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Influence of temperature on the strength of resistance welded glass fibre reinforced PPS joints

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ABSTRACT

In this work, the effect of temperature exposure on the strength of resistance welded joints is analysed. Glass fibre reinforced polyphenylene sulphide (GF/PPS) adherends were joined using the resistance welding technique, using a stainless steel mesh as the heating element. Single lap shear tests were performed at temperatures ranging between −50 °C and 150 °C to evaluate the strength of the welded joints. The results showed that the lap shear strength decreased with increasing temperature, except for the region between 50 °C and 90 °C where it remained constant. Fractography analysis revealed that the main failure mechanism was glass fibre/matrix debonding and the connection between the mesh and the matrix was not the weakest link at the interface of the joint at any temperatures under study. The fibre/matrix interfacial strength and the stress distribution at the joint overlap were identified as the main factors influencing the behaviour of lap shear strength with temperature.

1. Introduction

Over the last years, high performance thermoplastics, notably polyetheretherketone (PEEK), polyetherketoneketone (PEKK), polyphenylene sulphide (PPS) and polyetherimide (PEI), have gained significant ground in the aerospace industry [1] due to advantageous qualities like their superior damage tolerance, excellent chemical resistance, infinite shelf-life, recyclability, and ability to be welded [2,3]. Aircraft structures are large and complex and cannot be manufactured in a single step, therefore, joining techniques are utilised in order to connect different parts together. Hence, joining of polymer composites is of significant importance for the aerospace industry due to the need of reliable, automated and cost-efficient joining methods.

Mechanical fastening is currently the primary joining method used in the aerospace industry, as it possesses several advantages such as process simplicity, through-the-thickness reinforcement and capability for disassembly. In spite of its attractive characteristics, mechanical fastening introduces several problems into a composite structure. In particular, the performance of a joint can be diminished by stress concentrations, delaminations due to hole drilling, additional weight, extensive labour, and coefficient thermal expansion (CTE) mismatch between the composite structure and the fastener [4]. Adhesive bonding minimises stress concentrations, allows for dissimilar materials to be joined and exhibits superior fatigue resistance [5]. However, adhesive bonding has considerable disadvantages as well, such as the need for extensive surface preparation, sensitivity to contamination (e.g. machining oils), limited storage life of uncured adhesives, and long curing times [5–7]. Fusion bonding (welding) has been considered as an effective alternative technique for the joining of thermoplastic composites, since it brings several advantages compared to the traditional techniques that can minimise most of these problems. In summary, the principal advantages of welding are the minimised stress concentration, the minimised labour, the very short cycle times and the minimal surface preparation of the substrates [7,8].

Amongst the various welding techniques, resistance welding is considered as a promising joining technique for thermoplastic composites, which can consistently produce high quality joints with short cycle times, and it has already been successfully used in secondary aircraft structures [1]. Resistance welding is based on Joule heating, which is caused by the circulation of electrical current through a resistive element. Heat dissipation in the resistive element results in polymer melting at the welding interface which allows intimate contact and interdiffusion of polymer chains to take place between the two adherends [7]. The work presented in literature about resistance welding of thermoplastic composites is primarily concerned with the optimisation of the processing parameters, the effect of the heating element and the characterisation of

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joint strength and failure modes at room temperature. Hou et al. found that the type of the heating element affected the temperature distribution at the weldline as well as the joint strength [9], while Dubé et al. investigated the influence of the metal mesh geometry; they found that the wire diameter as well as the open gap width had an important effect on the weld quality [10]. Welding time, welding pressure, and power density have been identified as the main factors which govern the welding process and, consequently, the weld quality [11–14]. Moreover, the failure modes of resistance welded joints have been classified by several authors, with intralaminar failure being the predominant mode for high quality joints [7,11,14].

However, aircraft operate in a wide range of temperatures and can be subjected to extreme conditions. For a transport aircraft, the minimum service temperature is considered −54 °C and the maximum temperature, 71 °C [15]. However, it is also mentioned that due to operation some components are subjected to temperatures as high as 93 °C [15]. Taking this temperature range into consideration, it becomes clear that more knowledge should be gained regarding the exposure of resistance welded thermoplastic composites joints to various temperatures.

In literature, there are extensive studies dealing with the effect of temperature on adhesive joints. The strength of adhesively bonded fibre reinforced polymer double lap joints has been reported to decrease with increasing temperature, while the failure mode at high temperatures changed from adherend failure to adhesive failure [16,17]. Adams et al. studied the exposure of adhesive single lap joints to a wide range of temperatures (−60 °C, 200 °C) and found that the joint strength decreased at low and high temperatures because the adhesive became brittle and soft respectively [18]. Da Silva and Adams studied the effect of temperature on titanium/composite double lap joints and found that the failure of the joints at −55 °C and 22 °C occurred through the thickness of the composite [19]. The same authors investigated the mixed modulus concept of low temperature and high temperature adhesives and suggested that for dissimilar adherend double lap joints, the use of a high modulus adhesive and a low modulus adhesive improved the performance compared to the high modulus adhesive alone [20].

Although as briefly outlined before much research is described in literature about the influence of temperature on bonded joints in fibre reinforced polymers, to the authors' knowledge there are no studies currently available on the influence of temperature on resistance welded polymer composite joints. Despite obvious similarities between bonded joints and welded joints (i.e. joint architecture, continuous joint nature, polymer-rich joint interface), they hold several fundamental differences which may cause different temperature-dependent mechanical performances. These fundamental differences concern the joining mechanisms, i.e. adhesive forces versus molecular inter-diffusion, and the architecture and nature of the joint interface, i.e. dissimilar polymer versus matrix polymer with embedded metal mesh. Likewise, available knowledge on the effect of temperature on the behaviour of fibre reinforced composites is not directly applicable to resistance welded joints owing to the complexity of the weld interface. In particular, the effect of varying temperature could be detrimental to the strength of the welded joints by virtue of the nature of the bond between the metal mesh and the polymer matrix at the weld interface. Resistance welded joints feature a rather complex resin-rich welding interface with an embedded resistive heating element, generally a metal mesh. It is known that the mechanism dictating the bond between metals and polymers is mechanical interlocking [5] [21]. During the welding process, the polymer matrix wets and penetrates the irregularities of the metal surface and the mesh open gaps, locking itself mechanically to the metal wires. This mechanism is promoted by the residual thermal stresses that are formed during the cooling process. As the thermoplastic cools down from its melt, it shrinks and contracts more than the metal due to their CTE mismatch, thereby, resulting in compressive stresses on the metal wire. Consequently, at room temperature the polymer matrix and the metal mesh form a strong connection, as was demonstrated in a previous study where the main failure at room temperature, in GF/PEI and GF/PPS resistance welded joints, was found to be glass fibre/matrix debonding [11]. However, when the joints are subjected to higher temperatures, the opposite effect will occur. In particular, at high temperatures the compressive stresses will be lowered due to the higher thermal expansion of the polymer over the metal wires, resulting in a diminished mechanical interlocking, which could have a detrimental effect on the joint strength. Therefore, even if the stainless steel mesh does not have a negative impact on the mechanical performance of resistance welded joints at room temperature conditions, it could still be the primary reason for joint failure at high temperatures.

Hence, two key questions arise which require further investigation in order to develop a comprehensive understanding of the behaviour of resistance welded thermoplastic composite joints at different temperatures.

- Is the connection between the metal mesh and the thermoplastic matrix the weakest link at the welding interface when the joints are subjected to elevated temperatures?
- How is the weld strength affected by temperature?

To fill this gap, this paper analyses the strength and failure mechanisms of resistance welded glass fibre reinforced PPS joints tested at a wide range of temperatures using a fully experimental approach. The major objective of this study is to evaluate in detail the relationships between the joint strength and the constituents of the joint, namely the fibres, the thermoplastic matrix and the metal mesh, under the influence of temperature.

2. Experimental procedure

2.1. Laminate manufacturing

The material used in this study was Cetex® woven (eight harness satin) glass fibre reinforced polyphenylene sulphide composite (GF/PPS) supplied by Ten Cate Advanced Composites, The Netherlands. Laminates measuring 580 mm × 580 mm were built from semi-impregnated GF/PPS layers with a stacking sequence of [(0°/90°)4]s. The laminates were consolidated using a hot platen press at 320 °C and 1 MPa pressure for 20 min. The cooling rate of the press plates was consistently set at 15 °C/min for all the laminates manufactured in this study. The stainless steel moulds used in the press consolidation process were first cleaned with acetone, then degreased with PFQD degreasing agent (Socomore) and finally coated with Marbocote 227CEE release agent. The final thickness of the consolidated laminates was 1.9 mm. Welding adherends and test specimens were cut from the consolidated laminates using a water-cooled diamond blade.

2.2. Resistance welding

The in-house developed resistance welding setup shown in Fig. 1 was used in this work. The main elements in this setup are: (a) DC power supply unit with a maximum power output of 45A/70 V (Delta Electronika, The Netherlands), (b) pneumatic cylinder to provide both the welding pressure and the clamping pressure, (c) copper connectors, (d) thermal insulation blocks made out of ceramic blocks, (e) computer equipped with dedicated LabView software for welding process control, (f) data acquisition system (DAQ). A plain woven stainless steel (AISI 304L) mesh with