Perpendicular ultrasonic joining of steel to aluminium alloy plates

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ABSTRACT

Standard and high strength steel plates were successfully joined to A2017 and A6061 aluminium plates by applying ultrasonic power perpendicular to the joint interface instead of tangentially, as in other ultrasonic joining methods. Using a 2.9 mm diameter tip, cross tensile strengths of 281 N and 460 N were obtained when joining 0.5 mm thick A6061 plates to 0.5 mm thick commercial and high steel plates, respectively. When joining 0.5 mm thick A2017 plates, the cross tensile strengths were 343 N and 437 N, respectively. Temperature measured at less than 1 mm from the joining interface did not exceed 135 °C in any case. The joining mechanisms and resulting joint characteristics are investigated and discussed, alongside parameters affecting the resulting joint performance. Under optimal joining conditions, the cross tensile tests and cross section observations revealed that material fracture resulted in plug failure. No intermetallic layer has been detected with SEM analysis. The joint strengths obtained under those conditions were the maximum attainable for the tip diameter used, provided that they correspond to the stress intensities required to propagate cracks in the aluminium. These results support the conclusion that this ultrasonic joining method, being operationally similar to the method used in resistance spot welding, and providing good performance joints, could be used successfully for high throughput industrial applications taking advantage of the available spot welding tooling and operational procedures, as tangential movement of the whole plate is not required.

Keywords:

Ultrasonic joining
Solid state joining
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1. Introduction

To improve the fuel efficiency, safety and driving performance of transportation devices, lighter, stronger or tougher materials, e.g. aluminium, magnesium, titanium or high-strength steel, should replace those currently being used. To take advantage of these properties, dissimilar materials need to be combined and this poses certain problems for their joining. Haddadi (2014), Yin et al. (2013) and Hibino (2010) demonstrated that high temperature is a crucial factor in the formation of brittle intermetallic compounds. Solid-state welding processes have been developed to avoid the formation of these brittle compounds. These solid-state welding techniques have a common joining principle, i.e. inclusions between the joined materials that obstruct adhesion are mechanically eliminated to generate a metallic-bonded interface in the solid-state welding processes. Because they do not go through a

melting process, the generation of brittle intermetallic elements at the joint interface, grain coarsening, residual stress, and defects related to liquation and solidification can be avoided in solid-state welding, and a metallic bonding can be achieved if the interface is free of oxides and contamination layers. Different solid state welding methods have been investigated: friction joining of different pure metals was studied by Meshram et al. (2007). Friction stir welding has been successfully used for joining dissimilar metals, as detailed by Watanabe et al. (2006). Parallel ultrasonic welding is popular for electronic parts, as stated by Bakavos and Prangnell (2010), and is successfully used in automotive and aeronautical applications, where durable joints, robust to variations in manufacturing parameters, are obtained (Hetrick, 2009). In this method, explained in detail by Devine (1993), a perpendicular force is applied to the parts to be joined in order to obtain intimate contact at the interface. High frequency vibrations parallel to the interface are then introduced to produce a frictional movement that generates a plastic stress field (Doumandis and Gao, 2004) which in turn promotes the bonding mechanisms. Chang and Frisch (1974) analytically and experimentally demonstrated that an optimum joining parameter combination (namely clamping force, ultrasonic power and joining time) exists that produces the maximum joint

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strength. Otherwise the joint will be either damaged or incomplete. [Annoni and Carboni \(2011\)](#) conducted a parametric study to experimentally determine this optimum combination, as well as the interactions between the parameters. The reduction of plastic onset in materials by means of ultrasonic energy is known as the Blaha effect, following the first studies in this subject conducted by [Blaha and Langenecker \(1955\)](#) and [Langenecker \(1966\)](#), which demonstrated that ultrasonic energy has an effect on the plastic stress that is similar to the effect produced by temperature. However, the implementation of parallel ultrasonic methods in high throughput industrial processes is difficult, as *in situ* joining without the need of complex tooling is necessary, in a similar fashion to that of the automated spot welding facilities. Furthermore, the application of parallel ultrasonic joining to large size metal sheets is difficult, as the whole metal sheet must vibrate parallel to the in-plane direction. A novel method employing ultrasonic joining perpendicular to the joining surface was proposed by [Mizushima et al. \(2011\)](#) for joining dissimilar materials. This method is operationally similar to the resistance spot welding used, for instance, in automotive applications. [Nanaumi et al. \(2014\)](#) successfully joined dissimilar metal plates, such as copper, titanium and steel, to an aluminium plate using the perpendicular ultrasonic joining method. However, the joining mechanisms for a steel plate with an aluminium alloy plate have not been elucidated. In a comparable fashion to previous research on parallel ultrasonic welding, this work analyses and demonstrates the mechanisms associated with joint formation and quantifies the influence of the operating parameters on those mechanisms and on performance. For the tip diameter used, optimum joining parameter combinations have been determined, which shows the method's potential industrial applicability and may be useful to other researchers in this area, as well as process engineers, in their search for further system improvements. To achieve these goals, an experimental setup was constructed to apply this joining method (Section 2), using a variety of different operational parameters. The observations of the resulting joints and joint interfaces (Section 3), made it possible to establish the joint creation mechanisms and to quantify their effect on joint strength (Section 4). Cross tensile strengths of 208 N and 460 N were obtained when joining 0.5 mm thick A6061 plates to commercial steel plates of the same thickness using a 2.8 mm diameter tip. Cross tensile strengths of 343 N and 437 N were obtained when joining A2017 plates to commercial and high strength steel plates, respectively. Temperature measured at less than 1 mm from the joining interface did not exceed 135 °C.

2. Experimental procedure

2.1. Joining system description

To check the performance of the joints created by means of this perpendicular ultrasonic joining method, an experimental setup was designed based on those used for mechanical clinching, which in turn is similar to that used in resistance spot welding. The necessary changes were made in order to allow for the application of ultrasonic power to the joint. The main components and a schematic representation of the joining method are shown in [Fig. 1](#). [Fig. 2\(a\)](#) shows the dimensions and layout of the die set. [Fig. 2\(b\)](#) shows the dimensions of the upper and lower tip that aim to maximise stress amplitude whilst minimizing displacement amplitude at the joint interface. A 500 kN displacement controlled press is used to compress and hold the workpieces by means of the stripper and the die. The holding force is limited by four spring strippers with a total spring constant of 12.5 MN/m. Once the maximum holding force is obtained, the tip/plate contact force is controlled by means of the subsequent press stroke. In this joining method,

no knurl pattern is needed, provided that the stress is induced in the normal direction instead of tangentially. The tip forces are measured by two independent load cells. The steel plate is positioned on the top to prevent the upper tip from producing excessive plastic deformation. The ultrasonic energy is conducted from the horn towards the upper tip. The tip shapes are slightly different so that vortex flow is induced. As the tooling was designed allowing for both mechanical clinching and ultrasonic joining, there is a small gap between the lower tip and its die. For just ultrasonic joining, a flow control plate positioned under the aluminium plate must be used to prevent plastic flowing towards the gap. A thermocouple was positioned under the aluminium plate, as close as possible (less than 1 mm) to the joint interface area, to estimate its temperature during the joining process.

2.2. Materials and methods

A 700 W ultrasonic transducer vibrating at 27 kHz was used, driven by an ultrasonic generator with phase-locked loop to adjust the excitation frequency (up to +0 Hz/−700 Hz) so that the system's natural frequency can be maintained. In order to investigate the effect of joining parameters on joint strength, 75 × 25 × 0.5 mm steel and aluminium plates were processed, tested and observed in the following combinations: SPCC (commercial quality, cold rolled carbon steel defined in Japanese standard JIS G3141)/A6061T4, SPCC/A2017T4, HTSS (cold rolled high tensile strength steel defined in Japanese standard JIS 1180Y)/A6061T4 and HTSS/A2017T4. These materials were selected because they are widely used in the automotive and aeronautical industry. [Table 1](#) shows their chemical composition and mechanical properties. For the joint strength measurement, cross tensile tests were performed on a uniaxial test device, according to JIS Z 3137. Crosshead speed was 5 mm/min for all the tests. [Fig. 3](#) shows the cross tensile test setup.

During the experiments the amplitude was ramped up to determine the amplitude ranges which led to effective joints, as well as the influence of the already formed joint on the joining mechanism occurring during the remaining joining time. Once the effective amplitude range was determined, constant amplitude tests were performed on each material pair with different power, time and tip force combinations. The plates joined at constant amplitude were then separated into two groups. The first group was not cross tensile tested: sections were prepared using a focused ion beam system for scanning electron microscopy (SEM) and an Auger Electron Spectroscopy study was performed to analyse the joint interface characteristics and check for the presence of intermetallic compounds. Hardness measurements were also performed at different positions along the thickness of the cross-cut interfaces. The second group was cross tensile tested and the broken interface was studied. The shape of the plug was evaluated and measured using a digital calliper and an optical microscope and the nature of the failure was determined by SEM fractography analysis at the plug lateral surface.

3. Results

3.1. Ramped amplitude joining

[Fig. 4](#) shows the evolution of the upper and lower tip forces, as well as temperature and temperature increase rates, when ultrasonic amplitude is increased at a rate of 7 $\mu\text{m}/60\text{ s}$. Also shown are the plugs and interfaces after the corresponding tensile tests for SPCC/A2017T4 joints after amplitude ramps from 0 μm to 7 μm (a) and from 0 μm to 4.25 μm (b). No relevant differences were found in the behaviour at different ramp times for either aluminium alloy. Before power engagement, the force exerted on the upper tip is

Fig. 1. Schematic diagram of ultrasonic joining set up design aiming to maximizing stress amplitude by minimizing displacement amplitude at joining interface.

Fig. 2. Schematic for a) die-set, b) tool layout.

Table 1
Mechanical properties.

	Young's modulus (GPa)	Tensile yield stress (MPa)	Tensile strength (MPa)	Shear strength (MPa)	Reference
SPCC	208	260	370	–	JSA (2011)
HTSS	210	890	980	–	Matsuoka et al. (2007)
A6061T4	68.9	145	241	165	ASM (2016)
A2017T4	72.4	276	427	262	ASM (2016)

greater than on the lower tip. At increasing vibration amplitudes, a reduction in the tip reaction forces, as well as a rise in temperature can be observed. From certain amplitudes of approximately $3.5 \mu\text{m}$, the temperature increase rate rises suddenly, and reaction forces decrease at a greater rate. For amplitudes of about $4.5 \mu\text{m}$ the temperature increase ratio drops substantially, indicating a decrease in the generated heat. A sudden decrease in the reaction forces can also be observed. A maximum amplitude exists at around $6 \mu\text{m}$, at which point further increases lead to unstable behaviour and a resonance break, causing the ultrasonic power system to stop. For HTSS plates, behaviour was also similar for both aluminium alloys, with maximum attainable power being somewhat greater, corresponding to amplitudes of $7 \mu\text{m}$.

3.2. Constant amplitude joining

Having determined the feasible amplitudes, constant amplitude experiments were carried out in order to determine the most adequate (tip load, power, time) combinations, leading to the highest cross tensile test strengths. For SPCC joints, amplitudes from $3.5 \mu\text{m}$ to $5.5 \mu\text{m}$, which correspond to powers between 225 W and 250 W, led to joints with observable aluminium content joined to the steel plate after the cross tensile test. This is coherent with the findings during the ramped amplitude tests described in Section 3.1. For HTSS joints, the cross tensile test showed that only the maximum allowable amplitude and power ($7 \mu\text{m}$, 300 W) led to joints with observable aluminium content.

Fig. 3. Cross tensile test setup. a) Plates b) holding tool. Dimensions in mm.

Fig. 4. Evolution of the joining parameters – upper tip load (P.Load) and lower tip load (CP.Load), temperature (degC) and temperature increase rate (dT/da) – in SPCC/A2017T4 joints in ramp-up amplitude experiments at a slope of 7 $\mu\text{m}/60\text{ s}$. a) 0–7 μm (stopped at 6 μm), b) 0–4.25 μm . Micrographs show the potential joint area on the SPCC plate after the cross tensile test.

Fig. 5 shows the cross tensile test loads for a SPCC/A2017T4 joint at different constant powers, times and tip loads. For each power and tip load, an optimal time, marked with arrows in the figure, can be observed in which the maximum resulting joint tensile load coincides with the minimum variability. At this point in time, failure mode in the cross tensile test is “complete plug” (for a graphical description of the differences between complete plug, partial plug and interfacial failure modes, please refer to Section 4.3). This optimal time increases as ultrasonic power decreases. An optimal tip load value can also be observed, corresponding to the largest cross tensile test load values over the whole ultrasonic power time application range. For greater than optimum times,

Table 2
Joining parameters leading to maximum cross tensile strengths.

Steel	Aluminium	Power W	Tip load kN	Time s	Cross tensile strength N
SPCC	A6061	250	3,6	20	281
	A2017	250	3,6	15	343
HTSS	A6061	300	4,5	20	460
	A2017	300	4,5	45	437

failure mode is “partial plug”. For lower than optimum times, failure mode is mixed: “partial plug/interfacial”. The behaviour is the same for the other aluminium-steel combinations. Table 2 shows

Fig. 5. Effect of ultrasonic power and tip load on the cross tensile strength in SPCC/A2017 joints. Letters used to identify samples in following sections. Arrows indicate optimal times.

Fig. 6. Evolution over time of the joining parameters for a typical joining process (SPCC/A2017T4, 3.6 kN tip force, 250 W, sample D in Fig. 5). Power switch off at 15 s.

the optimal power-time-tip force combinations for the remaining material combinations. Greater times and loads are necessary for A2017.

Fig. 6 shows the joining parameter evolution over time in a typical constant amplitude joining process (sample D in Fig. 5) at 250 W ultrasonic power, 3.6 kN tip force and the optimum time for an SPCC/A2017 joint. Just after power engagement, reaction forces decrease and temperature raises quickly, due to the heat generated

Fig. 8. Auger spectroscopy of the SPCC/A6061T4 interface.

by the plastic flow. Thermal equilibrium is reached at no more than 130 °C. Finally, after ultrasonic power switch-off, reaction forces decrease again. It is worth noting that the maximum cross tensile loads correspond to those joinings where the ultrasonic power is sustained until the temperature derivative over time reaches zero, that is, no more heat is generated (as in Figs. 4 a or 6). Cross tensile strengths are lower if ultrasonic power is switch off before reaching or beyond the zero slope point in the temperature-time curve.

3.3. Joint observations

3.3.1. Joint interface before cross tensile test

Fig. 7 shows SEM images of the SPCC/A6061T4 interface, corresponding to the optimum time of 20 s and a tip force of 3.6 kN at 250 W. No intermetallic layer can be distinguished. The presence of an intermetallic compound cannot be discarded entirely. However, intermetallic compounds, if any, would be in the order of nanometres, three orders of magnitude smaller than the intermetallic compounds found in other joining methods – for instance, those found by Hirose et al. (2005) – which considerably reduced the joint strength. Additionally, temperature measured at less than 1 mm from the joining interface did not exceed 135 °C in any case in this series of experiments. In contrast, more than 600 °C is needed to form an intermetallic layer at the interface (Watanabe et al., 2011). In this work, it is also shown that the intermetallic compounds are clearly observed by Scanning Electron Microscope.

No debris has been found at any position along the joint interfaces at any joining power, which has been reported in some works as trapped metal/oxide compounds (Bakavos and Prangnell, 2010).

Fig. 7. SPCC/A6061T4 interface at optimum joint parameters. a) Broken interface close to the joint centre. Arrow shows the adhered aluminium remainder. b) Interface close to the joint edge. Arrows show the voids at the interface. Bonded interface enclosed by dashed contours.

Fig. 9. SPCC/A2017T4 interface corresponding to sample E in Fig. 5. a) Joint centre. A void can be clearly seen along the depicted length. Arrow shows an adhered aluminium remainder providing evidence of previous Al-SPCC adhesion. b) Close to the edge of the joint interface. No interphase can be observed. Adhesion takes place along the whole depicted length.

Fig. 10. A2017T4 grain at a) joint interface edge, b) joint interface centre.

Fig. 11. HTSS/A6061T4 joint interface close to its edge. Adhesion along whole depicted length.

Broken interface zones, which were previously joined, can be found close to the centre of the joint interface, as can be observed in Fig. 7a. Aluminium-steel bonding can be clearly observed close to the joint edge (Fig. 7b), but isolated dark areas corresponding to voids can also be seen. The oxide layer seems to have been removed from the interface, as seen in the Auger spectroscopy of

the interface area depicted in Fig. 8, where the oxygen peak cannot be detected. Analysis of the SPCC/A2017T4, HTSS/A6061T4 and HTSS/A2017T4 interfaces led to similar results. Fig. 9 shows a SEM image of the SPCC/A2017T4 interface at 4.5 kN tip force (sample E in Fig. 5) and 250W, with no detectable interphase. Nevertheless, voids and broken interface zones can also be found. Fig. 10 shows

Fig. 12. Detail of the joints after cross tensile test in samples A to C in Fig. 5. a) Time smaller than optimum. b) Optimum time. c) Time greater than optimum.

the aluminium grains close to the joint interface edge and centre in the same joint. Deformed grains, whose major axes are aligned along paths at approximately 45° to the normal surfaces, can be clearly distinguished close to the joint interface edge across the whole plug thickness, whereas no preferred direction is found close to the interface centre, where a grain size gradient can be seen in the thickness direction. Fig. 11 shows the HTSS/A6061T4 interface at optimum joint parameters, where no evidence of an intermetallic layer can be detected. Neither voids nor broken interface areas can be observed.

3.3.2. Joint interface after cross tensile test

For further analysis of the influence of the different joining parameters on the joint strength and failure mode, additional optical microscope observations were performed. Fig. 12 shows three representative examples, corresponding to an SPCC/A2017 joint, depicted A to C in Fig. 5. None of the samples showed modified coloration compared to their initial state due to the temperature increase. This means that the temperature at the interface area did not exceed 250°C (Electric Power Research Institute, 1999), which is in line with the temperature measurements recorded. The following general characteristics were observed in all the samples:

- For less than optimum joining times, partial plug/interfacial mixed failure mode is found. In all cases, the plug diameter or the area where aluminium is found is smaller than the potential joint area (that is, the contact area between the plates produced by the tip plastic deformation). The location of the adhered aluminium tends to be far from the potential joint area centre or periphery (see Fig. 12a).
- For greater than optimum joining times, partial plug failure mode is found. However, adhered aluminium can be found around the plug, covering the whole potential joint area. The thickness of this adhered aluminium area around the plug can be as great as 50% of the plug thickness (see Fig. 12c). Interfacial cracks can be found in some angular positions at the base.
- For optimum joining times, complete plug failure mode is found (Fig. 12b), and the plug covers the whole potential joint area, where plug thickness corresponds to the whole aluminium plate.

As Fig. 12a shows, low joining times led to insufficient joint progression. Microbond initiation off the joint centre can be observed. Bonding then occurs towards the centre and the periphery of the plate contact area. If joining time is sufficient, the joint will occupy the whole contact area, as can be observed in Fig. 12b and c.

Since the ultrasonic energy produces a plastic flow and deformations and size changes have been encountered in the aluminium grains, a hardness measurement was carried out on a

Fig. 13. Hardness measurement at HTSS/A2017T4 joint.

HTSS/A2017T4 joint. No hardness modification was found, as Fig. 13 shows.

SEM was used for the plug observation. Fig. 14 shows the base and plug lateral surface of SPCC/A6061 and SPCC/A2017 joints joined under optimum conditions. For all plugs, observation of the plug lateral surfaces shows evidence of brittle fracture at some positions at the plug base, close to the steel plate short symmetry axis for both aluminium alloys (Fig. 14a, c), whereas more ductile, shear fracture – elliptical dimples with opposite directions in plug and hole – can be observed at positions 45° off that axis (Fig. 14b, d). Some traction dimples can be found at the plug base, surrounding the whole plug circumference (Fig. 14c), which implies an interfacial fracture with limited propagation.

4. Discussion

As a result of the above described tests and observation results, sufficient evidences are available for explaining the parameter evolution (Section 4.1), formulating the underlying joining mechanisms (Section 4.2) and consequently predicting the joint strength and expected failure mode (Section 4.3) and the influence of the materials and tip force on this value (Section 4.4). This way, the consistency of the presented joining method can be assessed.

4.1. Parameters evolution during the joining process

As observed in Fig. 4, the force exerted on the upper tip is greater than on the lower tip before power engagement, due to the steel plate bending stiffness. At increasing vibration amplitudes, the smaller permanent thickness of the plates due to plastic deformation leads to a reduction in the tip reaction forces. The temperature rises due to the energy dissipated by the structural damping of the

Fig. 14. SEM images of the A6061T4 (a, b) and the A2017T4 (c, d) plugs joined at optimum conditions.

material and the friction at the interface. The sudden increase in the temperature growth rate from amplitudes about $3.5\ \mu\text{m}$ can be explained by the heat generated at the onset of plastic flow in the aluminium plate, which in turn gives rise to the reduction in the tip reaction forces. The sudden decrease in the reaction forces from amplitudes of about $4.5\ \mu\text{m}$ evidences the joint formation: as the plates are now joined to each other, their elastic recovery forces are obviously reduced.

The decrease in the temperature growth ratio is also related to the joint formation, since joints are not formed for lower amplitudes, as seen in the same figure. The maximum attainable power for HTSS plates, corresponding to amplitudes of about $7\ \mu\text{m}$, can be explained by their bigger yield strength, making the plastic deformation produced by the tip on the HTSS plate smaller, even for high tip forces. This produces a larger plate contact area –see also Fig. 17 and, thus, lower ultrasonic energy density, requiring greater power to produce the joint, and giving rise to bigger needed joining times and tip loads, but also to bigger cross tensile strengths –see Table 2. The sudden decrease in the reaction forces observed at power switch off in Fig. 6 is explained by the reduction of the tip enforced deflection due to the cancellation of the piezoelectric effect, as well as the thermal contraction.

4.2. Joint creation

As observed in Fig. 12a, microbond nucleation occurs at points located between the centre and the periphery of the contact area of the plates. The process continues inwards and outwards from these points, while the plastic flow is maintained by the ultrasonic power. The joint extension will expand as joining time increases due to interface cleaning produced by the plastic flow. This facilitates the formation of microbonds at the interface, also due to mechanical clamping of the already bonded areas, which channels the ultrasonic energy to areas that are not yet bonded and protects any that

Fig. 15. (a) Joining process. (b) Interfacial failure mode. (c) Partial plug failure mode. (d) Complete plug pull-out failure mode. The red arrows show the crack propagation paths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are already bonded from further plastic flow. In addition, as the joined area increases the area yet to be bonded decreases, so ultrasonic energy density will increase over time if power is not reduced. Due to these three effects (cleaning, clamping-protection, energy density increase), microbond density will be greater at points close to joint initiation, whereas it will be smaller at the joint edge and centre. Little ultrasonic energy will reach the joint centre because it is clamped by the microbonds that have already formed, whereas at the outer edge of the joint, higher energy density will increase the probability of microbond destruction or weakening, even more so because the edge is only clamped from its inner and not outer side. These effects can be observed in Figs. 7 and 12 a.

4.3. Failure modes. Influence of joining time and power

Three different failure modes were observed and are schematised in Fig. 15. The failure mode which gives rise to the biggest joint tensile strengths is the complete plug pull-out mode (Fig. 15d) in

Fig. 16. a) Cross tensile strengths for different plug diameters in SPCC/A6061 joints at 250 W and 3.6 kN. Application times and necessary material toughness for crack propagation are included for reference. b) Stress intensities around the joint interface for a 1.8 mm diameter plug at 281 N according to the Sripichai model.

Fig. 17. Joint cross sections. a), b) SPCC/A6061T4, tip forces 3.2 kN and 4.5 kN. c) HTSS/A6061T4, tip force 4.5 kN.

which a circular fracture front with a diameter equal to the potential joint area propagates through the aluminium plate thickness and does not spread along the interface. This gives rise to a circular plug with a diameter equal to the joint area. In this failure mode, since the aluminium plate breaks and the plug diameter is equal to the potential joint area, it can be concluded that no bigger peeling force can be achieved unless a tip with a larger diameter is used. In the partial plug mode (Fig. 15c), a through-the-thickness crack front also exists. The fracture begins along the interface direction, but deviates to the through-the-thickness direction at some point, giving rise to a non-circular plug, or a circular plug with a truncated conical base. The interfacial failure mode (Fig. 15b) was also found in low power-low time joints with very low tensile strength. In this mode, the interfacial fracture front does not deviate to the through-the-thickness direction, and gives rise to an interfacial failure without plug.

Fig. 16a shows the plug diameter-cross tensile strength distribution as a function of the joining time. It seems logical that the failure mode for excessive time is partial plug, whereas for the optimum

time it is complete plug, provided that the strongest microbonds are located close to the joint initiation points, as explained above: if time is greater than optimum, a fracture will initiate at the edge of the joint interface, where the bond quality is worse and fracture toughness is thus lower. It propagates across the interface up to the point where the microbond quality is better and it then deviates to the through-the-thickness direction forming a partial plug (Fig. 12c). Alternatively, the fracture can begin propagating at an angle of 45°, according to the direction of the grains close to joint interface edge, as the same figure shows. For the optimum time, bonds at that edge are not damaged and fracture toughness is greater, so the crack propagates through-the thickness from the beginning of its formation, forming a complete plug.

The fracture will initiate when stress intensity is higher than aluminium fracture toughness, much lower than that of steel. Despite the fact that through-the-thickness shear stresses produced by the cross tensile test are not negligible, stress intensity at the joint interface is mainly due to the tensile stress caused by the plates bending. For the same tensile force, the stress intensity is smaller

for larger joint interface diameters. As studied by Lin et al. (2006), the crack propagation direction will depend on the K_{II}/K_I ratio, where K_I and K_{II} are the stress intensities for mode I (peel) and mode II (shear) crack opening. If the K_{II} value is not negligible, the crack will tend to propagate through the thickness. Different models to estimate stress intensities are available in the literature. The stress intensity calculation is complicated because of the complex stress state arising from the plate geometry layout needed for the cross tensile test, and also because of the need for a rigid nugget assumption in order to be able to establish an analytical model. Carboni and Annoni (2011) developed a FEM model and calculated the stress intensities around the plug in a lap joint using linear fracture mechanics. Lin and Pan (2008) developed an analytical, closed form solution for the stress state around the edge of the joint interface, which allowed the J-integral around the crack to be calculated and consequently stress intensity factors as well. Dancette et al. (2011) developed a finite element model for the same J-Integral calculation. Sripichai et al. (2013) developed a model based on the Lin and Pan model to calculate the stresses around the plug and, as a function of them, the stress intensity factors in plates with different thicknesses and mechanical characteristics, including finite element method-calculated correction factors for taking into account nugget flexibility. In this work, the Sripichai model has been particularized to the materials, dimensions and Young's moduli of the plates used in the cross tensile tests. Calculations were then performed for stresses around the plug, for mode I and mode II stress intensities K_I , K_{II} , as well as for the equivalent stress intensity $K_{eq} = \sqrt{K_I^2 + K_{II}^2}$ for different plug diameters and cross tensile loads. Consequently, the cross tensile load needed so that the equivalent stress intensity K_{eq} is equal to the aluminium fracture toughness can be calculated for any plug diameter. Fig. 16a shows this fracture initiation cross tensile load as a function of the plug diameter in SPCC/A6061T4. The figure shows that specimens joined with optimum joint parameters have a cross tensile strength which corresponds to a stress intensity very similar to the fracture toughness of the aluminium (30 MPa/ $\sqrt{m}$), which means that the maximum joint strength is achieved if the optimal joining parameters are used. It can also be observed that greater than optimum times give rise to strengths lower than the crack initiation value. A fracture toughness of 30 MPa/ $\sqrt{m}$ has been assumed for the aluminium alloys taking into account that the hardness measurements show no relevant work hardening. Fig. 16b shows the values of K_I , K_{II} and K_{eq} as a function of the plug circumferential angle, for a 1.8 mm diameter plug, at a force of 281N, in a SPCC/A6061 cross tensile test. The figure shows that K_{II} has a non-negligible value, which makes the fracture tend to propagate through the thickness as soon as interfacial adhesion is strong enough. In addition, maximum intensity value is located at 0° , in good agreement with brittle fracture evidence found close to the 0° angular position at the plug base (Fig. 14a and c). Once initiated, the crack propagates in peeling and shear mode though the thickness, as fracture dimples show in Fig. 14.

4.4. Effect of the tip force and the material mechanical properties

Tip forces create a plastic deformation on both plates, especially the steel one, reducing their thickness and creating a contact area, over which the joint can bond. Given the materials' stiffness and yield strength, the contact area size and shape are highly dependent on the tip force: if it is low, the contact area will be small. If it is too high, the contact area will be large, but not flat, which hinders joint bonding and creates stress concentration locations that will increase the stress intensity. It will also excessively reduce the plate thicknesses, as well as the plastic strain amplitude for a given ultrasonic power. Higher stiffness and yield strength will lead

to more uniform contact area topography. Fig. 17a and b shows a SPCC/A6061T4 joint cross section at two different tip loads. It can be demonstrated that an excessive tip load leads to a reduction in the aluminium thickness and to non-symmetrical topography. Fig. 17c shows the HTSS/A6061T4 contact area at the greatest tip force. It can be clearly seen how the contact area is smoother and larger due to the higher yield strength of the HTSS in comparison to the SPCC. Bigger size and smoothness lead to the much bigger cross tensile strength described, due to the larger potential joint area diameter and smaller stress intensity.

5. Conclusions

SPCC/A6061T4, SPCC/A2017T4, HTSS/A6061T4 and HTSS/A2017T4 were successfully joined by means of a perpendicular ultrasonic joining method. The feasibility and consistency of this method have been demonstrated by identifying the joining mechanisms, and discussing the influence of the joining parameters. By using this method, the joint cross tensile test breaking loads, when joined with optimum parameters, closely correspond to the stress intensities needed for the crack propagation in aluminium, which means that the maximum reachable joint strengths were obtained. Fracture initiated not at the interface but inside the aluminium plate. No intermetallic layer was observed at each joint interface. The study of the joining parameters revealed that joining power, time and initial tip force are important factors for joining performance. For a certain joining power, an optimum time has always been identified, which opens up an optimisation line with greater powers and smaller times. Joining times below this optimum level result in partial plug/interfacial mixed failure mode due to insufficient microbond formation. Joining times above this optimum point results in partial plug failure mode due to damage to the already created microbonds. Tip force affects the contact area size and consequently the maximum joint interface size and joint strength. The yield strength of the steel plate will determine the contact area size for a given tip force. As the operational mode is the same as that used in spot welding, this ultrasonic joining method could be applied successfully in industrial applications.

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