A study of weld quality in ultrasonic spot welding of similar and dissimilar metals

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Abstract. Several difficulties are faced in joining thinner sheets of similar and dissimilar materials from fusion welding processes such as resistance welding and laser welding. Ultrasonic metal welding overcomes many of these difficulties by using high frequency vibration and applied pressure to create a solid-state weld. Ultrasonic metal welding is an effective technique in joining small components, such as in wire bonding, but is also capable of joining thicker sheet, depending on the control of welding conditions. This study presents the design, characterisation and test of a lateral-drive ultrasonic metal welding device. The ultrasonic welding horn is modelled using finite element analysis and its vibration behaviour is characterised experimentally to ensure ultrasonic energy is delivered to the weld coupon. The welding stack and fixtures are then designed and mounted on a test machine to allow a series of experiments to be conducted for various welding and ultrasonic parameters. Weld strength is subsequently analysed using tensile-shear tests. Control of the vibration amplitude profile through the weld cycle is used to enhance weld strength and quality, providing an opportunity to reduce part marking. Optical microscopic examination and scanning electron microscopy (SEM) were employed to investigate the weld quality. The results show how the weld quality is particularly sensitive to the combination of clamping force and vibration amplitude of the welding tip.

1. Introduction
Ultrasound welding can be defined as a solid-state joining process in which materials are held together by a normal force whilst a high-frequency shear vibration is applied. During this process the vibration deforms, shears, and flattens surface asperities, scatters interstitial oxides and contaminants, and increases the contact area of the parts being welded [1]. The first demonstration of ultrasonic welding was in the early 1950s and was limited to grain refinement and soldering [2], but now the technique can be applied to various softer and harder metals [3]. Ultrasonic welding has become an efficient joining technique for many industrial and scientific applications, using lighter and more versatile equipment to produce a stronger, smaller, and more precise weld [2]. Furthermore, ultrasonic welding does not require any solder or filler and therefore has some associated environmental and economic benefits [4]. Ultrasonic welding systems consist of a power supply, transducer, booster, horn and anvil. The horn is tuned to operate in the longitudinal mode but precise design and characterisation are required to ensure the required dynamic characteristics of the device are achieved and the subsequent weld is of high strength and quality.

In this study, two investigations have been carried out to improve weld strength and quality; numerical design and subsequent experimental characterisation of an integrated ultrasonic spot welding horn to enhance the vibration characteristics at the welding surface, and secondly an experimental study of the effects of process parameters on the weld itself, considering issues such as tool/workpiece adhesion and weld quality. The weld strength is characterised experimentally in terms of the results of repeated tensile shear tests. Weld quality is also investigated by using microscopic observations of the deformed surface areas under different welding conditions. The ability to use
amplitude profiling to increase weld strength, enhance weld quality and reduce part marking of joining similar and dissimilar materials is also demonstrated.

2. Design and characterisation of the welding system

2.1 Numerical design of the ultrasonic spot welding horn

A design of a lateral-drive ultrasonic welding system has been carried out to meet the requirement for high ultrasonic amplitude and low clamping force that are necessary to weld thinner parts [5], Fig. 1.

Several factors are considered in the design of such an ultrasonic spot welding horn including resonant frequency, frequency separation, amplitude amplification, amplitude uniformity and stress concentration. The horn is made from steel to give good acoustic properties and acceptable wear characteristics. An integrated spot welding tip with knurled flat surface was designed. High amplitude amplification and low stress are obtained from adopting a catenoidal horn profile which is clamped at a nodal plane. Finite element (FE) analysis has been carried out to extract the shape of the operating vibration mode and those of some of the surrounding modes, as shown in Fig. 2.

![Figure 1. Lateral-drive ultrasonic welding device.](image)

![Figure 2. FEA predicted torsional (13.2 kHz), longitudinal (20.8 kHz) and bending (22.6 kHz) modes](image)

2.2 Experimental characterisation of the ultrasonic spot welding horn

The numerical results are compared to the results of an Experimental Modal Analysis (EMA), shown in Fig. 3, carried out using a 3D laser Doppler vibrometer (LDV) and random excitation over a frequency range from 0 to 40 kHz. The amplifications, resonant frequencies and mode shapes of the horn are found to be in agreement and the system is therefore considered to operate as designed.

![Figure 3. EMA measured torsional (13.7 kHz), longitudinal (20.8 kHz) and bending (23.5 kHz) modes](image)
3. Welding Experiments

3.1 Experimental set up

The welding stack (horn connected with transducer) is driven by a 1 kW ultrasonic generator (Sonic Systems), to provide a mechanical vibration at 20.8 kHz. A tensile test machine (Zwick Roell) is employed to secure the welding stack by holding it at the nodal plane, as shown at left in Fig. 4(a). The upper moving cross-head of the test machine is equipped with a 2 kN load cell to measure the clamping force, which is recorded as a function of time. The knurled flat welding tip surface contacts the upper specimen of the weld coupon during welding, while the lower specimen is held by a knurled anvil as shown in Fig. 4(b). In this study, the weld samples were cut from aluminium and copper strips, and their properties were obtained from ASTM [6] and BSI [7] codes. The specimens were prepared to 50 x 10 mm size from roll sheets with 0.1 mm and 0.5 mm thickness, and the overlap between specimens was set at 10 mm to accommodate the constant spot diameter of 6 mm of the welding tip, as shown in Fig. 4(c). Dummy plates were added to avoid bending due to structural misalignment of specimens during the test. Five tensile tests at each set of weld conditions were carried out, the results were averaged, and the standard deviation for the tests was obtained. Welding of similar and dissimilar metals was performed with different arrangement of stacking order such as: (Al-Al), (Cu-Cu), (Al-Cu) and (Cu-Al). Welds were obtained (Fig. 4(c)), for different sheet thicknesses and several tests were carried out to ameliorate the problem of horn sticking. However, a few tests failed either due to insufficient power or applied load.

![Figure 4. Experimental set-up of welding tools, knurled surfaces, specimen layout and welded coupons.](image)

3.2 Stepped amplitude

Most welding systems operate with constant ultrasonic amplitude. An alternative, namely amplitude stepping, performs a weld using two different ultrasonic amplitudes. The trigger between the transitions of the amplitude setting can be made by time, energy level or power value [1]. A stepped amplitude weld starts with a higher amplitude value that the weld interface requires to provide the higher velocities for surface scrubbing to create a solid-state weld at intimate surfaces. Then the amplitude is dropped to reduce frictional heating and softening of the sample, reducing shear as the weld forms and thus minimising damage. A series of experiments have been conducted using stepped amplitude to investigate opportunities for enhanced weld strength and weld quality.

3.3 The effect of constant and stepped amplitude on weld strength in similar and dissimilar materials

Various welds of different specimen thicknesses were obtained from applying different constant and stepped vibrational amplitudes. Fig. 5 plots the weld strength against clamping force, in joining of similar materials of thickness 0.1 mm. The error bars represent one standard deviation of the five tests for each parameter set. Welding strength is seen to increase with clamping force, although it is noted that excessive clamping force may generate high friction and suppress the relative motion of the
surfaces, resulting in a reduced weld strength [9]. Further, the higher ultrasonic amplitude, in this case 40 µm, although resulting in increased weld strength, also resulted in higher standard deviation and increased tool/workpiece adhesion with significant part marking. In Fig. 5, the benefit of using stepped amplitude, 40-17 µm, is seen. When stepped amplitude is applied the result is a reduction in the size of the error bars (lower standard deviations) and increased weld strength up to a critical value of clamping force. Slightly higher weld strength is recorded in joining of Al-Al than Cu-Cu under identical process parameters.

Figure 5. Variation of weld strength vs. clamping force for joining (Al-Al) and (Cu-Cu).

In welding dissimilar materials it is important to determine which specimen is placed on top, as the results in Fig. 6 suggest a superior bond is created when the horn bears against aluminium for the two metals tested in this study. It is also noted that sticking becomes more prevalent at higher clamping forces, particularly when the clamping force is above 500-600 N, and the weld strength for constant and stepped amplitude becomes progressively lower. It was also observed that the material hardness and surface roughness significantly affect the weld strength.

Figure 6. Variation of weld strength vs. clamping force for joining (Al-Cu) and (Cu-Al).

3.3 Microscopic observation and scanning electron microscopy (SEM) investigation
The fracture surfaces of the weld coupons after tensile tests were observed using an optical microscope. Fig. 7 show the weld zone of the Al-Cu specimens, observed on the Al side and Cu side in Fig. 7 (a) and (c) respectively, with their respective enlargements shown in Fig. 7 (b) and (d). These results show the microscopic features, in the weld zone, of the plastic flow of the metal due to an applied force of 500 N and ultrasonic amplitude of 17 µm. The fracture surfaces of the broken weld show much clearer evidence of deposition of Al on Cu the side, while there is little Cu located on the Al side. Furthermore, the difference in hardness and surface roughness between the Al and Cu specimens strongly affects metal deformation during ultrasonic welding, with the harder metal (Cu) undergoing less deformation, producing no increase in welding area that could improve weld quality. Figure 8 shows higher magnifications, using a scanning electron microscope, of the fracture surfaces for the Al side and Cu side of the Al-Cu weld specimens, for the welding conditions of 500N clamping force, 17 µm ultrasonic amplitude and 1 sec welding time. The x-ray diffraction reveals a chemical composition for Al of 79.48 (wt %), which confirms the high deposition of Al on the Cu side. Little
Cu is present on the fracture surface of the Al side, and the spectrum analysis of reaction surface records a chemical composition for Cu of 11.29 (wt %).

Figure 7. Microscopic photograph for Al-Cu joint from Al side (a) and (b), and from Cu side (c) and (d).

These results suggest that the weld coupon metal susceptibility to plastic deformation under ultrasonic vibration and static clamping load is related to the metal hardness and surface condition such as roughness, oxides and contaminants. Al is a softer metal than Cu and is therefore more readily deformed plastically during ultrasonic welding. The higher surface roughness of the harder metal also strongly affects the bond strength and can cause lower weld quality. The oxide layer of the metal has to be removed to create intimate surfaces for high quality welds.

Figure 8. (SEM) fractograph and x-ray patterns from Al-Cu weld showing fracture surfaces for Cu and Al sides.
4. Conclusions
Design and fabrication of a lateral-drive ultrasonic spot welding system has been carried out to investigate the welding of thin metal strips. It has been observed that vibration amplitude, clamping force and material arrangement order, have a significant effect on weld strength. Al-Al welds are stronger than Cu-Cu welds and weld strength in both cases tends to increase with clamping force up to a critical value, where higher clamping forces restrict the lateral movements essential for welding. When dissimilar metals are considered, slightly stronger welds are obtained when the aluminium layer is placed on top and in direct contact with the ultrasonic horn and, in general, there is a decrease in weld strength when clamping forces above approximately 500 N are applied. Amplitude stepping (40-17 µm) allows better joining and slightly increases weld strength and lowers standard deviations in comparison with those tests that used a constant ultrasonic amplitude (17 µm) or (40 µm). However, tool/workpiece adhesion and part marking was worsened when higher clamping forces were used. Microscopic investigations show how observation of the fracture surfaces of tensile tested Al-Cu welds illustrate the differences on the Al side and on the Cu side. The fracture surfaces show clearer evidence of softer metal (Al) deformation in the weld zone than the harder metal (Cu). This relates to the material hardness, oxide layer hardness and surface roughness. SEM magnification determined the chemical compositions of the metal deposition on the fracture surfaces. A low percentage of Cu (11.29 wt %) confirms that the roughness and oxide layer of the relatively harder material significantly affects the bond strength and reduces weld quality. Higher weld quality is obtained through knowledge of the best combination of welding process parameters for the specific metal joining configuration.

5. References

[1] E. deVries, 2004, Mechanics and Mechanisms of Ultrasonic Metal Welding, PhD Thesis Ohio State University.
[2] K. Graff, 2005, Ultrasonic Metal Welding, in New Developments in Advanced Welding Cambridge, 241-269.
[3] M. Bloss and K. Graff, 2009, Ultrasonic Metal Welding of Advanced Alloys: The Weldability of Stainless Steel, Titanium, and Nickel-Based Superalloys, Trends in Welding Research Proceedings of the 8th International Conference, ASM International
[4] S. Kim, H. Sung, E. Kim and D. Park, 2010, Vibration Analysis of Ultrasonic Metal Welding Horn For Optimal Design, Proceedings of the International Conference on Mechanical, Industrial, and Manufacturing Technologies, Sanya China.
[5] P. Staff, 1997, Handbook of Plastics Joining, William Andrew Publishing/Plastics Design Library.
[6] ASTM International Codes, 2009, Standard Test Methods for Tension Testing of Metallic Materials, 1-24.
[7] British Standard Codes, 2009, Test Pieces and Test Methods for Metallic Materials for Aircraft, Metric units 1-7.
[8] M. Hiraishi and T. Watanabe, 2003, Improvement of Ultrasonic Weld Strength for Al-Mg Alloy by Adhesion of Alcohol - Ultrasonic Welding of Al-Mg Alloy, Quarterly Journal of the Japan Welding Society, 21(2), 295-301.