a robust process for joining aluminium alloys and that the resulting joints displayed consistent strength under tensile loading with minimal influence of change in operating parameters [7]. They benchmarked the strength of FSBR joints against that of resistance spot welded joints of aluminium alloys with nugget size comparable to the rivet diameter and showed that FSBR generated joints with superior static and fatigue strength than those produced using RSW in aluminium alloys [7].

In this paper, we further investigate the FSBR process by studying the effects of the main process parameters, the rotational speed and feed rate, as well as the rivet design, on the nature of the joints produced using a range of aluminium alloys. A major objective of the work was to determine the influence of the process parameters and the rivet design on the rivet insertion force, torque and cycle time and the static strength of the resulting joints. The applicability of the process for dissimilar materials joining was examined for the specific cases of joining a wrought aluminium alloy to a die cast alloy as well as to a magnesium alloy.

EXPERIMENTAL PROGRAM

MATERIALS

Most of the FSBR experiments were conducted using 2 mm thick AA 5005-H34 alloy which has a nominal chemical composition (in wt.%) of 0.5-1.1 Mg, 0.7 max Fe, 0.2 max Mn, 0.4 max Si, 0.25 max Zn with balance Al. Extruded Al-Mg-Si alloys AA 6013-T6, AA 6260-T6 and AA 6005A-T5, and coupons of Aural-2 Cast die cast alloy, potential candidates for use in aluminium front end applications, were tested as representing automotive grade aluminium alloys. The chemical compositions of these alloys were analysed and are presented in [Table 1](#). The other materials tested included die cast aluminium alloy A380 and twin roll cast magnesium

alloy AZ31B-O sheets, both 2 mm thick. The nominal chemical composition of the A380 alloy is 7.5-9.5% Si, 3-4% Cu, 1.3% Fe, 0.1% Mg, 3% Zn, 0.5% Mn, 0.5% Ni, 0.35% Sn and balance Al; that of AZ31B is 2.5-3.5% Al, 0.7-1.3% Zn, 0.2-1% Mn, 0.1 max Si and balance Mg. These latter two materials were used exclusively for dissimilar materials joining experiments in combination with AA 5005-H34. Typical mechanical properties of all the alloys tested and the sheet thickness used in each case are shown in [Table 2](#). Lap joints produced thus had stack-ups in the range 3.2-6.0 mm.

Commercially available carbon steel blind rivets (also referred to as breakstem rivets) with a nominal size of 4.8 mm were used in this investigation. Two distinct rivet designs were selected: one with a solid mandrel head and the other with a hollow mandrel head. Avdel® Avibulb® rivets fall under the first category [5] while Avdel® Monobolt®, Avdel® Interlock® [5] and Huck Magna-Lok® [8] all have hollow mandrel heads. Avibulb® rivet (0BN01-00614) used has a grip range (sheet thickness range for which the rivet is designed) of 3.5-6 mm. In the case of the three hollow mandrel head rivets, two grip ranges were covered, and these are referred to as “short” and “long” hereafter. Monobolt® 02771-00613 and 02771-00617 cover grip ranges 1.63-6.86 mm and 1.63-11.10 mm, respectively, and Interlock® SSP1-06-04 and SSP1-06-07 covers grip ranges 1.57-6.35 mm and 5.44-11.10 mm. Magna-Lok® MGLP-R6-4 and MGLP-R6-7 cover the same grip ranges as the two Interlock® rivets. [Figure 2\(a\)](#) shows photographs of these various rivets used in the study while [Figure 2\(b\)](#) presents schematic illustrations of the rivets and cross-sectional views of the conventionally made joints using these rivets. It should be noted that Interlock® (long) (C2 in [Figure 2\(a\)](#)) has a longer mandrel head than Magna-Lok®(long) (D2) although both specify the same grip range. All rivets used were zinc plated and clear trivalent chromated [5,8].

RIVETING EXPERIMENTS

The FSBR experiments were conducted using a computer numerically controlled (CNC) milling machine (HAAS Model# VF-3SS) under displacement control. A test rig incorporating either a 100 kN load cell or a force and torque sensor (± 10 kN load, ± 25 N.m torque) coupled with a high speed data acquisition system, was clamped on the bed of the machine as shown in [Figure 3](#). The sheet coupons to be joined were firmly clamped in a lap configuration on the rig directly above the load cell, such that the rivet insertion force and torque during FSBR could be continuously monitored. A typical process cycle included the following steps:

- Clamp blind rivet on to the machine head using appropriate collet/holder to just above the cap.
- Accelerate spindle to preset rotation speed.
- Advance blind rivet at rapid feed rate until just above (0.02 mm) the top of the workpiece.



- Advance the rotating rivet into the workpieces at preset rate.
- When maximum penetration is reached (underside of cap just touches the workpiece), stop the spindle advance and rotation.
- Unscrew the rivet from the holder.
- Return the machine head to its original position.
- Upset the rivet using an appropriate rivet setting tool.

FSBR experiments on AA 5005-H34 were conducted with all the rivets in the study, using four rotational speeds: 6000, 8000, 10000 and 12000 rpm. At each rotational speed, three feed rates were used: 200, 400 and 600 mm/min. In the case of the other alloys as well as the dissimilar material combinations, as material available was limited, only selected hollow mandrel head rivets and FSBR parameters could be tested. Lap joints were produced using strips 100 mm long and 45 mm wide, with an overlap of 45 mm, such that the rivet was placed in the centre of the overlapping region. At least four such specimens were produced for each combination of rotational speed and feed rate, for each rivet and alloy combination. Three of these were used for tensile shear testing for evaluation of the joint strength; the fourth was for metallographic examination. A cross-head displacement rate of 1 mm/min was used during tensile shear testing using a universal testing machine. As per standard practice for tensile shear testing, spacers of coupon thickness were used to ensure that the tensile axis was parallel to the specimen surface at the start of the test, thus minimising bending moments. The failure loads of the lap joints under tensile shear loading, and the energy absorbed prior to failure (the area under the load-displacement plot), were determined. The samples for metallographic examination were sectioned through the centre of the riveted joint, mounted in cold setting epoxy and prepared for examination using standard metallographic techniques.

RESULTS AND DISCUSSION

As noted earlier, much of the detailed characterisation of the effects of FSBR parameters and rivet design on rivet insertion forces and the static strength properties of the resulting joints was conducted using AA 5005-H34 sheets with a thickness of 2 mm. We will discuss these results first and then examine the results obtained for FSBR of the automotive grade aluminium alloys and dissimilar materials joining.

EFFECTS OF OPERATING PARAMETERS AND RIVET DESIGN

Rivet insertion force measurements

Effect of mandrel head design

[Figures 4\(a\)](#) and [4\(b\)](#) display the variation in rivet insertion force and torque during FSBR of overlapping AA 5005-H34

sheets (stack-up 4 mm) at a rotational speed of 6000 rpm and a feed rate of 200 mm/min using Avibulb® with a solid mandrel head and Monobolt® with a hollow mandrel head, respectively. In both cases, the rivet insertion force rises rapidly to a peak value and then drops to nearly zero before rising again to a second peak. The first peak corresponds to the penetration of the overlapping sheets and the highest point in the peak corresponds to what we have termed the peak rivet insertion force. In the case of Avibulb®, a single first peak was observed while a splitting of the first peak into two distinct peaks was observed in the case of Monobolt® as well as the other hollow mandrel head rivets. A calculation of the distance traversed using the time point in the cycle where the split occurred and the feed rate indicated that the splitting of the peak corresponded to the rivet penetrating to the interface between the overlapping sheets. The second sharp peaks observed in the force vs. time plots occurred at ~4.1 s in [Figure 4\(a\)](#) and at ~5.2 s in [Figure 4\(b\)](#) and, again, calculations based on the rivet dimensions and the feed rate proved that these second peaks in each case occurred when the under side of the rivet cap touched the top surface of the upper sheet. The location of these second peaks thus provides a measure of the time taken for the complete penetration of the sheets by the rivet body; the total FSBR cycle time also includes the time taken for upsetting the rivet (which is independent of the FSBR process parameters). In many instances, for example [Figure 4\(b\)](#), this second peak, corresponding to the touching of the rivet cap, was often higher than force peaks representing the actual penetration of the sheets. Our experiments have shown that this peak can be minimised or even eliminated by appropriately controlling the rivet vertical displacement during FSBR. It is evident from [Figures 4\(a\)](#) and [\(b\)](#) that the variation of torque with time during FSBR with two rivets displayed a similar pattern of peaks to those observed in the force vs. time plots.

The significant observation from [Figures 4\(a\)](#) and [\(b\)](#) is the vastly different peak rivet insertion forces observed for rivets with solid and hollow mandrel heads for FSBR of the same material using identical process parameters: ~ 3.8 kN for Avibulb® compared with ~ 1.1 kN for Monobolt®. In contrast, the peak insertion torque for the solid mandrel head Avibulb®, ~ 2 N.m, is only slightly higher than the peak torque observed for Monobolt®, ~1.4 N.m.

Effect of FSBR process parameters

[Figure 5\(a\)](#) displays the variation in rivet insertion force with time during FSBR of AA 5005-H34 sheets with a stack-up of 4 mm using Interlock® rivets as the rotational speed was increased from 6000 rpm to 12000 rpm while the feed rate was maintained at 200 mm/min. [Figure 5\(b\)](#) shows insertion force-time plots obtained as the feed rate was increased from 200 mm/min to 600 mm/min while the rotational speed was held constant at 10000 rpm. It is evident from [Figure 5\(a\)](#) that increasing the rotational speed at a given feed rate

significantly lowered the peak rivet insertion force: a doubling of the rotational speed from 6000 rpm to 12000 rpm has resulted in a decrease of the peak insertion force from ~ 1.2 kN to ~ 0.7 kN, which represents approximately a 40% reduction. Similar results were obtained for the other rivets in the study. Thus, during FSBF of AA 5005-H34, stack-up 4 mm, at a feed rate of 200 mm/min, doubling the rotational speed from 6000 rpm to 12000 rpm, resulted in $\sim 23\%$ reduction of the rivet insertion force for the solid mandrel head; in the case of hollow mandrel head rivets, the corresponding reduction was of the order of 40-60% depending upon the rivet. It appears that the greater frictional heating generated by higher rotational speeds may cause enhanced localised softening of the material at the contact region, which in turn can lead to lower rivet insertion forces.

Similarly, [Figure 5\(b\)](#) shows that during FSBF using Interlock® rivets at rotational speed of 10000 rpm, decreasing the feed rate from 600 mm/min to 200 mm/min also has a beneficial effect on the peak insertion force, reducing it by about 45%. However, as also seen from [Figure 5\(b\)](#), the same reduction in feed rate increased the FSBF cycle time corresponding to the penetration of the sheets from approximately 1.6 s to about 4.8 s.

[Figure 5\(c\)](#) summarises the effect of feed rate on peak insertion force during FSBF of AA 5005-H34 at a rotational speed of 10000 rpm, for the four rivets in this study: the reduction in insertion force for the solid mandrel head rivet was $\sim 16\%$; for the three hollow mandrel head rivets, the reductions were $\sim 38\%$. It is also clearly evident that significantly lower insertion forces were obtained for the three hollow mandrel head rivets relative to those for the solid mandrel head rivet for this set of FSBF parameters.

Tensile shear test results

[Figure 6](#) summarises the results of the tensile shear tests conducted on lap joints of AA 5005-H34, stack-up 4 mm, produced using a range of FSBF parameters with Avibulb® (solid mandrel head). [Figure 6\(a\)](#) presents the tensile shear failure loads for joints produced using four rotational speeds in the range 6000-12000 rpm with four feed rates being used for each rotational speed. [Figure 6\(b\)](#) displays the energy absorbed prior to failure during the testing of these joints. For comparison, results of tests conducted on joints produced in the conventional manner with predrilled holes are also shown. In all cases, the data is presented as the mean and standard deviation of results from at least three coupons. [Figures 6\(a\)](#) and [6\(b\)](#) show that the failure loads and the energy absorption data of FSBF joints made with Avibulb® were insensitive to large variations in the FSBF parameters (4.01 ± 0.16 kN and 29.3 ± 1.6 J, respectively, from all data using various parameters). This observation is in agreement with that of Gao et al. for a different rivet with a solid mandrel head; these authors remarked on the minimal

influence of operating parameters on joint strength, reflecting the robustness of the process which would allow it to be carried out without high-end equipment and without requiring precise initial set up [7]. It is also evident that both the failure loads and the energy absorption of the FSBF joints were lower by about 12% and 28%, respectively, than those for joints produced by conventional blind riveting. As shown in the photographs in [Figures 6\(c\)](#) and [6\(d\)](#), the failure mode of these joints produced using Avibulb® rivets was invariably by rivet body fracture.

[Figure 7](#) summarises the results of tensile shear tests conducted on lap joints of AA 5005-H34, stack-up 4 mm, produced using Interlock® rivets (hollow mandrel head) and a range of FSBF parameters. [Figure 7\(a\)](#) presents the tensile shear failure loads for joints produced using four rotational speeds in the range 6000-12000 rpm with four feed rates being used for each rotational speed. [Figure 7\(b\)](#) displays the energy absorbed prior to failure during the testing of these joints. Again, for comparison, results of tests conducted on joints produced in the conventional manner with predrilled holes are also shown. These results show that, as in the case of Avibulb®, the response to tensile shear loading of the FSBF joints produced using Interlock® rivets was largely insensitive to variations in the process parameters (3.18 ± 0.24 kN and 10.1 ± 3.5 J, respectively from all data using various parameters). As evident from [Figures 7\(a\)](#) and [7\(b\)](#), the failure loads of the FSBF joints were as much as 35% higher than the failure loads for the conventionally made joints, and the energy absorbed prior to failure, more than double those of the conventionally made joints. The failure mode for these Interlock® joints was mostly by rivet pullout, as shown in the photographs in [Figures 7\(c\)](#) and [7\(d\)](#).

Comparison of the results presented in [Figures 6](#) and [7](#) shows that joints produced by Interlock® displayed failure loads that were $\sim 26\%$ lower than those of Avibulb® joints, but showed significantly lower energy absorption prior to failure. The differences in energy absorption observed can be attributed to the different failure modes of the joints produced by these two rivets: failure by rivet body fracture for Avibulb® and by rivet pullout for Interlock® joints. It should be mentioned that the failure modes of joints produced using the other hollow mandrel head rivets were also by pullout.

It should be noted that the results reported here were all obtained using off-the-shelf commercially available rivets. With rivets specially tailored and optimised for FSBF, indications are that superior joint strength performance can be achieved [10].

Metallographic examination

[Figures 8\(a\)](#) shows the cross-sectional view of an FSBF joint made using Avibulb® at a rotational speed of 10000 rpm and a feed rate of 200 mm/min. It can be seen from [Figure 8\(a\)](#)