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Continuous resistance welding of thermoplastic composites: Modelling of heat generation and heat transfer

Huajie Shi [a], Irene Fernandez Villegas [a,*], Marc-André Octeau [b], Harald E.N. Bersee [a], Ali Yousefpour [b]

[a] Structural Integrity & Composites, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands
[b] Aerospace Portfolio, National Research Council Canada, 5145 Decelles Avenue, Montréal, Québec H3T 2B2, Canada

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ABSTRACT

A process model composed of electrical and heat transfer models was developed to simulate continuous resistance welding of thermoplastic composites. Glass fabric reinforced polyphenylenesulfide welded in a lap-shear configuration with a stainless steel mesh as the heating element was considered for modelling and experimental validation of the numerical results. The welding temperatures predicted by the model showed good agreement with the experimental results. Welding input power and welding speed were found to be the two most important parameters influencing the welding temperature. The contact quality between the electrical connectors and the heating element was found to influence the distribution of the welding temperature transverse to the welding direction. Moreover, the size of the electrical connectors was found to influence the achievable welding speed and required power input for a certain welding temperature.

1. Introduction

Compared with thermoset composites, thermoplastic composite materials have several advantages such as intrinsically higher toughness, better environmental resistance, and sustainability [1,2]. Furthermore, thermoplastic composites offer the possibility of cost-effective manufacturing and assembling through thermoforming and welding [3,4]. Resistance welding has been identified as one of the most promising welding techniques for joining thermoplastic composites [5–7]. It features short cycle times and potentially inexpensive equipment requirements. Static resistance welding (RW), which entails one-shot welding of the entire welding area, has been widely used for welding of coupons or small- to medium-size components [8–12]. However, for larger applications, RW has some drawbacks such as significant non-uniform temperature distribution at the weld interface, high force needs to be applied on the adherends, difficulties to maintain uniform pressure at the weld area and a high power demand [5,11]. Sequential resistance welding (SRW) was introduced to address these issues [13,14]. SRW relies on the use of multiple heating elements for a multiple-step welding process, and it successfully overcomes some of the drawbacks of RW for the welding of large parts. However, it introduces some difficulties derived from the handling of multiple heating elements [13,14]. More recently, a continuous resistance welding (CRW) process has been developed [15]. CRW simplifies the welding process as compared to SRW by using a single-piece heating element and a rack of multiple adjacent copper block connectors, which are parallel to the welding direction and located on both sides of the welding overlap, as depicted in Fig. 1. Two copper wheels, connected to the power supply unit, are rolled along the block connectors to generate heat and to create a local molten zone, which moves along the entire welding overlap. Compared to RW, both SRW and CRW introduce new parameters in the welding process and, hence increased complexity but they make it possible to weld larger areas with minimum force and power requirements.

As shown in literature, process modelling combined with experimental validation allows for a better understanding of welding processes and the influence of critical parameters [16–21]. Until now, substantial effort has been devoted to the development of process models for the RW process but no simulation model is available in the open literature for the SRW or the CRW processes. The bigger complexity of both SRW and CRW however justifies the development of dedicated models to improve our understanding of the processes and to fully profit from their advantages.

The objective of this study is to investigate the thermal behaviour of thermoplastic composites during the CRW process as well

* Corresponding author. Tel.: +31 (0)15 278 9745; fax: +31 (0)15 278 1151.
E-mail addresses: H.Shi@tudelft.nl (H. Shi), I.FernandezVillegas@tudelft.nl (I.F. Villegas), marc-andre.octeau@nrc.ca (M.-A. Octeau), H.E.N.Bersee@tudelft.nl (H.E.N. Bersee), Ali.Yousefpour@cnrc-nrc.gc.ca (A. Yousefpour).

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as the influence of the key welding parameters on the welding temperature. To this aim, a dedicated 3D process model was developed consisting of an electrical and a heat transfer model. The electrical model provided the distribution of resistive heat generation in the heating element. The heat transfer model used this distribution to simulate the welding temperature. Likewise, a parametric study was conducted to understand the effects of electrical clamping pressure, input power, welding speed and size of the electrical connectors on the welding temperature.

2. Experimental

2.1. Materials

The thermoplastic composite material used in this study was 8HS woven E-glass fabric reinforced polyphenylenesulfide (GF/PPS). GF/PPS laminates were manufactured out of eight layers of CETEX® GF/PPS prepreg, supplied by Ten Cate Advanced Composites, The Netherlands, with a $[(0°/90°)]_{4S}$ stacking sequence. The stack of prepreg was consolidated in a hot platen press at 320 °C and under 1.0 MPa pressure for 15 min to obtain 1.9 mm-thick laminates with 50% resin volume fraction.

A plain woven AISI 304L stainless steel mesh, with a wire diameter of 0.04 mm, a gap of 0.09 mm between consecutive wires, and 0.08 mm thickness, was used as the heating element. Stainless steel mesh sheets, dimensions 254 mm × 60 mm, were used at the welding interface. In order to fill the gaps of the mesh and to provide a resin rich area at the welding interface, one layer of 90 μm-thick neat PPS film was placed between the mesh and each adherend prior to welding.

2.2. Continuous resistance welding

The continuous resistance welding setup developed by the National Research Centre of Canada was used in this study [15]. As shown in Figs. 2 and 3, the welding setup consisted of a power supply, a pneumatic system for welding compaction, a pneumatic system for electrical clamping, a linear actuator system, block and wheel connectors and thermal insulators. An XDC 60-200 digital DC power supply, I_{max} = 200 A and U_{max} = 60 V, was used to provide the welding input power. For thermal insulation, 12.7 mm-thick GPO3 fibre glass sheets, provided by K-Mac-Plastics (USA), were placed below and above the adherends. As shown in Fig. 3, single-lapped GF/PPS joints were welded with an overlapping area of 254 mm × 25.4 mm. Two racks of electrical connectors, each one consisting of twenty copper blocks were used to introduce the electrical power into the heating element. Each copper block was 16 mm long, 12.7 mm wide and 6 mm high. One rack of these

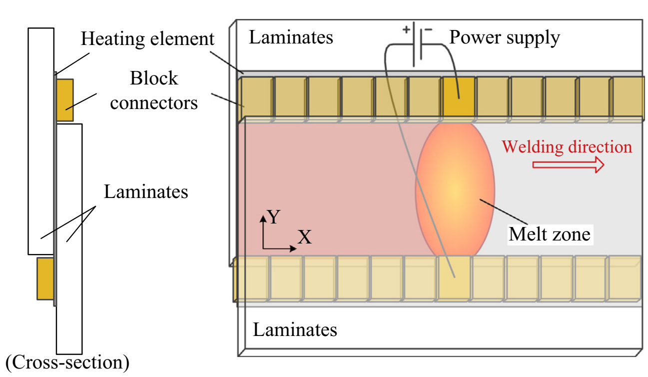

Fig. 1. A schematic diagram of continuous resistance welding of single-lap joints. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

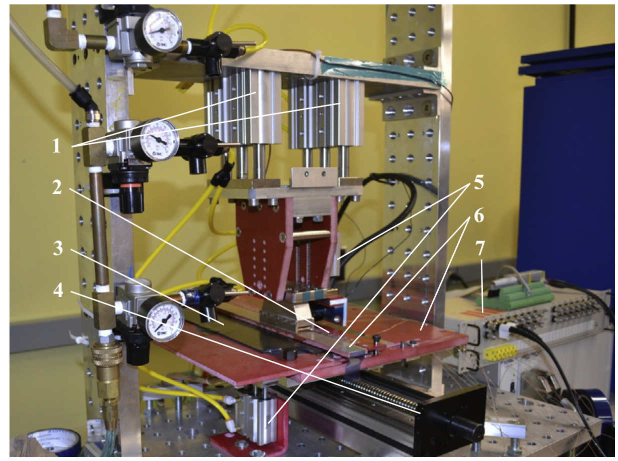

Fig. 2. Continuous resistance welding setup, consisting of (1) pneumatic system for welding compaction, (2) block connectors, (3) laminates, (4) motion system, (5) pneumatic system for clamping, (6) insulators, and (7) power supply. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

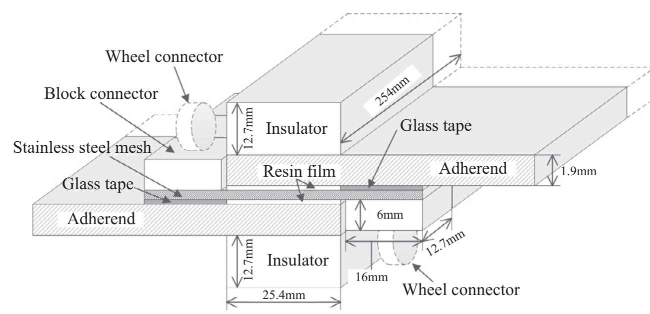

Fig. 3. Geometry of continuous welding setup for the welding of single lap shear joint.

block connectors was placed on top of one of the adherends and the other one was placed underneath the other adherend to weld a single lap joint (see Fig. 3). A 1 mm-long clamping distance [12] was left between the edges of the overlap and the block connectors. A 55 N electrical clamping force, which equals to approximately 0.30 MPa clamping pressure, was applied to the block connectors through two copper wheel connectors connected to the power supply unit and to a pneumatic cylinder (see Fig. 2). Likewise, 500 N welding compaction force was applied to the welding stack through a series of adjacent compaction rollers connected to a second pneumatic cylinder. During the welding process, the platform on which the adherends, heating element, insulator blocks and block connectors were located was horizontally displaced by a high torque step motor. The connector wheels and the compaction rollers, the support of which remained stationary, were consequently forced to roll at the same constant speed on top of the block connectors and the uppermost insulation block, respectively. An in-house developed LabView program was used to control and record the main welding parameters, namely input power and welding speed, as well as thermocouple readings during the welding process. The welding process was carried out at a constant welding voltage of 4.3 V.

3. Modelling

A flowchart for the CRW process model is presented in Fig. 4. This process model is divided into an electrical model and a thermal model. The electrical model was developed to simulate the