Solid state spot joining of sheet materials using consumable bit

著者	佐藤　裕
journal or publication title	Science and technology of welding and joining
volume	14
number	1
page range	72-77
year	2009
URL	http://hdl.handle.net/10097/46686

doi: 10.1179/136217108X341193

Solid state spot joining of sheet materials using consumable bit

M. P. Miles*[1], K. Kohkonen[1], S. Packer[2], R. Steel[2], B. Siemssen[1] and Y. S. Sato[3]

A new spot joining technology relying on a consumable joining bit has been developed and evaluated on dual phase (DP) 980 steel and a dissimilar combination of aluminium alloy 5754-O and DP 980. This new process, called friction bit joining (FBJ), uses a consumable bit to create a solid state joint in sheet materials by the action of cutting and frictional bonding. FBJ lap shear fracture loads were 14·7 kN for 1·4 mm DP 980 compared to 16·6 kN for RSW, for the same spot diameters. FBJ of a dissimilar combination of aluminium alloy 5754-O and DP 980 produced joints with average lap shear fracture load of 6·3 kN. This strength is greater than lap shear fracture load obtained by self-piercing riveting (SPR) in HSLA 350 bonded to AA 5754-O.

Keywords: Spot joining, UHSS, Aluminium

Introduction

Spot welding of automotive sheet metal has become more complex in recent years, with growing use of ultrahigh strength steel (UHSS) and light metals in the fabrication of automotive structures. Applications of these materials are being developed by automakers in an effort to reduce vehicle weight. The use of these materials presents challenges of formability and weldability, because UHSS has lower ductility and greater alloy content than lower strength steels and because light metals cannot easily be joined to UHSS using traditional resistance spot welding (RSW).

For example, UHSS can experience weld property degradation when joined by RSW.[1–3] Resistance spot welds in UHSS, and especially those with tensile strengths above 800 MPa, can be brittle. These brittle welds can exhibit interfacial failure modes under impact loading conditions, resulting in relatively low impact resistance compared to lower strength steels. In addition, resistance spot welds in UHSS are prone to cracking, caused by brittle microstructures in the weld region which are essentially fully martensitic. These brittle microstructure phases present concerns of hydrogen induced cracking which could reduce the durability of a vehicle. Weld property degradation associated with RSW in UHSS is a barrier to widespread use of UHSS in the automotive industry.

Spot friction welding (SFW) is an alternate process that was developed initially to overcome some of the difficulties and expense of spot joining aluminium sheets.[4] This process can also be applied to spot joining of steel, although the tool material must be wear and heat resistant to hold up under repeated welding cycles. Polycrystalline cubic boron nitride tools have been employed for SFW of high strength steel, with reasonably good results.[5] However, mechanical strength levels in lap shear and cross-tension testing are much lower than those produced by RSW.[6]

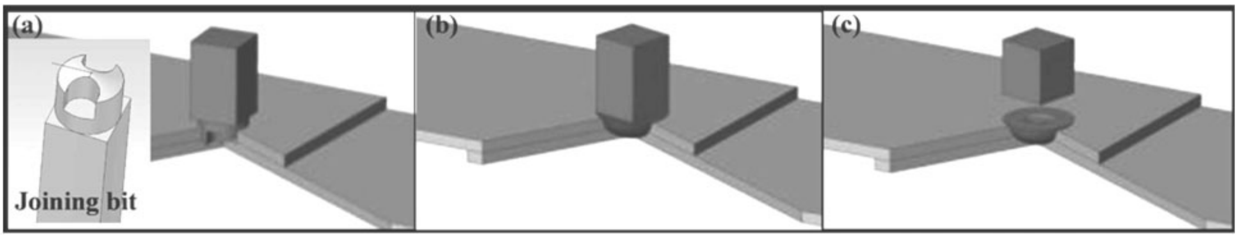
Spot joining of dissimilar alloys, like aluminium to steel, has been tried using various methods. While fusion spot joining of aluminium and steel is not normally feasible, some attempts have been made to introduce a sheet of aluminium clad steel at the interface, thereby creating a material layer compatible with both alloys.[7,8] Results provided reasonably good strengths, but lower energy absorption than self-piercing rivets. SFW was used to join a 6061 aluminium alloy sheet and a galvanised mild steel sheet, where the material thicknesses were $\sim$1 mm and where various coating properties of the mild steel sheet were evaluated.[9] The best lap shear tension result obtained using SFW for these materials was about 4 kN. Mechanical joining, by self-piercing riveting (SPR), is another method that has been used for joining aluminium, steel, steel/aluminium dissimilar combinations and multiple layers of aluminium and steel.[10,11] This method has the advantage of avoiding problems of metallurgical incompatibility when joining dissimilar alloys and has been shown to produce good performance in fatigue, equal to or better than RSW when comparing similar alloy joints. One limitation of this method is seen when joining thick materials or UHSS, because the material interlocking created by SPR may not be sufficient for good joint strength.[12]

In order to address some of the difficulties of spot joining UHSS and of dissimilar combinations of UHSS and aluminium, a new concept is introduced in this paper, where a consumable joining bit is applied to the joining of sheet materials. The sheets may have different thicknesses and be composed of different alloys. This concept relies on a cutting procedure, where the bit cuts through the top layer (or layers) of material, followed by

[1]Manufacturing Engineering Technology, Brigham Young University, Provo, UT 84602, USA
[2]Megastir Technologies, West Bountiful, UT 84087, USA
[3]Department of Materials Processing, Tohoku University, Sendai, Japan

*Corresponding author, email mmiles@byu.edu

Published by Maney on behalf of the Institute
Received 3 March 2008; accepted 11 July 2008
DOI 10.1179/136217108X341193



a cutting step; *b* joining step; *c* rapid stop of the spindle
1 Schematic illustrations of friction bit joining process

a joining operation where the bit and surrounding sheet materials are heated by friction and where the bit becomes filler material that joins the sheets together. The objective of developing this new process is to enable the joining of steels, light metals, and combinations of steels and light metals or other materials, for production of automotive or other structures. As will be described in the section on 'Results' of this paper, process cycle time was ~5 s, longer than the cycle time for RSW, which is typically of the order of 1 s, depending on the alloy.[13,14] The 1 s cycle time includes more than weld time, which is usually ~20 cycles. There is also typically a squeeze time before welding and hold time after welding, adding up to about 1 s of total process cycle time.

Experimental

Spot welding was carried out using the new friction bit joining (FBJ) process and traditional RSW. Spot joints made using these two methods were evaluated mechanically by lap shear and cross-tension testing. For dissimilar alloy joints of aluminium and steel, the FBJ results were compared to data from the literature. Details of the experimental procedures are described in this section.

FBJ spot experiments

The FBJ process relies on a consumable joining bit to cut and then friction join sheet materials (the process is patent pending). A generalised illustration of how the process works is shown in Fig. 1.

This joining process was carried out in two main steps: a cutting step and a joining step. For the results presented in this paper, the joining bit was rotated at a relatively slow speed (300–800 rev min^{-1}) during the cutting phase, where the bit cut through the top layer of the two sheets to be joined. After cutting through the top sheet, the rotation speed of the bit was increased to generate heat and to facilitate bonding of the bit to both sheets (1000–1600 rev min^{-1}). At the lower levels of rev min^{-1}, the bit is able to maintain its cutting edge, while at higher levels of rev min^{-1}, the heat from friction softens the bit material and the cutting edge is smoothed over as it bonds with the steel sheet. In terms of feedrates, the joining bit was plunged into the sheet at rates that varied from 25 to 150 mm min^{-1}, where again the lower plunge rate typically occurred during the cutting phase and the higher rate occurred during the joining phase. At the end of the joining process, the spindle of the welding machine was stopped very rapidly (within 25 μs) and then restarted to separate the joining bit from the weld. A picture of the C frame welding machine used for experimentation is shown in Fig. 2.

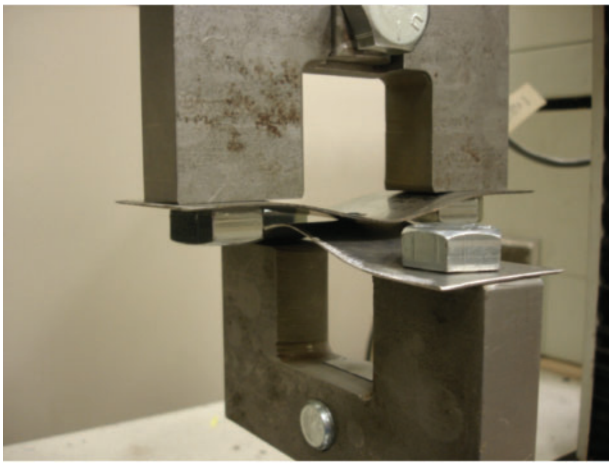
DP 980 steel sheets of 1·4 mm gauge were joined using this new method. DP 980 is a UHSS with applications in automotive structures, having a microstructure composed of about 40% ferrite and 60% martensite, with an ultimate tensile strength (UTS) of ~980 MPa. The bit used for joining DP 980 was made of D2 tool steel, heat treated to a hardness of ~63 HRC. This material was used after initial trials with alloy 4140, heat treated to a hardness of ~55 HRC.

In addition to joining DP 980 steel, the FBJ process was used to create dissimilar alloy joints of AA 5754-O and DP 980. AA 5754-O had UTS of ~230 MPa, making it much softer than the DP 980. This combination of alloys would likely pose problems for SPR, where deformation of the DP 980 material by the rivet would be very difficult. For the aluminium/steel joints, a 4140 alloy was used for the joining bit, with a hardness of ~30 HRC. When joining aluminium and steel, the softer aluminium alloy is placed on top, and the 4140 bit cuts through this top surface before bonding to the steel underneath.

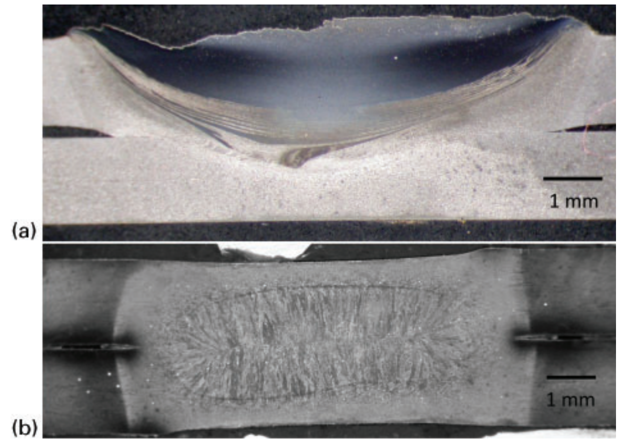
RSW experiments

Resistance spot welded specimens were compared to the FBJ joints. The RSW of the DP 980 material was carried out at 6·7 kA, with a clamping force of 4·9 kN and a cap diameter of 6 mm. The welding process employed a squeeze time of 25 cycles, a weld time of 17 cycles and a hold time of five cycles.

2 C frame welding machine used for FBJ experiments



3 Experimental fixtures for pulling cross-tension specimens in test frame



a friction bit joint; *b* resistance spot joint

4 Comparison of spot joints in 1·4 mm DP 980: *a* cross-section of joint produced by FBJ with D2 steel bit, where spot diameter is ∼6 mm; at joint interface, mixing of DP 980 and D2 is seen, where bands of D2 (darker material) and DP 980 alternate; for comparison, RSW joint is shown in *b* for same material, where approximate spot diameter of joint is also 6 mm

Mechanical testing

The strength of the welded joints was evaluated using lap shear and cross-tension testing. Lap shear testing was carried out on specimens that were 25·4 mm in width and 101·2 mm in length, with a 25·4 mm overlap in the joint area. Welds were produced in the centre of the overlap area. Spacers were used to ensure that the specimen was centred along the tensile axis in the test frame.

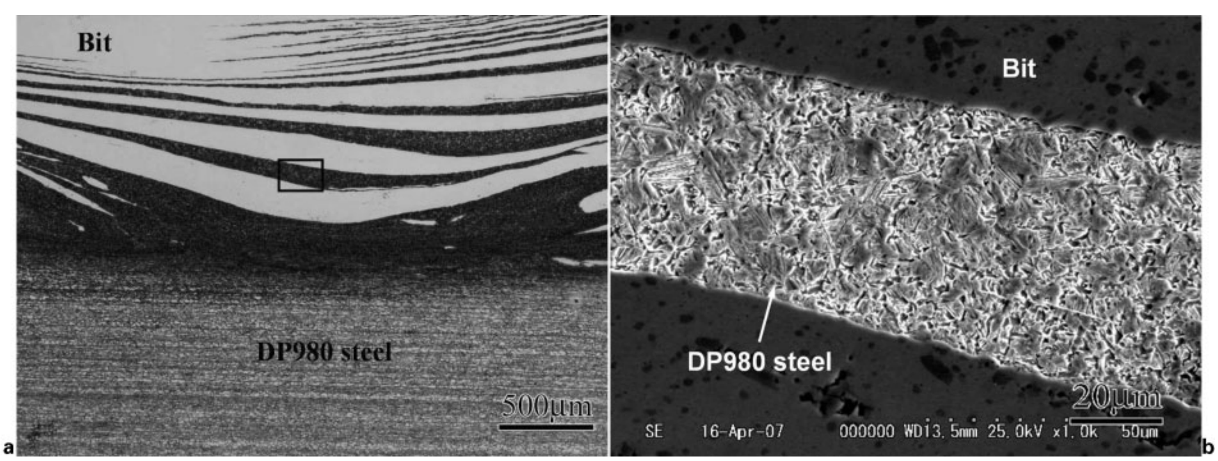
Cross-tension specimens were 50·8 mm wide and 101·4 mm long and overlapped in the centre. The experimental set-up for testing spots welds in the cross-tension configuration is shown in Fig. 3.

Results and discussion

Spot joining of UHSS

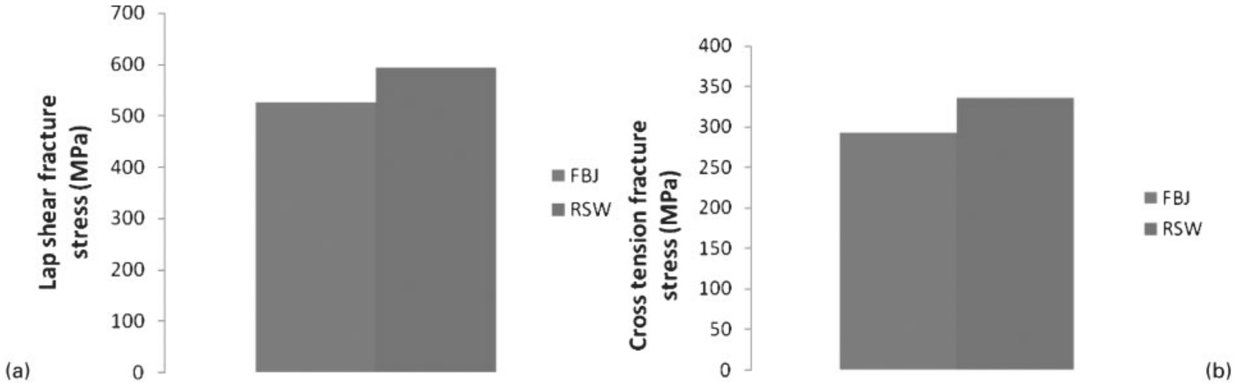
FBJ development initially focused on spot joining of UHSS, and in particular of joining 1·4 mm DP 980 sheets, where several bit materials and cutting profile designs were evaluated for strength and cycle time performance. The bit material must be hard enough to perform the initial cutting operation, which depends on the materials to be joined. In the case of DP 980 steel, 4140 alloy steel and D2 steels were tried. The bits that were fabricated using alloy 4140 were heat treated to a hardness of 52–54 HRC, which resulted in a long cutting operation of 35 s, to avoid dulling the bit. This was followed by a joining operation of ∼5 s, for a total cycle time of 40 s. This is far too slow to be considered for production, as the typical cycle time for RSW is ∼1 s, as discussed in the section no 'Introduction'. The average lap shear fracture strength, for five specimens, obtained with this bit on 1·4 mm DP 980, was ∼10 kN. Further development was carried out using D2 steel for bit fabrication. These bits were heat treated to a hardness of 62–64 RHC. This allowed for much faster cutting and joining, resulting in cycle times of ∼5 s, as well as improved lap shear strength of 14·6 kN, as an average of five specimens. Cross-sections of a resistance spot welded joint and a spot friction welded joint are shown in Fig. 4.

The microstructure of the friction bit joint is shown in Fig. 5.



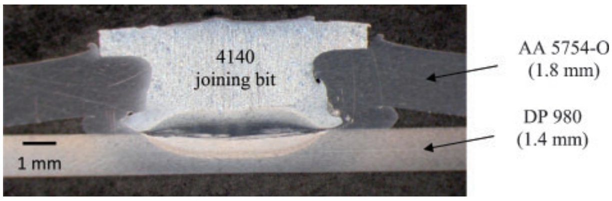
a macroview of bonding interface; *b* microview of area indicated by box in *a*, where lighter alloy is DP 980 and darker material is bit material (D2 tool steel)

5 Micrographs of banded structure in joint: note that material which appears dark in optical micrograph in *a* appears light in SEM image shown in b



a lap shear fracture stress; *b* cross-tension fracture stress

6 Comparison of *a* lap shear fracture stress and *b* cross-tension fracture stress for FBJ and RSW: bonded areas in both FBJ and RSW joints were same, at ~28 mm^2



7 Macrocross-section of AA 5754 (top layer) joined to DP 980 (bottom layer): steel 4140 bit was used in joining process

Alternating bands consisting of the DP 980 steel and the D2 bit material were formed at the bonding interface. A view of the bands, marked by a black rectangle in Fig. 5*a*, is magnified in Fig. 5*b*. Here the martensite structure is clearly observed in the band of the DP 980 steel. Metallurgical bonding between the DP 980 and the D2 bit material was achieved with no visible cracks or flaws in the joint.

The vertical load on the spindle was relatively stable at ~11 kN for the FBJ trials that were carried out on DP 980 steel. This compares to 8 kN for RSW. FBJ welding parameters used during this particular trial are shown in Table 1.

These process conditions were selected after a series of experiments, during which the cutting speed was varied from 400 to 800 rev min^{-1}, and the joining speed was varied from 1000 to 2000 rev min^{-1}. The chosen parameters are not necessarily optimised, but were used because they produced the highest lap shear and cross-tension fracture loads during the experiments that were conducted.

Lap shear tension testing was carried out on all specimens. In order to compare these results, the bonded areas for each joint were determined by measuring spot diameters from fractured specimens, where an average of two diameters 90° apart was taken on each sample. The FBJ and RSW results were compared directly, because the weld bond areas were 28 mm^2 in each case.

Table 1 FBJ welding parameters used for joining DP 980 steel

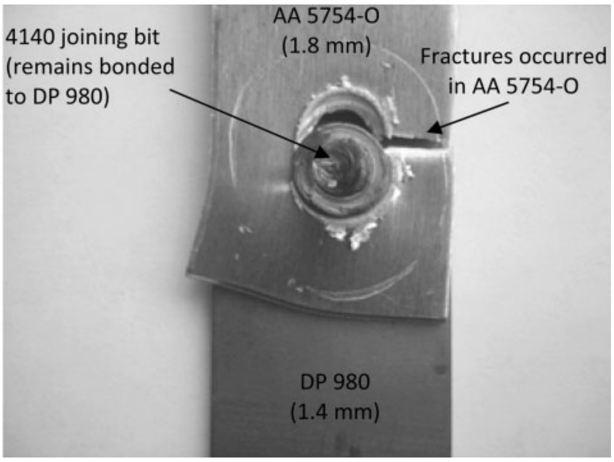
Cutting speed, rev min^{-1}	725
Cutting feedrate, mm min^{-1}	100
Joining speed, rev min^{-1}	1200
Joining feedrate, mm min^{-1}	150

Lap shear fracture loads were 14·7 kN for FBJ and 16·6 kN for RSW, as an average of five specimens. Cross tension fracture loads were 8·2 kN for FBJ and 9·4 kN for RSW, as an average of five specimens. When the loads were divided by the bond area of 28 mm^2, the authors obtained fracture stresses, as shown in Fig. 6 for FBJ and RSW.

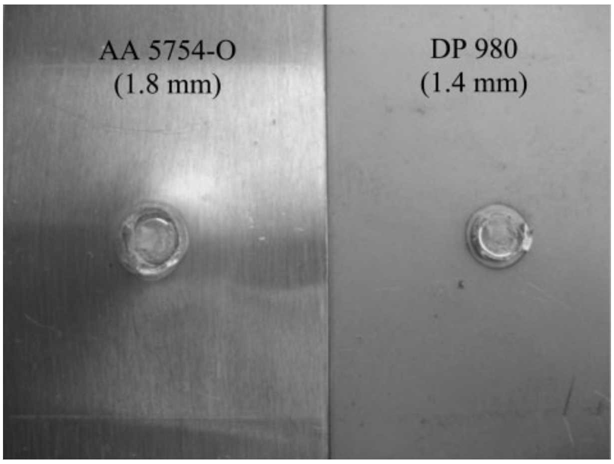
Joining of aluminium and steel

While FBJ has been applied to spot joining of UHSS, it may have more potential in joining of dissimilar alloys like aluminium and steel. As stated in the section on 'Introduction', various methods have been tried in joining of aluminium and steel sheets for automotive structures. Resistance spot welding with a layer of compatible material at the interface, SFW of galvanised steel and aluminium and SPR of aluminium and mild steel are all examples. One particular advantage of the present process, especially in comparison to SPR, is its ability to join a very hard material to a softer material. As an example, 1·8 mm aluminium alloy 5754 was joined to 1·4 mm DP 980. A cross-section and top view of the Al/steel joint is shown in Fig. 7.

The bonded interface between the 4140 joining bit and the DP 980 sheet is the main source of strength in the



8 Failed lap shear joint: fracture has occurred in aluminium, around joining bit, but no fractures occurred at interface between joining bit and DP 980 steel coupon; visible portion of joining bit (which is larger than weld diameter of 6 mm) is ~8 mm



9 Typical cross-tension failure where joint itself has fractured: bit material is bonded to both AA 5754 sheet and to DP 980 sheet, therefore, this fracture occurred within bit material itself, which was link between two sheets

Table 2 Lap shear and cross-tension fracture loads for spot joints of 1·8 mm AA 5754 and 1·4 mm DP 980: 10 consecutive specimens were joined and then tested

Sample	Lap shear fracture load, N	Cross-tension fracture load, N
1	6243	3155
2	6679	2256
3	6626	2541
4	6319	3124
5	6052	2933
6	6533	2123
7	6097	2488
8	5883	2483
9	6283	1833
10	6555	2265
Average	6327	2520
SD	267	435

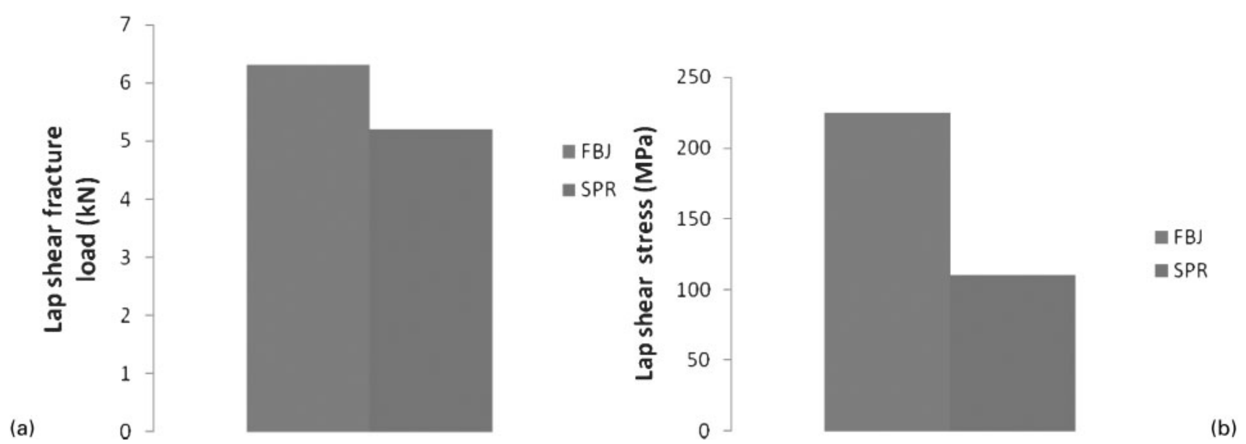
joint, because the joint always failed in the aluminium coupon during lap shear tension testing, as shown in Fig. 8.

However, in a cross-tension test, the failure does occur at the interface. The fracture is not flat, which would indicate a pure interfacial failure. Instead, the surface shows that the joining bit itself has failed, with portions of the joining bit remaining bonded to both the AA 5754 coupon and to the DP 980 coupon after testing. An image of a failed cross-tension sample is seen in Fig. 9.

Average lap shear values for the aluminium/steel joint averaged 6·3 kN for 10 samples. The cross-tension strength averaged 2·5 kN. These results were obtained using a cutting speed of 300 rev min^{-1}, a joining speed of 1000 rev min^{-1} and a process cycle time of $\sim$5 s. This joint strength was achieved with a vertical load on the spindle of 6·7 kN, as an average value over 10 samples. Individual strengths for lap shear and cross-tension specimens are shown in Table 2.

There is not a direct comparison, using a different joining technology, of this particular dissimilar alloy joint available in literature. However, there have been SPR experiments performed on dissimilar combinations of HSLA 350 and AA 5754 which can provide a basis for comparison, especially because the weaker material is the same in both joints. In order to effectively compare these two joints, the bond areas must be known, because bond area affects the strength of the joint. For SPR, an effective area can be estimated by considering the rivet geometry, material thickness, and failure mode (rivet head pullout or a rivet tail pullout).[12] The bond area for the FBJ joints was determined by optical measurement of the fracture surface across two diameters of the weld, 90° apart. SPR results can be found in Ref. 12 for a joint composed of 1·6 mm HSLA 350 and 2·0 mm AA 5754-O. These material thicknesses are slightly greater than those of the joints presented in this paper, which were 1·4 mm DP 980 and 1·8 mm AA 5754. But as stated before, the weaker materials are the same alloy of similar gauge, so joint strengths were compared using bond areas. The lap shear failure loads and failure stresses are shown in Fig. 10, where the failure stress was computed as the failure load divided by the bond area.

The failure mode for FBJ was a fracture of the AA 5754-O material around the joining bit (Fig. 8). Failures in the SPR joint occurred by head pullout through the AA 5754-O material.[12] FBJ fracture stress is seen to more than twice that of SPR in lap shear for



10 *a* fracture load and *b* fracture stress for FBJ and SPR joints: bond area for FBJ was 28 mm^2 while for SPR, effective bond area was 47 mm^2; in both cases, weak material in joint was AA 5754, where failure occurred during lap shear testing

these joints, with failures in both cases occurring in the weaker AA 5754-O component of the joint assembly.

Summary and conclusions

A new process for spot welding of sheet materials, employing a consumable joining bit, was evaluated by producing spot welds in 1·4 mm DP 980 steel, and in dissimilar combinations of 1·4 mm DP 980 and 1·8 mm AA 5754-O. The lap shear fracture loads for FBJ welds in DP 980 averaged 14·8 kN, approaching the strength of RSW joints in the same material (16·6 kN), where bond areas in both cases were $\sim$28 mm^2. Cross-tension fracture loads were 8·2 kN for FBJ welds and 9·4 kN for RSW welds.

The FBJ process was also used to produce dissimilar alloy joints of 1·4 mm DP 980 and 1·8 mm AA 5754-O. Lap shear fracture loads averaged 6·3 kN, while cross-tension fracture loads averaged 2·5 kN. A comparison of these FBJ results with some SPR data from the literature on joints of 1·6 mm HSLA 350 and 2·0 mm AA 5754-O showed that FBJ joints supported more than twice the lap shear fracture stress of the SPR joints, where failures in both types of joints occurred in the weaker AA 5754-O component of the joint assembly.

Acknowledgements

Resistance spot welding samples used for comparison with FBJ were provided by T. Pan of Ford Advanced Research and Engineering and C. Jiang of AET Integration. Steel sheet material was provided by Arcelor–Mittal Steel and aluminium sheet material was provided by ALCOA.

References

1. S. Ferrasse, P. Verrier and F. Meesemeacker: *Weld. World*, 1998, **41**, (2), 177–195.
2. W. Peterson: Proc. Int. Conf. on 'Advances in welding technology', Columbus, OH, USA, September 1997, ASM International, 331–346.
3. S. G. Shi and S. A. Westgate: 'Resistance spot welding of high-strength steel sheet', Corporate Research Program report no. 767/2003, The Welding Institute, Cambridge, UK, 2003.
4. T. Gendo, N. Katsuya and A. Motoyasu: *J. Jpn Inst. Met.*, 2006, **70**, (11), 870–873.
5. Z. Feng, M. L. Santella, S. A. David, R. J. Steel, S. M. Packer, T. Pan, M. Kuo and R. S. Bhatnagar: *J. Mater. Manuf.*, 2005, **114**, 592–559.
6. M. P. Miles, J. Sederstrom, K. Kohkonen, R. Steele, S. Packer, T. Pan, W. J. Schartz and C. Jiang: Proc. Conf. MS&T 2006, Cincinnati, OH, USA, October 2006, ASM International, 103–106.
7. X. Sun, E. V. Stephens, M. A. Khaleel, H. Shao and M. Kimshi: *Weld. J.*, 2004, **83**, 188S–195S.
8. M. Yasuyama, K. Fukui, K. Ogawa and T. Taka: *Sumitomo Met.*, 1996, **48**, (4), 87–95.
9. T. Gendo, K. Nishiguchi, M. Asakawa and S. Tanioka: *J. Soc. Automot. Eng. Jpn*, 2007, **61**, 83–86.
10. L. Han and A. Chrysanthou: *Mater. Des.*, 2008, **29**, 458–468.
11. L. Han, A. Chrysanthou and K. W. Young: *Mater. Des.*, 2008, **28**, 2024–2033.
12. X. Sun and M. A. Khaleel: *Sci. Technol. Weld. Join.*, 2005, **10**, (5), 624–625.
13. M. Marya, K. Wang, L. G. Hector, Jr and X. Gayden: *J. Manuf. Sci. Eng.*, 2006, **128**, 287–298.
14. M. I. Khan, M. L. Kuntz and Y. Zhou: *Sci. Technol. Weld. Join.*, 2008, **13**, (1), 49–59.