INFLUENCE OF TEMPERATURE ON STRENGTH AND FAILURE MECHANISMS OF RESISTANCE WELDED THERMOPLASTIC COMPOSITES 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 polyphenylene sulphide (GF/PPS) laminates were joined using the resistance welding technique and a stainless steel metal mesh as the heating element. Single lap shear tests at temperatures between 20°C and 150°C were performed to evaluate the strength of the welded joints and fractography was used to investigate changes in the failure mechanisms at elevated temperatures. The results show a strength reduction of 10-15% for the samples tested at temperatures up to 90°C, and a strength reduction of 22% and 38% for the samples tested at 120°C and 150°C, respectively, while the fracture surfaces observation revealed changes in the failure mechanisms of the welded joints tested at elevated temperatures.

INTRODUCTION

Joining of polymer composites is of significant importance for the aerospace industry due to the need for large and complex structures that cannot be manufactured in a single step. Many parts such as wings, spars, ribs and stiffeners have to be joined together in order to manufacture a complete airplane structure, requiring reliable, automated and cost-efficient joining methods. Mechanical fastening is the most widely used joining technique in aerospace industry, especially for primary structures, while the other traditional technique, adhesive bonding, is an established choice as well, although it faces certification issues concerning its use on primary aircraft structures [1]. Fusion bonding (welding) is considered as an interesting alternative technique for the joining of thermoplastic composites since it brings several advantages compared to the traditional techniques. Mechanical fastening introduces several problems such as stress concentration, delamination, additional weight, extensive labour, and coefficient thermal expansion (CTE) mismatch between the composite structure and the fastener, problems which can all be eliminated or minimised by using a welding technique. Adhesive bonding requires thorough surface preparation, is sensitive to contamination (e.g. machining oils) and storage, and curing is usually long [2-4]. In summary the advantageous qualities of welding are [3,4]:

- Minimised stress concentration
- Minimised labour
- Very short cycle times
- No extensive surface preparation

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. The principle of resistance welding is based on Joule heating, which is caused by the circulation of electrical current through a heating element. Heat dissipation results in polymer melting at the welding interface which allows the interdiffusion of polymer chains to take place across the two adherends [4].

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 the joint strength at room temperature. The effect of temperature on adhesive composite joints has been investigated by several researchers. Keller et al. studied the effect of temperature on adhesively-bonded glass fibre reinforced polymer double-lap joints and found that at temperatures higher than the Tg, the strength and the stiffness of the joints decreased, and the failure mode changed from fibre tearing to adhesive failure [5]. Ashcroft et al, investigated the effect of temperature on quasi-static strength and fatigue resistance of carbon fibre reinforced epoxy double-lap joints and suggested that the failure mode changed from failure in the composite adherend to failure in the adhesive [6]. However, very little work is presented in literature on the performance of resistance welded composite joints, and welded composite joints in general, under varying temperatures. Such knowledge is crucial for the aerospace industry since aircraft structures are exposed to various temperatures. Resistance welded joints feature a rather complex resin-rich welding interface with an embedded resistive heating element, generally a metal mesh. At room temperature the polymer matrix and the metal mesh form a strong connection due to mechanical interlocking due to their CTE mismatch. This results in intralaminar failure as the main failure mode in resistance welded joints [7]. However, the effect of temperature in this phenomenon is currently not well known. To fill this gap, this paper analyses the strength and failure modes of resistance welded joints tested at different temperatures using a fully experimental approach.

EXPERIMENTAL PROCEDURE

Materials & consolidation process

The material used in this study was a Cetex® 8 harness satin weave glass fabric reinforced polyphenylene sulphide composite (GF/PPS) supplied by Ten Cate Advanced Composites, The Netherlands. Laminates of 580mm x 580mm dimensions were built with a stacking sequence of $[(0°/90°)_4]_s$, using a Rinco ultrasonic spot welder to stack the eight layers of GF/PPS together. The stainless steel moulds were cleaned with acetone and a degreasing agent (PFQD), and coated with a Marbocote 227CEE release agent. Consolidation of the laminates was achieved by using a hot platen press, and thermal insulation plates were used in order to ensure temperature homogeneity over the laminates. The process was controlled via a LabView programme, having the following processing parameters:

Processing Temperature	320°C
Consolidation Pressure	1.0 MPa
Consolidation Time	20 min
Cooling Rate	15 °C/min
Thickness	1.9 mm

Table 1 Consolidation parameters.

Heating element

A stainless steel (AISI 304L) mesh was used as the heating element. In a previous study it was shown that the use of a M200 metal mesh (0.04mm wire diameter, 0.09 open gap width) resulted in resistance welded joints of excellent properties, therefore, it was chosen for this study [8]. The width of the heating element was 13mm and the length was 300mm in order to contact the copper connectors of the set-up. In addition, a neat amorphous PPS film of 90 μm thickness was placed between the M200 metal mesh and the top adherend in order to fill the open areas of the mesh and to provide a resin rich area between the heating element and the GF/PPS adherends.

Resistance Welding

An in-house developed resistance welding set-up was employed in this work (Fig. 1). The welding energy was provided via a computer-controlled power supply unit (Delta Elektronika) and the pressure was applied via a pneumatic cylinder. Composite panels with dimensions of 171mm x 102mm were welded in a single lap configuration with an overlap length of 13mm. The adherends and the heating element were cleaned with a degreasing agent (PFQD) prior to welding. The welding parameters are presented in Table 2.

Constant Power Input	80kW/m^2
Welding Pressure	0.8MPa
Heating Time	55s

Table 2 Resistance welding parameters.

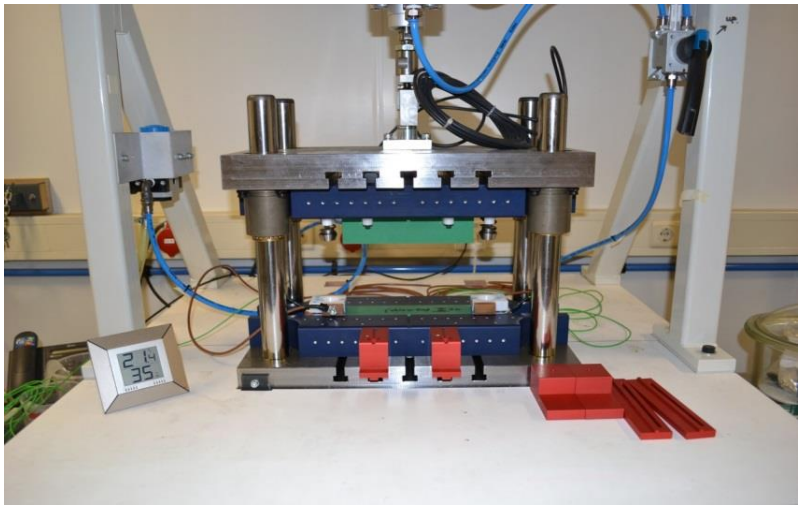


Figure 1 Resistance Welding Set-Up.

Testing

For each welded panel, five single lap shear specimens (188mm x 25.4mm) were cut using a water cooled diamond saw. A 250kN Zwick/Roell tensile machine was employed for performing the single lap shear (SLS) tests according the ASTM D1002 standard and a Zwick temperature chamber was used for performing the tests at elevated temperatures. The apparent lap shear strength (LSS) of the resistance welded joints was calculated as the maximum load divided by the total overlap area. All tests were performed at a constant crosshead speed of 1.3mm/min and all specimens were conditioned

at the test temperature for 30 minutes prior to testing. Table 3 provides the welded panels ID (name and testing temperature) which are used in this paper.

Welded panel ID (RWxx)	Testing temperature (°C)
RW20	20
RW50	50
RW70	70
RW90	90
RW120	120
RW150	150

Table 3 Specimen information.

A Zeiss stereo microscope (stereo Discovery.V8) was employed in order to study the morphology of the fracture surfaces.

RESULTS & DISCUSSION

Results

The purpose of this experimental work was to evaluate the influence of temperature on the strength and failure mechanisms of resistance welded joints. Consequently, several series of GF/PPS resistance welded samples were prepared and tested at elevated temperatures. Figure 2 illustrates the effect of temperature exposure on joint strength. At temperatures higher than room temperature the LSS showed an overall decreasing trend. The weld strength experienced a 12% drop from 20°C to 50°C, but then it was found to remain constant up to 90°C. A more significant drop in the strength was, however, found at 120°C and 150°C, amounting to 22% and 38% of RW20 strength, respectively.

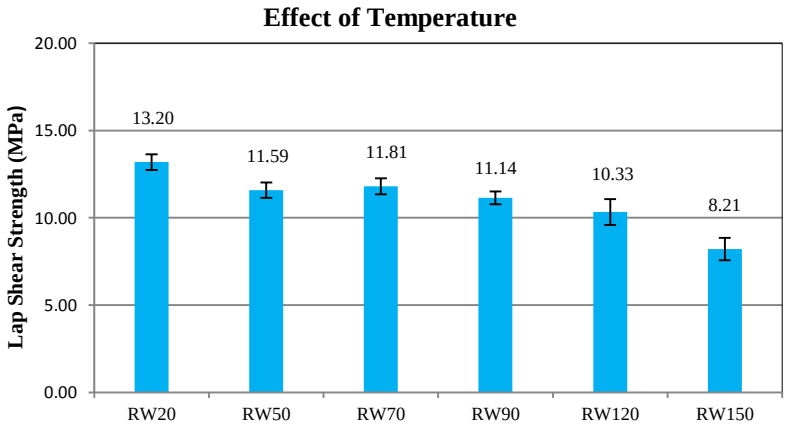


Figure 2 Illustration of joint strength in relation with testing temperature.

Investigation of the fracture surfaces revealed changes in the failure mechanisms of the samples tested at temperatures higher than 50°C. RW20 and RW50 (Fig. 3) showed intralaminar failure as the dominant failure mode, accompanied with some small areas of cohesive failure around where mesh tearing occurred, similarly to what has been previously reported [7]. The failure is considered as cohesive when it occurs within the weld line, consisting of mesh-resin debonding and resin rupture

[7]. In addition, as also illustrated in Figure 3, cracks initiate at both ends of the overlap and progress at similar speed towards the middle of the overlap, where they meet causing mesh tear (Fig. 4).

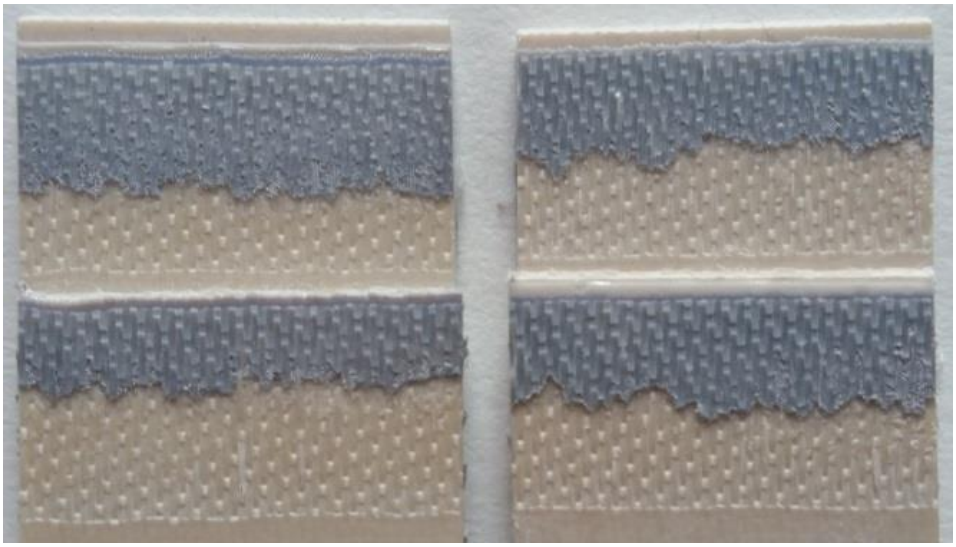
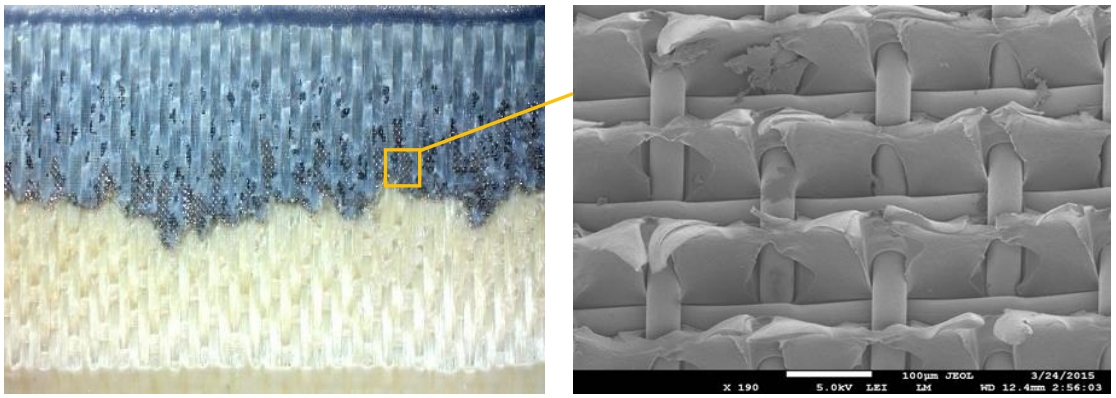


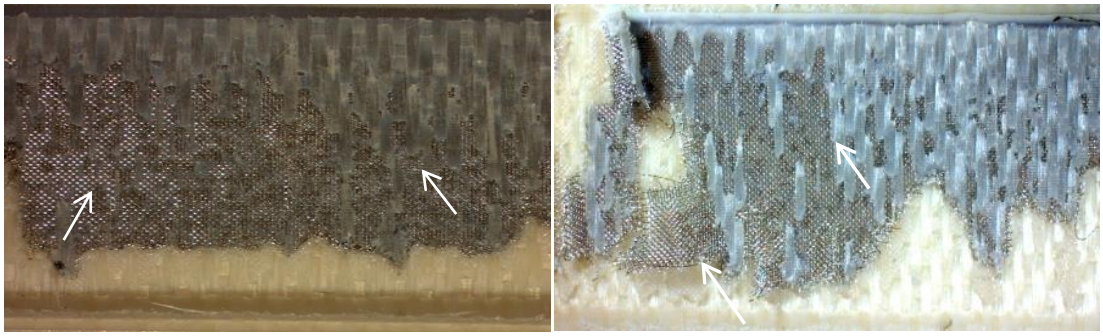
Figure 3 Typical failure modes of samples tested at 20°C (left) and 50°C (right).



(a) (b)

Figure 4 (a) Close-up of a 20°C sample fracture surface: the cohesive failure area is located in the surroundings of the middle of the overlap (highlighted areas), (b) Mesh is still impregnated by PPS, but during testing the resin ruptured, and debonded from the mesh, exposing some areas of the metal mesh (micrographs obtained using a JEOL JSM-840 scanning electron microscope)

The failure mode seemed to change at 70°C, since crack growth was found to mostly occur at one of the sides of the weld line (either above or below the mesh) and the cohesive failure areas were not purely located around the areas where the mesh was torn, as it is depicted in Figure 5. For samples tested at 90°C, 120°C and 150°C the crack grew predominantly or entirely on one side of the weld line (Fig. 6). A schematic representation of this phenomenon is illustrated in Figure 7.



(a) (b)

Figure 5 Fracture surfaces of RW70 samples (a) and RW120 samples (b). At higher temperatures the locations of the cohesive failure areas were not localised where mesh tearing occurred, but scattered around the weld line.

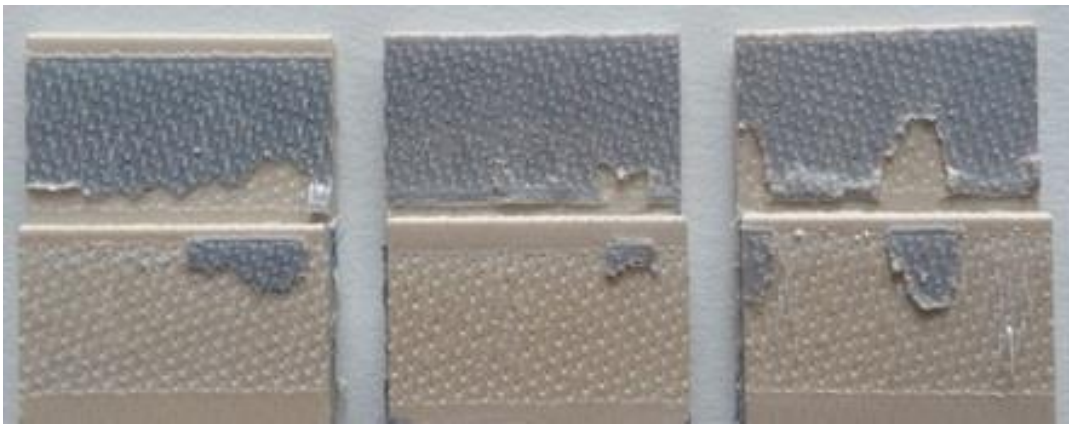


Figure 6 Fracture surfaces of RW90 (left), RW120 (centre) and RW150 (right) samples. The cracks grew predominantly on one side of the overlap, as opposed to the two-sided crack growth of RW20 and RW50 samples.

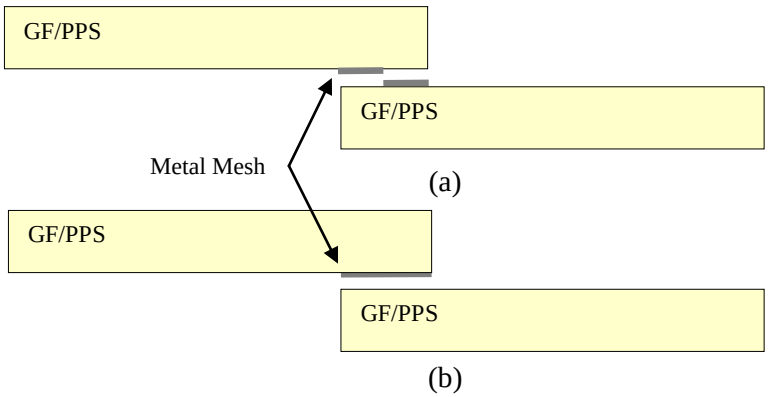


Figure 7 Schematic representation of failure (a) at both sides of the weld line, and (b) at one side of the weld line only.

Discussion

One plausible explanation for the lower LSS and the change in failure modes at elevated temperatures, is the behaviour of the polymer near and above the glass transition region. For measuring the glass transition temperature and determining the storage modulus of the polymer a Dynamic Mechanical Analyser (Pyris Diamond DMA, Perkin Elmer) was used. The relation of modulus with temperature is illustrated in figure 8, in which an abrupt drop of the storage modulus is noted around 95°C, and the glass transition temperature is measured at 103.8°C (from the loss modulus peak). Considering that the glass transition temperature is higher than 90°C, the polymer structure of samples tested at 20, 50, 70 and 90°C could be expected to remain unaffected at these temperatures, However, the LSS has a 12% drop from 20 to 50°C, which is, therefore, not related to changes in the stiffness of the adherends. Furthermore, at 100°C, PPS enters the rubbery state, and eventually reaches the rubbery plateau at temperatures above 140°C. Accordingly, RW120 and 150 show a 22% and 38% reduction in their LSS values, respectively. This LSS drop could be an outcome of the marked resin softening in that temperature region, which could be inducing higher bending deformation of the single lap shear samples and, thus, higher peel stresses at the edges of the overlap.

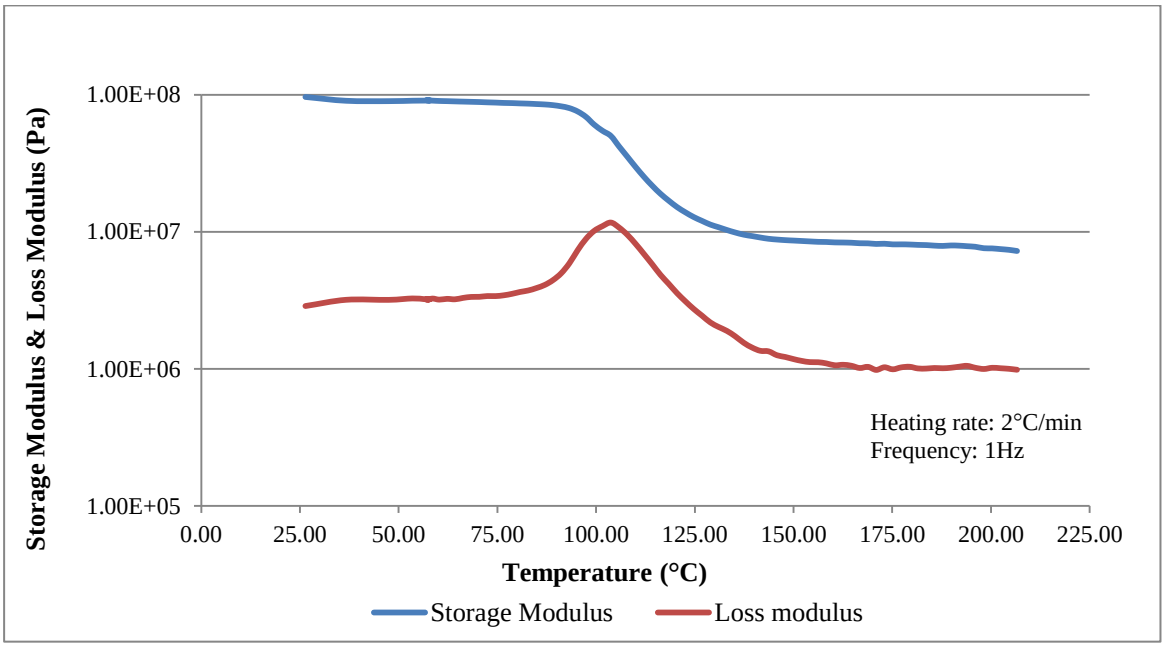


Figure 8 Dynamic Mechanical Analysis of PPS. The loading mode was 3-point bending, the span length 40mm and the dimensions of the sample were 48mm x 15mm x 2mm.

Due to the mismatch between the coefficients of thermal expansion (CTE) of the polymer matrix and the metal mesh, high temperatures are expected to influence the performance of the welded joints. Prior to the analysis of the fracture surfaces, a brief description of the mechanism of the connection between the polymer matrix and the metal mesh is given. The connection between thermoplastics and metals is a physical bonding type, at which a combination of mechanical interlocking and surface adsorption occur [9,10], the former being the primary mechanism of physical bonding. Mechanical interlocking involves the entanglement of polymer chains around the features of the metal surface (i.e. pores) [9,10], and, in the case of resistance welding, around the wires of the metal mesh. This phenomenon is believed to be enhanced by the mismatch between the coefficients of thermal expansion (CTE) of polymers and metals. During the final stage of resistance welding (cooling stage),

the polymer cools down from the melt, and eventually consolidates. The mismatch between the CTEs will cause the polymer matrix to contract more than the metal mesh (the CTE of PPS is approximately three times higher than the CTE of stainless steel at room temperature [REF 11] resulting in the matrix to compress around the wires of the metal mesh.

Table 4 presents the CTE values of PPS at certain temperature intervals and Figure 9 illustrates the temperature dependence of PPS. It can be seen that around 90°C the thermal expansion of the polymer changes, as it approaches the glass transition temperature. At room temperature conditions the connection is strong, however, with increasing temperature the polymer matrix will expand more than the metal mesh which might relieve the compressive forces "squeezing" the metal wires at room temperature, and, eventually weaken mechanical interlocking.

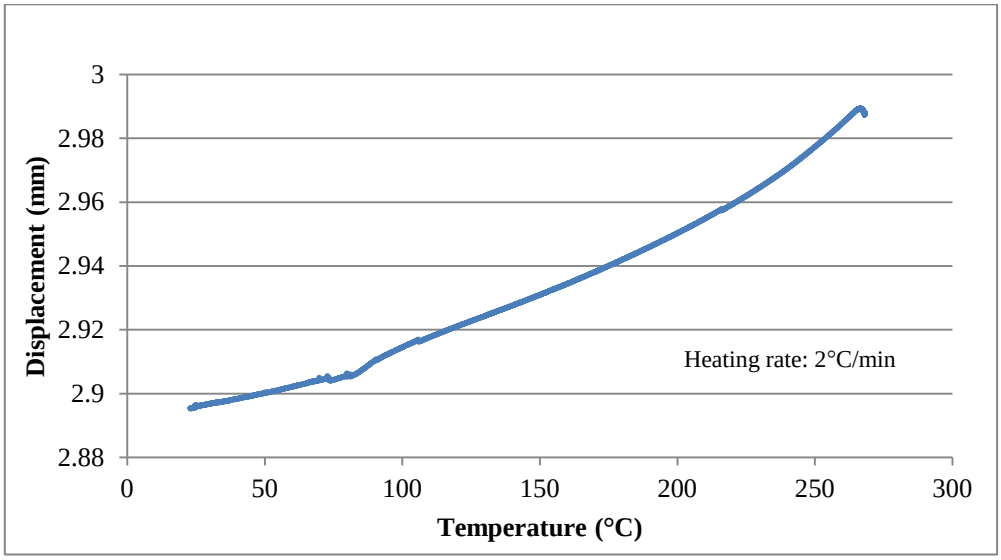


Figure 9 Thermal expansion of PPS. The measurements were performed using a Pyris Diamond TMA (Perkin Elmer).

	30°C – 60°C	**85°C – 150°C**	**150°C – 220°C**
α ($°C^{-1}$) *10^{-6}	63.53	121.85	143.74

Table 4 Temperature dependence of PPS thermal expansion coefficient.

The fracture surfaces of RW20 and RW50 specimens have similar features (mesh tearing at the middle of the overlap, accompanied with small cohesive failure areas) but for higher temperatures the failure mechanism changes. In the first place, the extended cohesive failure areas of RW70 and RW120 in Figure 5 suggest that the difference in thermal expansion between metal mesh and matrix could have reduced the effectiveness of mechanical interlocking. Figure 5b also shows a part of metal mesh that has been detached from the matrix (is not attached to any of the adherends) which further suggest the influence of increasing CTE and increasing temperature on weakening of the mechanical interlocking.

Secondly, the crack growth occurred predominantly on one side of the weld line (Fig. 6), as opposed to the two-sided crack growth for RW20 and RW50 samples (Fig. 3), which cannot be explained in terms of increasing thermal expansion coefficient. Nevertheless, this behaviour was independent of the specimen griping position. For each separate weld, the crack grew always on the

same side of the weld line, regardless if the top or bottom welded adherend was clamped between the top grips or the bottom grips. Hence, the specimen griping position did not influence the failure mechanism of the joints. Moreover, the crack growth occurred consistently on the same side of the weld line but appeared to be independent of the adherend position during the welding process (crack could grow either on the top or the bottom welded adherend).

Similarly to the polymer/mesh connection, the fibre/matrix interface in thermoplastic composites relies on mechanical interlocking as well, which could be affected at high temperatures due to the CTE mismatch between the fibres and the matrix (CTE of matrix is approximately 10 times higher than the CTE of fibres). The fibre/matrix CTE mismatch could potentially lead to fibres being pulled-out at higher temperatures, however, observation of the fracture surfaces showed that fibre pull-out occurred for all samples, regardless of the testing temperature.

CONCLUSIONS

The objective of this investigation was to evaluate in detail the influence of temperature exposure on the strength and failure mechanisms of resistance welded GF/PPS joints. The main conclusions of this work are the following:

- Lap shear strength decreased by 12% at 50°C, but it was found to remain relatively constant up to 90°C. Further increase of temperature up to 150°C, resulted in a 38% drop in strength. This strength reduction coincides with the matrix stiffness reduction at temperatures higher than 90°C, indicating a possible effect of matrix softening on the joint strength.
- At 20°C and 50°C the failure mechanism is consistent, consisting of intralaminar failure, accompanied with some small cohesive failure areas around the middle of the overlap, where mesh tearing occurred, and the crack growth is equal on both sides of the weld line. From 90°C to 150°C the cracks tend to initiate and grow primarily on one side of the weld line only, and the phenomenon is, sometimes, accompanied with extensive cohesive failure areas as well.
- The CTE of PPS at temperatures higher than 85°C is almost twice as the CTE of PPS at room temperature, which could explain the larger cohesive failure at high temperatures.

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