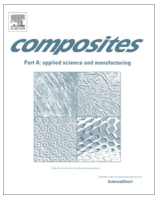
Composites: Part A 74 (2015) 1–9

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa



A displacement-detection based approach for process monitoring and processing window definition of resistance welding of thermoplastic composites

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ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form 24 February 2015
Accepted 2 March 2015
Available online 20 March 2015

Keywords:
A. Polymer-matrix composites (PMCs)
A. Thermoplastic resin
E. Joints/joining

ABSTRACT

The evolution of weld displacement, or the thickness of welding stack, with welding time during resistance welding of thermoplastic composites was characterised, and based on this the possibility of using displacement data for process monitoring and processing window definition was investigated. Resistance welding of glass fabric reinforced polyetherimide using a metal mesh as the heating element was studied, and weld displacement was detected using a laser sensor. The effect of welding parameters on the displacement curve was studied. Welding defects, such as voids and squeeze flow, could be detected by monitoring the weld displacement. Fast definition of the welding processing window was found to be possible using displacement curves, and the predicted processing window showed good agreement with the processing window determined from mechanical tests.

1. Introduction

Resistance welding, a technology to join two materials using resistive heating of a heating element placed at the interface, is a time and cost-effective joining method for thermoplastic composites [1–3]. The resistance welding process needs to be well controlled to get good welding quality, in particular for applications in the aircraft industry. The main process parameters in resistance welding are input power, heating time and welding pressure. The welding pressure, which needs to be applied throughout the welding process, promotes intimate contact between the welding surfaces and prevents de-consolidation of the adherends. The input power determines how fast the welding temperature can be reached at the welding interface and hence how steep the through-the-thickness temperature gradient is. For each input power level there is a range of heating times that lead to welded joints with a sufficient degree of consolidation in absence of thermal degradation [3,4]. Within the development of resistance-welded thermoplastic composite structures, processing windows, which establish the combinations of input power and heating time that provide acceptable welds for a certain welding pressure, must be defined.

Processing windows for resistance welding are usually defined through mechanical testing, e.g. measuring the strength of the joints welded over a series of heating times for different power levels and comparing the strength values so obtained with a threshold value [5–10]. The heating time that results in a higher weld strength than the threshold for each power level is regarded to be within the processing window. This method requires, however, a large number of tests, which are time consuming and costly. Research on process modelling of resistance welding of thermoplastic composites [11–16] has made it possible to define processing windows based on welding temperature and consolidation degree as simulated through a process model [14,16,17]. The accuracy of this method, deeply related to the quality of the data entered in the model, has nevertheless not yet been fully validated. In literature [14,16], the predicted processing windows have sometimes been found to be slightly larger than the processing window defined using mechanical tests, especially for welding at a low power input.

An alternative approach entails the definition of the right heating time through in-situ process monitoring in closed-loop resistance welding processes. Villegas proposes in [18] a method for process control of resistance welding based on indirect temperature feedback from monitoring the resistance of the heating element. Despite the straightforwardness of this method, different ways of characterizing the resistance versus temperature relationship of the heating element can lead to significant temperature

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http://dx.doi.org/10.1016/j.compositesa.2015.03.002
1359-835X/

deviations. Additionally, the resistance data cannot be directly linked to the quality of the welded joints. For this purpose, a relationship between welding temperature and joint quality has to be defined, for instance via mechanical testing.

Since the reduction of the weld line thickness and the lap shear strength of welded joints are related [5,7,19], monitoring the weld line thickness during welding could be another possible way for the definition of processing windows as well as for process monitoring. The thickness of the weld line is however difficult to measure during the welding process, but the vertical displacement of the whole welding stack (i.e. adherends and heating element), known as "weld displacement curve" or "melting curve" [7], can be more easily monitored [5,7]. During resistance welding the thickness of the welding stack is influenced by thermal expansion/contraction, weld consolidation/deconsolidation and resin squeeze flow. Extending the basic Duhamel-Newman relation [20], the strain of the welding stack, ε, can be expressed by:

$$\varepsilon = S\Delta\sigma + \alpha\Delta T \pm \beta\Delta X - \Delta\varepsilon_{consolidation} + \Delta\varepsilon_{deconsolidation} - \Delta\varepsilon_{flow} \qquad (1)$$

where σ is stress, T is temperature, X is the crystallinity of matrix (applicable to semi-crystalline polymers), S is the material compliance, α is thermal expansion, β is crystallization induced volume shrinkage, $\varepsilon_{consolidation}$ is consolidation-induced strain, mainly due to intimate contact, $\varepsilon_{deconsoliadtion}$ is deconsolidation-induced strain, including void generation, and ε_{flow} is strain related to thickness reduction caused by resin squeeze flow. Thermal expansion and contraction have been identified in the weld displacement curves [7]. Nevertheless, a deeper understanding of such curves and their relationship with the weld quality is still needed, especially for state-of-the-art resistance welding with a metal mesh heating element [5,21,22].

In this study, resistance welding displacement curves were analysed, and the possibilities of using displacement data for process monitoring and processing window definition were explored. Firstly, the relations between the physical phenomena occurring during the welding process and the weld displacement curve were investigated. Secondly, the influence of welding parameters, such as power input, time and welding pressure, as well as the quality of the composite adherends on the weld displacement curve was studied. Thirdly, a method was proposed to define adequate ranges of heating times for different power levels based on the weld displacement curve and validated through mechanical testing.

2. Experimental

2.1. Material and heating element

The material used for the welding experiments was made of 8 layers of 8HS satin woven glass fabric reinforced polyetherimide (GF/PEI), CETEX®from TenCate, The Netherlands, with a stacking sequence of $[(0/90)]_{4S}$. The GF/PEI laminates, with dimensions 580 mm × 580 mm, were consolidated in a hot platen press at a processing temperature of 320 °C and under a consolidation pressure of 2.0 MPa for 20 min. The resulting 1.8 mm-thick laminates were inspected using ultrasonic C-scan and cut into 192 mm × 100 mm adherends using a water-cooled diamond saw.

A plain woven stainless steel (AISI 304L) mesh with wire diameter of 0.04 mm and open gap of 0.09 mm was used as the heating element. Mesh strips of 250 mm × 13 mm were cut from a big sheet of mesh and used for the welding process. To provide a resin rich area at the welding interface, the meshes were impregnated with two layers of 60 μm thick PEI resin films in a hot platen press at a processing temperature of 300 °C and under a consolidation pressure of 0.3 MPa for 2 min, prior to the welding process. The impregnated meshes had a final thickness of approximately 0.08 mm.

2.2. Resistance welding

An in-house developed setup was used [23] for resistance welding of the adherends. A computer controlled power supply unit, Delta Elektronika, with a maximum DC output of 45 A and 70 V, was used to provide the welding energy. Two pneumatic systems were used to apply the welding pressure and clamping pressure individually. Two blocks of high-density fibre (HDF) wood were used as insulators placed below and above the welding assembly, and the welding pressure was applied on the top insulator. Two GF/PEI adherends were single-lap welded with an overlap length of around 15 mm, with 1 mm-wide gap left on both sides of the mesh at the welding overlap, as shown schematically in Fig. 1. The welding process was in all cases performed under a constant power input and a constant welding pressure.

During welding, vertical displacement was measured using a laser sensor, LK-G series from KEYENCE, U.S., with ±0.5 μm system error, which was vertically pointed to the top surface of the top insulator holder. The welding and displacement measurement setups are shown in Fig. 2. Three weld displacement curves were obtained for each set of welding conditions used in this research in order to check the repeatability of the measurements. Average weld displacement curves are shown in the Results section of this paper. It must be noted that the displacement reading provided by the laser sensor was a combination of thickness changes in the welding stack and in the insulation blocks during welding. The displacement of the welding stack alone could not be directly measured due to the fact that it was covered by the insulation blocks during the whole welding process. As shown and explained in the Results section of this paper, this approach consisting of measuring the combined displacement of the welding stack and the insulation blocks, was still able to provide sufficient insight into the physical transformations caused by the welding process in the welding stack, i.e. adherends and heating element. The resistance welding process was controlled by a Labview program, and all the parameters, such as current, voltage, temperature and displacement, were recorded during the welding process using a data acquisition system.

2.3. Testing methods

Single lap shear tests were performed on the resistance welded joints according to the ASTM D1002 standard to evaluate the welding quality. Six specimens with a width of 25.4 mm were cut from each welded assembly, and they were tested using a Zwick/Roell 250 KN testing machine with a constant crosshead speed of 1.3 mm/min. The tests were performed at room temperature (20 ± 3 °C) with a relative humidity of 50 ± 5%. The apparent lap shear strength (LSS) of each specimen was calculated by dividing the maximum load by the overlap area of the joints, where the overlap area was calculated using the width of the specimen and the width of the heating element (13 mm). The results for all six specimens were used to calculate an average lap shear strength and corresponding standard deviation for the corresponding set of welding conditions used to produce each welded assembly. Cross-sections of the welded specimens were examined using optical microscopy.

In some of the experiments performed, the welding temperature was measured at the welding interface using 0.1 mm-diameter K-type thermocouples. The head of the thermocouples was insulated with Kapton®, polyimide tapes, DuPont™, to prevent any electrical contact during welding. Owing to the non-uniform temperature distribution along and across the weld line, which is