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On avoiding thermal degradation during welding of high-performance thermoplastic composites to thermoset composites

Irene Fernandez Villegas *, Pablo Vizcaino Rubio

Structural Integrity and Composites, Delft University of Technology, Kluyverweg 1, 2629HS Delft, The Netherlands

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ABSTRACT

One of the major constraints in welding thermoplastic and thermoset composites is thermal degradation of the thermoset resin under the high temperatures required to achieve fusion bonding of the thermoplastic resin. This paper presents a procedure to successfully prevent thermal degradation of the thermoset resin during high-temperature welding of thermoplastic to thermoset composites. The procedure is based on reducing the heating time to fractions of a second during the welding process. In order to achieve such short heating times, which are much too short for commercial welding techniques such as resistance or induction welding, ultrasonic welding is used in this work. A particularly challenging scenario is analysed by considering welding of carbon-fibre reinforced poly-ether-ether-ketone, with a melting temperature of 340 °C, to carbon-fibre reinforced epoxy with a glass transition temperature of 157 °C.

1. Introduction

Thermoplastic composites (TPC) are very attractive to several industries as a result of their cost-effective manufacturing and cost-effective assembling through welding. One of the most cost-effective manufacturing techniques applied to thermoplastic composites is press forming. Flat pre-consolidated thermoplastic composite laminates can be press formed into near to net-shape parts in several minutes [1]. In the aerospace industry, press forming is widely used for the manufacturing of small, e.g. clips or cleats used as structural connecting elements in the fuselage, to medium-sized, e.g. ribs or stiffeners, thermoplastic composite parts. An example of this are the several thousands of thermoplastic composite clips used for the fuselages of the new composite passenger aircrafts, Airbus A350 and Boeing 787 [2]. The manufacturing of bigger components such as fuselage or wing sections or panels relies, however, on the use of, more traditional, thermoset composites (TSC), which currently show cost advantages as compared to thermoplastic composites. The usage of both thermoplastic and thermoset composites for optimal manufacturing of different parts in the aircraft requires assembling of dissimilar TPC/TSC structures, which nowadays is solved through mechanical fastening [2]. However, the ability of thermoplastic composites to be welded with little surface preparation and short assembling times, makes it interesting to investigate whether thermoplastic and thermoset composites can be welded together using current welding techniques for thermoplastic composites. Reliable thermoplastic to thermoset composite welding processes could be expected to offer a significant reduction in assembly times, assembly costs and weight reduction as compared to mechanical fastening.

The two main challenges in welding of TPC/TSC structures are, firstly, adhesion between the thermoplastic and thermoset composites and, secondly, thermal degradation of the thermoset composite when subjected to the relatively high temperatures generated during the welding process. Regarding the adhesion between thermoset and thermoplastic composites, researchers seem to agree on the necessity of coating the thermoset composite with a thermoplastic-rich layer through a co-curing process in order to achieve sufficient adhesion between the thermoset and the thermoplastic polymer prior to the welding process [3–8]. The thermoplastic-coated thermoset composite parts are then either welded together or welded to thermoplastic composite parts by locally melting the thermoplastic/thermoplastic interface. Adhesion between the thermoset composite and the thermoplastic-rich coating layer can be based on micro- and/or macro-mechanical interlocking. Micro-mechanical interlocking entails the migration of thermoset pre-polymer molecules into the thermoplastic to create a semi-interpenetrating network. Semi-interpenetrating networks have been successfully created between compatible thermosetting and amorphous thermoplastic

* Corresponding author. Tel.: +31 152789745; fax: +31 152781151.
E-mail address: I.FernandezVillegas@tudelft.nl (I.F. Villegas).

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polymers, such as epoxy with polysulfone (PS) or polyethersulfone (PES), and bismaleimide (BMI) with PS, PES or polyetherimide (PEI) [4]. In these cases, the amorphous nature of the thermoplastic polymers and, therefore, their low resistance to solvents allow the uncured components of the thermoset component to migrate through the interface. Moreover, Hou et al. state in [5] that there are combinations of semi-crystalline thermoplastics and thermosets with matching solubilities, such as polyvinylidene fluoride (PVDF) and epoxy, which can as well create semi-interpenetrating networks. Macro-mechanical interlocking can be created through the co-curing of a composite hybrid layer partially impregnated with thermoplastic resin onto the thermoset composite laminate, as proposed by Jacaruso et al. in [6].

Regarding thermal degradation of the thermoset composite during the welding process, a possible solution entails the selection of a thermoplastic/thermoset combination such that the welding temperature is lower or similar to the glass transition temperature of the thermoset resin. Such is the case of PVDF to epoxy welding. PVDF has a melting temperature of 170 °C and therefore, it allows the welding process to be performed at a temperature that does not cause severe overheating of epoxy composites cured either at 177 °C or 127 °C [5,7]. This method, however, greatly limits the nature of thermoplastic composites that can be welded to thermoset composites.

An option to avoid degradation in high-temperature welding of thermoplastic and thermoset composites is reducing the temperature the thermoset resin is exposed to during the welding process. Van Toren proposes in a patent application [8] two approaches to ensure that a thermoset composite coated with a thermoplastic-rich layer does not reach its maximum operating temperature during welding. One of the approaches proposed is based on the usage of heat sinks either within the thermoplastic coating or externally applied to it. The other approach relies on, as quoted from Ref. [8], "the thermoplastic coating having a heat capacity per unit length larger than the heat applied to the assembly per unit length". From the perspective of the authors of the present paper, this last approach would entail increasing the heat capacity of the thermoplastic coating layer, by either modifying its nature, and/or by increasing its thickness. Preferred welding processes proposed in this patent application are induction, resistance and laser welding. No experimental results to support these approaches to prevent degradation are, however, presented in this document. Ageorges and Ye also showed in Ref. [9] that, by using a glass-fibre reinforced hybrid coating layer co-cured with the thermoset composite adherend, resistance welds between carbon fibre CF/PEI and CF/epoxy (+hybrid coating layer) composites with lap shear strength levels between 20 and 25 MPa could be obtained. Even though thermal degradation of the epoxy resin was not experimentally assessed in that paper, the strength levels obtained, considered as acceptable by the authors, might indicate however that no significant degradation took place. From our viewpoint, the usage of glass, and hence thermally insulating, fibres in the thermoplastic coating of the CF/epoxy adherends contributed to shielding the epoxy resin from the relatively high temperatures developed during welding. However, this method introduces a foreign material at the welding interface that typically has a lower strength to failure than the adherends themselves.

Our alternative approach to preventing degradation during high-temperature welding of thermoplastic and thermoset composites is primarily based on significantly reducing the heating time during the welding process. Several welding techniques applicable to thermoplastic composites are known to be capable of very short heating times, between a few tenths of a second and a few seconds, such as ultrasonic, laser or microwave welding, as opposed to other, more mature, welding techniques such as induction or resistance welding with heating times in the order of minutes [10]. Very short heating times during the welding process result in: (a) a very short time for heat to be transferred through the thermoplastic coating layer used to generate adhesion with the thermoset composite adherend, which will decrease the temperature at which the thermoset composite adherend is exposed to; and (b) a very short time for degradation mechanisms to occur in the thermoset composite adherend, which if short enough, could potentially hinder the occurrence of any degradation [11]. An approximate quantification of the influence of heating time on the temperature beneath the thermoplastic coating layer, and thus on the surface of the CF/epoxy adherend closest to the welding interface, can be obtained through the one-dimensional heat transfer model proposed by Holmes and Gillespie in Ref. [12] for resistance welding of carbon-fibre (CF) reinforced polyether-ether ketone (PEEK) composites. The model considers that a neat PEEK layer is placed between the heating element and the thermoplastic substrates (for the original resistance welding process considered by the authors), which makes it suitable for an approximate analysis of temperatures developed during welding of adherends with thermoplastic coating layers. Resulting from this model, Fig. 1 shows that, for heating times under 1 s, temperatures below 200 °C can be obtained beneath the PEEK coating layer when the temperature at the welding interface is 400 °C. A similar temperature reduction is achieved by increasing the thickness of the thermoplastic coating layer above 2 mm in a typical resistance welding process with 90 kW/m^2 input power at the welding interface (Fig. 2). However, for thin-walled aircraft structures a 2 mm-thick coating can be expected to severely weaken the joint through high secondary bending moments. Alternatively, fast welding processes with heating times below 1 s can offer a feasible alternative to prevent degradation while maintaining coating thicknesses of at least one order of magnitude lower than the thickness of the adherends. It must be noted, however, that the graphs shown in Figs. 1 and 2 are based on the material properties for CF/PEEK and PEEK provided in Ref. [12] and, therefore, they just offer an approximate result for thermoplastic to thermoset welding.

This paper presents the results of a fully experimental study focused on prevention of thermal degradation during welding of CF/PEEK to CF/epoxy composites through very short heating times. Very short heating times are achieved in this study through the use of ultrasonic welding, which is widely acknowledged as one of the most appropriate welding processes for thermoplastic composites [3] and it is capable of heating times well below 1 s [13] Two sets of welding parameters with significantly different average heating times, namely 460 and 830 ms, were used in order to assess the effect of heating time on degradation during ultrasonic welding

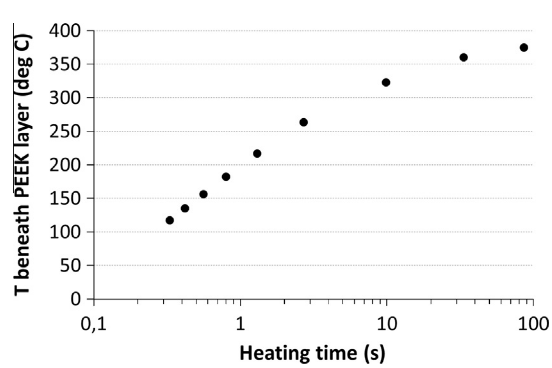

Fig. 1. Temperature beneath a 0.25 mm-thick PEEK coating layer (applied on a CF/PEEK adherend) for different heating times (i.e. different heat inputs) when the temperature at the welding interface is 400 °C (based on Holmes & Gillespie 1D heat transfer model [12]).