Developments towards high-volume resistance spot welding of aluminium automotive sheet component

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INTRODUCTION

Resistance Spot Welding (RSW) is the most common joining method for steel body panels in the automotive industry. Its principal benefits of high speed and low-cost operation, plus the ability to weld a wide range of joint configurations with the same gun, can also be exploited for joining aluminium. The main barrier to the adoption of RSW for aluminium vehicles is the short life of the welding electrodes and the associated reduction in weld quality as the electrodes degrade.\cite{1,2,3} Most automated car production lines require a minimum electrode life of one eight-hour shift, which typically entails between 3,000 and 10,000 welds.

In the last decade, many automotive steel RSW assembly lines have realised the benefits of extended electrode-life and improved weld consistency by carrying out occasional electrode dressing. Rotating shaped cutters are used to control the growth in electrode face diameter (often referred to as “mushrooming”), remove pits and surface contamination. Electrode dressing has significantly improved the problem of reduced electrode-life caused by the move towards higher strength steels and the increased use of coatings to reduce in-service corrosion.

Without electrode maintenance, the quantity of aluminium spot welds that can be achieved on a set of electrodes before the weld quality drops below a minimum threshold is typically between 300 and 3000 welds.\cite{2,3} The reason that the electrode-life is so variable is the randomness of when and where aluminium starts to deposit on the copper electrode face. Once significant aluminium accumulation has occurred, deterioration of the weld consistency and quality is rapid. Unless some form of electrode maintenance is employed to recover the condition of the electrode, the remaining electrode-life will typically be less than a few hundred further welds.

Commercially available electrode dressing equipment that employs hardened steel cutting blades can be applied to aluminium RSW electrodes, but the finite amount of copper available to machine away from the electrode face means that dressing with a cutter can only be applied around twenty times. Occasional electrode dressing is only practical for aluminium spot welding if a monitoring system is used to identify when the aluminium deposits occur and trigger a dressing cycle.

A study at Warwick University following on from work conducted by Alcan’s Banbury Research Laboratory has demonstrated the potential of using a gentle polishing wheel rather than an aggressive dressing cutter to regularly remove aluminium deposits from the electrodes. Using a polishing wheel enables the electrodes to be cleaned within the index time between every component, with only a minimal change in electrode geometry even after hundreds of cleaning cycles.

The study has demonstrated that more than 10,000 high-quality welds can be achieved using standard zirconium-copper electrodes by either cleaning the electrodes between every component, or monitoring the electrode condition to trigger a cleaning or dressing operation when an aluminium deposit is detected. Further work is underway to determine which of these electrode maintenance approaches is more suitable for an automated car production environment.

The development of new electrode maintenance processes is showing great potential for preventing the build up of aluminium deposits on the electrodes, overcoming a major stumbling block that has been holding back the adoption of aluminium sheet for high-volume lean-weight vehicle applications.
ALUMINIUM SPOT WELDING EQUIPMENT

A big advance in RSW of steel and aluminium has been the development of Medium Frequency Direct Current (MFDC) welding power supplies, which offer significant process control improvements over 50/60 Hz Alternating Current (AC) systems. MFDC inverters also offer the advantage of operating at low currents with none of the waveform distortions associated with AC systems. A particular benefit of operating at high frequency (1000 Hz) is the reduced size and mass of the welding transformer, enabling robot manipulation of the higher-current guns needed for aluminium RSW.

Most of the spot welding guns presently employed in the automotive industry use pneumatic actuators to apply the electrode clamping force. Many new installations are now opting to install electric servomotor actuators eliminating the need for pneumatics on the assembly line. Unlike pneumatics, servo guns with force feedback control operate accurately at both low and high gun forces. Servo guns also offer the potential for faster cycle times by controlling the electrode aperture and closing speed. Figure 1 shows a robotic MFDC servo gun installed at Warwick University in November 2005 ready for the next stage of the project.

The main difference between the equipment required for aluminium spot welding compared to steel is the force and current capability of the gun. For steel RSW, a force range of 0.2 to 4 kN and welding currents under 15 kA are usually sufficient. For aluminium RSW, a force range of 0.2 to 8 kN and welding currents up to 40 kA are typically required. Low force capability is useful for on-line electrode dressing operations. High force capability is needed to control expulsion when welding thicker gauge aluminium materials & for weld-bonding. The dramatic improvement in the process window (range of parameters that give acceptable welds) obtained by using a high force gun for aluminium RSW is shown by comparing Figure 2 and Figure 3. In each case identical alloys and stack-ups have been welded using the same gun.

Figure 1, Robot-mounted MFDC servo gun for aluminium RSW at Warwick University.

Figure 2, No process window at 3 kN electrode force with a 10 mm face domed electrode.
An MFDC servo gun specified for welding aluminium is fully capable of welding both steel and aluminium, therefore a production cell set-up for aluminium RSW can offer the flexibility of also welding the full range of automotive steels. But the same cannot be said the other way round.

In automotive assembly operations, component shape variations can lead to gaps between the parts being welded. If these gaps occur in stiff joints (e.g. those containing high-strength materials, highly shaped parts or thick sections), then the external gun force applied to the parts may not be completely transmitted to the welding zone. Because a proportion of the external force is being consumed in keeping the joint gap closed. The latest generation of force-feedback servo guns offer the interesting possibility of calculating the effective force at the electrodes and adjusting the external gun force to achieve a welding force within the process window. Another interesting prospect for servo guns is the opportunity to increase or decrease the electrode force during the weld to influence nugget initiation and growth.

**ELECTRODE LIFE**

Unlike steel, where the bulk material has a high level of electrical resistance, the majority of heat in aluminium spot welding is generated from the resistance generated in the oxide layer at the sheet surfaces. The meeting of two oxide surfaces in the middle of the joint makes the resistance higher in the middle than on the outside where there is only a single thickness of oxide. A long electrode-life in RSW of aluminium requires the selection of weld parameters that minimise the occurrence of aluminium melting at the electrode-sheet interface in order to prevent the build up of aluminium on the electrode.

An accumulation of aluminium on the electrode face is undesirable because it leads to increased resistance heating at the electrode-sheet interface causing even more aluminium to melt and stick to the electrode. Without some form of electrode maintenance to break this degradation cycle, the electrode rapidly becomes completely coated in aluminium and pitting of the electrode face becomes inevitable. The loss of a uniform electrode shape due to pitting, combined with the extra surface heating due to a coating of aluminium, makes the RSW process harder to control. This has a detrimental effect on the consistency, shape and quality of the welds produced. Typically, the incidence of undesirable weld expulsion (splash) increases and nugget size decreases as the electrode condition deteriorates. A damaged electrode also has an unsightly effect on the appearance of the surface indentation left by the electrode.

Figure 4 shows an example of what can happen after just 700 welds without electrode maintenance to break the cycle of degradation. Figure 5 contrasts the very significant benefits that can be gained by frequent electrode maintenance.
Selecting appropriate welding parameters to avoid overheating significantly helps to prevent aluminium frequently sticking to the electrodes, but not stop it from happening occasionally. When aluminium does stick to an electrode it must be removed by some form of electrode maintenance within a few welds, otherwise the increase in resistance heating at the surface leads to more aluminium melting and more serious electrode damage. Two different methods for in-situ electrode maintenance are being investigated in this study, namely ‘dressing’ and ‘cleaning’.

**ELECTRODE DRESSING**

A wide range of commercially available electrode dressing equipment has been developed for steel RSW, including hand-held dressers for manual guns and stand-mounted systems for robot guns as shown in Figure 6.[7] The powerful motors employed on stand-mounted dressers offer better cutting performance than hand-held dressers, which are fitted with low-power motors to ensure the cutter will stall before reaching a force that could injure an operator.

A variety of cutter blade types have been developed for steel RSW, ranging through solid single blades to multi-blade designs, reversible blades and replaceable cutting inserts. Some commercially available examples are shown in Figure 7.
A common feature of cutters designed for steel RSW is the emphasis on reshaping the sides of the electrodes to remove mushrooming and thereby maintain welding current density. In aluminium RSW, mushrooming of the electrode does not occur and the main requirement of the cutter is to take light cuts from the face to remove aluminium, oxides and pits.

Conducting an electrode dress operation every few hundred welds is very effective for steel RSW, but is not a full solution for aluminium because more frequent attention is required to maintain weld quality. There are only so many times a copper electrode can be re-machined with a cutter after which substantial changes in its geometry require it to be replaced. A potential solution for aluminium RSW is to use a less aggressive means for maintaining the electrode (such as a cleaning wheel), and only employ a dressing cutter when the tip is too badly damaged to be restored by cleaning.

**ELECTRODE CLEANING**

In this study, a wide range of commercially-available abrasive wheels were tested for their electrode cleaning performance. Some examples of these products are pictured in Figure 8.

One of the wheels (shown in Figure 9) was found to be extremely effective at removing aluminium from the electrode face. This particular wheel gave a long service life achieving more than four thousand cleaning operations. It has the additional advantage of being shapeable to accommodate and maintain the profile on domed electrodes as shown in Figure 10.
Electrode-life tests were conducted to compare the difference between using no tip cleaning and regular tip cleaning. The alloy was automotive grade AA5754-O in the as-received, pretreated and lubricated condition. The joint stack-up was 1.5 + 1.5 mm. The welding equipment was a Bosch Rexroth 40 kA MFDC inverter connected to a portable pneumatic gun capable of forces up to 8 kN. The welding parameters employed were; electrode force 6.0 kN, squeeze 700 ms, up-slope from 1 kA to 23 kA over 40 ms, main-weld 23 kA for 70 ms, hold 200 ms. The electrode was a standard 19 mm diameter male electrode made of zirconium-copper, tapered to a 10 mm diameter face with a 50 mm radius profile. Figure 11 shows the fabricated joint geometries. The samples were welded as larger sheets of size 100 mm x 300 mm and then cut into test pieces 40 mm wide. The first un-shunted weld was discarded, as this weld tends to receive more current and have a larger nugget. Six replicates of each joint were quasi-statically tensile tested in batches to establish the average maximum failure load.

When no electrode cleaning was used, signs of electrode damage were observed on the external weld indent as early as 200 welds; continuing to weld resulted in the weld button size dropping below the minimum diameter commonly employed in automotive production (\(4\sqrt{1.5} = 4.8\) mm) within just 700 welds.

This rapid process deterioration was not seen in the tests where regular electrode cleaning was employed. No changes in weld button size or joint strength were detected after 10,000 welds in tests where the electrodes were cleaned either every 15 welds (~600 cleans for 10,000 welds). The same result was achieved when the electrodes were only cleaned when aluminium was visually detected on the electrode face (~20 cleans for 10,000 welds). The main difference
between regular cleaning and cleaning only when aluminium is detected on the electrode being the total number of cleaning operations required.

The reason for the significant improvement in robustness gained from electrode cleaning is thought to be due to the removal of any aluminium deposits on the electrodes, making the process less susceptible to uncontrolled changes in electrical resistance and the localised variations in force and current density occurring on pitted electrodes.

The improvement in electrode condition and weld nugget size gained by regular cleaning was shown previously in Figure 5. The reduction in quasi-static joint strength after a few hundred welds without cleaning is compared to the unchanged joint strength obtained by regular cleaning in Figure 12. The values shown are the average of the maximum strength measured from batches of six replicate samples.

Figure 12, Change in strength of Lap shear and T-peel joints with and without regular cleaning.

The preferred cleaning wheel was found to be very effective at removing aluminium from the electrode face; repeated cleaning between each component also showed the capability for gradually removing small pits. Cleaning removes only very small amounts of material and is therefore not capable of remedying deep pits in the electrode, such as the one shown in Figure 13. Deep pits can only be rectified either using a tip dressing cutter or replacing the electrode.

There are potential process stability benefits from being able to automatically detect four electrode conditions; when no action is required, when an electrode needs cleaning, when an electrode needs dressing with a cutter and when the damage is too serious to fix by dressing and the electrodes need replacing.

Figure 13, A partially pitted electrode can usually be remedied using a dressing cutter.
BENEFIT OF CLEANING THE ELECTRODES BEFORE WELDING

A likely time for electrode damage to occur is on the very first weld with a new electrode, especially if the electrode is making a weld in a position where there are no existing welds or pathways within 50 mm to share some of the current. Tests in this study have indicated that the main reason for this damage is overheating at the electrode-aluminium interface due to a previously established air-formed copper oxide layer on the electrode. The suggested remedy to this problem is to remove the copper oxide layer by either dressing or cleaning a new electrode shortly before starting to make welds.

An experiment was conducted on 3.0 ± 3.0 mm AA5754-O automotive sheet using a high current setting which was found to consistently damage new electrodes on their first weld, but caused no damage to electrodes that had already made more than one weld. Six brand-new electrodes all suffered damage on the first weld, of the level shown in Figure 14. In contrast, twelve electrodes suffered no damage when they were either dressed or cleaned to remove the copper oxide layer prior to making the first weld, as shown in Figure 15.

![Figure 14](image1)

Figure 14, A new electrode with an established oxide layer can be damaged by the first weld.

![Figure 15](image2)

Figure 15, Freshly dressed (left) or cleaned electrodes (right) are undamaged after the first weld.

To investigate this further, six new electrodes were cleaned and then left for three days to form an oxide layer in air before making the first weld. When welding with the same current setting described above, these electrodes suffered the light damage shown in Figure 16. This light amount of damage was easily fixed by cleaning, whereas the more heavy damage caused by a well established oxide layer, shown in Figure 14, required correction with a dressing cutter.
To investigate this further a separate test was conducted measuring the electrical resistance through the electrodes on the welding gun by closing the gun and passing a small (10 Amps) current. For this test we employed a Matuschek weld timer equipped with the capability to monitor and record the voltage, current and resistance during welding. The gun configuration employed was the same as that used for the experiments conducted using the Bosch Rexroth weld timer.

When a brand new electrode with an established oxide layer was cleaned the resistance measurement obtained from making a low power weld with the electrodes touching halved. The measurements were repeated every 20 minutes (with no spot welds being made on components) and the resistance value measured returned to its original value after two hours. This finding indicates that the probability of electrode damage occurring on the more powerful un-shunted welds can be reduced by cleaning electrodes that have not been used for welding in the previous hour to remove most of the oxide layer.

Whilst regular cleaning or dressing can provide excellent electrode-life, the success of this technique still depends to a large extent on the suitability of the welding parameters for the components being welded. Even with regular cleaning, electrode damage will occur if the current delivered by the welding sequence is too powerful for the joint stack.

A sensible approach to achieving long electrode-life is to turn down the welding current by a small margin (say 1 - 5 kA) when making isolated “geometry” welds, to compensate for the lack of current sharing. The potential gains in electrode-life and weld quality are well worth the extra effort of setting up a weld gun with two sequences; one with a reduced power level for geometry welds, and one with the normal power level for making the welds in-between.

Having a dresser on every gun offers the benefits of lining up the electrodes if the electrode holders are not exactly lined up and reducing the frequency of electrode changes. A lower-cost alternative to fitting dressing equipment on every gun might be to have a single bench-top electrode dressing machine and remove electrodes which are too badly damaged to fix by cleaning to send them all to this one machine for dressing. The results from this initial study indicate that when an off-line dressing approach is employed, an on-line electrode cleaning process should be considered to remove the oxide layer shortly before welding commences (or recommences after a break).

**MECHANICAL PERFORMANCE**

Comparing different joining processes for a high-volume production line is a complex task with many factors to consider. These include equipment cost, equipment flexibility, equipment reliability, risk of equipment not functioning as expected, consumables cost, process cycle time, joint stack-up and sheet thickness capability, quasi-static and dynamic joint performance, vehicle performance (stiffness, NVH, etc.), fatigue life and durability in hostile conditions, repairability, end-of-vehicle-life (ELV) concerns, and so on.

One of the most important factors to consider is the quasi-static mechanical performance of the joint and it is often necessary to investigate both T-peel and shear loading conditions to get a more compete picture. It is also important to understand the joint’s performance under dynamic...
(e.g. fatigue, impact) loading and in the case of adhesively bonded hybrid joints the durability of the pretreatment-adhesive combination under hot-wet conditions.\cite{8} A number of fatigue studies have been carried out for aluminium RSW and are available in the published literature.\cite{9,10}

Figure 17 and Figure 18 show the quasi-static tensile test results for 2.0 × 2.0 mm AA5754-O joints made using three different point-joining methods; Resistance Spot Welding (RSW), Self-Pierce Riveting (SPR) and Spot Friction Joining (SFJ). The triangles marked on each curve indicate the point of maximum load. A more detailed comparison of these three joining methods can be found in reference \cite{11}.

In aluminium sheet, the maximum load of RSW and SPR joints are similar. Load-extension curves for SPR joints usually show larger energy absorption before failure due to the mechanical deformation of the sheet needed to pull out the interlocked rivet. SFJ joints are comparable both in terms of tensile strength and process cycle time for 1.0 + 1.0 mm joints, but do not currently offer the same level of mechanical performance or short cycle times as RSW or SPR in the thicker gauges typically used in the structural parts of the vehicle.\cite{11}

**WELDBONDING**

The requirement to assemble parts and hold them in position in very short cycle times (in the order of seconds), makes it unlikely that the heat-curing adhesives employed in most of today’s aluminium car structures could become the *sole* joining method on high-volume aluminium
cars. Spot welding and mechanical joining techniques are much better suited to making rapid point joints that can hold parts together enabling the adhesive in the joint to be cured later, usually at the paint-bake stage.

Adhesives provide continuous joints with excellent stiffness and fatigue properties that are considerably improved over the point-joining techniques.\(^{12,13}\) The main drawback of adhesives is their limited mechanical strength in peel-loading situations. Fortunately, this can be compensated by combining the adhesive with a point-joining method such as SPR or RSW to increase the peel performance and acting as peel stoppers in the bond line.\(^12\)

The combination of spot welding with adhesive bonding is known as weld-bonding. Resistance spot welding through an uncured epoxy adhesive requires a high-force welding gun and domed electrodes to squeeze out the bulk of the viscous adhesive from between the sheets before the main weld pulse is initiated. This clearance zone can be clearly seen in Figure 19.

![Figure 19, Weld button pulled from a weld-bonded joint; uncured (left), cured (right).](image)

**CONCLUSIONS**

- For aluminium resistance spot welding, frequent electrode maintenance makes a huge improvement in the number of consistent high-quality welds obtainable from one set of electrodes.

- Removing the copper oxide layer from the electrodes immediately prior to welding helps prevent early electrode damage, extending the electrode-life in aluminium resistance spot welding.

- High-force guns improve the process robustness for aluminium resistance spot welding and enable the process to be combined with adhesive bonding.

- Aluminium resistance spot welding is cost-effective, fast and flexible process.\(^{11,14}\)

- Combining aluminium resistance spot welding with structural adhesive bonding significantly enhances the stiffness and fatigue performance of the joints.

- Combining MFDC weld inverters with high-force servo-guns offers the useful flexibility of welding both aluminium and steel components in the same cell.
REFERENCES


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