An Investigation of the Control Parameters for Aluminium 3003 under Ultrasonic Consolidation

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Abstract
In this article, we investigate an innovative solid-state welding technique called Ultrasonic Consolidation (UC) that is being developed as a freeform process for the layered fabrication of aluminium tapes. UC involves the use of high frequency, low amplitude mechanical vibrations that induce combined static and oscillating shear forces to produce elastic-plastic deformation at the work-piece interface. This tends to break up and disperse aluminium oxide and permits atomic diffusion to occur. The work centres on material characterisation of aluminium tapes for aerospace and tooling applications. This paper will look at the mechanical properties of aluminum 3003 specimens prepared by UC using different control parameters that will lead to the determination of a general process window.

1 Introduction

Ultrasonic Consolidation (UC) is an innovative solid-state fabrication process that combines ultrasonic seam welding of metal and layered manufacturing techniques to build up a solid freeform object. The process is capable of fabricating laminate metal parts by the continuous welding of foil layers to previously deposited material during which the profile to each layer is created by contour milling. UC is a proprietary process developed by Solidica, Inc in the United States and is intended as a 'direct' metal component and tooling solution capable of overcoming some of the issues associated with laser fusion freeform techniques. The Rapid Manufacturing Research Group at Loughborough University is currently undertaking research with Solidica and BAe Systems to characterise the UC process for monolithic and advanced materials within aerospace applications. The objectives of the Ultrasonic Consolidation process are the reduction of production lead-times, capable of welding a variety of commercially available materials leading to lower capital equipment and fabrication costs [1]. The key advantages of the UC process over conventional fusion techniques are:

- Welds can be produced at half the fusion temperature. Heat generated though the action of UC are between 30 to 50% of the melting temperature of the base metal resulting in welds with no melted structure [2], thus reducing thermal gradients that can lead to distortion and embrittlement as found in laser fusion techniques.
- The process is suited for welding materials that are hazardous in powder form where laser fusion techniques are used (e.g. Al, Mg and Ti).
- The process can be used to weld both difficult and dissimilar metals.
- Where a tenacious oxide layer is present, for example on the aluminium 3003 foil, then no preparation is required before welding commences. The UC process works by breaking up and dispersing the oxides to form atomic bonds.

During the welding process, highly localized oscillating shear forces are generated at the interface between the two surfaces that break up any oxide films and contaminants permitting metal-to-metal contact. Under the action of pressure, the combined static and oscillating

shear forces cause dynamic internal stresses at the interface between work pieces that produce elastic-plastic deformation and allow atomic diffusion across the interface [4]. Surface films that are broken up by stress reversals and plastic deformation may be displaced in the vicinity of the interface or may simply be interrupted in continuity in random areas within the weld zone [3]. Typically weld strength is almost equal to the material strength when welded end-to-end, such that metal parts adjacent to the welded areas were broken by the tensile load [2,5].

The objective of this EPSRC funded research is to determine the optimum processing parameters for a series of aerospace grade materials that could be used to produce a freeform fabrication process. These include aluminium 2024, 6061, 7075 and titanium Ti6Al3.5V. A physical experimental approach was taken whereby multilayer specimens were produced from a range of input variables. The welds between the layers that made up the specimens were then tested. This paper describes the first phase of this experimental work, which was to quantify the process variables and characterise aluminum 3003 under UC conditions to achieve maximum weld strength between the welded foil layers. 3003 was chosen as it forms one of the primary materials used in the Solidica process and has been characterised sufficiently for this process. Characterisation for aerospace applications would require a more in depth analysis and form a basis for comparison between the work conducted under this project and work previously conducted by Solidica.

2 Defining the Control Parameters

There are three control parameters within the UC system: amplitude of oscillation, contact force and weld speed. Successful welding is dependent on the proper setup of these three variables. Within certain limits, the variables can be changed relative to one another in order to achieve a similar outcome [3]. High amplitude and a short welding time will usually produce welds that are superior to those achieved with low amplitude and a long welding time [4]. Excessive welding time generally leads to a poor surface appearance, internal heating and internal cracks and to prevent this the three variables had to be measured under varying conditions to understand how their interaction results in effective welds.

2.1 Amplitude

Both a data logger and Laser Doppler Vibrometer (LDV) were used to measure output amplitude from both the power supply and sonotrode. The data logger measured dc output signals, which corresponded to the output amplitude via an output connector on the power supply unit. Where LDV was used, longitudinal amplitude was measured by directing laser light at the end of the sonotrode, whilst radial amplitudes were measured along the length of the sonotrode. Under ultrasonic excitation the sonotrode reciprocates longitudinally along its axis and swells and contracts radially around its circumference. Both oscillations act to deliver force to the workpiece but the proportion of each had to identified as it is the longitudinal action that creates the scrubbing action required in the process.

The analysis showed that the output amplitude did not correspond to the dial increments on the power supply. Figure 1 shows the linear increment of output amplitude for the increments of 10% to 90% on the dial. The LDV analysis showed that output longitudinal amplitude ranged from 6.5 to 14.5 microns and matched closely the output response from the data logger. Radial amplitude at the weld region was found to be approximately 1-2 microns demonstrating that main contribution to the weld performance was the longitudinal amplitude. The analysis confirmed that the output amplitude does not change with changes made to the other control parameters (contact pressure and welding speed) because the

system has electronic amplitude compensation built in to ensure a constant energy is delivered to the workpiece.

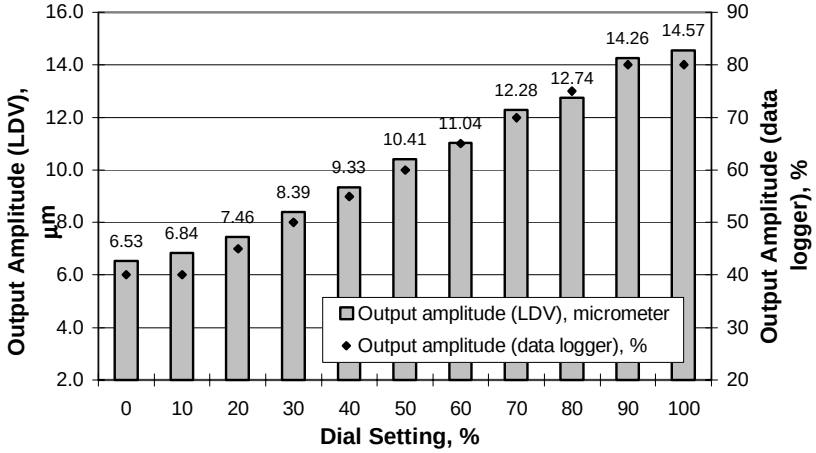


Figure 1. Longitudinal output amplitude measurements.

2.2 Contact Pressure

3003-H18 specimens were welded at different pressure settings and observations made for changes in weld formation. Generally, a higher load (contact pressure) imparted by the pneumatic cylinder results in increased force being applied to the material with greater contact points being observed on the surface of the workpiece. For a contact pressure below 103 kPa (15 psi) no weld could be produced. Similarly welds could not be produced at pressures greater than 276 kPa (40 psi) as excessive deformation of the foil occurred that led to foil 'sticking' to the anvil and damaging the anvil finish.

2.3 Weld Speed

The weld speed for the test apparatus ranged from 0 to 77 mm/s. Figure 2 shows the relationship between the dial settings and the actual welding speeds.

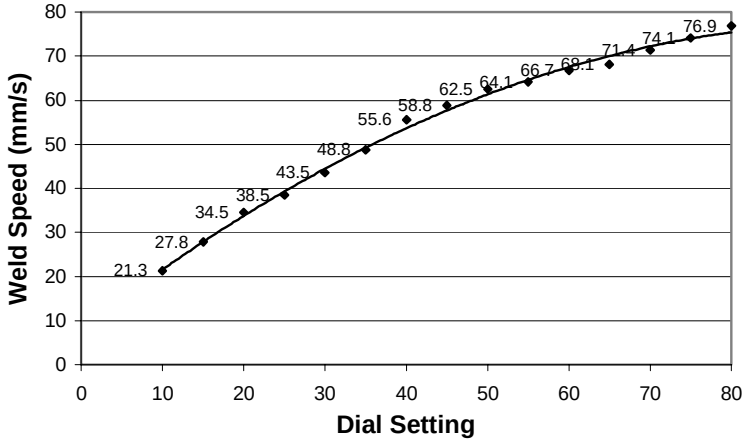


Figure 2. Relationship between dial settings and welding speeds.

A slower weld speed increases the ultrasonic energy delivered to the workpiece as the longer weld time promotes elastic-plastic deformation at the weld interface. At speeds of <21.3 mm/s aluminium 3003-H18 stuck to the horn and anvil.

3 Experimental Methodology

For this research lap-shear, peel test and microstructural analysis were used to assess the effectiveness of the welds produced. Specimens were prepared using 3003-H18 foil at 24mm wide by 100μm thickness as supplied with no surface treatment.

Specimens were produced using a range of pressure settings from 138 to 241kPa (20 to 35 psi) at 35 kPa (5 psi) increments. A range of amplitude settings from 10% to 90% at 20% increments were used which reflected the capability of the UC machine and equated to sonotrode displacement of 6.8, 8.4, 10.4, 12.3 and 14.3μm respectively. Two weld speed (traverse speed) settings of 34.5 and 43.5mm/s were selected which represented a fast weld speed and slow weld speed based on previous observations. Five specimens were produced for each combination of the control parameters and tested in accordance with British and International Standards where possible.

3.1 Lap-shear Test

No current lap-shear standard exists for foils at 100μm. Where possible BS EN 1465: 1995 was followed even though it relates to thicker foils (1.6±0.1mm). For example a strain rate of 2mm/min was used and an overlap length of 12.5mm for a 200mm long specimen. Specimens were prepared by welding two overlapped foils together and attaching them to a standard tensile test machine.

3.2 Peel Test

The peel test was performed in accordance with BS EN 2243-2:1991, which was designed for the determination of the strength of structural adhesives on clad metal sheets based on the maximum load a specimen can withstand under peeling action. A peeling apparatus was constructed and attached to a standard tensile test machine for the testing of UC samples as shown in Figure 3. The speed of the pulling grips was 50 mm/min.

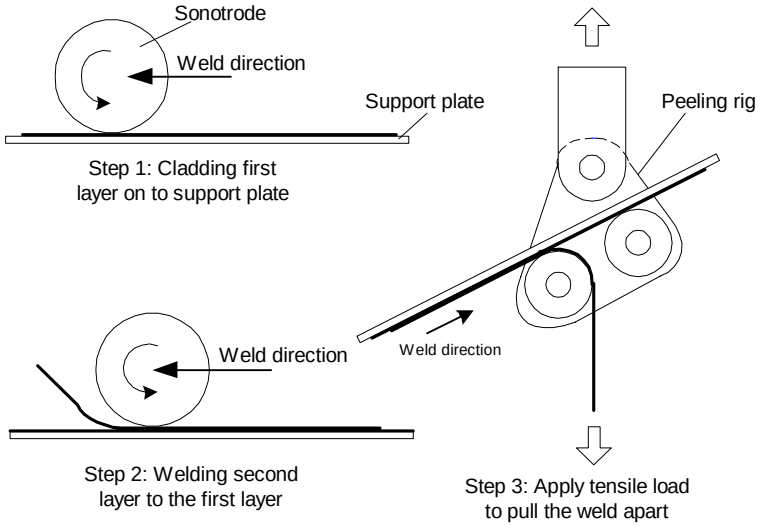


Figure 3. Sample preparation and peeling test apparatus.

Specimens were prepared by first cladding a layer of 3003-H18 foil to an aluminum 1050-T0 supporting plate (Step1 in Figure 3). A second layer of foil was welded to the first (Step 2 in Figure 3). The supporting plate was necessary to prevent the 3003 specimens from flexing when in place in the rollers. All samples were prepared and tested in the same procedures.

As failure occurred the maximum load was recorded and plotted to show how the sample failed.

3.3 Microstructural Analysis

The aim of the microstructural analysis was to establish the proportion of bonded to un-bonded area in a specimen. The term 'weld density' is used in this paper to represent the proportion of bonded 'contact points' to un-bonded areas. The higher the proportion of the bonded area across the specimen the greater the weld density and vice versa. From each of the 3 welded samples produced for each control parameter setting, a specimen was cut from the centre portion (approx. 20 mm from where the weld commenced). This was mounted, polished and etched with Keller's solution to etch the surface for about 30 seconds before being examined by optical microscope. Five images from the cross sections of each of the samples were taken along the interface as shown in Figure 4 (Step 4). Bond lengths across the weld interface were physically measured from the microscopy images taken.

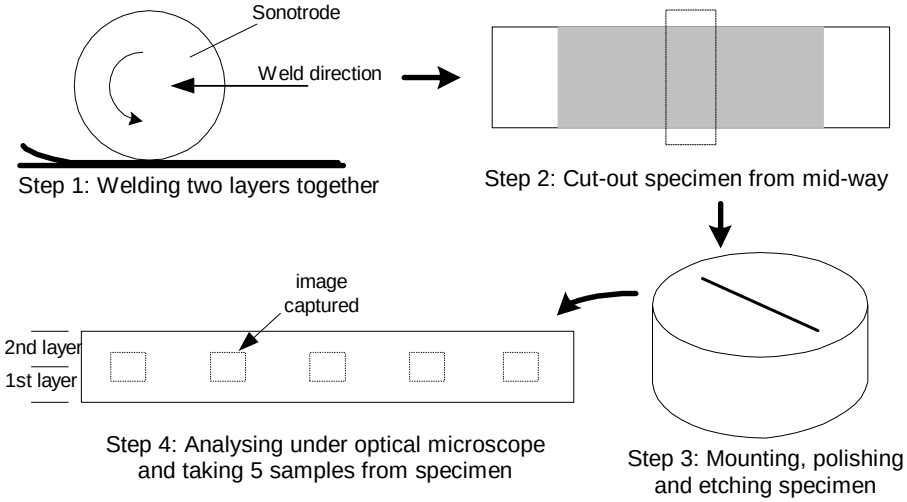


Figure 4. Sample preparation for microstructural analysis.

The proportion of sampled weld area to actual weld area was very small from the captured images taken (0.31x 0.2mm each) representing only 6.5% of the entire weld area (40x24mm). Though small, the intention was partly to explore whether a specimen giving a good mechanical response could have un-bonded areas along the weld interface.

4 Results and Discussion

4.1 Results from Lap-shear Test

From the specimens tested, all broke within the base metal adjacent to the bonded area. In none of the specimens did breaks occur within the weld zone even where visibly poor welds were produced. With thin gauge foil a negligible turning moment is applied to the lapped region and causes the specimens to break in tensile rather than shearing mode. As in tensile testing, specimens failed at locations with minimum cross-sectional area (i.e. the base metal, instead of the lapped region which had twice the cross-sectional area). Moreover, at higher load and amplitude settings deformation (necking) due to the impact load of the sonotrode at the start of the weld was also a factor as demonstrated in Figure 5.

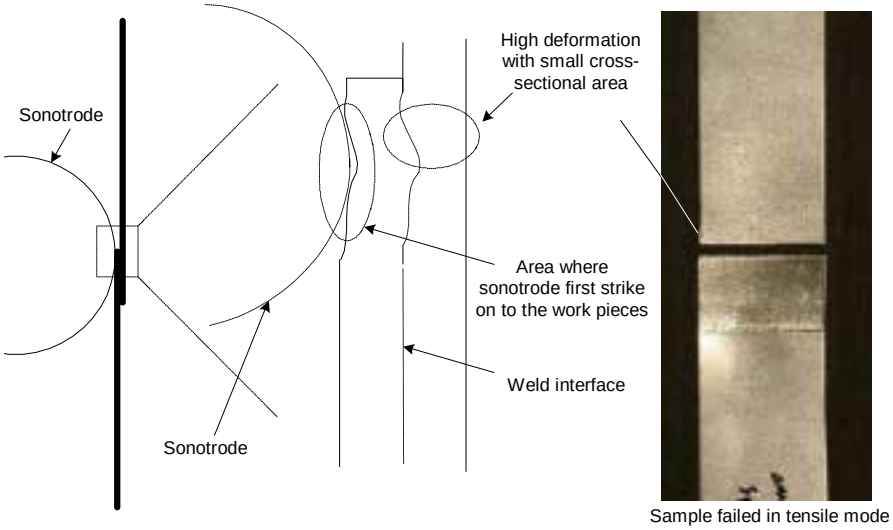


Figure 5. Failure mode of lap-shear test specimens

This can be seen in the data presented in Figure 6. The specimens welded at 138 and 172kPa (for both weld speeds) and specimens welded at 207kPa at 43.5mm/s speed failed at a load that approaches the tensile load (570 N) regardless of the amplitude settings. As contact force (pressure) and amplitude were increased, the level of deformation became significant resulting in weld failure at lower loads. Data response shows diminishing loads for samples welded with 241kPa (35 psi) in both speeds and in all amplitude settings.

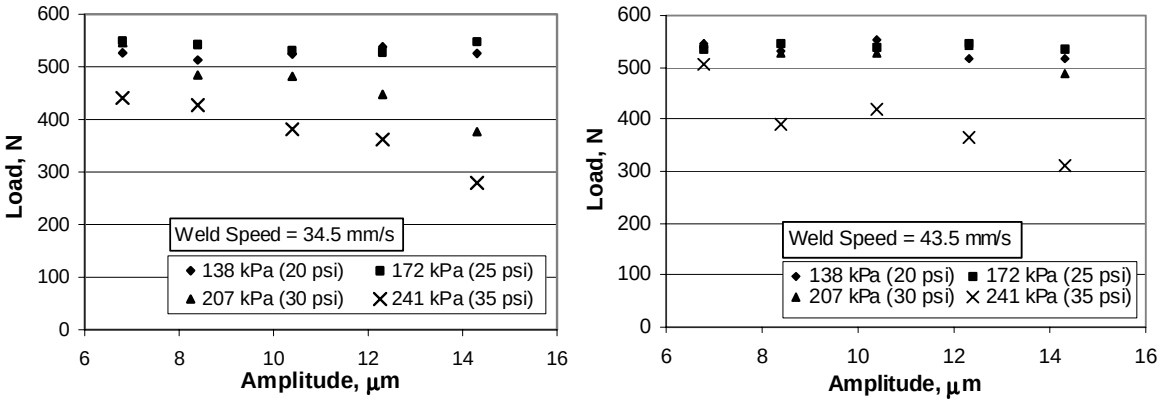


Figure 6. Lap-shear test results

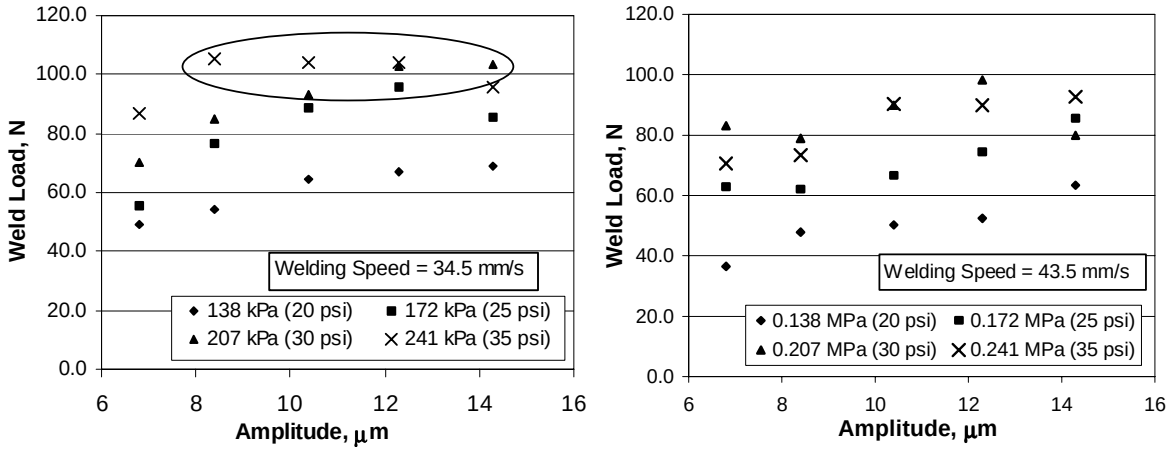
Based on the decrease in failure measurements as the process parameters were increased the lap shear test had to abandoned.

4.2 Results from Peel Test

The peel test was found to be effective in determining the weld effectiveness. Figure 7 shows the data for each of the process variables with the maximum load that resulted in peeling from each of the 5 specimens (mean value). The maximum and optimum resistance to peeling was achieved with 34.5 mm/s weld speed at 207 and 241kPa (30 and 35 psi) pressure and 8.4 to 14.3µm amplitude settings (circled). Increases in amplitude show an improved resistance to peeling with some exceptions at the 14.3µm setting where resistance to peeling diminished. The specimens produced at 138kPa (20psi) loading gave low values compared to the remaining specimens produced across the range of load settings. From the data it was

found that the pressure applied does not contribute to the overall weld performance once the sample reaches an optimum resistance to peeling (weld load). This can be seen in the data recorded at 241kPa (35 psi) which produced results that overlapped with the results from the specimens produced at 207kPa (30psi) loading. In this situation, weld loads only change with weld speed. In other words, the weld speed limits the maximum weld load that can be applied by any set of pressure or amplitude settings. Decreasing the weld speed increases the maximum weld load (resistance to peeling) from 98.4N at 43.5mm/s to 105.1N at 34.5mm/s as shown. This can be explained as longer weld times result in greater plastic deformation and hence a greater extent of atomic diffusion across the weld interface (weld zone).

Figure 7. Peel test results for samples welded with different control parameters



From the specimens tested two categories of failure mode were observed and are shown in Figure 8.

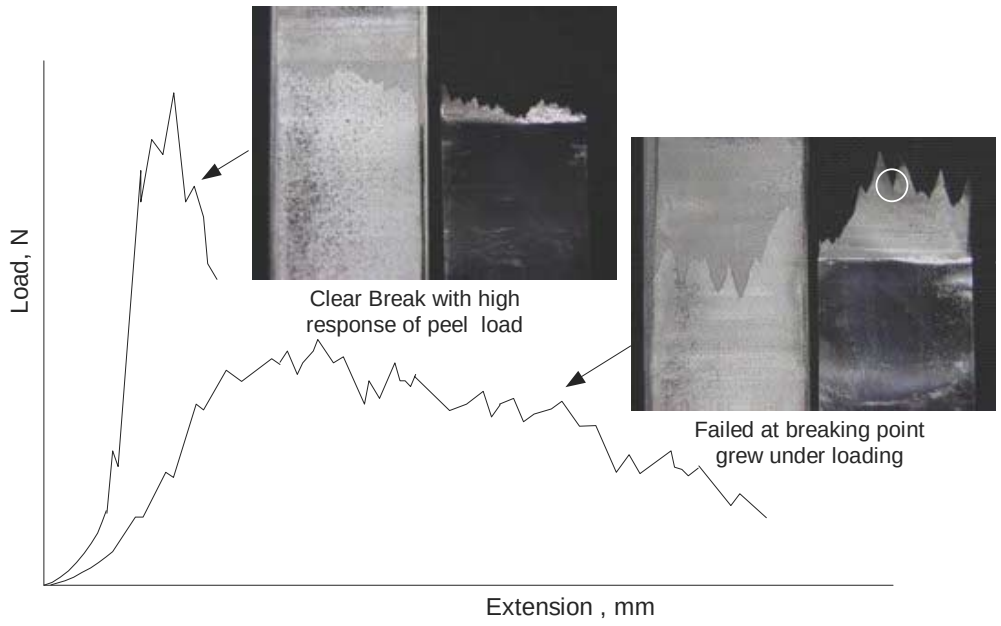


Figure 8. Weld load vs. extension curve showing two failure modes for Al 3003-H18.

The two failure modes were:

1. Where there was a clear break at the beginning of a weld region (when a load was applied) indicating an effective weld giving a high load ranging from 68-111N.
2. Where a sample did not break at the beginning of weld region but failed as the breaking points grew under loading. Typically such failure resulted in weld loads of less than 75N.

The maximum failure loads resulting from the peel test were much lower than the maximum tensile load for Al 3003-H18 which is 570N (237MPa) for a cross-sectional area of 2.4mm^2 (2.4mm x 0.1mm). The peel test used in the UC experiments did not behave in the same way as a peel test applied to adhesive bonds which tend to fail uniformly across the bond interface. When applied to UC welded specimens the method of failure was different and tended to propagate from a series of 'contact points'. A contact point is defined as a small region within the weld zone that was fully bonded. Under peeling action a contact point remains bonded with un-bonded material around it tearing during failure (one point is circled in Figure 8) to give the effect of 'teeth'. The more contact points present in a welded sample the higher the resistance to peeling with shorter 'teeth' being observed. The fact that teeth were present on all the samples produced would explain why relatively lower failure loads were recorded than would be expected for the UTS figure alone.

This indicated that even though welds were produced there may be regions where no atomic bond was present either through insufficient force being applied or through the presence of oxide at the interface. From this analysis the peel test could not be considered accurate for welded samples under UC conditions. The peel test results were essentially a qualitative measure of failure of the many contact points within a weld interface (with contact points failing at differing loads). However, the test proved useful as an indication of overall weld effectiveness and did produce a proportional load response. The true nature of a weld could only be ascertained through microscopic observation.

4.3 Results from Microstructural Analysis

Identifying, sampling and measuring the proportion of bonded to un-bonded area (defined as the weld density) within a specimen proved a useful tool when used to indicate the bonding behaviour of the UC process. From the specimens measured, the maximum average weld density was found to be 87% on the specimens welded at 207kPa (30psi) load, 34.5mm/s weld speed and 14.5µm amplitude. Figures 9 shows the weld density of specimens prepared at different contact pressure, amplitude and speed settings.

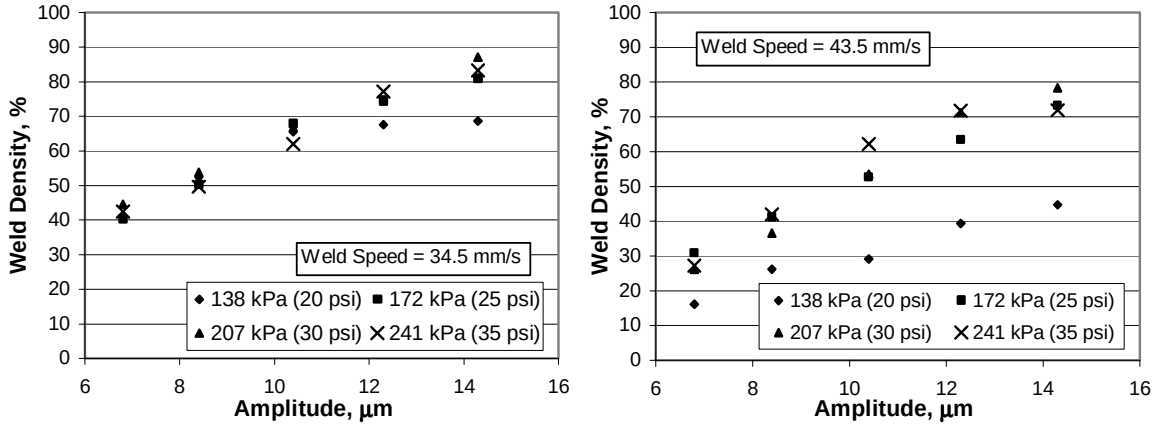


Figure 9. 3003 weld density data for specimens welded at differing control parameters.

The data showed that statistically the number of contact points within a given weld area increases as the data approaches the optimum control parameters. Deviation within the data

for each set of specimens produced for each parameter setting was ±10%. The data shows that above 138kPa (20psi) the contact pressure did not contribute to weld density. Weld density, in this situation, only changed with amplitude and weld speed. At 34.5mm/s weld speed, the specimens produced using a contact load of 138kPa (20psi) had as high a weld density as those produced at 172kPa (25psi), 207kPa (30psi) and 241kPa (35psi) until 12.3 and 14.3µm amplitude was reached. The same trend did not show up in the samples welded at 43.5mm/s where the contact pressure of 138kPa (20psi) resulted in low weld density figures. Except at 138kPa (20psi) weld density increased linearly with each increase in amplitude at both weld speeds.

Figure 10 shows the weld interface with (a) partially bonded, (b) 100% un-bonded interface and (c) 100% bonded. Measured weld density figures varied greatly within welded sections ranging from 100% bond to 0% bond that would normally not be considered representative. However, this analysis was intended to quantify the contact points observed in the peel test even though the sample size was small compared to the total weld area. The conditions shown in Figure 10 a, b, and c were observed in all specimens including those with the greatest resistance to peeling. This affect is most likely due to surface irregularities on the foils and the slip mechanisms of the material which force the faying faces to shear over each other resulting in an incomplete bond across the weld interface.

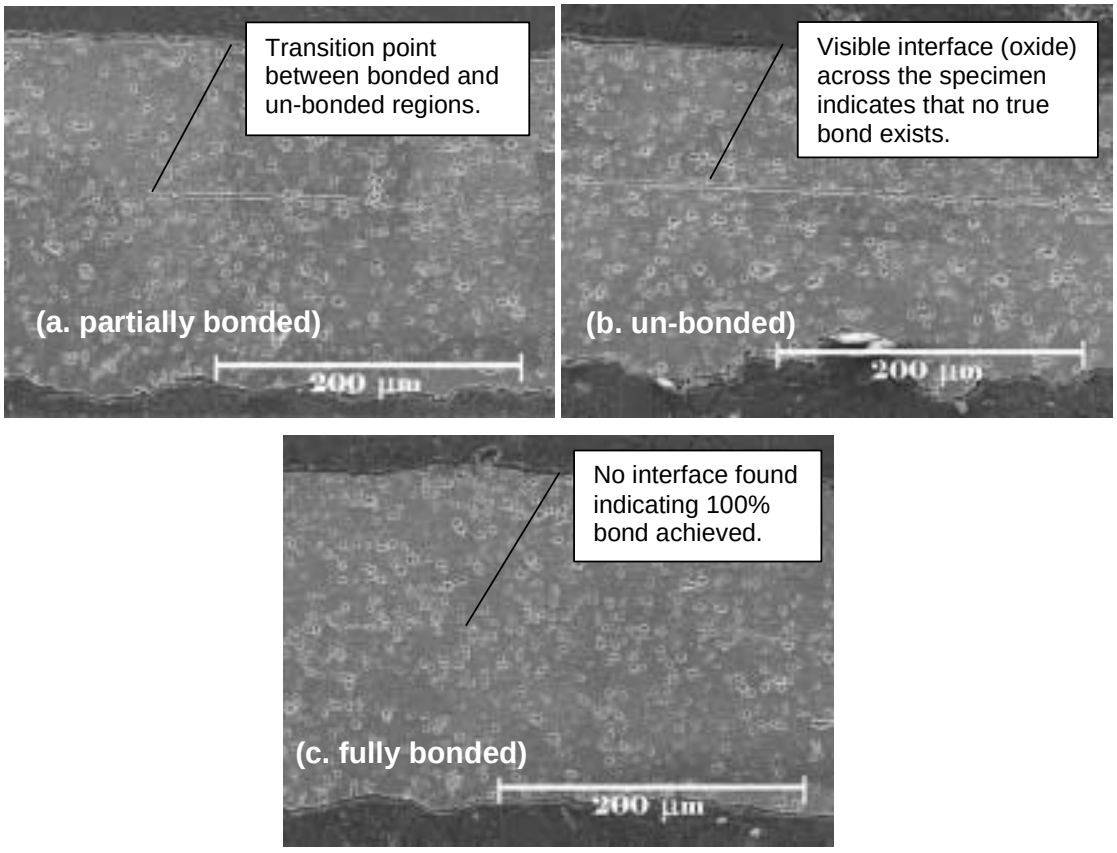


Figure 10. SEM Cross-sections of samples welded at 10.4 µm amplitude, 172kPa (25psi) pressure and 34.5mm/s weld speed

5 Identifying the Process Window for 3003-H18

By comparing the results from the peel test with the weld density data a low microscopic weld density does not necessarily indicate an ineffectiveness weld. For example, at lower

traverse speeds (34.5mm/s) and amplitude settings (8-10μm) the results from specimens produced at higher contact pressures (241 kPa) do not correlate and may be an indication that even though fewer contact points exist they may be larger and able to resist peeling more effectively. Alternatively, this may have been an indication that that sample size for the weld density analysis was not representative of the bonds produced, however, this was not born out by the relatively linear curves plotted for weld density.

Where large contact areas were observed then areas adjacent to these zones showed an elevated level of oxide deposit. From the SEM micrograph in Figure 11 it was possible to establish that the oxides in this zone were compacted indicating that as oxide is broken up by the action of scrubbing induced by the UC process some oxide may be dissipated into the underlying base metal and some may be translocated along the interface where it can cluster. Any further scrubbing to dissipate this oxide into the base metal will normally result in excessive deformation in the foils being welded leading to material sticking to the sonotrode or anvil.

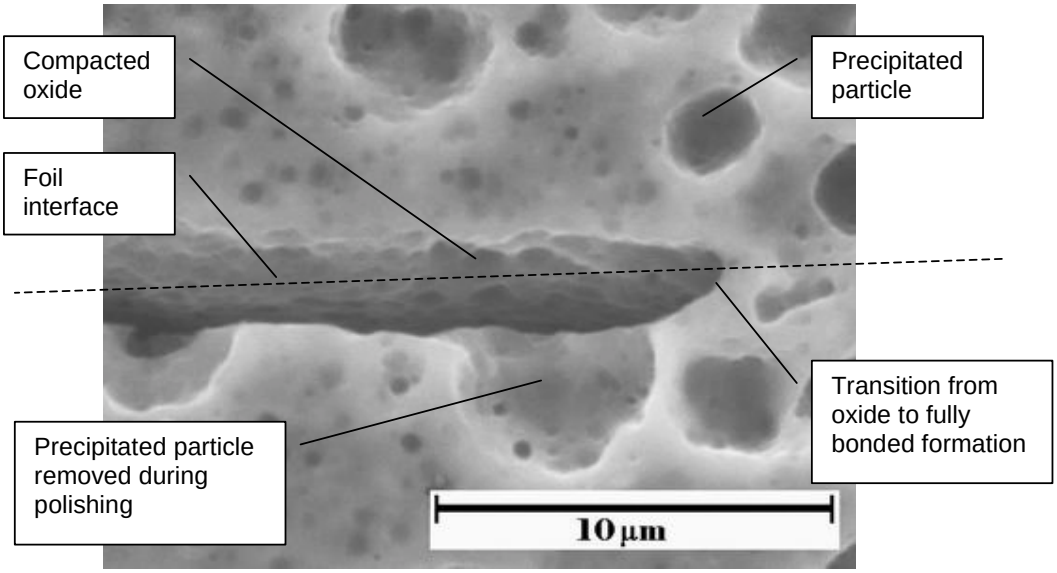


Figure 11. SEM Micrograph showing compacted oxide fused within weld interface

Identifying the optimum process parameters for 3003-H18 under UC conditions could not be quantified precisely but the comparison of both peel test data and weld density does allow for the identification of the general process window that is shown in Figure 12. This region lies within the process parameters:

a. Amplitude from 8.4 to 14.3 μm.
b. Contact Pressure from 172 and 241kPa (25–35 psi).
c. Weld speed at 34.5 mm/s or slower (but not less than 27.8 mm/s).

The optimum processing regions for the two tests show a region of overlap. At this stage, the intersection cannot be assigned as statistically more likely to produce better welds than non-intersecting regions. The graph shows the interaction of each of the three process variables.

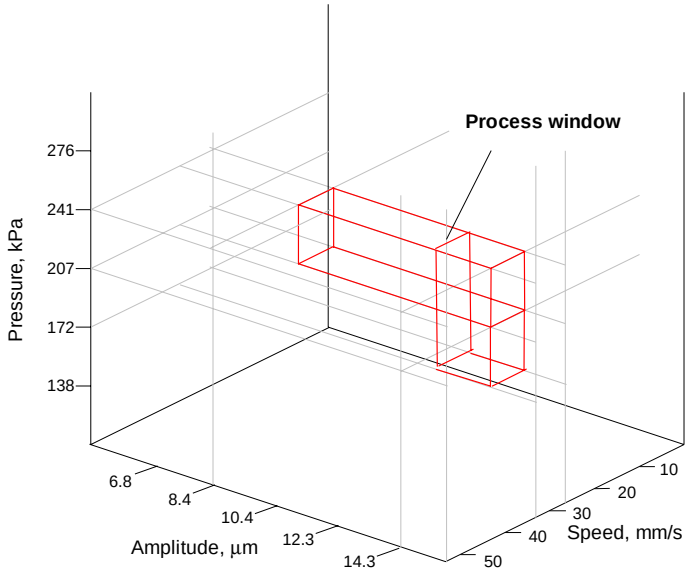


Figure 12. Identification of process window for 3003 H-18.

6 Conclusions

The process window for aluminium 3003-H18 foils at 100µm thick lies between 172-241kPa (25-35psi) contact pressure, 8.4-14.3µm amplitude and ≤34.5mm/s weld speed. Specimens produced at 138kPa (20psi) contact pressure produced poor results compared to the remaining specimens produced across a range of pressure settings. Weld speeds at ≥43.5 mm/s led to premature failure during peel testing. Reducing the weld speed allows for a longer weld time and results in greater plastic deformation and atomic diffusion across the weld interface.

Peel test results were used to determine the general process window of the UC apparatus based on the optimum weld load. This approach, however, produced different failure modes from those that would normally be associated when peel testing of adhesively bonded specimens. The peel tests identified that bonds were achieved through the atomic diffusion between foils at specific contact points. True bonds were achieved at these locations due to the surface finish of the sonotrode and anvil. Around the contact points bonding between the foils was either incomplete or interrupted by compacted oxide deposits formed during the scrubbing action under ultrasonic consolidation. Peel test results in the order of 105N ±5% occurred where more contact points were present in a specimen. This approach could only give a qualitative and not a quantitative measurement of weld effectiveness.

In order to identify the dispersion and size of the contact points within welded specimens microstructural analysis was performed on random samples produced under varying control parameters. Though the sample size was small the data did produce a linear response indicating that the method may be effective. Increasing the amplitude had a positive effect on the weld density. Oxide and surface contaminants within the weld interface may be dispersed by higher amplitude settings and produce a higher weld density. There was evidence that surface contaminants may be retained in the interface and fused together to form part of the weld zone. Overall, neither approach could accurately quantify failure in a weld however used in conjunction a reasonable assessment was possible. Better results may be possible using multiple layered specimens (>20 layers of foil) where peeling is assessed between multiple bonded layers and impact testing is possible.

Acknowledgements
The authors would like to take the opportunity to thank the project partners Solidica Inc. and BAe Systems as well as the Engineering and Physical Sciences Research Council (EPSRC) for supporting this work.

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