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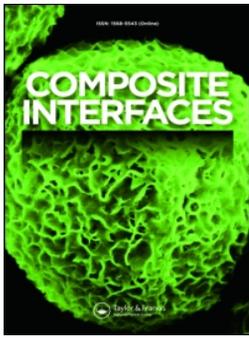
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On the effect of flat energy directors thickness on heat generation during ultrasonic welding of thermoplastic composites

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ABSTRACT

This paper presents a detailed experimental assessment of the effect of the thickness of flat energy directors (ED) on heat generation at the interface during ultrasonic welding. Power and displacement data showed clear differences caused by the change of thickness, related to heat concentration at the weld line during the process. The extent of the heat-affected zone was assessed by welding specimens without consolidation at different stages of the process. It was confirmed through optical microscopy that heat is generated at the interface and transferred to the bulk adherends earlier in the process for thinner ED. The analysis of their fracture surface under optimum welding conditions revealed signs of matrix degradation, leading to less consistent quality, likely due to faster heat generation rate in both the ED and the substrates, and incidentally, higher temperatures surrounding the energy director.

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1. Introduction

Owing to its very short cycle times, ultrasonic welding (USW) of thermoplastic composites (TPCs) has great potential for industrialization, especially for mass-produced parts in the aerospace and automotive sectors.[1] However, upscaling of the process towards practical applications where large overlaps need to be welded is likely to present several challenges. To promote heat generation between the substrates, energy directors (ED), made of the same polymer as the composite's matrix, are placed at the interface.[2–5] Preliminary investigation into upscaling has shown a possible issue with limited flow of the ED at the bond line.[6] Thinner EDs could solve this problem because of the reduced volume of polymer that needs to be melted and squeezed out at the interface. Therefore, it is essential to establish if the USW process fundamentally changes with the thickness of the energy director, in order to appropriately upscale and control the welding method.

Typically, EDs are shaped like triangular, semi-circular or rectangular protrusions.[7–13] However, a simpler shape, so-called 'flat energy directors', made of a neat polymer

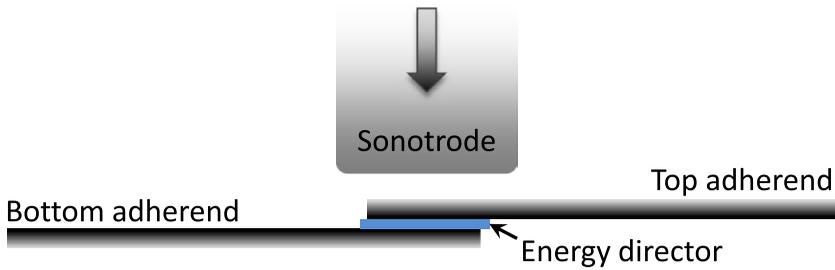


Figure 1. Ultrasonic welding process with flat energy director. Dimensions are not to scale.

layer, has been shown to lead to excellent weld quality for both thermoplastics [14,15] and TPCs,[1,16–18] with ED thicknesses varying between 0.25 and 0.70 mm. Figure 1 shows a schematic representation of the process using such an ED between two adherends. Preferential heat generation at the weld line is based on higher cyclic strains which results from the lower compressive modulus of the neat thermoplastic resin as compared to the TPC specimens.

For TPCs, several studies investigated the shape of energy directors and its effect on weld quality,[12,19,20] temperature field at the interface,[11,21] weld penetration,[11] flow of the ED [13] and heat-affected zone (HAZ).[12] It is clear from the literature that the geometry of the energy director plays a major role in the events occurring at the bond line. Thus, it can be expected that the use of flat EDs thinner than 0.25 mm could lead to important differences in the USW process.

Consequently, in order to progress towards upscaling of USW of TPCs, the aim of this work is to perform a detailed experimental assessment of the effect of the thickness of flat energy directors on heat generation at the interface during the process. Firstly, the output data from the welder, power and sonotrode displacement, were compared to determine how they are affected by different ED thicknesses. Secondly, in order to assess the effectiveness of the energy directors in preferential heat generation, the extent of the HAZ in the TPC substrates was evaluated by welding specimens without consolidation at different stages of the USW process and observing the cross-sections for deconsolidation. These observations were correlated to the mechanical performance and the fracture surfaces obtained under optimum welding conditions. Finally, heat generation at the interface and optimum vibration time for all ED thicknesses were discussed from the viewpoint of process applicability.

2. Experimental procedures

2.1. Materials

In this study, Cetex[®] CF/PEI (carbon fibre/polyetherimide) five-harness satin fabric reinforcement, manufactured by TenCate Advanced Composites (The Netherlands), was used. Laminates with a $[0/90]_3$ stacking sequence were consolidated in a hot-platen press at 320 °C and 20 bar for 30 min. Specimens measuring 101.6 × 25.4 mm were cut using waterjet. After cutting, the samples were dried in an oven at 135 °C for 6 h. Three thicknesses of flat PEI energy directors were compared: 0.50, 0.25 and 0.06 mm. The last two thicknesses (0.25 and 0.06 mm) were available as films directly from the manufacturer (SABIC). To create

0.50-mm-thick EDs, two 0.25-mm films were stacked and fixed with adhesive tape on the bottom adherend before the welding process.

2.2. Welding procedure

Individual samples were welded with a Rinco 3000 microprocessor-controlled ultrasonic welder in a single-lap configuration using a custom-made welding set-up, as seen on Figure 2. The cylindrical sonotrode had a diameter of 40 mm. For all welds, the parameters were 500 N force and 86.2 μm vibration amplitude (peak-to-peak). The solidification force and time were kept constant at 1000 N and 4000 ms, respectively. After each weld, the USW machine provided the following output curves with respect to time: dissipated power and vertical displacement of the sonotrode.

The USW machine allows for the process to be controlled based on vibration time, dissipated energy or vertical displacement of the sonotrode. For the case of single-lap shear samples with flat energy directors, it is preferable to use ‘displacement-controlled’ welding to consistently obtain high-strength welds.[1] It has been shown that the optimum weld quality is achieved when stopping the process at the displacement value corresponding to the second peak in the power curve. This optimum stage of the process occurs when the upper layers of the composite substrates start melting.[16] This optimum displacement value was identified for all ED thicknesses by first gathering power and sonotrode displacement data after welding with a displacement equal to the ED thickness. To investigate the extent of the HAZ in the substrates when using 0.06-mm-thick EDs, the process was stopped at different stages and the welding force was removed right after the vibration phase.

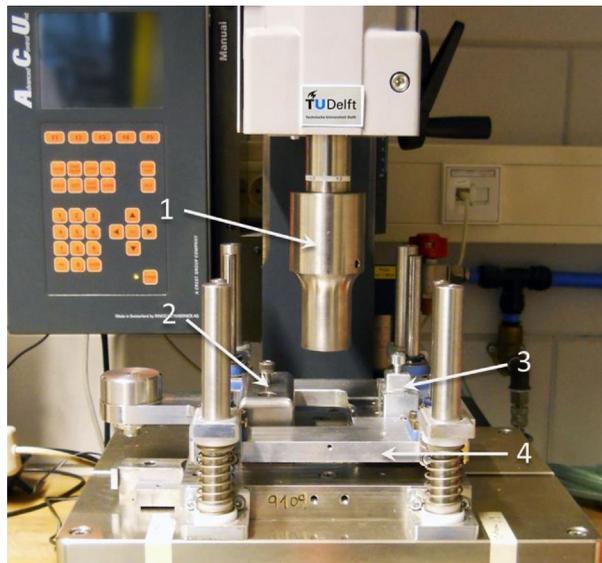


Figure 2. Welding set-up used to carry out experiments. 1: sonotrode, 2: clamp for the lower sample, 3: clamp for the upper sample and 4: sliding platform.

2.3. Testing and characterization

After welding, the samples were tested for lap shear strength (LSS) with a Zwick/Roell 250 kN universal testing machine, according to ASTM D 1002 standard, at a crosshead speed of 1.3 mm/min (at least three samples per ED thickness). Fracture surfaces were analysed with naked eye, a high-resolution Keyence stereomicroscope and a JEOL JSM-7500F scanning electron microscope (SEM). For cross-sectional microscopy, samples were cut with a water-cooled diamond saw, embedded in acrylic resin, then sanded and polished.

3. Results and discussion

3.1. Power and displacement curves

Figure 3 shows representative power and displacement curves for samples welded with all three ED thicknesses (two samples shown per configuration): 0.50 mm (a), 0.25 mm (b) and 0.06 mm (c). The specimens were welded until the displacement of the sonotrode reached a value equal to the thickness of the ED (100% displacement). A general examination of the power curves quickly reveals that they differ when significantly decreasing the thickness of the energy director. The behaviour of the curves for 0.25-mm-thick EDs for CF/PEI was previously discussed in detail in Ref. [1]. Figure 3(a) and (b) confirm that, for 0.50- and 0.25-mm-thick EDs, the curves clearly follow the typical stages of the USW process. Once

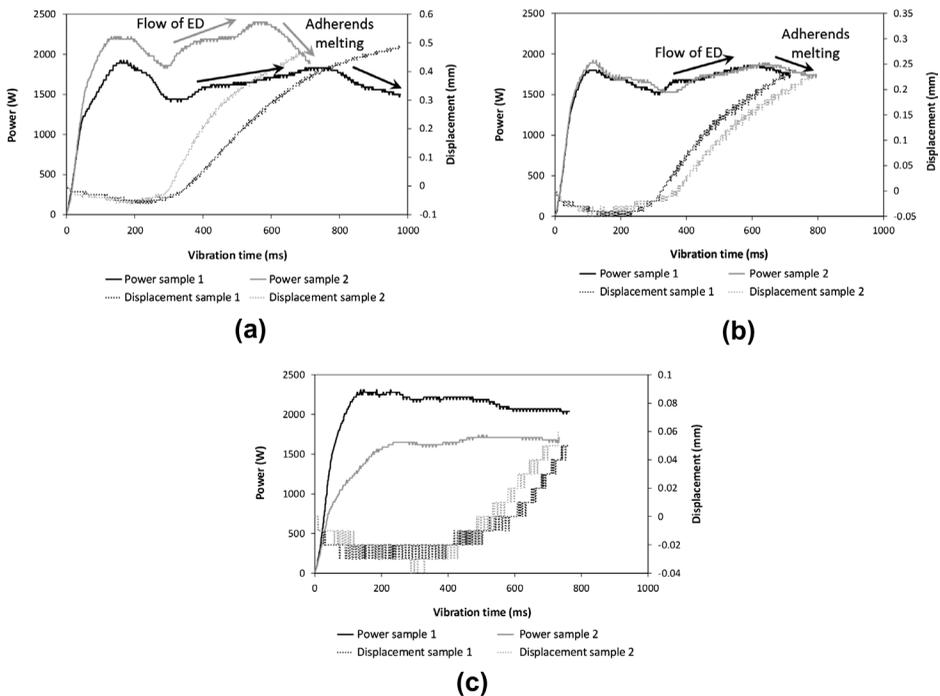


Figure 3. Representative power and displacement curves for CF/PEI samples welded with (a) 0.50-mm EDs, (b) 0.25-mm EDs and (c) 0.06-mm EDs at 100% displacement. Two samples are shown for each ED thickness and two data-sets are reported. Hundred percent displacement is equal to the thickness of the ED. The welding parameters were 500 N force and 86.2 μm vibration amplitude.

the ED starts to flow, the downward displacement of the sonotrode increases. This corresponds to a raise in power due to the increased impedance of the molten ED. This power increase is counterbalanced by a power decrease associated to local melting of the adherends at the welding interface, which results in a second power peak and a subsequent power drop. This demonstrates that for specimens welded with 0.50- and 0.25-mm-thick EDs, the energy director melts and flows out of the interface before the substrates start melting.

However, for 0.06-mm-thick EDs (Figure 3(c)), this is not the case. After the initial peak, the power curves are almost horizontal, which might indicate that the ED and the adherends melt at the same time, creating a counterbalancing effect in the dissipated power.

3.2. Heat-affected zone: comparison between 0.06- and 0.25-mm energy directors

In order to confirm a potential early melting of the adherends for 0.06-mm-thick EDs, a detailed experimental study was performed to assess the extent of the HAZ. To do so, samples were welded at different stages of the process, but pressure was removed right after the vibration phase. Deconsolidation was expected to occur where resin reached a temperature above T_g and cross-sections were observed through optical microscopy to confirm the HAZ. Based on Figure 3(c), different points were selected along the displacement curves. Vibration time was used to stop the process before any displacement of the sonotrode took place. After that point, displacement mode was employed. Table 1 lists the selected values for vibration time (400 and 450 ms) and displacement (0.02 and 0.04 mm). It was noted that the average vibration times for samples welded with a travel of 0.02 and 0.04 mm were equal to 514 and 598 ms, respectively.

Figure 4 shows representative power and displacement curves for a sample welded with 0.06-mm-thick ED, as well as the corresponding cross-sectional micrographs at the time and displacement values listed in Table 1, referred to as points A–D (starting at 400 ms). Figure 4, point A, is a cross-sectional micrograph of a sample welded without consolidation after 400 ms. The composite substrate appears to have undergone no significant changes as there is no delamination or voids present between the layers. At this stage, the displacement curve indicates that squeeze flow of the energy director has not started yet. This is confirmed through Figure 5, a picture of the fracture surface of a sample welded and consolidated at the same vibration time, 400 ms. The fracture is resin-rich and the white arrow indicates the presence of an intact piece of ED. While the majority of the ED is melted, it has not been pushed out of the interface.

Figure 4, point B, is a cross-sectional micrograph of a specimen not consolidated after a vibration time of 450 ms. At this stage, the HAZ extends to the adherends, as evidenced by delamination within the first ply. This indicates local melting of the matrix due to heat generated at the interface. The displacement curve reveals that squeeze flow of the ED starts around 450 ms. When the process is stopped after a displacement of 0.02 mm (Figure 4, point C), important delamination and porosity are seen underneath the first layer of

Table 1. Vibration time and displacement values selected for investigation of the extent of the HAZ at different stages of the USW process, with 0.06-mm-thick EDs.

Vibration time (ms)		Displacement (corresponding vibration time) (mm)	
400	450	0.02 (514 ± 19 ms)	0.04 (598 ± 21 ms)
Point A	Point B	Point C	Point D

Note: Corresponding points in Figure 4 are indicated in the bottom row.

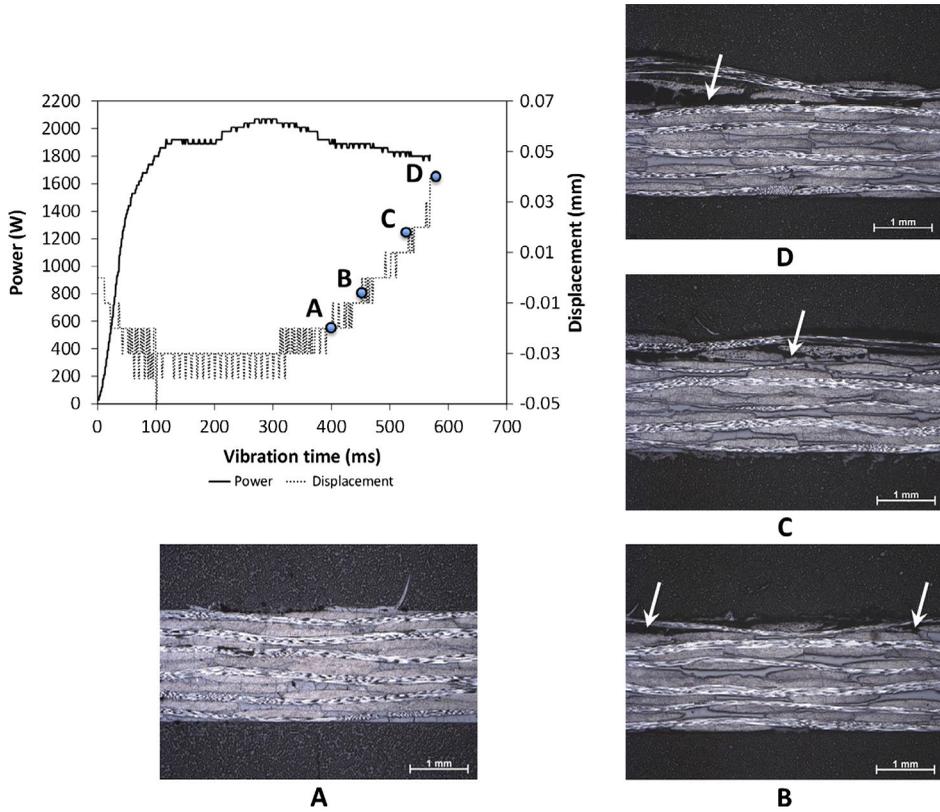


Figure 4. Representative power and displacement curves for 0.06-mm-thick ED with corresponding cross-sectional micrographs of welds not consolidated at different stages of the USW process. Point A: 400 ms, point B: 450 ms, point C: 0.02 mm displacement and point D: 0.04 mm displacement. Arrows point at deconsolidation voids. The welding parameters were 500 N force and 86.2 μm vibration amplitude.

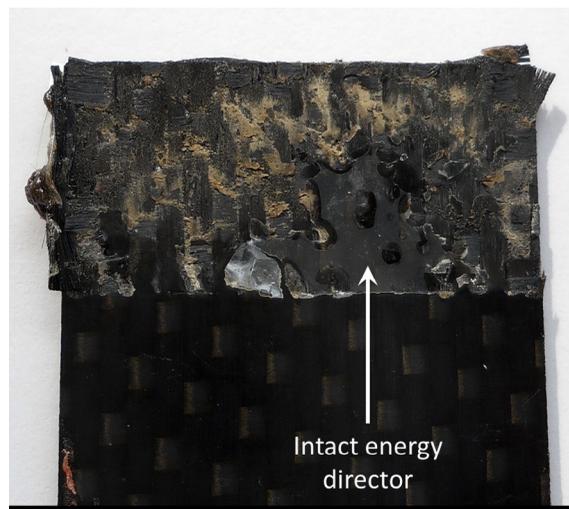


Figure 5. Fracture surface of a CF/PEI sample fully welded after a vibration time of 400 ms (500 N welding force and 86.2 μm amplitude).

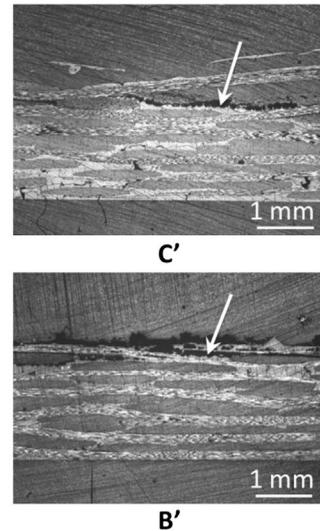
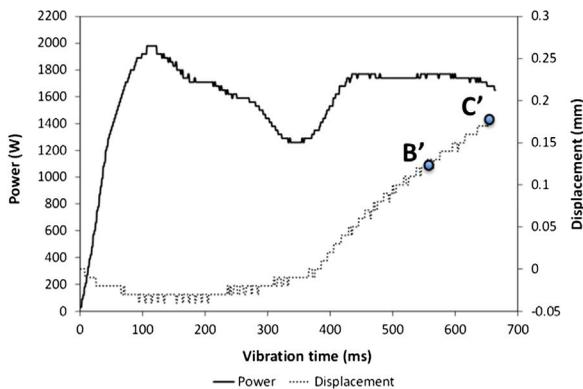


Figure 6. Representative power and displacement curves for 0.25-mm-thick ED with corresponding cross-sectional micrographs of welds not consolidated at different stages of the USW process. Point B': 550 ms (corresponding to point B in Figure 4) and point C': 650 ms (corresponding to points C and D in Figure 4). Arrows point at deconsolidation voids. The welding parameters were 500 N force and 86.2 μm vibration amplitude. Source: Modified from Ref. [16].

the composite. Furthermore, after a displacement of 0.04 mm (Figure 4, point D), severe delamination within the second ply of the substrate occurs.

A parallel can be drawn with similar results presented in our previous work for CF/PEI specimens welded with 0.25-mm energy directors without consolidation at different stages of the USW process.[16] As explained in Section 2.2 of this paper, the best weld quality is obtained at the second power peak, at the moment when the resin in the first layer of the composite starts to melt. It was shown that in this stage, delamination within the first ply, similar to Figure 4, point B, was found. This cross-sectional image is reproduced in Figure 6 for 0.25-mm-thick ED, with the corresponding point B'. The displacement curve shows that this occurred at a displacement value of approximately 0.13 mm, well beyond the onset of the squeeze flow of the ED. The importance of the delamination in Figure 4, for points C and D, can be correlated to what was reported for welds within the last stage of the USW process, as shown in Figure 6, point C', leading to significant fibre bundles deformation and lower LSS.[1,16] Point C' corresponds to a displacement value of 0.18 mm, indicating further squeeze out of the energy director, along with the composite matrix.

3.3. Mechanical performance and fracture surfaces

To adequately assess the mechanical performance of welded samples with different ED thicknesses, it was first necessary to determine the optimum welding parameters. Based on the power and displacement curves for 0.25- and 0.50-mm-thick EDs and the procedure described in Section 2.2, displacement values of 0.16 and 0.36 mm, respectively, were selected for best weld quality, as shown in Figure 7. For 0.06-mm energy directors, power and displacement curves (Figure 3(c)) demonstrated that there is no clear optimum due

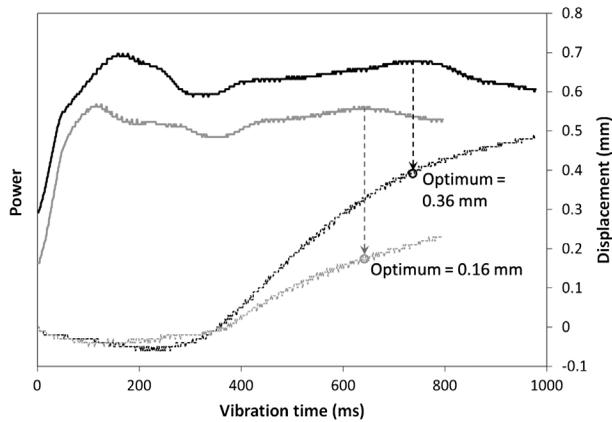


Figure 7. Power and displacement curves for CF/PEI samples welded with 0.25- and 0.50-mm-thick EDs. The vertical dashed lines show the position of the optimum travel value. Power curves were shifted on the vertical axis for clarity. The welding parameters were 500 N force and 86.2 μm vibration amplitude.

to the absence of a second power peak. The cross-sectional micrographs presented in the previous section support that the best weld quality would be located at approximately 450 ms, at the onset of the displacement of the sonotrode, which is the moment when local melting of the matrix in the first ply of the adherends was observed. LSS tests were carried out and a time of 475 ms was found to lead to the highest strength. It is important to specify that as displacement of the sonotrode did not consistently start before 475 ms, time control had to be used to weld the specimens. Under the optimum welding conditions, average LSS for 0.06-, 0.25- and 0.50-mm-thick EDs was equal to 32.9 ± 2.2 , 37.3 ± 0.9 and 36.5 ± 1.8 MPa, respectively.

In order to further investigate how the thickness of the ED affects heat generation and weld quality at the interface under optimum conditions, fracture surfaces of samples welded with 0.06- and 0.25-mm-thick EDs were analysed through visual inspection, SEM and stereomicroscopy. Figure 8(a) shows a picture of the fracture surface for an optimum weld with 0.06 mm ED. Broken fibre bundles are present and demonstrate that the adhesion developed at the interface by the diffusion of the polymer chains extended into the substrates. However, resin flakes, voids and a brown colour on the surface of the fibres are present. Figure 8(b) shows a high-resolution stereomicroscope image of the circled area in Figure 8(a). It contains voids and resin flakes exhibiting a darker polymer colour. In addition, Figure 8(c) and (d) present SEM images at two different magnifications of the approximate same area. Resin flakes, as well as numerous voids, are clearly observed. These signs are believed to be closely linked to thermal degradation for PEI.[22,23]

The fracture surface of an optimum weld with 0.25-mm ED is illustrated in Figure 9(a). It is similar to Figure 8(a) with several broken fibre bundles, but the surface appears smoother and shinier. A closer look at the circled area with SEM in Figure 9(b) demonstrates a clear contrast with Figure 8(c). The presence of resin flakes, voids or other signs of degradation is inexistent. This provides insight into the high quality of the weld using 0.25-mm-thick EDs, in comparison to the lower quality of 0.06-mm-thick ED.

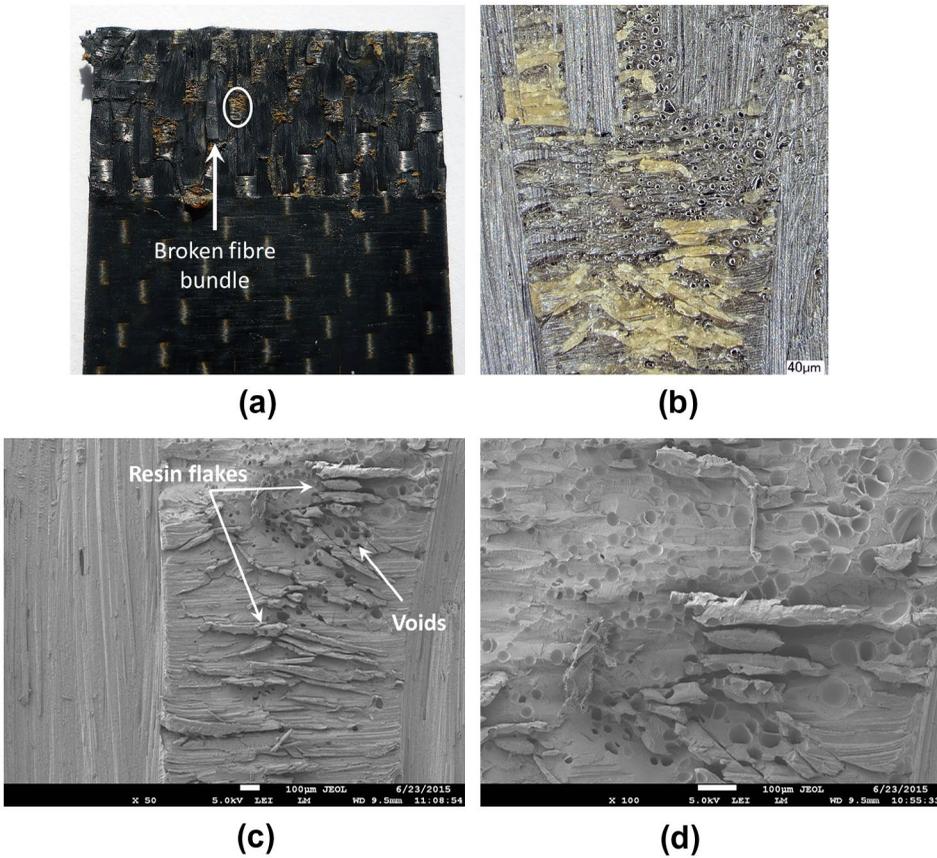


Figure 8. (a) Representative fracture surface of a CF/PEI sample welded at an optimum vibration time of 475 ms with 0.06-mm ED. (b) Stereomicroscope image of the circled area in (a) with resin flakes, indicating PEI degradation (Scale: 40 μm). (c) and (d) SEM images of the circled area in (a) showing voids and resin flakes (Scale: 100 μm). The welding parameters were 500 N force and 86.2 μm vibration amplitude.

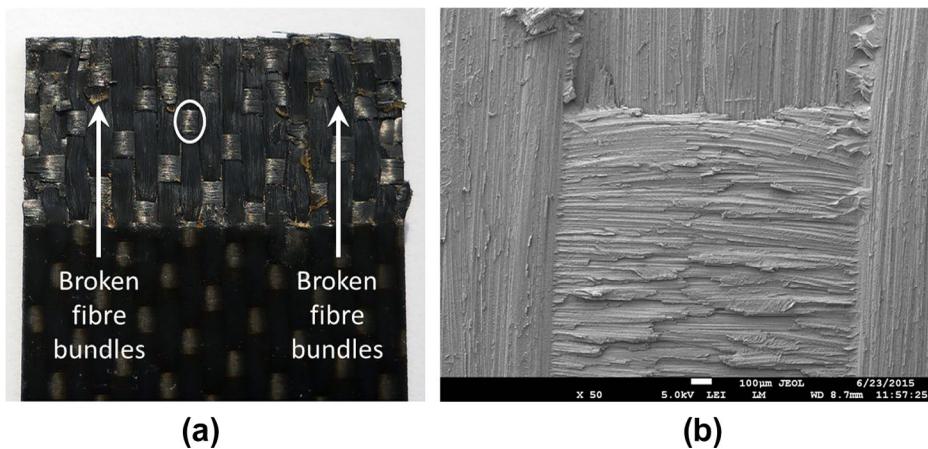


Figure 9. (a) Representative fracture surface of a CF/PEI sample welded at an optimum displacement value of 0.16 mm with 0.25-mm-thick ED and (b) corresponding SEM image circled in (a) (Scale: 100 μm). The welding parameters were 500 N force and 86.2 μm vibration amplitude.

3.4. Discussion

Based on the results presented in Sections 3.1–3.3, the dissimilarities between thin (0.06 mm) and thick (0.25 and 0.50 mm) energy directors can be further discussed with respect to heat generation at the interface.

Energy directors heat up preferentially as a result of higher cyclic strains and concentrate heat generation at the interface through two mechanisms: interfacial and viscoelastic friction.[5] The former is responsible for the initial heat generation and is affected by the welding force as well as the relative displacement between adherends and energy director. It is dominant before the glass transition temperature, T_g . When the latter is reached, viscoelastic heating (\dot{Q}_v) becomes more important and contributes to bringing the energy director to its processing temperature.[7] Viscoelastic heat generation rate can be described by Equation (1) [4]:

$$\dot{Q}_v = \frac{\omega \cdot \varepsilon_0^2 \cdot E''}{2} \quad (1)$$

where ω is the vibration frequency, ε_0 is the cyclic strain and E'' is the loss modulus of the material. The comparison between 0.06- and 0.25-mm-thick EDs supports that for the former case, heat is transferred to and generated in the bulk adherends much earlier in the process, just when the onset of the displacement of the sonotrode occurs (Figure 4, point B). During the USW process, the cyclic strain, ε_0 , results from a combination of static (welding force) and dynamic (vibration amplitude) strains. As the static strain is several orders of magnitude lower than the dynamic strain, it can be assumed that only the latter will have a significant effect on heat generation.[14] For a constant amplitude of vibration, and considering an elastic analysis, the dynamic strain increases in both the adherends and the energy director when the thickness of the latter decreases.[21] According to Equation (1), this translates into faster heating of the substrates from two sources: (1) heat generated and transferred at a higher rate from the ED and (2) ‘bulk’ viscoelastic heating, i.e. viscoelastic heating of the adherends themselves. As a consequence, heating and melting of the adherends occur earlier when thinner EDs are used. Moreover, hotter surroundings to the energy director can lead to overheating, as observed in Figure 8. This can explain how, despite using the optimum welding parameters for 0.06-mm-thick EDs, the average LSS is lower than for 0.25- and 0.50-mm energy directors. Likewise, the resin flow outside of the overlap increased with the ED thickness, which could as well have a positive influence on the LSS by acting as a fillet and lowering the peak stresses at the edges of the overlap.

The vibration time to reach optimum quality with 0.06-mm-thick EDs was 475 ms, and hence somewhat lower than for 0.25- and 0.50-mm EDs, with average times of 565 and 605 ms, respectively. The fact that the optimum heating time increases with the thickness of the energy director can be understood if one takes into account that the cyclic strains in both the energy director and the adherends decrease when the thickness of the energy director increases,[14] which will reduce both the surface friction and viscoelastic heating rates.[21] The differences among the ED thicknesses considered in this study might suggest bigger differences in the vibration times for optimal quality. However, the reader should notice that, apart from the cyclic deformation of the materials under the sonotrode, there

are other phenomena, such as the hammering effect, which have a very significant impact in heat generation [21,24] and might have been influenced by the changes in thickness of the EDs. Finally, even though vibration times were lower for the 0.06-mm-thick EDs, the optimum weld quality is achieved at the onset of the displacement, which implies that displacement-controlled welding is not applicable.

4. Conclusions

In this paper, a detailed experimental assessment of the influence of the thickness of flat energy directors on heat generation during USW of TPCs was presented. Three thicknesses were investigated: 0.50, 0.25 and 0.06 mm. The combined results shown in this research, when comparing power and displacement curves, extension of HAZ and fracture surfaces, led to the following main observations:

- Both 0.50- and 0.25-mm-thick EDs show a similar behaviour in their power and displacement curves, with a clear definition of the stages of the USW process. Overall, the curves for the thickest ED are slightly delayed, which is attributed to lower cyclic strains in the ED and hence, lower heating rates.
- When using thin EDs (0.06 mm), heating and melting of the energy director and adherends occurs simultaneously. When the energy director is thicker (0.25 and 0.50 mm), it distinctly heats up and melts first, before the substrates, during the process.
- For 0.06-mm-thick EDs, their optimum weld quality is reached approximately at the onset of the displacement of the sonotrode. Consequently, displacement control, which has been demonstrated to lead to consistent quality welds, cannot be used. Instead, either vibration time or welding energy must be considered as the control parameter. Moreover, even under the optimum conditions, welds present signs of overheating and degradation, likely due to faster heat generation rate in both the ED and the substrates, and incidentally, higher temperatures surrounding the energy director. Finally, using significantly thinner energy directors does not proportionally reduce the welding time.

Despite the apparent disadvantages of 0.06-mm-thick energy directors, they nevertheless exhibit an acceptable average LSS, above 30 MPa. The motivation of this research was to investigate the effect of the thickness of EDs to appropriately upscale and control the USW process. In the case where larger overlaps need to be welded, there is a possible issue with the use of displacement-controlled welding and limited flow of the ED at the interface. Further research into 0.06-mm-thick EDs may mitigate these problems as their optimum weld quality can be achieved at the onset of the flow of the ED, using time or energy control.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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