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Weld-bonded stainless steel to carbon fibre-reinforced plastic joints

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ABSTRACT

This paper investigates a resistance spot welded reinforced adhesive (weld-bonded) joint between 304 stainless steel to carbon fibre reinforced plastic (CFRP), where welds are made both with and without the reinforcing carbon fibres present. Successful welds with the fibres present could only be produced with high electrode pinch forces, which helped reduce contamination of the weld nugget. Similar joint strengths were achieved in both cases, however the joints without fibres exhibited an increased strain to failure. Both joints were significantly stronger than either an adhesive joint or a comparable bolt reinforced adhesive joint. These techniques provide an alternative for joining thin metallic components to CFRP structures where increased strength and integrity is required.

1. Introduction

The subject of composite metal joining has received increasing attention in recent years because of the desire to obtain optimised properties at different locations of a structure. In many applications the introduction of composites can contribute to an overall weight saving, however joints with the metallic structure are challenging.

Bolting can be used, but they lead to significant stress concentrations around the bolt holes and add weight. Breto et al. (2015) stated that adhesively bonded joints can overcome these shortcomings, have high structural integrity and improved corrosion performance. However the stress concentrates at the end of the bond-line causing failure which is often catastrophic. The performance may be improved by 70% by grading the properties of the adhesive.

Zhang et al. (2012) stated that the limitations of bolted and adhesively bonded joints are addressed by combining the two processes, however this often defeats the original objective of size, weight and cost savings. Therefore several techniques have been developed that involve creating features on the metallic part to reinforce the joint. This includes the Comeld process which uses an electron beam to create features on the metal surface that improve strength. Similar work by Ucsnik et al. (2010) used a Metal Inert Gas based welding process called Cold Metal Transfer to create pins that had a variety of shapes including balls that helped prevent pull-out. These joints prevented the catastrophic failure of the adhesive only joints, dramatically increasing the strain to failure. There are a large number of publications that investigate pin failure and pull out with a good recent article being published by Nguyen et al. (2017). In this article the pins were manufactured via an additive manufacture technique, Selective Laser Melting, and surface features on the pins were added to improve energy absorption by 60%.

Weld bonding, which is the subject of this study, was first reported by Schwartz (1979) who stated that it had been developed for metal to metal joints in the USSR and it combined a resistance spot weld (RSW) with adhesive bonding. Darwish and Ghanya (2000) describe how two variants of the process have been developed: weld-through and back-infiltration. In the weld-through process an adhesive is applied to faying surfaces. The surfaces are then brought together and a RSW is applied prior to adhesive cure so the weld penetrates the adhesive layer. In the back-infiltration process metal parts are directly joined by resistance spot welding followed by the application of a low viscosity adhesive to the edge of the overlap, which fills the gap by capillary action. The method has a number of advantages over mechanical fastening including reduced manufacturing costs, high static and fatigue strengths, and improved corrosion performance. Subsequent finite element modelling of weld-bonded joints by Al-Samhan and Darwish (2003) demonstrated how incorporating the RSW with the weld-bonded joint distributed the stresses over a wider area, increasing the overall strength. Santos et al. (2004) conducted a thorough study on weld-bonded joints and used a finite element code, SORPAS to model the

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resistance spot welding process and understand the effect of the adhesive. Mechanical tests were undertaken to assess performance, demonstrating the synergistic effect of weld-bonding which provided a greater displacement to failure than either spot welding or adhesive bonding on their own.

More recently these techniques have been applied to joints between metals and composites. Berger (2010) demonstrated joints where the fibres were removed at the locations that the resistance spot welds were applied. Shah et al. (2010) produced similar joints and showed that the load carrying capacity of the weld-bonded joint was similar. However failure of these joints was less catastrophic as the spot weld continued to provide strength after failure of the adhesive. Furthermore the fatigue strength of the joints was improved and once again failure when it occurred was less catastrophic. The most recent work on these kinds of joints by Li and Sun (2014) involved numerical modelling of joint performance and predicted the failure modes as a function of the adhesive layer thickness. In addition, they investigated the effect of impact damage on joint strength.

Joesbury (2016) extended the weld-bonding method showing how the RSW could be made *through* the carbon fibre fabric. A diagram of the joint investigated is shown in Fig. 1. This joint has an interleaved stack of metal and dry carbon fibre across which a RSW is made. The fibres are partially expelled and partially absorbed into the metallic welded joint. A number of metals were compared and stainless steel was shown to be more effective than either titanium or aluminium. The most successful joints with this metal used three layers of 0.9 mm thick stainless steel between 2 × 2 plies of carbon fibre fabric. The small metal sheet in the middle has the same area as the bonded interface and is critical to the success of the joint. As will be demonstrated within this paper, the resistance of the layup scales with the number of fibre to metal interfaces. Hence the addition of the middle sheet creates more heat and facilitates absorption of the fibres within the weld metal. The second stage involved epoxy resin infusion into the carbon fibre fabric. The resin has two functions, it forms the polymer matrix system of the composite laminate and also an adhesive joint between the composite laminate and metal.

This paper describes the effect of process parameters on the RSW process. This is followed by the design and manufacture of proof of concept joints that were mechanically tested to determine joint performance.

2. Methodology

2.1. Equipment

The welds require accurate control of the electrode pinch force. To achieve this, an AWL-Techniek WP63RL-K resistance spot welder was used where the upper electrode was pneumatically actuated (max load 4.5 kN). This equipment is shown in Fig. 2 as well as the arrangement of the weld and a small tent enclosure that was filled with argon to minimise oxidation of the metal and combustion of the fibres during welding. The oxygen concentration was kept below 500 ppm. The copper electrodes had a contact diameter of 3.5 mm and were dressed regularly on any sign of wear or contamination to ensure consistent welds. The welding machine was instrumented in a number of ways: a calibrated inline pressure transducer; current and voltage probes; and a Polytec CLV-1000 Laser vibrometer to measure electrode displacement. All these devices were connected to a Dewetron DEWE-2600 data logger.

2.2. Parametric weld study

The parametric weld study was conducted to determine optimum resistance spot welding parameters for the interleaved material stack shown in Fig. 1, i.e. a weld was created between three sheets of 0.9 mm thick 304L stainless steel and 2 × 2 ply sheets of 0.25 mm Hexcel G1157 carbon fibre fabric which was laid up in a 0°/0° orientation. The size of the middle metal sheet was the same as the bonded interface − 30 × 30 mm and the combined thickness of the joint was 3.7 mm.

To determine appropriate parameters for this study, the through thickness resistivity needed to be determined as a function of the electrode pinch force. A Sensy INDI-PSD handheld force transducer indicator together with a 9QUAL 10 kN load cell was used to measure pinch force and a Master Instruments D3700 micro ohmmeter was used to measure electrical resistance. The following material stacks were investigated:

- Metal to metal − 0.9 mm 304L stainless steel/0.9 mm 304L stainless steel
- Multi-material stack 1–0.9 mm 304L stainless steel/1x Hexcel G1157 carbon fibre fabric ply/0.9 mm 304L stainless steel
- Multi-material stack 2–0.9 mm 304L stainless steel/2x Hexcel G1157 carbon fibre fabric plies/0.9 mm 304L stainless steel/2x Hexcel G1157 carbon fibre fabric plies/0.9 mm 304L stainless steel

Fig. 3 shows the measured through-the-thickness resistivity as a function of the pinch force. In all cases an increasing pinch force resulted in a reduced resistance, which asymptotes to a particular value that corresponds to flattening of the surface asperities with metal to metal contact and increased nesting density of the carbon fibre for the multi-material stacks.

The dominant characteristic that affects the resistivity appears to be the number of carbon fibre to metal interfaces: there is only *one* ply and two interfaces in multi-material stack 1 (red square data points); while there are *four* plies and four interfaces in the multi-material stack 2 (blue circle data points). Since the resistivity is approximately doubled and the resistivity of stainless steel is relatively low, it would appear to scale with the number of interfaces.

Using this information, four series of experiments were performed on the interleaved material stack (Fig. 1) and the parameters are summarised in Fig. 4 the main parameters that were varied were the welding power, and the electrode pinch force. The current application time was varied during the experiments, but generally had a small effect once a weld has been made. Values between 1.3 and 2 s were used.

Series 1 trialled various power levels while keeping the electrode pinch force constant at 1990 N − the asymptote for multi-material

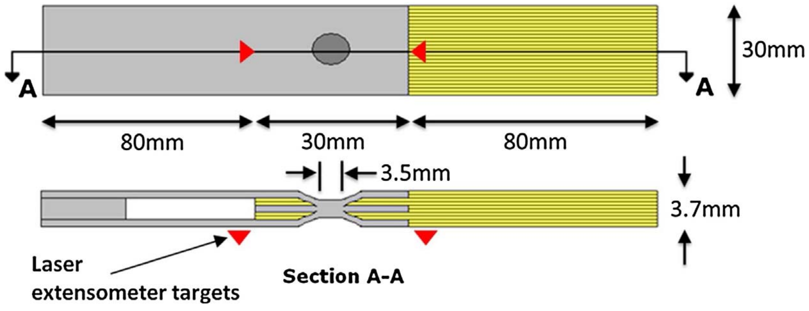

Fig. 1. Diagram of the metal to carbon fibre spot weld-braze reinforced adhesive joint. Note: this diagram shows the preferred interleaved stacking sequence.