De-welding of thermoplastic composites: next step in sustainable joints

C. de Vos, M. Obbink, S. Sterk, O. Erartsin
Netherlands Aerospace Centre, Marknesse, The Netherlands
M. de Jong, University of Twente, Enschede, The Netherlands, and
Netherlands Aerospace Centre, Marknesse, The Netherlands

Abstract:
"De-welding" of welded joints offer the prospect of repositioning the welded parts due to assembly errors, or removing a damaged part for repair or recycle; contributing to more sustainable manufacturing and assembly of aerospace components. In this study, feasibility of resistance heating for de-welding of thermoplastic composites is investigated at coupon level, along with the processing window required for de-welding. For coupon tests, multidirectional C/LM-PAEK adherends were co-consolidated in single lap shear (SLS) configuration with LM-PAEK or PEI based carbon fabric reinforced prepreg heating element and glass fabric reinforced insulators between them. In coupon de-welding tests, shear load was applied after the interfaces of the SLS coupons were heated to various de-welding temperatures. Coupon tests, and subsequently microscopic analysis, showed that thermoplastic composites can successfully be de-welded by resistance heating without introducing damage to adherends. Low de-welding forces were obtained above the melting and glass transition points of LM-PAEK and PEI based heating elements, respectively. PEI based heating element significantly reduced the temperature required for de-welding.

Keywords: De-welding, Disassembly, Resistance heating, Thermoplastic composite

Introduction

"De-welding" refers to the reverse of the "welding" process in which the bond between the welded parts is removed by first heating the interface, and subsequently applying de-welding forces. As welded thermoplastic joints are becoming more common, "de-welding" of the welded joints is also gaining an increasing interest in the aerospace industry. De-welding can be employed to reposition the welded parts due to assembly errors, or remove a damaged part for repair or recycle, contributing to more sustainable manufacturing and assembly of aerospace components. Within NextGen High-Tech E-mobility program, de-welding equipment is being developed as one of the main areas of focus is increasing circularity and recycling in the manufacturing of next generation aircraft parts.

In the de-welding or disassembly process, heat can be applied via various methods such as induction, microwave or resistance heating [1-3]. Both induction and microwave heating lead to the heating of carbon fibre-reinforced adherends, which make it hard to focus the heat to the interface. This can lead to the deconsolidation of the adherends, and edge effects in the case of induction heating, as observed by De Weert [2] who studied disassembly of co-consolidated and ultrasonically welded C/PEEK adherends by induction heating. On the other hand, when the interface is heated by resistance, heat is focused at the interface, although adherends are still exposed to heat due to the heat conduction. To the authors' knowledge, the only study on disassembly or de-welding employing resistance welding was focused on glass fibre-reinforced low performance thermoplastics. Hence, there is no study in literature that focuses on de-welding of high-performance thermoplastic composites by resistance heating.

In this study, we aim to investigate the feasibility of resistance heating for de-welding of C/LM-PAEK composites at coupon level and to determine the processing window for de-welding. A LM-PAEK-based heating element was used for reference tests and a PEI-based heating element was employed to investigate the influence of having an interlayer with low processing temperature on the de-welding temperatures and forces. De-welding tests were performed on co-consolidated specimens as co-consolidation is considered to represent "perfect weld" condition. SLS tests were performed after heating the interface to various de-welding temperatures. After de-welding tests, fractography was carried out to determine the fracture behaviour and post-de-welding state of the adherends. Results of the coupon tests will serve as an input for the design of the de-welding equipment within the NextGen High-Tech E-mobility program.

Experimental details

A single lap shear test formed the basis for the coupon de-welding tests, where the substrates were co-consolidated in the autoclave to represent a perfect weld. The ASTM D5868 norm was taken as a guideline, with the overlap region set at 25.4 x 25.4 mm. The substrates each consisted of 16 layers of unidirectional carbon/LM-PAEK tapes (Toray Cetex® TC1225 T700/LM-PAEK) arranged in a (45,90,-45,0)$_{2S}$ layup. Two interface configurations were tested: One with LM-PAEK and one with PEI matrix. A PEI interface was presumed to be better suited for de-welding due to the lower softening temperature. Co-consolidating PEI with PAEK type polymers is common practice and has been proven to result in high-quality bonds thanks to good miscibility between them [4,5]. The interface region consisted of a single layer of carbon fibre woven prepreg (TC1225-5HS-T300JB-281g/m^2; TC1000-5HS-FT300B-280g/m^2), which was used as a resistance element to heat the interface (see Fig. 1). Glass fibre reinforced woven prepreg (TC1225-4HS-EC5-105g/m^2; TC1000-4HS-EC9-220g/m^2) was used as an electrical and thermal insulator between the heating element and the adherends. As Toray does not offer a PEI matrix glass scrim, a thicker insulator layer had to be used. An added layer of resin film (LM-PAEK or PEI) was placed on either side of the interface to improve bonding between the substrate and insulator layer. All constituents were stacked in a single manufacturing step and autoclave consolidated (365 °C, 7 bar, 30 min dwell). Specimen length was 177.8 mm for LM-PAEK and increased to 254 mm for PEI in order to easier accommodate the copper clamps for current introduction. Attenuation C-scanning was used to confirm that no voids were present in the interface. Alignment tabs of 50.8 mm in length were placed before the specimens were cut out.

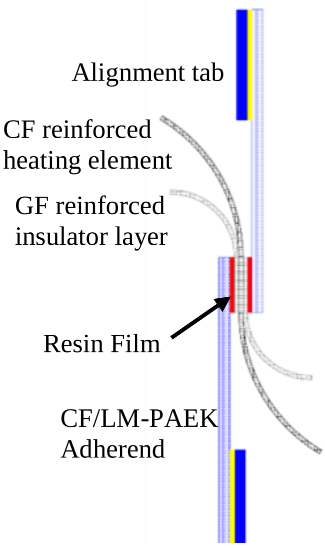

Fig. 1: *Schematic image of de-welding specimen*

The test setup is shown in Fig. 2. An Instron 100 kN universal testing machine was used. The current source was attached to the resistance element through brass clamps. These were placed as close to the interface as possible to avoid heating the carbon fabric outside of the overlap region. Before clamping, the fabric heating element had to be stripped of resin to ensure good conduction. A FLIR A70 thermal imaging camera was used to record the surface temperature of the samples during heating. The temperature was measured and averaged for a circular region in the centre of the interface. Test specimens were heated manually by adjusting the current. After reaching the target temperature, shear loading was applied until failure.

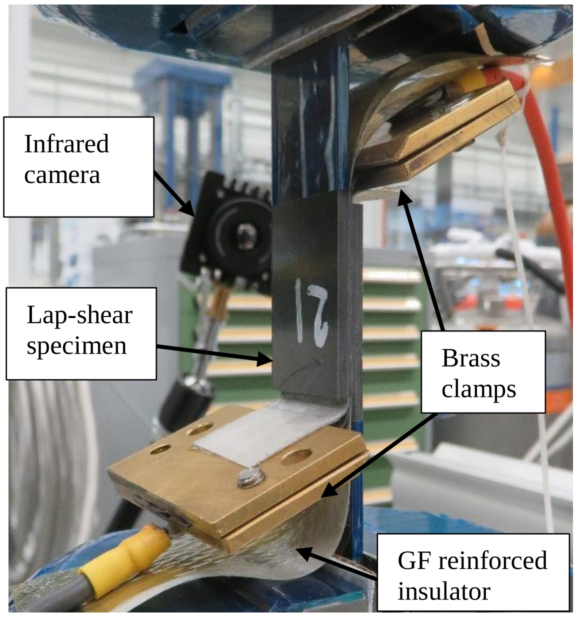

Fig. 2: *Test setup*

For the LM-PAEK interface, de-welding tests were conducted within a temperature range roughly in between the glass transition temperature T_g (147 °C) and melting point T_m (305 °C) of the matrix material. Initially, an interface temperature of 160 °C was targeted to ensure that T_g was reached everywhere in the overlap region. Later, de-welding temperatures were gradually increased up to 330 °C, with four samples tested at each temperature. PEI is known to weaken substantially well below its T_g of 217 °C and was tested from an interface temperature of 190 °C upwards. Three samples tested at room temperature served as a reference.

Results and Discussion

Fig. 3 plots the dependence of the measured shear strengths on the de-welding temperature. The surface temperatures represent measured values while the interface temperatures are estimates obtained from comparison of the temperature-dependent shear strength with DMA behaviour of LM-PAEK and PEI, linking transition points in the de-welding behaviour to the glass transition and melting temperature of the polymers. In a study comparable to the present one, Frederick et al. [3] have found the ratio between interface and surface temperature (in °C) to be near constant within an appropriate temperature range. Judging from the material behaviour, these ratios were estimated at 1.22 for LM-PAEK and 1.28 for PEI, which used a thicker glass insulator layer. The interface temperatures displayed in Fig. 3 are projections using these ratios.

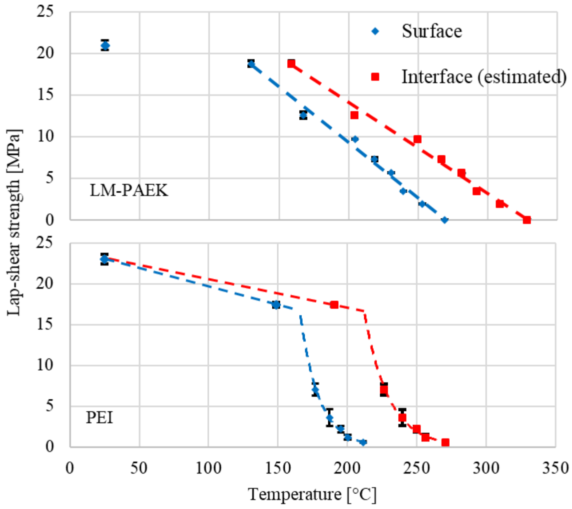

Fig. 3: *SLS strength at various surface and estimated interface temperatures. Lines are guides-to-the-eye.*

The two interface materials show vastly different behaviours under heating. LM-PAEK retains virtually constant lap-shear strength up to its T_g, after which it decreases linearly until zero-strength is reached around melting temperature (Fig. 3).

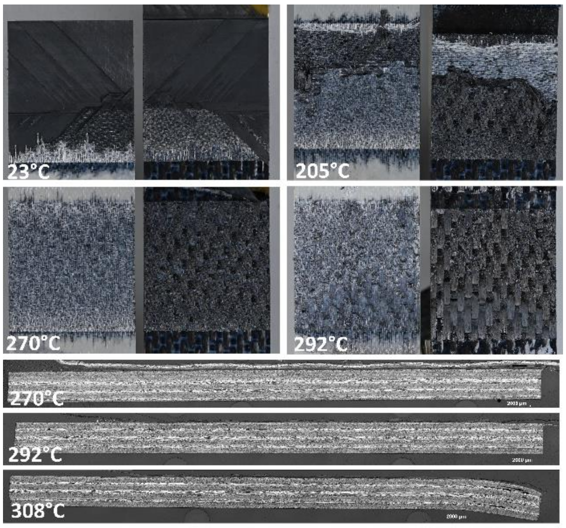

Fig. 4: *Fracture surfaces and cross-sections of SLS coupons with LM-PAEK interface at various estimated interface temperatures. Fracture surfaces of both adherends are shown while cross-sectional images are only from one of the adherends.*

The fracture surfaces after testing at various temperatures are shown in Fig. 4 and Fig. 5. For LM-PAEK, cross section microscopy images of the adherends are shown as well. Below and near T_g, failure initiates in the adherends. Further heating transitions fracture into the interface region, occurring either in the insulator or the heating element. From 265 °C onwards, clean de-welding becomes possible with inter-ply separation between the insulator and the heating element. As can be observed in the image, heating to 290 °C shows a change in the constitution of the matrix. At this temperature, specimens had to be fully separated by the test bench or they would fuse together again after separation. This means that melt was initiated at this point in the interface. The cross section microscopy image at 292 °C however shows that the adherends remain intact, likely due to the glass fabric providing a thermal barrier. Only when exceeding the true melting point of 308 °C in the interface, sagging and deconsolidation occurred near the edges of the adherend, amplified by the weight of the brass clamps pulling on the heating element. This means that adherend damage occurs before zero-strength was reached at 328 °C (270 °C at the surface).

Note the higher SLS strength of the PEI interface at room temperature. This is attributed to the increased specimen length leading to reduced bending stresses in the interface. At the initial testing temperature of 190 °C, a high drop-off in SLS strength occurs already, well below the T_g of PEI. Fracture at this point occurs in the heating element, while at room temperature, adherend failure was dominant (see Fig. 5), similar to LM-PAEK. Exceeding T_g, the SLS strength decreases extremely rapidly but levels out later, retaining some strength up to 270 °C. T_g also marks the transition to matrix dominated specimen separation, with the same behaviour observed at all temperatures tested beyond. This behaviour is typical for amorphous polymers, which soften rapidly when surpassing their glass-transition temperature. The different findings for the crystalline LM-PAEK and the amorphous PEI are also observed in literature, where the behaviour of crystalline and amorphous PPS is compared [6,7].

Comparing Fig. 4 and 5, the separation behaviour in the cleanly de-welded samples is noteworthy. While the LM-PAEK specimens universally split between the heating and the insulator element, PEI-interfaces

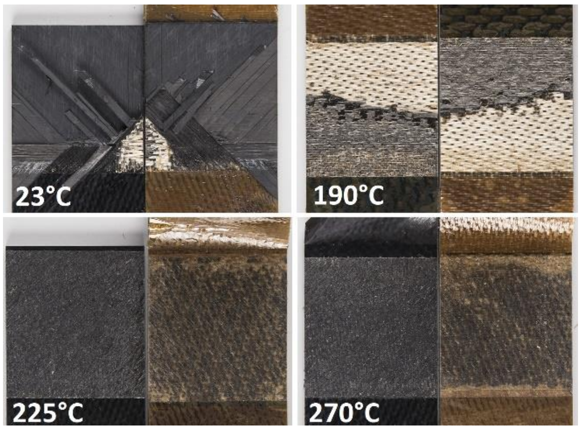

Fig. 5: *Fracture surface of SLS coupons with PEI interface at various estimated interface temperatures.*

continuously separated in the matrix rich region between the insulator and the adherend. This is likely to be a result of the interface between the two polymers representing a weak point.

Conclusion

The present paper proves the feasibility of de-welding by resistance heating. Two thermoplastic adherends were separated through resistance heating and shear loading without causing adherend damage across a wide temperature range with both LM-PAEK and PEI interfaces. Clean de-welds were obtained in the LM-PAEK interface within a temperature range between ca. 270 °C and 308 °C at the interface. “De-welding” at lower temperatures results in fibre fracture within the weld substrates or the heating element while heating to higher temperatures causes melt induced damage in the adherends. At this upper limit, the interface retains a shear strength of about 3.5 MPa. From an industrial standpoint, this is undesirable as powerful machines and jigs will be necessary when de-welding larger structures. Higher interface temperatures are desirable but will require cooling in the adherends to avoid deconsolidation. Having a PEI interface drastically reduced the de-welding temperatures and, unlike LM-PAEK, allowed for separation at the zero-strength point. It also allowed for a wider processing window with good de-welds achieved from 225 °C upwards. Higher temperatures are possible – in theory up to 305 °C, when damage in the LM-PAEK matrix adherends can be expected. From a purely de-welding perspective however, heating beyond the zero-strength point of 250 °C serves no purpose and only increases energy consumption.

The point of separation and the resin distribution between the adherends is of high importance for re-welding. Separation between the insulator and the adherend could prove problematic to the adherend integrity if substrate matrix material is removed during this step.

The observed behaviour makes PEI an interesting material to be used for joining LM-PAEK matrix composites. Due to the problematics linked to the chemical resistance of PEI, such a technology is unlikely to find its way into structural components in aerospace but could be of high interest for aircraft interiors and structural automotive parts. Furthermore, novel polymers might be available in future, which are miscible with LM-PAEK and have lower processing temperature than that, but at the same time with a stronger chemical resistance than PEI. In this case, such novel matrices can be used as a replacement for PEI and the method explained in this study can be applied to enable de-welding at low temperatures without the deconsolidation of adherends.

Future work will focus on coupon-level de-welding tests with other loading configurations, such as pull-off tests of L-stiffened flat panels, better estimation/measurement of the interface temperature during de-welding, and de-welding by applying a heat sink to alleviate deconsolidation of the adherends. Further research should also focus on modified de-welding methods, for instance peeling and vibration. Currently a resistance heating based welding and de-welding equipment is being designed, which will be used later for de-welding tests of sub-components such as long L-stiffened flat panels commonly encountered in aircrafts.

Acknowledgements

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