Effect of aluminium sheet surface conditions on feasibility and quality of resistance spot welding

L. Han[1*, a], M. Thornton [1, b], D. Boomer [2, c], M. Shergold [3, d]

1, Warwick Manufacturing Group, University of Warwick, Coventry, CV4 7AL, UK
2, Innoval Technology Limited, Banbury, Oxfordshire, OX16 1TQ, UK
3, Jaguar Land Rover, Abbey Road, Whitley, Coventry, CV3 4LF, UK

a, li.han@warwick.ac.uk, b, martin.thornton@warwick.ac.uk, c, douglas.boomer@innovaltec.com,

d, mshergo1@jaguarlandrover.com

*Corresponding author: Tel: +44(0)2476575385; Fax: +44(0)24767575366

Abstract:

A study investigating the effect of sheet surface condition on resistance spot welding (RSW) of aluminium has been carried out at the University of Warwick. This concentrates on two commercial automotive aluminium alloys; AA5754 and AA6111, used for structural and closure applications respectively. The results show the marked effect that surface condition can have on the RSW process. For AA5754 sheet incomplete removal of a 'disrupted surface layer' prior to surface pretreatment is shown to have a detrimental effect on the RSW process. Another potential influence is the solid wax lubricant used to assist metal forming. This lubricant leads to unpredictable changes in contact resistance, which affects the process stability. In practice, a welding schedule devised to displace the lubricant prior to the main weld pulse can provide a solution. For AA6111 closures the final surface topography can influence the RSW process. Standard 'mill' and electro discharge textured (EDT) finish sheet surfaces were examined and preliminary results suggest that both are suitable for welding. The successful application of RSW of aluminium sheet requires careful consideration of the sheet surface condition, and this requires close collaboration between material suppliers and automotive manufacturers, to ensure that optimum process parameters are applied at all stages of the manufacturing.

Key words: Resistance spot welding, Aluminium alloy sheet, Automotive

1 Introduction

Resistance Spot Welding (RSW) is the most popular joining technique used by the automotive industry for the manufacture of steel body structures. Despite the process being well established for steel it cannot be directly transferred for use with aluminium. Aluminium reacts with oxygen in the atmosphere and an oxide film forms on the metal surface, giving protection to the metal but also resulting in a highly resistive layer. During RSW, the tenacious oxide layer needs to be broken down uniformly to allow weld nugget formation to progress in a controlled manner. This generally requires a high electrode force, as reported by Auhl and Patrick (1994). Coupled with the high electrical and thermal conductivity of aluminium alloys, nearly three times the weld current and two times the electrode force are required for welding bare aluminium compared to welding bare steel. These parameters in turn dictate that suitable equipment has to be used for welding aluminium, rather than using existing welding equipment designed for steel. Even with suitable equipment in place, any increase in the surface contact resistance at the electrode to sheet interface will increase ohmic heating raising the temperature of the copper electrodes. This leads to increased diffusion of aluminium into copper and the formation of brittle intermetallics degrading the electrode surfaces. Therefore the short life of the welding electrodes and the associated reduction in weld quality as the electrodes degrade, presented significant challenges for adoption of RSW in volume production, as suggested by Leone and Altshuller, (1984), as well as Patrick *et al*. (1984).

Previous research also examined the effects of sheet surface condition on the aluminium RSW process from different aspects. Ronnhult *et al*. (1980) studied the weldability of aluminium alloy AA5252, both as-received and after etching in NaOH and oxalic acid, and proved that removing the oxide layer led to a significant improvement in weld quality. The same principle was applied for AA6111 automotive body closure sheet by Pickering and Hart (1994), who noted that acid cleaning significantly widened the process window compared to a standard mill finish surface. Li *et al*. (2007) investigated the effect of as received (no treatment), degreased, chemically cleaned and electric-arc cleaned surface treatments on electrode life for alloy 5A02. Their research demonstrated that the chemically cleaned surface, which had the thinnest oxide layer, provided the longest electrode life. In addition, Rashid *et al*. (2007) established the effect of lubricant on electrode life by using commercially available mill finished AA5182 with different types and weights of lubricant. It was discovered that the combination of this surface with one of the lubricants tested extended the electrode life by 200%. In research carried out by Thornton *et al*. (1997), etched, mill finish and pretreated/lubricated AA5754 surfaces were examined. Their results suggested that etched surfaces, which had a thin and uniform oxide layer, gave the most consistent surface resistance and weld strength, and in good agreement with previous research by Ronnhult *et al*. (1980), Pickering and Hart (1994), Li *et al*. (2007). Thornton *et al*. (1997) and Miller *et al*. (2000) also pointed out that a chemical cleaned surface is not time-stable, and has other issues regarding handling, forming and adhesive bond durability. These issues generally make etched surfaces unsuitable for volume manufacturing. Therefore further treatment is necessary and as discussed by Thornton *et al*. (1997) and Hunter *et al*. (2000), only a pretreated/lubricated surface satisfied all of the requirements for a mass-produced automotive weld bonded structure. Although different methods and materials were employed by the previous researchers, the effect of an underlying disrupted layer has not been explicitly identified in any previous work. This layer is present on all aluminium sheet products as a consequence of the high level of local surface shear strain generated by direct contact of the sheet surface with the steel roll. For high magnesium alloys, the disrupted layer is more severe due to surface oxidation that occurs during hot rolling.

From previous research, a common theme has been established regarding the importance of surface condition for the RSW process, and its effect on electrode life and the associated weld quality. This knowledge has taken on renewed relevance with the more widespread use of aluminium for automotive structures today. Although the majority of existing aluminium vehicle structures are joined using self-piercing riveting (SPR), often combined with structural adhesive bonding, there are limitations. The fact that the key process parameters (e.g. rivet and die geometry) cannot be changed during production restricts the flexibility of the SPR process. In addition, the use of rivets adds weight and considerable unit cost as well as presenting some recycling issues. Therefore, the interest in using RSW for volume production remains. Recent developments have removed further barriers to the adoption of this joining process. In 2003, Boomer *et al*. described a potentially non-intrusive method to increase electrode life and improve weld quality and Spinella *et al*. (2005) discussed the advantages of RSW of aluminium together with some potential non-destructive evaluation technologies. More recently, a research team at the University of Warwick, Briskham *et al*. (2005, 2006), has reported significant improvements in electrode life and consequently weld quality. A rigorous approach to process control incorporating stringent electrode maintenance procedures prevents the potentially rapid deterioration in electrode condition, and the detrimental "downward spiral" effect on weld quality. These achievements have put RSW technology a step closer to volume production. But the materials to be welded still require appropriate and consistent surface condition. It is important to determine now whether RSW can be considered for volume production, alongside the processes currently being used to join the range of commercially produced aluminium automotive sheet materials.

2 Material requirements for automotive applications

For structural and closure automotive applications, AA5754 and AA6111 are widely available commercial sheet alloys as reported by Miller *et al*. (2000). As far back as 1987, a concept for producing automotive structures using press formed aluminium sheets was proposed by Wheeler *et al*. using Alcan's aluminium vehicle technology (1987). This approach, which has been evaluated by leading manufacturers for volume production, as mentioned by Bull and Netherland in 1998, and White in 2006, utilises surface treatments that are intended to be compatible with each part of the manufacturing process. For the long-term durability of structural adhesive bonding it is necessary for 5xxx series alloys to be effectively cleaned (to remove the mill oxide and disrupted surface layer) and then pretreated to provide bond adhesion and durability. For the material supplier, this requires coil-line compatible cleaning processes to remove/control the surfaces at a rate that is acceptable for volume production. In order to establish whether the level of cleaning used for adhesive bonding/SPR applications is sufficient for the more stringent requirements of aluminium RSW, two surfaces, which were produced with different degrees of electrolytic cleaning on AA5754 sheet, were studied during this project. Further considerations are the lubricants, such as wax based products applied for improving formability. Although the effect of lubricant on electrode life has been reported by Rashid *et al*. (2007), the effect of wax type lubricant on the RSW process window and weld quality was not considered. In addition, the sheet surface may also have different textures. For closure sheet, traditional mill finish (MF) may be replaced by electro discharge texture (EDT) or electron beam texture that can improve forming behaviour as described by Miller *et al*. (2000). Whether the surface texture has an effect on RSW process feasibility and quality is not clear. This paper therefore focuses on evaluating full cleaning or reduced cleaning, and with or without wax lubricant using commercially supplied AA5754, and AA6111 with either MF or EDF surfaces.

3 Experimental Procedure

3.1 Equipment at the University of Warwick

There are two dedicated cells for RSW of aluminium. One cell contains two manual welding stations operated pneumatically, whilst another has a robot welding capability with a servo scissor gun. Both are equipped with medium frequency direct current (MFDC) timers and capable of delivering 40 kA welding current. Each gun can be operated up to 8.0 kN welding force with minimal gun-arm deflection. Both cells have electrode maintenance facilities.

3.2 Materials

3.2.1 AA5754 Structural automotive sheet

Due to its good forming ability, AA5754 aluminium sheet normally is supplied as structural inner panel. In this study, AA5754 in 2.0mm gauge was used throughout the project. As mentioned earlier, the cleaning process determines the level of oxide film/disrupted layer remaining at the sheet surface. In order to examine the effect of disrupted surface layer on RSW process, two batches of AA5754 were studied. One batch had full electrolytic cleaning, pretreatment PT2 and solid wax lubricant ALO70; whilst the other had been given a reduced cleaning process, but received the same specification of pretreatment and lubricant. Both batches of AA5754 fulfil the present requirements for Self-Piercing Riveting (SPR) and adhesive bonding. Tests were also carried out on the AA5754 sheet with the wax lubricant removed to assess the combined effect between pretreatment and wax on the feasibility and quality of the process. The composition and mechanical properties of the AA5754 are shown in Table 1; whilst Table 2 lists the surface conditions tested for the AA5754 sheet.

Table 1: Compositions and mechanical properties of AA5754 alloy

<table>
<tr><td colspan="5">MECHANICAL PROPERTIES</td></tr>
<tr><td>Young’s Modulus (GPa)</td><td>Tensile strength (MPa)</td><td>Elongation</td><td colspan="2">Hardness (H_V)</td></tr>
<tr><td>70</td><td>240</td><td>22%</td><td colspan="2">63.5</td></tr>
<tr><td colspan="5">NOMINAL COMPOSITION(BALANCE Al) wt%</td></tr>
<tr><td>Si</td><td>Fe</td><td>Cu</td><td>Mn</td><td>Mg</td></tr>
<tr><td>0-0.40</td><td>0-0.40</td><td>0-0.10</td><td>0-0.50</td><td>2.60-3.60</td></tr>
</table>

Table 2: Surface conditions for AA5754 sheet

Variant	Cleaning	Lubricant
1	Full cleaning	Wax lubricant
2	Reduced cleaning	Wax lubricant
3	Full cleaning	None (removed)

3.2.2 AA6111 Closure automotive sheet

For automotive closure applications AlMgSi alloys are generally specified. This is because of their bake hardening properties, which are utilized to increase the strength of formed panels during the paint bake. In this evaluation, AA6111-T4 sheet with a gauge of 0.9 mm was used. Two surface textures: mill-finish (MF) and electro discharge textured (EDT) that have different tribological behaviour during forming, was examined for the AA611-T4 sheet in order to assess the effect of surface texture on the process. The mechanical properties and surface conditions of the AA6111-T4 sheet are listed in Table 3 and Table 4 respectively.

Table 3: Composition and Mechanical properties of AA6111

MECHANICAL PROPERTIES					
Young's Modulus (GPa)		Tensile strength (MPa)	Elongation	Hardness (H_V)	
70		308	26%	93	
NOMINAL COMPOSITION(BALANCE Al) wt%					
Si	Fe	Cu	Mn	Mg	Al
0.20-1.70	0.70	0.90	0.80	0.10-1.40	Balance

Table 4: Surface conditions for AA6111 sheet

Variant	Surface finish	Lubricant
4	Mill	Mineral oil
5	EDT	Mineral oil

3.3 Contact Resistance Measurements

The German guideline DVS2929 (1985) was originally devised to assess surfaces that have been etch cleaned to ensure sufficient cleaning has taken place, prior to spot welding. Although the guideline does not encompass pretreated surfaces, the methodology can be used to discriminate between different surface treatments and give an indication of the scale of the surface contact resistance. For each of the surfaces static contact resistance measurements were carried out according to the guideline DVS2929. Measurements were made on single and double strip stacks using a dedicated scissor gun fitted with a Tinsley micro-ohm meter. For each combination five readings were taken at regular intervals along coupons (40 x 330 mm).

3.4 Sample preparation and measurement

The standard procedure, adopted to establish the process windows for a joint stack-up was to produce a nugget growth curve. This is described in detail in a previous paper by Han *et al*. (2008). In brief, the criteria for establishing the process window are the current required for achieving a minimum nugget diameter, usually $4\sqrt{t}$, (where t is the thinnest sheet thickness in a stack) and the onset of expulsion. These criteria were extended to include the recording of electrode/sheet sticking. This has been found to be increasingly important if electrode maintenance is to be successful as damage to the electrode surface caused by sticking cannot be tolerated.

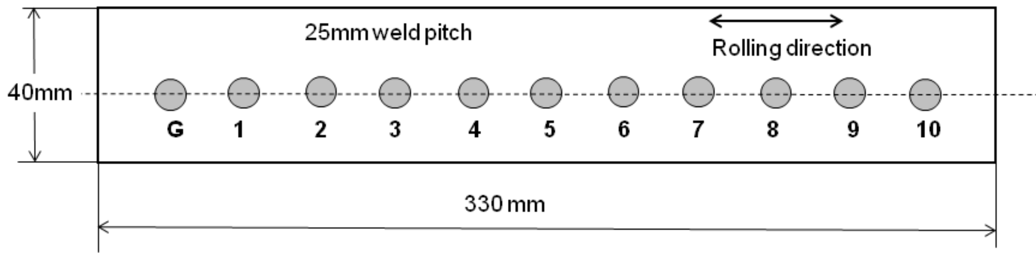


Figure 1: Coupon dimensions – for growth curve generation (Not to scale)

Initial tests were carried out to establish the optimum weld time and electrode force for the standard AA5754 and AA6111T4 products. These parameters were then fixed with current as the only variable to assess the remaining surface treatments. For each growth curve a pair of fresh electrodes was used. A coupon containing eleven welds, as shown in Figure 1, was made at each current step at intervals of 1.0 kA. To maintain electrode condition, the electrode tips were buffed after every coupon.

During welding, sticking and expulsion were recorded and in all cases either severe sticking or expulsion was defined as a completion point of the growth curve. After welding, the outer surfaces of the strip were inspected visually under a microscope to assess the surface finish of the welded product. Following visual inspection, the strip was peeled starting from the first “geometry” weld (marked as G). After peeling, the resulting buttons were checked visually for shape, any sign of expulsion, etc. The maximum and minimum diameter of the buttons where then measured manually using a digital vernier.

Following growth curve generation, the process window was determined based on the criteria as described early. The current required to achieve a minimum $4\sqrt{t}$ nugget diameter defined the lower bound. The upper bound was the current at which 20% or more of the welds on a strip expelled, or the current where electrode sticking occurred (sticking current). It follows that the wider the process window, the better the process feasibility as more manufacture variablity can be accommodated. Weld indentation, surface appearance and micro-sections were prepared from selected locations in order to check weld quality and examine the effect of process variables.

4 Results and Discussion

4.1 Effect of disrupted oxide layer

Figure 2 shows the growth curve for the full cleaned, pretreated and lubricated AA5754 sheet, Variant 1. With the parameters used, a process window with 5kA width was achieved. The minimum nugget diameter requirement for 2.0mm sheet, based on $4\sqrt{t}$ criteria, is 5.7mm and this was obtained at 24kA. The highest current before the onset of significant expulsion was 29kA. Extending the growth curve, by further increasing the current, shows that electrode sticking starts to occur at 32kA.

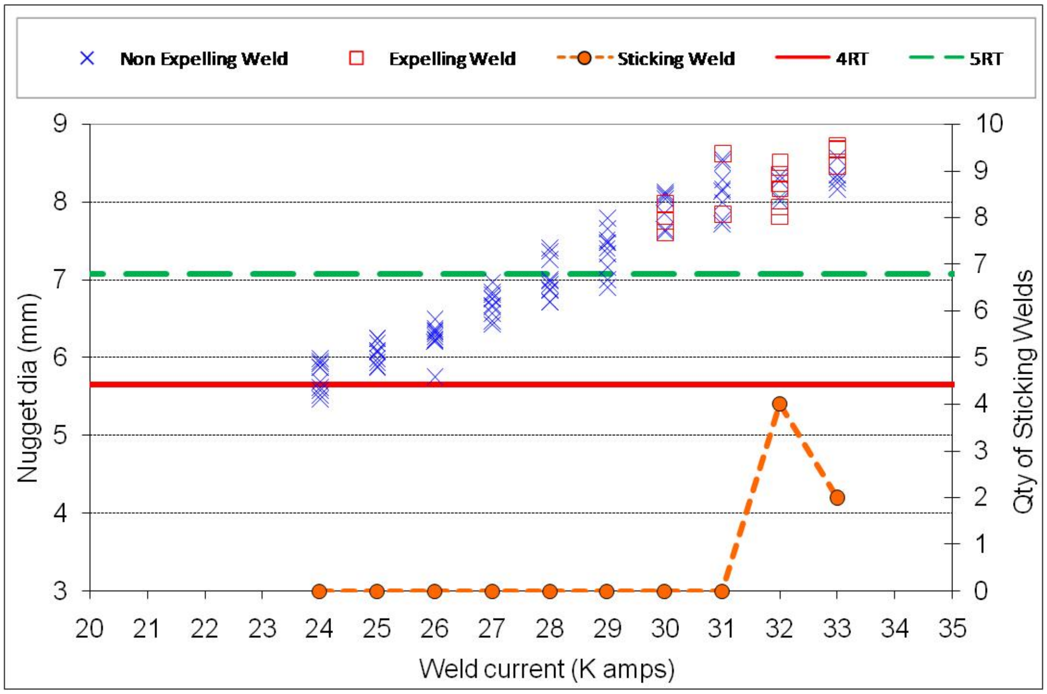


Figure 2: Weld growth curve for AA5754 with full cleaning (Variant 1)

For the AA5754 Variant 2, which had reduced cleaning prior to pretreatment, the growth curve is shown in Figure 3. Using the same parameters as for AA5754 Variant 1, a reduced process window of 2KA was obtained spanning from 22kA to 24kA. Significantly, the current required for minimum nugget diameter was 2kA lower than for Variant 1 and electrode sticking occurred as early as 25kA.

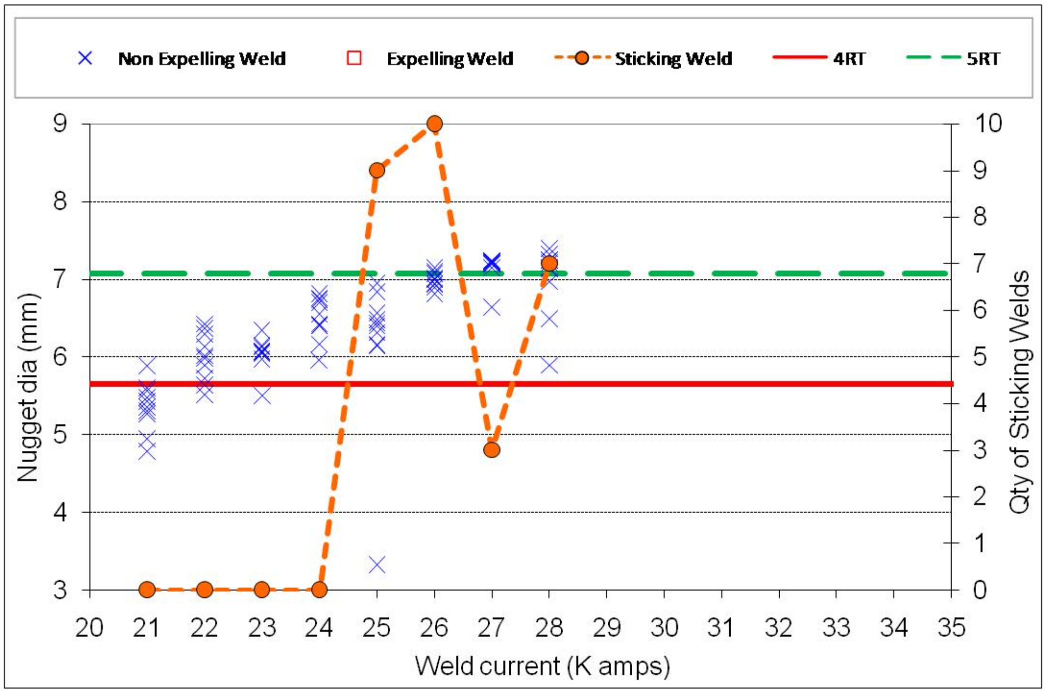
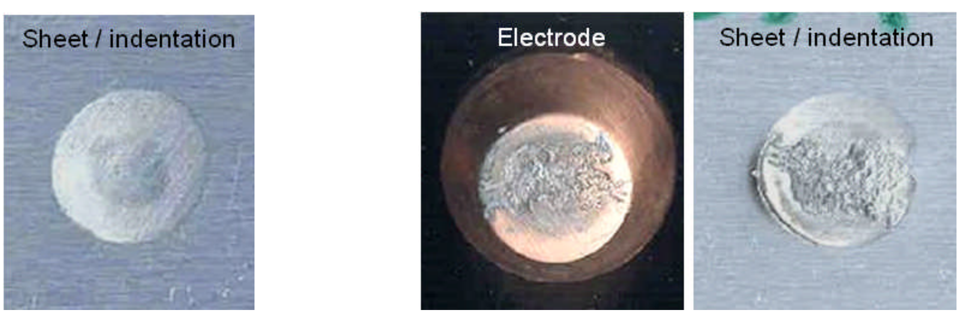


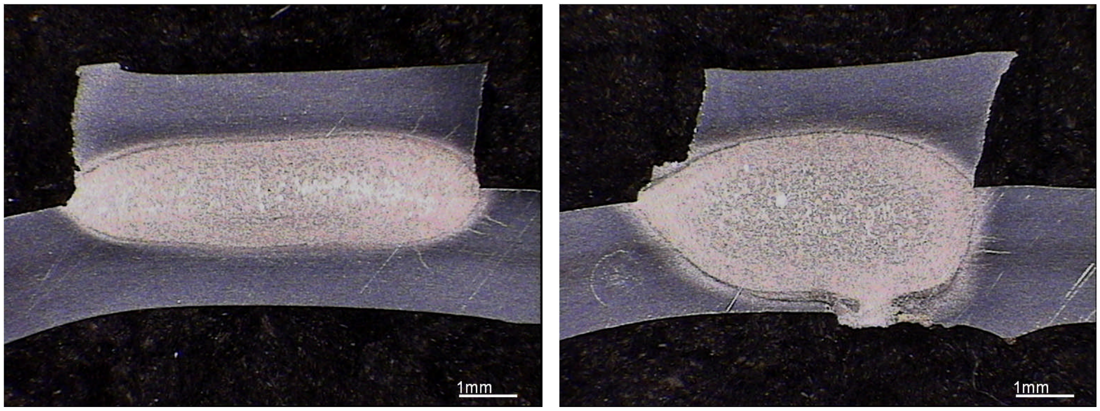
Figure 3: Weld growth curve for AA5754 with reduced cleaning (Variant 2)

Under identical welding conditions, Variant 1 had a wider process window and a lower tendency to sticking than Variant 2. Figure 4 shows the anode-electrode indentations in the respective sheet surfaces at the end of each growth curve test. For Variant 1 the surface indentation was still in a ‘clean’ state even at 33kA, whilst for Variant 2 at 28kA, severe weld indentation damage was obvious. Also shown in Figure 5 is the anode-electrode used to weld Variant 2, which shows the corresponding damage to the electrode caused by alloying and subsequent pitting through formation of brittle intermetallics compounds.



(a) 33kA-Variant 1 (b) 28kA-Variant 2 with corresponding electrode

Figure 4: Electrode / sheet indentations for AA5754 Variants 1 and 2 with corresponding anode electrode



(a) Variant 1 (b) Variant 2

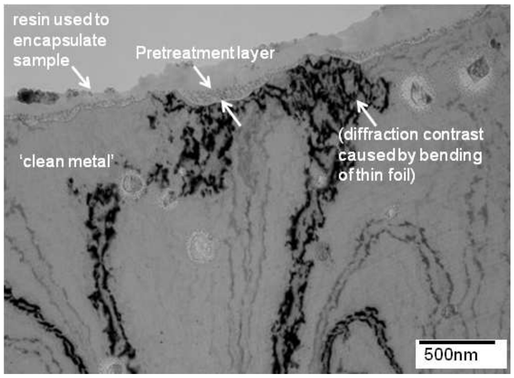
Figure 5: Micro sections of welds made at 25kA for Variants 1 and 2

Figure 5 shows micro sections of spot welds made at 25kA for Variants 1 and 2 respectively. Comparing these it can be seen that the weld nugget for Variant 1 has good shape and penetration; whilst for Variant 2 the weld nugget has over penetrated the sheets to the extent that melting has occurred very close to the anode contact surface.

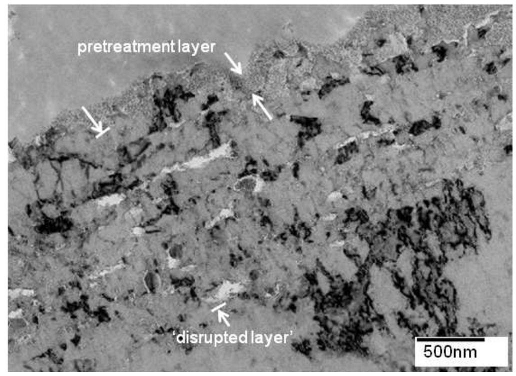
From the results shown, there are two key consequences resulting from the reduced cleaning:

(1) The onset of electrode/sheet sticking
(2) A significant shift in the position of the process window

Both of these effects can be attributed to the incomplete removal of the 'disrupted surface layer', as a result of the reduced cleaning of Variant 2 prior to surface pretreatment. Figure 6 shows Transmission Electron Microscope (TEM) images of ultra-microtomed sections taken perpendicular to the surfaces of Variants 1 and 2 respectively. The ultra-microtomy technique enables thin sections (less than 100nm thick) to be made, which are suitable for examination at high resolution in the TEM. Thus it is possible to examine the surface region of the sheet in cross section. Variant 1 shows the pretreatment layer in contact with 'clean metal', but for Variant 2 it can be seen that there is an area below the pretreated layer, which is more disrupted with some cavities and bands of oxide inclusions. This is the 'disrupted surface layer', produced during the thermo-mechanical processing of an ingot and subsequent cold rolling to final gauge sheet, referred to earlier. Utra-microtomy combined with TEM analysis are specialist techniques, not commonly available, which means it is difficult in a manufacturing environment to assess whether this layer has been fully removed. The disrupted layer may not necessarily affect other requirements of the automotive sheet, such as adhesive bond durability or mechanical fastening, but the contact resistance characteristics that are important for RSW will be altered at a microscopic level. Furthermore these changes in contact resistance will not necessarily be observed by static contact resistance measurements made according to the guideline DVS2929 (1985).



(a) Variant 1



(b) Variant 2

Figure 6: TEM sections of Variants 1 and 2

To maintain the electrode condition and provide consistent welds for an acceptable period, it is essential that the balance of resistance between the faying surface and electrode/sheet surface is optimised. In practice this means having very low contact resistances at the electrode/sheet interfaces. This is required to minimize ohmic heating preventing diffusion between aluminium and copper or localized melting, which can lead to sticking as seen in the results reported in Figure 4. The nature of the contact surfaces that meet at the faying interface is also important. To achieve acceptable weld consistency, the breakdown of resistance through asperity to asperity contact needs to be uniform and consistent. This will be affected if the innately irregular 'disrupted layer' is not completely removed prior to pretreatment.

An uncontrolled shift in the process window, resulting from incomplete cleaning, is not tolerable in a manufacturing situation for the process to remain in control. Therefore, the only way to maintain a stable process is to ensure the complete removal of the non uniform 'disrupted layer'. In other words, a 'full clean', will always be required if the surface is to be spot welded. This emphasises the importance of the relationship between material and processes, and between car makers and material suppliers. The point that car producers should work together with material supplier for specific applications was also stressed by Miller *et al*. (2000).

4.2 Effect of solid wax lubricant

Lubricant is a key component in the body panel stamping process that is essential to allow the deep drawing of formed parts. Therefore, the RSW process has to be able to accommodate the presence of lubricant, despite its tendency to increase the surface contact resistances. This is demonstrated in Figure 7, which shows that both single and double sheets with lubricant had significantly higher contact resistances than when the lubricant was removed from the surface.

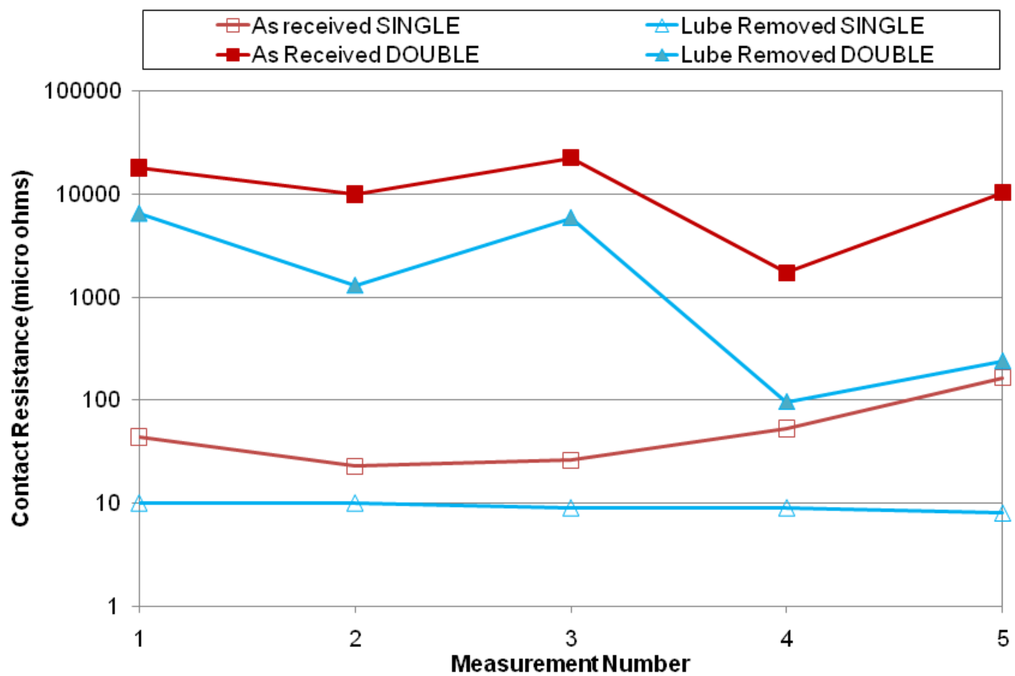


Figure 7: Contact Resistance measurements for AA5754 with full cleaning (Variant 1) and lubricant removed (Variant 3)

In order to minimize the effect of lubricant on contact resistance during welding, a low current pre-pulse was introduced into the weld parameters. This acts to displace the lubricant prior to the main weld current being applied and helps to maintain consistent welds. The weld growth curves for both Variant 1 and 2, shown in Figures 2 and 3, use this approach. The growth curve for Variant 3, where the wax had been removed prior to welding, is shown in Figure 8. Comparing the growth curves for Variants 1 and 3, shows that regardless of the difference in contact resistance for the two surfaces, similar welding results can be obtained. This can largely be attributed to the effectiveness of the low current pre-pulse. Figure 9 shows the effect of pre-pulse on weld quality through a comparison of the weld strips made with and without pre-pulse. The use of pre-pulse was first reported by Newton *et al*. (1997) for displacement of structural adhesives during weld bonding and the procedure works equally well for displacing wax lubricants.

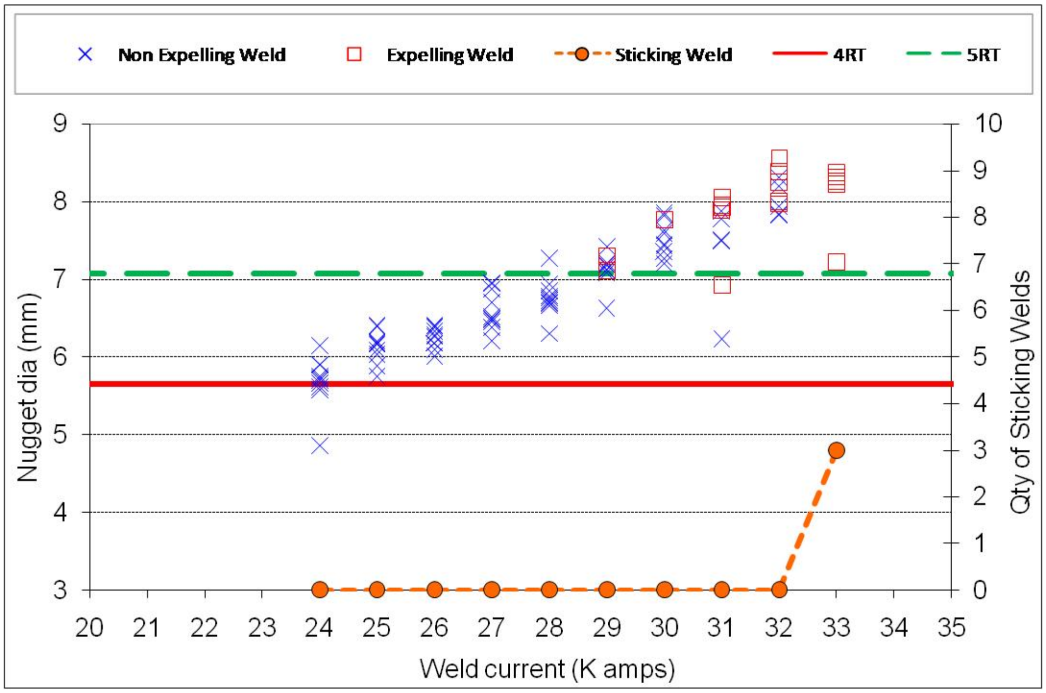


Figure 8: Weld growth curve for AA5754 with lubricant removed (Variant 3)

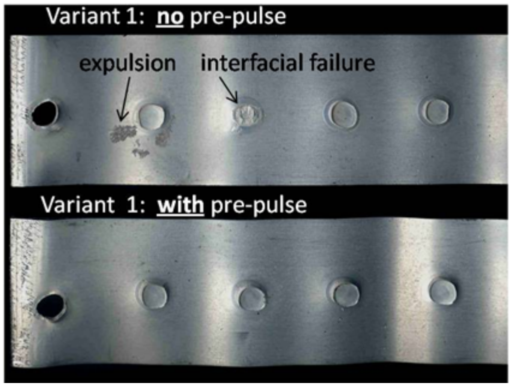


Figure 9: Weld strips with and without pre-pulse for AA5754 (Variant 1)

4.3 Effect of surface texture (AA6111T4 closure sheet)

The Weld Growth Curves obtained for the Variants 4 and 5 are shown in Figures 10 and 11 respectively. The MF Variant 4 has a respectable process window of 7kA with minimum nugget size ($4\sqrt{t}$) achieved at 22kA and a maximum usable current of 28kA, prior the onset of electrode/sheet sticking. This result is surpassed by the extensive 12kA process window obtained for the EDT Variant 5 evaluated and shown in Figure 11.

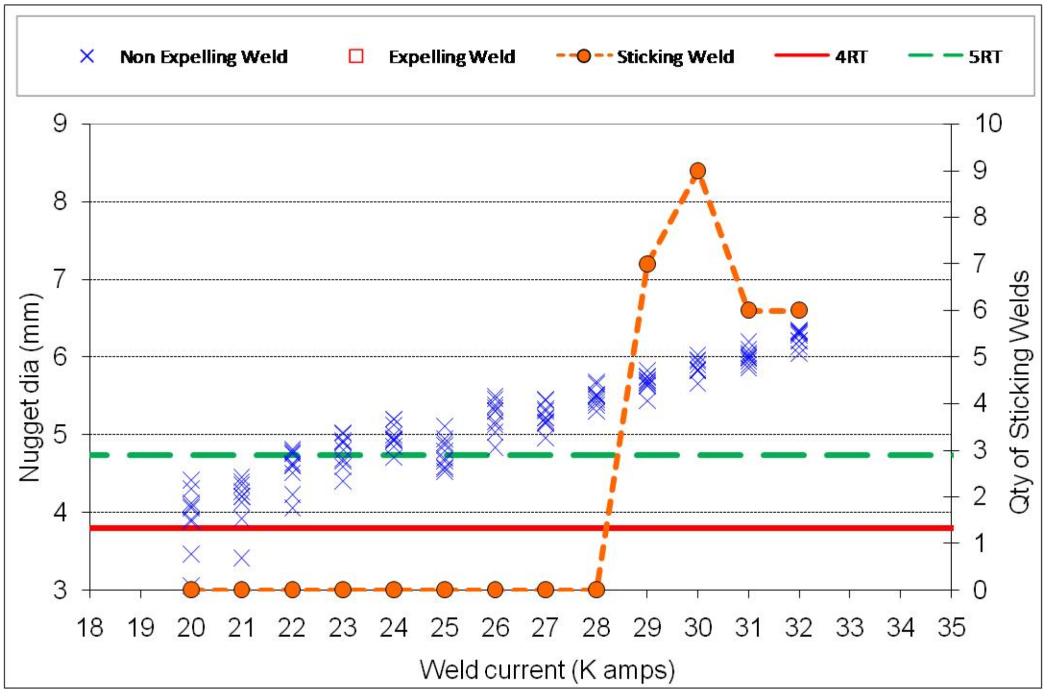


Figure 10: Growth curve for AA611T4 MF (Variant 4)

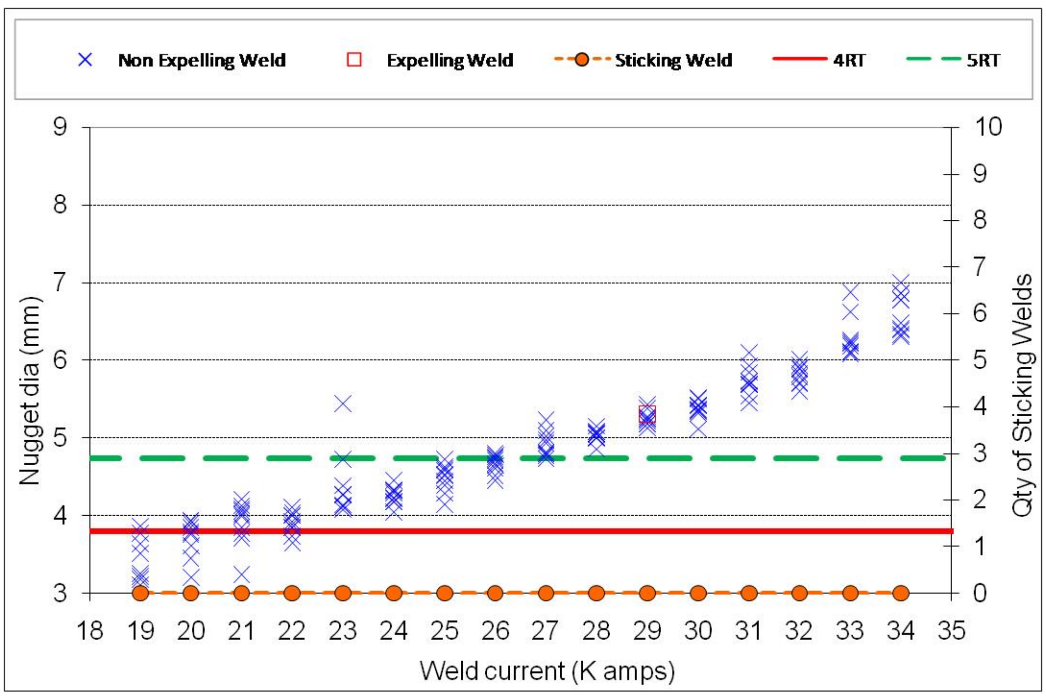
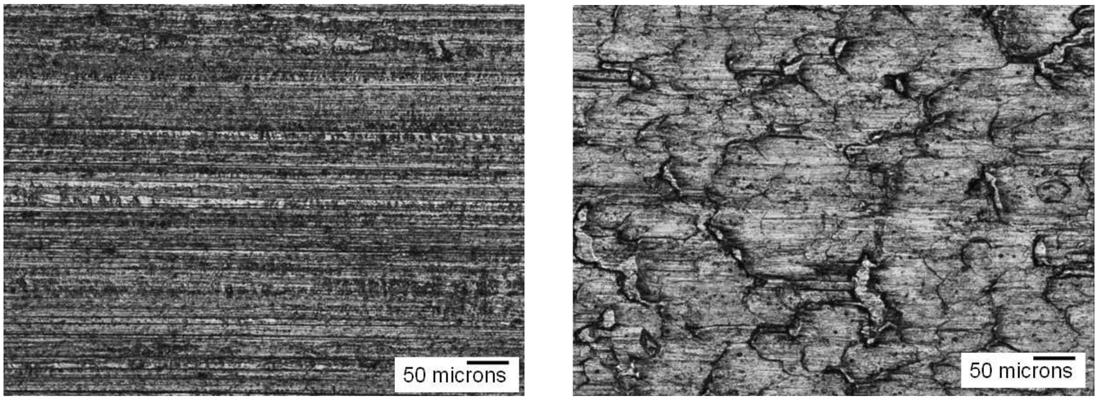


Figure 11: Growth curve for AA611T4 EDT (Variant 5)

Micrographs of the two AA6111T4 surfaces used in this evaluation; MF (Variant 4) and EDT Finish (Variant 5), are shown in Figure 12. These show the different surface topographies that result from the final roll textures used during sheet production. The standard roll grind (Variant 4) typically produces a linear texture aligned parallel to the rolling direction. In contrast, a less directional texture is produced when the final roll pass is made using EDT rolls. This procedure is used to enhance the deep drawing properties of the sheet by increasing lubricant entrapment, as suggested by Miller *et al*. (2000). The experimental results indicated that this less anisotropic surface may also provide improved spot weld consistency through more uniform asperity to asperity contact as the weld is initiated. This is in agreement with previous research reported by Crinon and Evans (1998).



(a) Variant 4 (b) Variant 5

Figure 12: Micrographs of AA611T4 MF (Variant 4) and EDT (Variant 5)

Despite the capacity to weld up to higher currents for Variant 5, it is not suggested that this should be adopted in a production welding situation. It is recommended that only sufficient current to attain the required diameter is used in order to reduce unnecessary electrode heating and consequently help to prolong electrode life. For these reasons the welding trial for the EDT Variant 5 was terminated at 34kA. Although a growth curve gives an indication of a surface's 'spot weldability', this is only one measurement and for production this needs to be verified by extended electrode life tests.

5 Conclusions

Based on the experimental work reported above, it is evident that the surface condition of the sheet material produced through different manufacturing processes has a significant effect on the RSW process, electrode condition and weld quality.

a) For RSW structural applications; an incomplete removal of 'disrupted surface layer' prior to surface pretreatment has a detrimental effect on the RSW process. Therefore 'full clean' manufacturing process is recommended to avoid the occurrence of sticking and to maintain the electrode condition. This should also ensure a consistent process window that is essential for a manufacturing situation.
b) Removing the wax lubricant reduces the static contact resistance, but in practice lubricant is a necessary component of the overall process. Therefore a weld schedule with a low current pre-pulse, made prior to the main weld can be used to displace the lubricant and normalize the surface reducing the risk of expulsion.

c) For RSW closure applications; AA6111T4 with either MF or EDT surface have acceptable spot welding process windows. The use of an EDT surface has been shown here to extend the useable welding range.
d) Close participation between materials suppliers and automotive manufacturing centre's is required to ensure optimum process parameters are applied at all stages of manufacturing for specific applications.

Acknowledgement
The authors wish to thank the development agency of Advantage West Midlands, Novelis, Jaguar Land Rover for their support throughout this project. Special thanks to Dr Xiarong Zhou at The University of Manchester for his help and expertise in providing the ultra-microtomed thin sections and carrying out the TEM imaging.

References
1. Alu Matter: Tribology, http://aluminium.matter.org.uk/
2. Aspinwall, D. K., Wise, M. L. H., Stout, K.J., Goh, T. H. A., Zhao, F. L., El-Menshawy, M. F., 1992. Electrical discharge texturing", International Journal of Machine Tools and Manufacture, 32, 183-193.
3. Auhl, J. R. and Patrick, E. P., 1994. A fresh look at resistance spot welding of aluminium automotive components, SAE Technical Paper, 940160.
4. Barnes, T. A and Pashby, I. R, 2000. Joining techniques for aluminium spaceframes used in automobiles, Part II – adhesive bonding and mechanical fasteners, Journal of Materials Processing Technology, 99, 72-79.
5. Boomer, D. R., Hunter, J. A., Castle, D. R., 2003. A new approach for robust high productivity resistance spot welding of aluminium", SAE 2003-01-0575.
6. Briskham, P., Boomer, D. and Hewitt, R., 2005. Developments towards high-volume resistance spot welding of aluminium automotive sheet component, Lean Weight Vehicle Conference.
7. Briskham, P., Han, L., Blundell, N., Young, K., Hewitt, R. and Boomer, D., 2006. Comparison of self-pierce riveting, resistance spot welding and spot friction joining for aluminium automotive sheet, SAE Technical paper, 2006-01-0774.
8. Bull, M. J. and Netherland, J. S., 2001. An Aluminum Liftgate Designed for High-Volume Production. SAE workshop on Light-Weight Materials for Advanced Vehicles. 16 February. Toronto, Canada.
9. Crinon, E., Evans, J. T., 1998. The effect of surface roughness, oxide file thickness and interfacial sliding on the electrical contact resistance of aluminium, Materials Science and Engineering A, 242, 121-128.
10. Critchlow, G. W., and Brewis, D. M., 1996. Riview of surface pretreatment fro aluminium alloys, Int. J. Adhesion and Adhesive, 16, 255-275.
11. DVS 2929, 1985. Resistance welding: Measurement of the transition resistance in aluminum materials. Deustscher Verband fur Schweisstechnik e.V Dusseldorf.
12. Han, L., Chen, Y. K., Chrysanthou, A., and O'Sullivan, 2002. J. M., Self-pierce riveting–a new way for joining structures, ASME, 2002; PVP-Vol. 446(2): 123-127.
13. Han, L., Young, K., Thornton, M., 2008. The Application of Resistance Spot

Welding to High Volume Aluminium Automobile Manufacture, The 2nd CIRP Conference on assembly technologies and systems, 21-23, Sept. Canada.

14. Hunter, J. A., Butler, C., Hirth, S., Foster, M. H., Bartsch, S., Kossak, R., 2000. Balancing conflicting property requirements in the development of AA6016 automotive closure sheet. 2nd International symposium of aluminium surface science and technology. 21-25 May UMIST Manchester
15. Komatsu, Y., Ban, K., Ito, T., Muraoka, Y., Yahabo, T., Yasunaga, K., and Shlokawa, M., 1991. Application of all aluminium automotive body for Honda NSX, SAE 910548.
16. Leitermann, W., and Christlein, J., 2000. The 2nd generation Audi space frame of the A2: A trendsetting all-aluminium car body concept in a compact class car, FISITA World automotive congress, June 12-15, 2000, F2000G360, Korea.
17. Leone, G. L., and Altshuller, B., 1984. Improvement on the resistance spot weldability of aluminium body sheet, SAE Technical Paper, 840292.
18. Li, Z., Hao, C., Zhang, J., and Zhang, H., (2007). Effects of Sheet Surface Conditions on Electrode Life in Resistance Welding Aluminum, Welding journal, April, 81-89.
19. Miller, W. S., Zhuang, L., Bottema, J., Wittebrood, A. J., Smet, P. De, Haszler, A., Vieregge, A., 2000. Recent development in aluminium alloys for the automotive industry, Materials Science and Engineering A, 280, 37-49.
20. Mortimer, J., 2006. Jaguar uses castings, extrusions to reduce parts count in new sports car, Assembly Automation, v 26, n 2, 115-120.
21. Newton, C. J., Thornton, M., Keay, B. F. P., Sheasby, P.G. and Boomer, D. R., 1997. How to Weld Bond Aluminium with Structural Adhesives", SAE Technical paper, 970018.
22. Patrick, E. P., Auhl, J. R and Sun, T. S., 1984. Understanding the process mechanisms is key to reliable resistance spot welding aluminium auto body components, SAE Technical Paper, 840291.
23. Pickering, E. R., and Hart, C. J., 1994. Optimizing resistance spot welding on aluminium alloy 6111 auto body sheet, SAE Technical paper, 940662.
24. Polmear, I. J., 1995. Light alloys, Third edition, Edward Arnold, .
25. Rashid, B. M., Fukumoto, S., Medley, J. B., Villafuerte, J., and Zhou, Y., (2007). Influence of lubricants on electrode life in resistacne spot welding of aluminium alloys, Welding research, March, 62-70.
26. Ronnhult, T., Rilby, U. and Olefjord, I., 1980. The surface state and weldablity of aluminium alloys, Materials Science and Engineering A, 42, 329-336.
27. Spinella, D. J., Brockenbrough, J. R., & Fridy, J. M., 2005. Trends in aluminium resistance spot welding for the auto industry, Welding Journal January, pp 34-40.
28. Thornton, M. C., Newton, C. J., Keay, B. F. P., Sheasby, P. G., and Evans, J. T., 1997. Some surface factors that affect the spot welding of aluminium, Trans IMF 75(4): 165–170.
29. White, M., 2006. Aluminum & the Automotive industry, JLR light weight vehicle strategy, Presentation, 21st International aluminium conference, Moscow, 18th Sep.