NOVEL INDUCTION HEATING TECHNIQUE FOR JOINING OF CARBON FIBRE COMPOSITES

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Abstract

Although thermoplastic composites (TPCs) can be processed rapidly by thermoforming, which makes them an attractive option for the aerospace industry, as yet there has not been a significant uptake of TPCs for structural applications. One reason behind this has been limited technology for joining. TWI has recently invented a new method for improving the control of induction welding thermoplastic composites without additional susceptors. Inserting a thin electrically-insulating layer (scrim) between adjacent layers containing non-aligned carbon fibres prevents electrical pathways from being formed and volumetric heating is disabled. TWI's technique has the advantage that the heat generated is concentrated at the joint interface, which avoids the problem of having to remove excess heat from the surface of the composite to avoid thermal damage, and therefore improves the control of the process. Joint strengths of up to 32MPa have been achieved using the technique.

1. Introduction

One of the limitations of composites is the joining of pre-fabricated parts. In the case of thermoset composites, there is a need for complex pre-treatment and heating mechanisms. Thermoplastic composites lend themselves better to joining but there is always a difficulty in ensuring that only the interface is heated without a foreign material left at the bond line.

The recent years have seen a renewed interest in thermoplastic composites for high-end applications, especially aerospace. The predicted production rates for single-aisle aircraft exceed the current economic production capabilities of thermoset composites. Compared to thermosets, thermoplastic composites can offer shorter processing times to meet rising production rates, with potential additional benefits of good solvent resistance, unlimited shelf life and better toughness. Thermoplastic composites can be processed more rapidly by heating the polymer matrix sufficiently to permit thermo-forming, in a process similar in concept to stamping of sheet metal components. This makes TPCs an attractive option for the aerospace industry, but as yet there has not been a significant uptake of TPCs for structural applications.

2. Joining

One reason behind this has been joining. Although the use of composites can offer near net-shape manufacturing, there is often a requirement for joining of components, for various reasons such as**:**

- It is more cost effective
- Components are too large to be produced as a single part
- Hybrid materials are used that require different production conditions
- Components are made in different physical locations

The fastening methods currently in use have been adapted from those used to join metal structures, as the aircraft industry has considerable performance data and confidence in the techniques. Thermosets have traditionally been joined using either mechanical fastening or adhesive bonding. Mechanical fastening requires production of holes that cut load bearing fibres and introduce stress concentrations around the holes. Adhesive bonding too is not without problems, and often requires large prefabricated parts to be heated in an oven, simply to cure the adhesive at a relatively small joint.

Unlike thermosets, TPCs can be joined by fusion bonding (welding); a process that does not use damage by making holes, and offers further advantages in terms of weight saving, through removal of the fastener, and speed, through elimination of a hole-drilling step. Welding of thermoplastic composites is any process that heats the interface to a temperature above the glass transition temperature, tg (for amorphous polymers) or the melting point, tm (for semi-crystalline polymers). Under the application of pressure, the polymer chains are able to diffuse across the interface, forming a welded joint on cooling [1]. the process can be quick, and requires little or no surface preparation.

Since the introduction of thermoplastic composite materials such as APC-2 (AS4 carbon fibre reinforced polyetheretherketone, or peek) in the 1980s, many studies have been carried out on fusion bonding of TPCs. Of the numerous fusion bonding techniques available, three in particular have been the subject of many research studies as they are considered most suitable for industrial applications; induction, resistive implant and ultrasonic [2].

In induction welding, heat is generated through joule losses from the induced eddy currents in response to an applied alternating magnetic field. The magnetic field is produced by an alternating electric current passing through a conducting work coil. The induced eddy currents can flow in a metal implant placed at the weld interface or in the carbon fibres in the parent composite materials.

Induction welding has been applied to joining thermoplastic composite materials in a number of applications in recent years. Fokker Aerostructures designed and developed the Gulfstream G650 tail section and industrialised a new induction welding method for the rudder and the elevator [3]. Fiberforge Corporation also applied the technique to join parts on the Sikorsky CH-53K. However, the technique has not yet been widely adopted, and one reason for this is poor control of the process to prevent thermal degradation [4]. What is required is a technique that focusses the heat where it is needed without additional susceptors placed at the weld interface.

3. TWI's Novel Induction Heating Technique

Current state-of-the-art induction welding of carbon fibre composites requires a highly thermally conductive heat sink material to be placed on the composite part closest to the induction coil [5]. Alternatively, a cooling nozzle has been used to control the surface temperate during welding through continuous optical pyrometer measurements [6]. Both these techniques can be used to remove the excess heat from the surface and allow the weld interface to heat up sufficiently. However, these thermal management systems rely on heat conduction through the composite and may not be as effective when joining thick composite parts.

TWI has considerable expertise in fusion bonding of thermoplastic composites [7] and has recently developed a novel technique to improve the control of the induction welding process [8]. It is well known that for eddy currents to be induced in continuous carbon fibre composites there must be adjacent non-aligned plies. A layered structure having all the reinforcing fibre uni-directionally aligned in the same orientation will not become volumetrically heated by induction since a closed electrical pathway cannot be formed [9]. Fortunately, most structural composite applications employ a quasi-isotropic layup to achieve their required mechanical performance, and therefore can be volumetrically heated by induction.

If the adjacent non-aligned plies of the quasi-isotropic laminate are separated sufficiently to prevent contact between the carbon fibres in neighbouring layers then the closed electrical pathways can no longer be formed, and volumetric heating is therefore disabled. This can be achieved by inserting a thin electrically-insulating layer (scrim) between adjacent layers containing non-aligned carbon fibres (Figure 1). Using a particular combination of parameters and properties, TWI's technique has the advantage that the heat generated is concentrated around the joint interface. This focusses the heat where it is required, and avoids thermal damage. The heat required to produce the welded joint is generated by omitting the insulating layers in the vicinity of the weld interface. Furthermore, as the intensity of the induced current in the conducting material decays exponentially from the surface, the insulating layers need only to be inserted in one of the parts being joined; the one in closest proximity to the work coil.

The heat generated is using this technique can be sufficient to be used for fusion bonding of thermoplastic composites but also for adhesive curing; a process used to join thermoset composites.

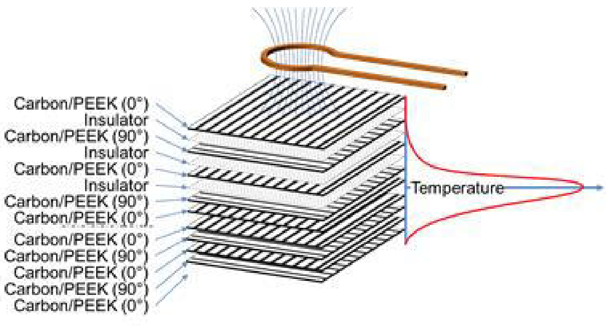

Figure 1. Temperature peak focussed at the weld interface.

In order to demonstrate the focused heating effect two thermoplastic composite laminates were manufactured, each containing three Carbon/PEEK plies at 0/90 orientation. One laminate ("conductor") was manufactured in the conventional way, allowing adjacent non-aligned plies to touch. The other laminate ("Insulator") was laid up using a thin insulating layer between adjacent non-aligned plies. The material used for the insulating layer was a 10gsm non-woven glass fibre surface tissue. A layer of PEEK film was placed either side of the insulating layer during manufacture; the additional PEEK was required to wet-out the glass insulating layer during consolidation of the laminate.

When placed together in the configuration shown in Figure 2; “Insulator” on top of “Conductor”, and therefore closer to the work coil, heating was concentrated at the interface between the two laminates. The two laminates were offset by 45 degrees to allow measurement of the surface temperature of the lower laminate using a thermal image camera. A Cheltenham Induction Heating TR1 1kW induction power supply was used to apply an alternating electromagnetic field via a four-turn solenoid coil at a frequency of 165kHz for a period of 60 seconds. Temperature at the two locations marked in Figure 2 was measured at ten second intervals during the tests using a FLIR T250 thermal image camera.

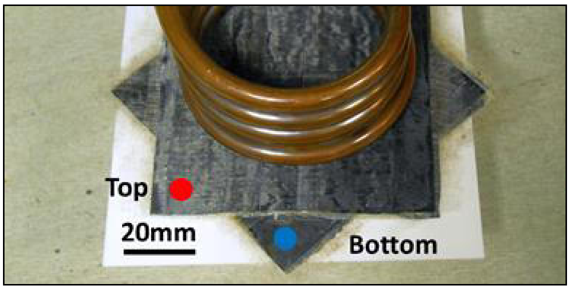

Figure 2. Heating trial setup. Top; “Insulator”, Bottom; “Conductor”.

4. Joint Evaluation

In order to demonstrate the strength of welded joints made using TWI’s technique single lap shear specimens were manufactured and tested according to ASTM D1002-10. Two nominal 4mm thick 0/90 cross-ply laminates were manufactured and joined; one containing 27 plies of carbon/PEEK (“Conductor”) and the other (“Insulator”) containing 24 Carbon/PEEK plies but with adjacent non-aligned layers separated by glass/PEEK insulating layers. The weld area was approximately 12.5mm wide and 150mm long. An Ambrell EasyHeat 8310 power supply tuned to a frequency of 240kHz was used to carry out the welding. A higher power setting was used compared to the previous heating trial, as the temperature required for welding was 400°C.

The laminates were arranged as shown in Figure 3, with the “Insulator” laminate closer to the work coil. A 100µm PEEK film was placed at the weld between the two laminates. The film acted as a PEEK rich layer at the interface to help the flow of polymer during welding, and to fill any undulations in the surfaces being welded. Pressure was applied to the weld area by means of a pneumatic actuator.

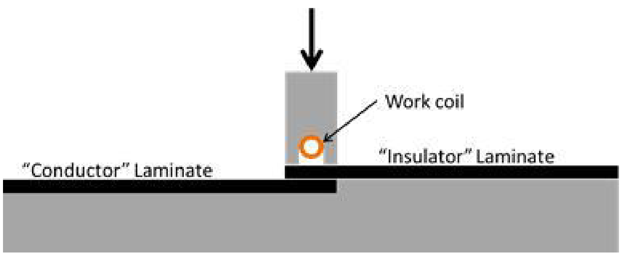

Figure 3. Weld configuration for joint evaluation.

Samples were taken from the welded laminates using a water-cooled diamond coated saw blade, and tested according to ASTM D1002-10, using a displacement rate of 10mm/min.

5. Results

Results of the temperature rise measurements are presented in Figure 4 and Figure 5, and show that, despite being closer to the source of the electromagnetic flux, the top laminate does not heat up as much as the bottom laminate. In fact, the top laminate experiences a maximum temperature rise of only 25 degrees after 60 seconds heating, whereas the maximum temperature rise of the bottom laminate in the same period is approximately 170 degrees. These results clearly demonstrate that induction heating had been disabled in the top laminate and heating had been focused at the interface between the two laminates. The slight heating of the top laminate was due to conduction of heat from the bottom laminate and is sufficiently small to prevent degradation of the top laminate.

Results of the joint evaluation tests show a range of single lap shear strength values of between 11 and 32MPa. Due to the geometrically critical nature of the induction welded specimens, the single lap shear specimens extracted from the ends of the welded laminates have a significantly reduced strength when compared to the lap shear specimens extracted from the centre.

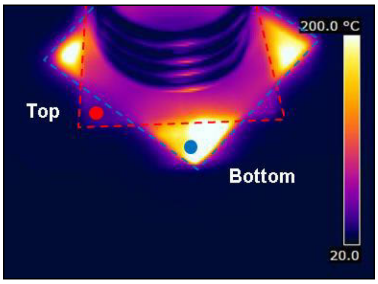

Figure 4. Thermal image after 60 seconds of heating.

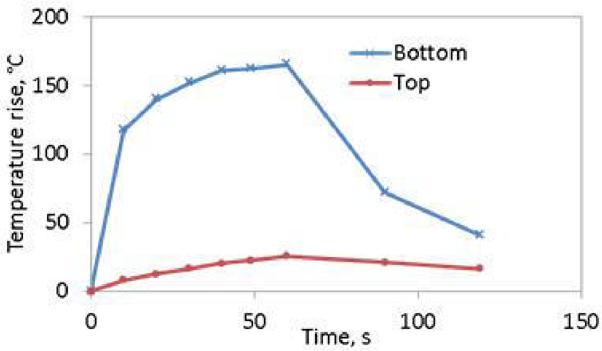

Figure 5. Temperature rise in Top and Bottom laminates.

6. Concluding Remarks

For the first time, induction heating can be precisely controlled through the thickness of carbon fibre reinforced thermoplastic composites. During lay-up of the composite components to be joined, thin electrically insulating layers (gauze) are inserted between plies where induction heating is not required. Inclusion of the thin insulating layers is only required between adjacent non-aligned layers of carbon in one of the parts being joined and only in the vicinity of the joint.

Heating trials have demonstrated that the technique successfully prevents the induced alternating electrical currents from being generated during induction heating. Electric current is induced between plies where no insulating layers (gauze) are present, to heat and melt the material in the usual way for welding or curing. In this way, the concentration of induction heating through the thickness of the material can be precisely controlled. This approach avoids any overheating of the outer surface of the components and improves the quality of the joints manufactured.

The technique may be considered as a candidate welding process that offers advantages over the current state-of-the-art processes, especially where thick parts are involved (greater than 4mm thick). Tooling costs are also minimised compared to the state-of-the-art. Wider application of the technique should be considered as a focussed heating process for applications such as adhesively bonding thermoset composites, where focussing the heat at the interface can be used to cure an adhesive.

7. Acknowledgements

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