Comparison of self-pierce riveting, resistance spot welding and spot friction joining for aluminium automotive sheet

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ABSTRACT

This work compares three aluminium sheet joining processes to determine their capability, efficiency and cost for mass production applications in automotive structures and closures. The joining processes investigated are Resistance Spot Welding (RSW), Self-Pierce Riveting (SPR) and Spot Friction Joining (SFJ). Quantitative comparisons have been made on the basis of tensile strength (shear and peel), process time, equipment price and running cost.

RSW is the most commonly employed joining method for steel sheet in the automotive industry. Its principle benefits are high speed and low cost operation, plus the ability to weld a wide range of joint configurations with the same gun. The main process limitations for aluminium are weld consistency and electrode-life, though recent work has shown that both of these can be largely overcome with regular electrode polishing [1,2].

SPR is already in use for volume production of aluminium body structures. Its principle benefits are superior mechanical strength and ability to join dissimilar materials. The main process limitations are the ongoing piece cost of the rivets and the limited range of joint configurations achievable on each gun. End-of-life recycling of aluminium parts is more complex when they contain steel rivets.

SFJ is derived from friction stir welding technology, its principle benefit being rapid low cost joining of thin sheet. SFJ can join some of the commonly used automotive alloys and is low in power consumption. The process is presently limited to simple joint configurations and requires long process times to join thick sheets.

INTRODUCTION

Automotive manufacturers are under increasing pressure to minimise the environmental damage caused by a vehicle’s total life-cycle from manufacture through to dismantling. The environmental impact caused by driving a vehicle can be significantly reduced by improving the fuel efficiency [3]. One proven route to improved fuel economy is to lower the mass of the body structure by substituting steel sheet with aluminium sheet. Prerequisites for achieving this in high-volume production are robust and cost-effective joining methods.

To encourage the increased use of aluminium bodied cars two of the main barriers to be overcome are the availability of lower cost sheet material and the adoption of low-cost sheet joining techniques. This paper focuses on the second of these barriers; comparing a proven production technique for low to medium volume with two methods that may offer cost advantages, particularly for high volume applications.

A number of aluminium companies have investigated and promoted the use of aluminium in automotive applications. The two basic design approaches being unitary made primarily from pressed sheet and spaceframes made from a combination of extrusions, castings and pressed sheet. The use of overlap joints rather than butt joints is the established method for joining sheet in high-volume automotive body-in-white (BIW) applications, where flanges along the edges of components are joined using a row of discrete “point” joints.

Extensive research by Alcan and British Leyland in the 1980s using the unitary route, culminated in the building of six aluminium bodied Metro test vehicles [4]. This led to the development of a patented Aluminium Vehicle Technology (AVT) system, including welding and weldbonding of specially pretreated and press-lubricated sheet material [5]. Alcan continued to improve the AVT process working with the automotive industry to incorporate technology improvements such as new alloys, chrome-free surface pretreatments and wax press-forming lubricants [6]. Examples of the AVT sheet technology were seen in prototype vehicles such as, the Ford Aluminium Intensive Vehicle (AIV), the Ford P2000 [7] and the General Motors EV1. More
recently, Jaguar employed a large part of the AVT technology to produce the XJ saloon, their first medium-volume aluminium production vehicle [8]. The main difference between the Jaguar XJ production system and the AVT concept being the use of self-pierce riveting instead of resistance spot welding [9].

The spaceframe approach to vehicle construction is suitable for low to medium volume production, and has been demonstrated in vehicles such as the Audi A2, Audi A8 and Lamborghini Gallardo [10]. Joints at the nodes in a spaceframe are made using techniques such as gas metal arc or laser welding. These continuous joining techniques are outside the scope of this paper.

RESISTANCE SPOT WELDING

Resistance spot welding of aluminium alloys has patents dating back to the 1930’s [11]. More recent material, equipment and welding process developments to extend electrode-life, enhance weld quality and reduce power consumption are making this process increasingly attractive to automakers [1, 12]. RSW is able to join multi-layer aluminium stacks comprising individual sheets from 0.9 mm to 4 mm in a wide range of alloys as shown in Figure 1. Note that the external surfaces are relatively smooth and flat on both sides of the joint. The weld button revealed after a joint stack has been peeled apart is shown in Figure 2.

Figure 1, Cross section of RSW in four aluminium sheets

The majority of spot welding guns presently employed in the automotive industry use pneumatic actuators to apply the electrode force. However, many new installations have installed electric servomotor actuators eliminating the need for pneumatics on the assembly line. These servo guns offer faster cycle times by improved control of the aperture and closing speed [11]. Servo guns also offer the interesting possibility of monitoring and adjusting the electrode force during the weld.

A big advance in RSW for steel and aluminium has been the development of Medium Frequency Direct Current (MFDC) welding power supplies, which offer significant process control improvements over 50/60Hz Alternating Current (AC) [14]. One of the particular advantages of MFDC for aluminium is the reduction in gun weight enabling robotic manipulation.

Figure 2, RSW button revealed by peeling a weld apart.

SELF-PIERCE RIVETING

Self-pierce riveting, shown in Figure 3, is a mechanical cold joining process used to join two or more overlapping sheets by pushing a rivet through the stack from one side without the need to drill a hole. The tubular rivet tail flares-out and interlocks the sheets inside a button formed proud of the lower sheet. Unlike RSW, SPR joints combine the ability to join multi-layer multi-material stacks with good shear and peel strengths [15]. SPR is relatively insensitive to the cleanliness of the aluminium surface and the condition of the oxide layer. Adding a corrosion inhibiting coating to a hardened steel rivet has enabled this technology to be used on aluminium components without causing galvanic corrosion problems [16]. One drawback of using steel rivets in an aluminium car is the need for separation of the two materials as part of recycling at the end of vehicle life.
The direction of rivet insertion and stack thickness configuration has a large influence on the strength of SPR joints. The main consideration is to avoid a much thinner lower sheet than the upper sheets in the stack. This is because the reduction of flare in a thinner lower sheet provides less interlock strength.

Ideally to minimise the possibility of galvanic corrosion and aid recycling, aluminium sheets should be joined using aluminium rivets. Aluminium rivets have been developed for aerospace applications\textsuperscript{[17]}, but self piercing aluminium rivets are not currently available. A distinct advantage of SPR is that it can be used for joining dissimilar materials such as aluminium to steel or aluminium to lightweight aluminium-polypropylene-aluminium laminates. The static and fatigue performance of SPR joints has been reported elsewhere\textsuperscript{[18]}. For instance, a study at Ford Motor Company showed the fatigue strength of SPR to be double that of RSW joints at $10^6$ cycles\textsuperscript{[18]}.

### SPOT FRICTION JOINING

Spot friction joining also known as Friction Stir Spot Welding (FSSW) is a relatively new discrete process derived from the continuous friction stir welding method developed at TWI\textsuperscript{[19]}. A typical joint is shown in Figure 5 and Figure 6. SFJ has not yet been studied in sufficient depth to realise its full potential. The process promises significant cost advantages in terms of simple equipment, minimal consumables and low power consumption\textsuperscript{[20]}. Most of the research published so far has focussed on two-layer joints but it is possible that three or four layer joints will be achievable with further process development. The effect of different tool designs and process parameters is being investigated by a number of research centres\textsuperscript{[21, 22]}. A fatigue study of SFJ for 6111 aluminium was recently published\textsuperscript{[23]}. Mixed material joints such as aluminium to steel and aluminium to magnesium have also recently been reported\textsuperscript{[24]}. This study was conducted on the basic non-traversing spot joining method. Traversing the rotating tool in a linear or swinging motion to produce short stitches rather than spot joints produces higher lap shear and cross tension strength\textsuperscript{[25]}.
COMBINING WITH ADHESIVE BONDING

The requirement to fix and hold the parts together in short cycle times means it is unlikely that the adhesive bonding technology currently available will become the sole joining method for high-volume aluminium cars. Adhesives can provide continuous joints with excellent fatigue resistance and stiffness. A continuous bondline has a beneficial effect on vehicle characteristics such as torsional rigidity and “noise vibration & harshness” (NVH). The main drawback of adhesives is limited mechanical strength in peel loading situations. But this can be compensated by combining adhesive bonding with point joining methods which perform well in peel loading and act as a peel stoppers. Combining point joining methods with adhesive bonding also aids more rapid assembly by holding parts together and not allowing them to move prior to the curing of the adhesive in the paint bake cycle [26].

The combination of SPR or RSW with adhesive bonding is known as riv-bonding and weld-bonding respectively. Resistance spot welding through an adhesive with a 10 mm face diameter electrode requires a high force gun (6 to 8 kN) to squeeze the viscous uncured epoxy adhesive from between the electrodes before the main weld pulse is initiated. Tests on spot friction joining conducted during this study indicated that the process does not perform well when there is a viscous layer of adhesive between the sheets. However, SFJ could be employed adjacent to adhesive bonding providing the parts being joined have large enough edge flanges to keep the adhesive away from the SFJ joints.

The in-service durability performance achieved by adhesive bonding is influenced by the underlying aluminium surface pretreatment. The automotive industry tends to favour simple low-cost surface treatments. Whilst not as durable as the anodising surface treatments widely used in the aerospace industry [27], these basic pretreatments have been demonstrated to exceed the requirements for even the most demanding of automotive applications [28]. Manufacturing practicalities, together with the need for energy absorption in crash situations, mean that adhesive bonding is likely to be combined with mechanical fasteners or spot welding for the foreseeable future.

OTHER DISCRETE JOINING METHODS

Mechanical clinching was not included in this study but should not be ignored as a useful joining method for non-structural parts. Hood and door flanges for example can be joined using inexpensive and readily automated clinching methods in combination with adhesive bonding. Ultrasonic spot welding (USW) of aluminium shows promise but is not yet sufficiently developed for inclusion in this comparison of proven production technologies [29].

COMPARISON OF JOINING METHODS

The main purpose of this paper is to compare joining technologies by assessing their functional and economic suitability for use in producing aluminium automotive structures. Some previous work has been conducted in this general field [30]; this present work focuses on discrete joining methods that are near-term candidates for high-volume production of aluminium vehicles.

A series of joint configurations were selected for quasi-static mechanical testing, the aim being to represent the full range of joint types typically employed in a sheet-intensive aluminium car body. The materials and joint thickness configurations are shown in Table 1. The materials were supplied by Novelis (formerly Alcan) in a pretreated and lubricated condition typical of that used in the automotive industry. In line with automotive practice, no further alteration was made to these surfaces prior to joining or bonding.

Table 1: Joint Configurations

<table>
<thead>
<tr>
<th>Joint</th>
<th>Material1</th>
<th>Material2</th>
<th>Material3</th>
<th>Material4</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>0.9 mm 6111-T4P</td>
<td>0.9 mm 5182-O</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J2</td>
<td>2.0 mm 5754-O</td>
<td>1.8 mm 6111-T4P</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J3</td>
<td>2.0 mm 5754-O</td>
<td>2.0 mm 5754-O</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J4</td>
<td>3.0 mm 5754-O</td>
<td>3.0 mm 5754-O</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J5 &amp; J5A</td>
<td>2.0 mm 5754-O</td>
<td>1.5 mm 5754-O</td>
<td>2.0 mm 6111-T4P</td>
<td>-</td>
</tr>
<tr>
<td>J6 &amp; J6A</td>
<td>2.0 mm 5754-O</td>
<td>1.5 mm 5754-O</td>
<td>1.8 mm 5754-O</td>
<td>2.0 mm 5754-O</td>
</tr>
</tbody>
</table>

Joints J1 to J6 inclusive were made without structural adhesive and were mechanically tested in the as-joined condition. Joints J5A and J6A were replicates of J5 and J6 with the addition of a structural single-part epoxy adhesive (Dow Betamate 4601) at selected interfaces, as shown in Figure 7 and Figure 8. The adhesive was cured at 180°C for 25 minutes to simulate a typical paint bake/adhesive curing cycle. In the case of the heat treatable alloy AA6111-T4P, the paint bake cycle increases the yield strength of the parent material, typically from 150 to 220 MPa [31], increasing the dent resistance of exterior body panels.
The two coupon geometries fabricated for mechanical tensile testing are shown in Figure 9 and Figure 10. Sets of six replicates of each joint stack were made for both T-peel and lap-shear testing. In the case of RSW joints, the six welds were made together on plates to simulate production conditions such as current shunting and component heating. The plates were subsequently cut into individual tensile coupons. T-peel specimens were first joined as flat strips or plates, and then bent in a fixture to form the required "T-shaped" geometry. The crosshead speeds used on the tensile testing machine were 10 mm/min for lap shear testing and 100 mm/min for T-peel testing.

In a three or four layer overlap joint the choice of which sheets are pulled apart from each other will influence the results. For example if a thin bottom sheet is pulled on its own the strength will be much less than if a thin bottom and thicker second sheet are pulled together. The loading configurations used in this work are shown in Figure 7 and Figure 8.

Joints J5, J6, J5A and J6A were made using only RSW and SPR, because the SFJ equipment available was not able to produce joints in three or four thicknesses of material or through adhesive layers. SPR and RSW are both capable of producing good joints when there is uncured adhesive present between the sheets.

The SPR equipment employed was a Henrob electrical servo-driven riveting gun inserting 5 mm diameter rivets. The RSW equipment used an Olofström GWT-500 pneumatically-actuated gun linked to either a Bosch PSU6000 or Matuschek IGEL MFDC inverter power supply. The SFJ equipment was a Kawasaki integrated SFJ servo gun and robot controller. The machine parameters in each process were optimised for each joint configuration.

RESULTS

The three discrete joining processes were compared to highlight differences in process time, quasi-static mechanical performance, process monitoring, energy consumption, consumables and equipment costs.

PROCESS TIME

The total time to produce each joint is shown in Figure 11. This chart does not include any allowance for robot indexing between the joints. To date, this study has concentrated on optimising joint quality rather than reducing process time, so some future improvements in the process speed are possible.
The total process time of 1.3 seconds for SPR was the same for all the joint configurations. The process time for RSW ranged from 1.2 to 1.6 seconds. The process time for SFJ was similar at 1 second for the thin material joints but increased substantially to 9 seconds for the thicker materials.

QUASI-STATIC BREAKING LOAD

Typical load versus elongation plots for each discrete process are shown in Figure 12 and Figure 13. The energy absorbed for each process can be determined by integrating the area under each curve. The triangles denote the position of maximum load on each curve.

For the purposes of this basic comparison we have assumed that the differences in the static and dynamic mechanical properties of the three joining methods would result in a lower number of SPR joints than RSW or SFJ joints in an equivalent body structure. Therefore the comparative costs have been based on a car body containing 3000 SPR or 4000 RSW or 4000 SFJ joints.

The maximum-load values for each of the 6 joint configurations are summarised in Figure 14 and Figure 15. These charts show the average for each batch of six replicate joints. Similarly, Figure 16 and Figure 17 show the average values for the energy absorbed in the tensile testing of each joint type.
The lap shear test results for the replicate weld-bonded and riv-bonded joints J5A & J6A shown in Figure 14 are similar. Indicating that after curing the adhesive becomes the dominant joining method for resisting shear loading.

Figure 15 shows that the T-peel strength of the SPR joints is generally the higher than for RSW or SFJ. The extra sheet deformation needed to tear out an SPR rivet interlock gives increased peel strength compared to RSW and SFJ joints.

The T-peel strength of the SFJ joints made for the two-stack joints J1 to J4 were lower than the SPR and RSW joints.

The addition of adhesive in the SPR joints J5A and J6A had little effect on the strength compared to J5 and J6. However, the addition of adhesive in the RSW joints J5A and J6A increased the T-peel strength, in particular for J6A bringing it up to a similar strength as the SPR joints.

The amount of energy absorbed in breaking an SPR joint under shear loading conditions is significantly higher than that for RSW or SFJ joints. The extra sheet deformation needed to tear out an SPR rivet interlock gives increased energy absorption compared to RSW and SFJ joints, which tend to fail by shearing across the nugget with much less sheet deformation. This can be clearly seen in Figure 12.

In the T-peel tests, the difference in energy absorption between the SPR and RSW joint types is not as large as that in the lap-shear tests (compare Figure 12 with Figure 13). This is because the RSW button has to be pulled out of the sheet material as shown in Figure 2. Pulling out the weld button is comparable to pulling out the interlock of an SPR nugget. The SFJ joints performed poorly in this test.

IN-PROCESS MONITORING, NDT AND TEARDOWN

Using a robust in-process monitoring system to maintain joint quality, combined with a fast and reliable non-destructive testing (NDT) technique can significantly lower costs by reducing the need to regularly teardown and inspect vehicle bodies. The frequency and cost of destructive teardown testing would be relatively similar for all three joining methods providing their in-process monitoring and NDT systems are equally effective.

An in-process monitoring system is commercially available to monitor the rivet setting operation in SPR. The quality of SPR rivet insertion can be verified by visual inspection and destructive testing combined with vehicle teardown and joint cross-section methods. A number of companies are working to develop ultrasonic NDT systems for SPR. Production-ready process monitoring and NDT systems are not currently available for SFJ. However, ultrasonic NDT systems are being investigated for linear friction stir welding and may eventually be adapted for SFJ.

Figure 15, Graph comparing average T-peel strength

Figure 16, Graph comparing the average energy absorbed to break in a lap shear test

Figure 17, Graph comparing the average energy absorbed to break in a T-peel test
RSW has a number of in-process monitoring options, the most popular being measurement of the electrical signals during welding \[33\]. Some recently available electrode-life monitoring systems look for changes in the electrical signals to determine when electrode maintenance is required. Ultrasonic in-process monitoring is available for RSW from a number of equipment manufacturers \[34\]. The main concerns are the additional expense and intrusion of the ultrasonic equipment and the need to mount a transmitter and receiver close to the electrode holders. The ultrasonic in-process monitoring systems already deployed in the automotive industry for steel RSW equipment are mainly being used to record weld data to generate quality assurance records rather than to regulate the welding process.

Acceptable weld quality in RSW is usually defined as a minimum size of button that will be pulled from one side of the joint by a destructive peel test \[35\]. This highly effective test is well established for both steel and aluminium joints. However, it requires the parts to be destructively tested and so is not practical as a frequent check of weld quality during volume production. The widespread use of steel RSW and the need to inspect welds to reduce teardown costs has led to the development of several post-weld ultrasonic NDT systems \[36\]. The same technology has been evaluated for aluminium spot welds in a number of published studies. The main disadvantage of ultrasonic NDT testing is the requirement for highly trained operators with sufficient skill to interpret the results \[37\].

**ENERGY CONSUMPTION**

The energy consumed by each process varies according to the different thicknesses of sheet and the different alloys being joined. Accurate measurements of the total power required by each process are difficult to obtain. For this study, the approximate power consumption of the three processes was determined by cross-checking our own readings with the manufacturer’s figures.

A RSW system based on MFDC inverter technology and capable of 40 kA maximum welding current was used at settings ranging between 22 kA and 34 kA. A recent study investigating the power consumption of MFDC spot welding reported the energy efficiency of converting electrical energy to heat energy in the weld as 37\% \[38\]. The typical power consumption measured from the spot welding guns at Warwick University was between 7 & 20 Watt hours per weld. Taking the highest figure of 20 Wh gives 20 kWh per thousand joints. Of the three joining processes being compared, RSW is the only one that needs a supply of cooling water. The energy cost of providing the chilled water supply has not been included in the cost analysis because the figure is much lower than the cost of the electrical power used for the welding.

The SFJ machine used for this study has two 2 kW servomotors to rotate and plunge the stirring tool. In SFJ it is possible to stop the servomotors between each stirring operation. The cycle time to make the different joints ranged from 1 to 9 seconds. The average cycle time of 3.5 seconds gives 2 kWh per thousand joints. The SPR system employed uses a 2 kW servomotor to charge a flywheel and generate the force to drive the rivet into the joint stack. Assuming the average cycle time to move the gun and insert each rivet is 4 seconds and the 2kW motor is run continuously the power used to make 1000 joints would be 2.2 kWh.

The cost of industrial and domestic electricity varies greatly according to the country and the region. For example in 2001 the cost of domestic electricity varied from 6 cents per kWh in Washington to 12 cents per kWh in New England. The cost of industrial electricity supplies is also influenced by the proximity of industrial power generation facilities such as hydro-electric dams and the unit price the company has negotiated. A typical cost of industrial power in the UK of 7.2 cents per kWh has been used for the calculations in this study.

The power consumption or producing one car body containing 3000 rivets or 4000 welds is: $5.76 (80 kWh) for RSW, $0.57 (8.0 kWh) for SFJ, and $0.47 (6.6 kWh) for SPR. Multiplying the cost for one car body by a typical medium-volume build of 35,000 units per year the price of electricity is $201,600 for RSW, $19,950 for SFJ, and $16,450 for SPR. The cost comparison graphs in Figure 18 and Figure 19 suggest that significant increases in the cost of electricity would not have a major effect on the overall cost for each process.

**CONSUMABLES**

The cost per rivet is likely to be lower for high volumes. For the purpose of this study, the average price that different UK companies charge for self-piercing rivet has been used. If the cost of a rivet is four cents, then the cost for producing a car body with 3000 rivets is $120. Multiplying by 35,000 cars per year gives a cost of $4.2 million. The five and ten-year cost comparison graphs in Figure 18 and Figure 19 respectively, suggest that the rivets would have to be free of charge to bring the cost of the SPR process down to a similar level as RSW or SFJ.

The short life of the copper electrodes in RSW is the main stumbling block for the adoption of this process for aluminium. Recent work at Warwick University following on from tests at Alcan International’s Banbury Research Laboratories \[1\] has shown that an electrode-life in excess of 10,000 welds can be achieved by adopting regular electrode cleaning between components to keep the electrodes in good condition. The motivation for maintaining the electrode condition is that high quality welds can be produced consistently, providing the electrode has a minimal level of damage \[6\]. The typical cost for a pair of copper zirconium electrodes is $2. With regular electrode maintenance a conservative electrode-change frequency of every 4,000 welds was assumed for the cost comparison. 35,000 units, each with 4,000 welds, would require an average of one pair of...
electrodes per unit. At $2 per pair, the cost of electrodes would be $70,000 per year.

Production trials have shown that an SFJ tool costing $450 can have life in excess of one million joints on thin materials [21]. If 164 SFJ guns were required and one new tool was fitted every three years the tooling consumables cost per year would be $24,600.

**EQUIPMENT COST**

Aluminium’s higher electrical and thermal conductivities mean that welding currents and gun forces larger than those used for steel are needed. Thus, heavier guns and higher payload-capacity robots are required for RSW of aluminium [1, 12]. Guns for SPR and SFJ are of similar mass to those for RSW of aluminium. Robots with 150 kg payload-capacity will typically be required and the cost of these robots will be similar for each gun type. The main effect of robot cost on the overall expenditure for producing 35,000 units per year is the increased number of robots needed for the less “flexible” joining methods.

RSW can make a wide variety of joint types on a single gun, compared to the need for a range of guns and gun or tool-changing systems on robots to produce the same range of joints with SPR or SFJ. The potential cost savings from purchasing a single lower-price “flexible” gun and fewer robots for RSW compared to more gun types and robots for SPR or SFJ are shown in the cost comparison graphs in Figure 18 and Figure 19. Approximations based on the typical indexing time between joints were used to determine the number of guns and robots required in the overall cost comparison described in the later section.

Vehicle manufacturers are currently trying to be more environmentally friendly by refurbishing the robots they already have, instead of buying new ones. Most of the UK car plants that have been installing “new” weld systems for steel, have been standardising on MFDC weld controls, thus building-in flexibility by ensuring they can cover a wide current range. The cost differential between MFDC systems for steel and the higher weld current systems needed for aluminium are not significant but must be included in a cost comparison.

Allowing for geometry-defining welds and other special gun set-ups required for components with limited access, it was estimated that to produce 35,000 units per year, the number of guns required would be; 160 for SPR, 125 for RSW and 240 for SFJ. The costs from the manufacturers’ standard prices are estimated to be in the region of $63,000 for SPR, $30,000 for RSW, and $45,000 for SFJ. Combining these figures, the estimated joining equipment outlay for producing 35,000 units per year is $10 million for SPR, $4 million for RSW and $11 million for SFJ.

By employing gun-changers on the robots it was estimated that the number of robots required to produce 35,000 units per year would be; 80 for SPR, 62 for RSW and 120 for SFJ. If the typical robot price is $90,000 then the cost of the robots to produce 35,000 units per year is $7 million for SPR, $5.5 million for RSW and $11 million for SFJ. Electrode maintenance equipment for RSW costs around $2,500 per robot or $155,000 for 62 robots.
RSW usually requires the installation of an electrical sub-station for every ten weld guns. The approximate cost for buying and installing a sub-station of $120,000, or $12,000 per gun, has been added to the equipment cost calculation for RSW. If the vehicle is to be built at an existing car plant, then the existing electrical infrastructure for steel RSW may be suitable, particularly considering the reduced mains current drawn by modern three-phase MFDC inverter power supplies, as compared to their single-phase AC predecessors.

MAINTENANCE

The cost of maintenance (labour on call and new parts) per gun can be expected to be similar for all three joining methods. However, the number of guns, robots, part movers and cells required will be higher for the less-flexible joining processes. Therefore, it is reasonable to suggest that that cost of maintenance could be lower for RSW. Maintenance costs have not been included in this cost comparison because the differences are likely to be insignificant compared to other figures.

LABOUR COST

The number of manual stations requiring operators (rather than robots), is likely to be very similar for all three joining methods. The labour cost to change the cassettes of rivets every 1000 joints is not significantly different to changing the RSW electrodes every 4000 welds. Therefore the cost of labour has not been included in the overall cost comparison.

OVERALL COST COMPARISON

For the purpose of enabling a relatively simple cost comparison, the three point joining methods were compared on the basis of making all of the joints on a body in white with one method. This approach should give useful indication of the comparative costs for a production line where one of the joining methods is used to make the majority of the joints in a body in white.

To compare the number of joints required to make a complete body in white using each joining method; the number of SPR joints required to make a typical passenger-vehicle BIW would be approximately 3000, whereas the number of RSW or SFJ joints would be closer to 4000.

This equipment cost comparison used average values for each equipment type based on prices from competitor suppliers. This study focussed on identifying costs that would be significantly different for each joining method. Non-joining related costs and other general overheads were ignored because they would be similar for each process. The numbers used in the overall cost comparison shown in Figure 18 and Figure 19 were based on buying new joining equipment and producing 35,000 units per year. They do not represent the full cost of installing and operating a line.

The estimated costs for buying, running and maintaining the joining equipment were combined in a spreadsheet to identify the factors that have the most effect on the overall cost. This spreadsheet was found to be a useful tool for sensitivity analysis; identifying values where small changes have a significant effect on the overall cost and conversely, values where large changes have little overall effect.

The results identified RSW as a more economically favourable option than SPR or SFJ for the task of producing the majority of the joints on a body in white. The analysis indicates that it is the ongoing cost of the rivets that makes SPR the most expensive process. For RSW, the largest cost factors identified were energy consumption and frequency of electrode replacement.

DISCUSSION

Almost certainly a combination of joining methods will be utilised in any aluminium-based BIW. There is no single joining method that is perfectly suited for producing all of the joints on an aluminium car body, especially if the BIW is made using a mixture of sheet, extrusion and cast aluminium components and combined with some high-strength steel parts. At present, all three of the joining processes compared in this study are restricted to two-sided access because a backing tool or electrode is needed on the other side of the joint. This limits the options for joining extruded tubes to designs where there is an incorporated flange or designs where large access holes can be drilled through one side of the extrusion.

For simplicity, the joining methods were compared on the basis of them each being used to produce the majority of the joints in an aluminium car body. This “broad-brush” assessment indicates that RSW incorporating frequent electrode maintenance is the most economical process. However, a more detailed analysis would probably highlight specific assembly operations where it is more economical to use SFJ, SPR or clinching.

An RSW gun designed for welding steel is unlikely to provide enough current or electrode force for welding aluminium; however, a RSW gun designed for welding aluminium can be fully capable of welding steel (i.e. a MFDC inverter power supply coupled with a servo-actuated gun). This configuration offers the valuable flexibility of being able to spotweld both steel and aluminium components using the same equipment. To fully optimise the process for either material would simply require a changeover of electrode geometry and adoption of a slightly different electrode maintenance strategy. SPR offers this same flexibility, with the added advantage of being able to join mixed materials. However, it is very unlikely that a predominantly steel car would be assembled using SPRs due to the rivet cost. A cost factor for SPR that was not included in this study is the complexity of using different rivet lengths and die profiles to produce a range of total joint thicknesses.
Requiring additional rivet and die changeover procedures.

In the future, it may be possible to produce three or four thickness joint-stacks using SFJ, the equipment used in this study can produce two-layer stacks. At the moment, a different SFJ tool geometry is needed for most joint configurations. The long process time of five to nine seconds needed to join thick sheets and the wide flanges needed to place adhesive separately to the side of the SFJ joint would be considered undesirable for most automotive applications. Further development work of this relatively new process may resolve these limitations.

RSW is more sensitive to the condition of the sheet surface and thickness of the oxide layer than either SPR or SFJ. Unlike steel, the majority of the heat required for aluminium RSW is generated by electrical resistance at these surface layers. For the process to be consistent it is very important that these aluminum surface layers remain stable both over time and from batch to batch. Materials supplied for RSW in the automotive industry will have been carefully cleaned and pretreated, usually by the aluminium company, to provide suitable surfaces. Pretreated surfaces can be remarkably robust; in this study no problems were experienced when welding pretreated material a year past its shelf-life with numerous light surface scratches. An important consideration for RSW is to ensure pretreated panels are not stored in damp conditions which promote oxide film growth. A significant increase in oxide thickness due to poor storage conditions can lead to over heating of the weld resulting in reduced electrode life.

The higher energy absorption before failure of SPR under tensile loads may be advantageous for improved crash performance and increased consumer safety. Therefore the benefits of SPR should be considered for critical joint areas where these properties are desirable.

CONCLUSION

Self-pierce riveting (SPR) offers superior performance in mechanical testing for maximum quasi-static load and energy absorbed. The main process-related limitations are the requirement for different rivet / die configurations to produce different joint types and the need for the bottom sheet to be sufficiently thick for the rivet to flare and produce a strong interlock. The ongoing piece-cost of the rivets is the biggest economic issue of SPR; this could be reduced by using SPR only where the extra mechanical performance justifies the additional cost, or when mixed materials are to be joined.

The resistance spot welding (RSW) process offers the flexibility to make different joint configurations on a single gun and the ability to switch between steel and aluminium. With a low consumables and investment cost, RSW is the most economical process for high-volume production. The well known problems of short electrode-life and poor consistency can be overcome with suitable gun programming and electrode maintenance procedures. The car industry currently lacks confidence in high volume RSW of aluminium and more studies are needed to overcome this.

Spot friction joining (SFJ) uses a low amount of energy per joint and is an attractive process for applications where many similar joints are required in thin materials e.g. closure panels. If the problems of long process time in thicker materials, limited tool flexibility and joining multi-layer stacks can be addressed, then SFJ could become a widely used process in the future.

The combination of a discrete joining process with a structural adhesive to form hybrid joints offers the potential to exploit the best features from each method whilst compensating for deficiencies in the other. The ability of SPR and RSW to produce a wide range of joints, both with and without the presence of adhesive, makes them attractive to manufacturing engineers.

Inevitably, in a complex structure such as a vehicle body in white, several different joining techniques will be required. Whilst it might seem appropriate to employ numerous joining methods highly optimised for specific applications, too many techniques in a single manufacturing operation will be prohibitively expensive to install and maintain. Getting the correct balance of joining methods will be interdependent on many factors including; vehicle design, performance requirements, intended production volumes, economics, environmental concerns, repairability and others.

The main features of the three discrete joining methods compared in this study are summarised in Table 2.

<table>
<thead>
<tr>
<th>Table 2, Summary of the positive and negative features of the three joining methods compared in this study.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Self-Pierce Riveting</strong></td>
</tr>
<tr>
<td>+ Best mechanical properties</td>
</tr>
<tr>
<td>+ Mixed material joints</td>
</tr>
<tr>
<td>– Ongoing cost of rivets</td>
</tr>
<tr>
<td>– Gun flexibility</td>
</tr>
<tr>
<td><strong>Resistance Spot Welding</strong></td>
</tr>
<tr>
<td>+ Low cost of equipment</td>
</tr>
<tr>
<td>+ Gun flexibility and automation</td>
</tr>
<tr>
<td>– Consistency remains to be proven</td>
</tr>
<tr>
<td>– Electrode maintenance needed</td>
</tr>
<tr>
<td><strong>Spot Friction Joining</strong></td>
</tr>
<tr>
<td>+ Joining thin materials</td>
</tr>
<tr>
<td>+ Low running costs</td>
</tr>
<tr>
<td>– Long process times for thick materials</td>
</tr>
<tr>
<td>– Gun flexibility</td>
</tr>
</tbody>
</table>
FURTHER WORK

A wider comparison using additional automotive aluminium alloy candidates is in progress. The next phase of this project may include comparative fatigue testing. This would be conducted without cured adhesives because their addition to fatigue strength masks the fatigue properties of the discrete joints.

The usefulness of adjusting electrode force on a servo spot welding gun while the weld is being made is presently being investigated. A high strain-rate testing machine may also be employed to conduct some comparative energy absorption tests on joints at speeds simulating crash conditions.

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REFERENCES


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