ULTRASONIC WELDING OF THERMOPLASTIC COMPOSITES WITH FLAT ENERGY DIRECTORS: INFLUENCE OF THE THICKNESS OF THE ENERGY DIRECTOR ON THE WELDING PROCESS

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ABSTRACT

This paper presents a detailed experimental examination of the influence of the thickness of flat energy directors (ED) on the ultrasonic welding (USW) process for carbon fibre/polyetherimide composites. Three thicknesses of flat ED were compared: 0.06 mm, 0.25 mm and 0.50 mm. Power and displacement data for 0.06 mm-thick EDs did not clearly show the stages of the process and the location of the optimum for best weld quality. Consequently, an investigation of samples welded at different stages in the welding process had to be performed. For 0.06 mm-thick EDs, the optimum was determined to occur at the beginning of the downward displacement of the sonotrode in the vibration phase. The output parameters at the optimum conditions for all thicknesses were compared. Average lap shear strength was found to be lowest for 0.06 mm-thick EDs. Based on the analysis of the fracture surfaces, resin flakes and voids were observed when using the thinnest energy directors, indicating thermal degradation. These observations suggest that thin energy directors are not as efficient as thicker EDs (i.e. 0.25 mm) to achieve preferential heat generation at the weld line, leading to less consistent weld quality.

1 INTRODUCTION

Ultrasonic welding is a promising technique for assembling thermoplastic composites (TPC). It has short cycle times (less than a few seconds), does not require foreign materials regardless of the type of fibres in the composites, on-line monitoring of the welding process can provide feedback on the weld quality, and it is well suited for automation [1].

Typically, energy directors, made of the same polymer as the composite’s matrix, are placed at the interface between the adherends. For unreinforced thermoplastics, EDs are directly moulded on the surfaces to be joined and are shaped like triangular, semi-circular or rectangular protrusions [2]. They heat up preferentially as a result of higher cyclic strains and concentrate the heat generation at the interface through interfacial and viscoelastic friction [2, 3]. However, Villegas has shown that for TPCs, successful results with a simpler ED shape, a flat polymer layer, can also be obtained [4, 5]. Figure 1 shows a schematic representation of the process using a flat ED between two composite samples.

Figure 1: Ultrasonic welding process with flat energy director (dimensions are not to scale).
With microprocessor-controlled ultrasonic welders, it is possible to monitor the joint quality by measuring the dynamic mechanical impedance of the parts during welding. The idea was first introduced by Benatar and Gutowski based on the dissipated power and the acceleration of the baseplate [6]. It was later expanded upon by Villegas using dissipated power and displacement of the sonotrode to describe the physical changes occurring at the interface during the vibration phase [4, 7]. This data can be used to identify the optimum process parameters for best weld quality. The process is divided into five steps, as shown in Figure 2:

**Stage 1:** The beginning of the process is characterized by a strong increase in power and an upward displacement of the sonotrode to accommodate for the vibrations.

**Stage 2:** The ED starts melting through nucleation and growth of random hot spots, characterized by a slow decrease in power and no significant displacement.

**Stage 3:** The beginning of the squeeze flow of the ED can be clearly seen by the downward displacement of the sonotrode. The increase in power comes from the increase of mechanical impedance of the interface when all melt fronts (growth of the hot spots) meet.

**Stage 4:** This stage is characterized by a power plateau. The ED continues to flow and the upper layers of the composite samples start melting. The best weld quality is obtained during this phase.

**Stage 5:** In this stage, the ED is completely squeezed out of the overlap and there is a power decline. The composite matrix continues to melt, squeezing out the polymer along with the fibres.

The ultrasonic welding machine allows for the process to be controlled based on vibration time, dissipated energy or displacement of the sonotrode. It was shown that for the case of lap shear samples with flat energy directors, high-strength welds can be consistently achieved when using the displacement of the sonotrode in stage 4 as the control parameter, hereafter referred to as “travel-controlled welding” or “displacement-controlled welding” [4].

Previous research established a solid understanding of the welding process using 0.25 mm-thick flat EDs [4, 7]. However, it is expected that a change of thickness could have a considerable effect on power and displacement data, welding strength, and output parameters (welding time and energy). Consequently, the aim of this research work is to go one step further and present a thorough experimental examination of the influence of ED thickness on the USW process. Firstly, the power and displacement curves were compared in order to assess if the different stages of the process, as

![Figure 2: Typical power/displacement curves during the vibration phase of the USW process for CF/PEI (500 N welding force and 86.2 μm amplitude). Positive values in the displacement indicate downward displacement of the sonotrode [7].](image-url)
shown in Figure 2, are clearly defined for all thicknesses. Secondly, the optimum welding parameters were identified. Thirdly, the weld quality and output parameters for the optimum welding conditions were compared and discussed.

2 EXPERIMENTAL PROCEDURES

In this study, Cetex® CF/PEI (carbon fibre/polyetherimide) 5-harness satin fabric reinforcement was used. Laminates with a [0/90]₃s stacking sequence were consolidated in a hot-platen press at 320°C and 20 bar for 30 minutes. Specimens measuring 101.6 mm x 25.4 mm were cut using waterjet. After cutting, the samples were dried in an oven at 135°C for 6 hours.

Individual samples were welded with a Rinco microprocessor-controlled ultrasonic welder in single lap configuration using a custom-made welding setup, as seen on Figure 3. The cylindrical sonotrode had a diameter of 40 mm. For all welds, the welding 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. Three thicknesses of flat PEI ED were compared: 0.06 mm, 0.25 mm and 0.50 mm. The first two thicknesses (0.06 mm and 0.25 mm) were available as films from the manufacturer. To create 0.50 mm-thick EDs, two 0.25 mm-thick films were stacked and fixed with adhesive tape on the bottom adherend before the welding process. After each weld, the USW machine provided the following output parameters: vibration time, energy and maximum power.

Travel of the sonotrode was used as the control parameter. To determine the optimum travel value, power and displacement data were first gathered for all ED thicknesses at 100% travel (equal to the ED thickness). The optimum was identified toward the end of the power plateau, as presented in Figure 2 [4, 5, 7]. In some cases, the welding force was removed right after the vibration phase in order to investigate the extent of the heat affected zone in the substrates indicated by the presence of porosity and delamination.

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 least three samples per ED thickness). Fracture surfaces were analyzed with naked eye and a high-resolution Keyence stereo microscope. Cross-sections were observed using a Zeiss optical microscope.

Figure 3: Welding setup used to carry out experiments presented in this paper. 1: sonotrode, 2: clamp for the lower sample, 3: clamp for the upper sample, and 4: sliding platform.
3 RESULTS AND DISCUSSION

3.1 Power and displacement curves for 100% travel

Figure 4 shows power (a) and displacement (b) curves of samples welded until the displacement of the sonotrode reached a value equal to the thickness of the energy director: 0.06 mm, 0.25 mm and 0.50 mm. The power curves for 0.25 mm and 0.50 mm-thick EDs follow the five stages of the ultrasonic welding process, as presented in the introduction of this paper (Figure 2). The optimum travel value was identified in stage 4. It was selected as 0.16 mm and 0.36 mm for 0.25 mm and 0.50 mm-thick EDs, respectively (Figure 4 (b)).

However, the power curve for 0.06 mm-thick ED does not clearly display the stages of the process. The first power peak is not as distinguishable as in the other two cases. It then levels off with very little power variation until the end of the process, making the identification of stages 2, 3 and 4, as seen in Figure 2, uncertain. In order to assess the repeatability of this behaviour, two additional samples were welded under the same conditions for comparison. The power and displacement curves are presented in Figure 5. Generally, the presence of a power plateau is noted for all samples (indicated by black vertical lines), but it occurs over a wide range of vibration time and does not correspond to the same phase of the displacement curves from one specimen to another. Based on this observation, it was hypothesized that heat generation at the interface for very thin energy directors develops differently than what has been previously reported in the literature for 0.25 mm ED. Therefore, a detailed investigation of samples welded with 0.06 mm-thick energy directors at different stages of the USW process was carried out, as will be shown in Section 3.2.

![Figure 4](image_url)

Figure 4: Power (a) and displacement (b) curves of CF/PEI samples welded with 0.06 mm, 0.25 mm and 0.50 mm-thick EDs at 100% travel, with 500 N welding force and 86.2 µm vibration amplitude. The power curves were shifted on the vertical axis for clarity. Optimum travel values were determined as 0.16 mm and 0.36 mm for 0.25 mm and 0.50 mm-thick EDs, respectively.
3.2 Optimum welding parameters for 0.06 mm-thick energy directors

To determine the optimum parameters for 0.06 mm-thick EDs, samples were welded at different stages of the process to examine the heat affected zone and assess the weld quality. Based on Figure 5, different points were selected along the displacement curves. As was previously demonstrated by Villegas, it is preferable to use travel as the control mode during USW because it leads to more consistent weld strength [4]. However, in the present case, the power curves of two samples suggest that the power plateau in stage 4 could occur at the very beginning of the downward displacement of the sonotrode, making the travel mode impractical. Consequently, it was decided to use vibration time as the control mode to investigate the behaviour at the interface before any displacement of the sonotrode takes place, and to use the travel mode when travel occurs. Table 1 lists the selected values for vibration time (350 ms, 400 ms and 450 ms) and displacement (0.02 mm and 0.04 mm). It was noted that the average vibration times for samples welded with a travel of 0.02 mm and 0.04 mm were equal to 514 ms and 598 ms, respectively.

For each time and displacement value, one sample was welded without solidification to first observe the cross-sections by optical microscopy to assess how the adherends were affected by heat generation.

<table>
<thead>
<tr>
<th>Vibration time [ms]</th>
<th>Displacement (corresponding vibration time) [mm]</th>
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<tbody>
<tr>
<td>350</td>
<td>0.02 (514 ± 19 ms)</td>
</tr>
<tr>
<td>400</td>
<td>0.04 (598 ± 21 ms)</td>
</tr>
<tr>
<td>450</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Vibration time and displacement values for investigation of optimum welding parameters with 0.06 mm-thick EDs.
In terms of the effect of heat generation on the substrates, a vibration time of 350 ms led to similar results to 400 ms. Therefore, only images for the latter will be presented in this paper. Figure 6 (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. Figure 6 (b) shows the fracture surface of a sample fully welded and consolidated at the same vibration time, 400 ms. The fracture is resin-rich and the white arrow indicates the presence of a piece of non-molten ED. At this stage of the process, while the majority of the energy director is melted, squeeze flow has not started yet, according to the displacement curves in Figure 5.

Figures 7 (a) to (c) correspond to cross-sectional micrographs of specimens not consolidated after a vibration time of 450 ms (a) and displacement values of 0.02 mm (b) and 0.04 mm (c). Figures 7 (d) and (e) illustrates representative power and displacement curves for each case. After 450 ms, the heat affected zone extends to the adherends. Delamination under the first ply is observed, which indicates local melting of the matrix due to heat generated at the interface. When the process is stopped after a displacement of 0.02 mm (Figure 7 (b)), important delamination and porosity is seen underneath the first layer of the composite. Furthermore, after a displacement of 0.04 mm ((Figure 7 (c)), severe delamination within the second ply of the substrate occurs.

Similar results were presented in the literature for CF/PEI specimens welded with 0.25 mm energy directors without consolidation [7]. As was previously explained in the introduction of this paper, the best weld quality is obtained in stage 4, at the moment when the resin in the first layer of the composite is starting to melt. It was shown that in this stage, delamination between the first and second plies, similarly to Figure 7 (a), was found. The importance of the delamination in Figure 7 (b) and (c) corresponds to what was reported for welds within the fifth stage of the USW process (Figure 2), leading to significant fibre bundles deformation and lower lap shear strength [4, 7].

Based on these findings, it is expected that the best weld quality would be located between 450 ms and 514 ms. In order to confirm the location of the optimum in terms of strength, samples were also welded at 475 ms. The LSS results for vibration times of 400 ms, 450 ms and 475 ms, as well as travel values of 0.02 mm (514 ms) and 0.04 mm (598 ms), are shown in Figure 9. The maximum average, 32.9 MPa, is obtained at a vibration time of 475 ms, followed by 31.9 MPa at 450 ms. The standard deviation suggests that the difference between these two vibration times is not significant. However, a decision was made according to the highest average strength and a vibration time of 475 ms was chosen as the optimum value leading to the best quality for samples welded with 0.06 mm-thick EDs.

Figure 6: (a) Cross-sectional micrograph of a weld not consolidated after a vibration time of 400 ms, with a 0.06 mm-thick ED. (b) Fracture surface of a sample fully welded after a vibration time of 400 ms. Both samples were welded with 500 N force and 86.2 µm amplitude.
Figure 7: Cross-sectional micrographs of welds not consolidated after (a) 450 ms, (b) 0.02 mm and (c) 0.04 mm. Arrows point at delamination and porosity under the first ply in (a) and under the first and second plies in (b) and (c). Corresponding representative power and displacement curves are shown in (d) and (e), respectively. The curves were shifted on the vertical axis for clarity.
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Figure 9: LSS of CF/PEI samples welded at different vibration times, with 0.06 mm-thick ED, 500 N welding force and 86.2 μm vibration amplitude. The last two points on the right, specimens welded at 514 ms and 598 ms, were controlled using displacement and correspond to 0.02 mm and 0.04 mm, respectively (Table 1).

3.3 Lap shear strength and output parameters under optimum welding conditions

For each ED thickness, five samples were welded according to the optimum conditions determined in Sections 3.1 and 3.2. Table 2 presents a summary of the vibration time, maximum power, energy and weld strength (LSS) for all thicknesses. On average, vibration time and energy increases with thickness, which is consistent with the resin volume that needs to be melted and squeezed out of the interface. The maximum power remains constant for all cases, taking into consideration the standard deviation. The average LSS is similar for samples welded with 0.25 mm and 0.50 mm-thick EDs, but it is lower for 0.06 mm, with a slightly higher standard deviation. In order to investigate these differences, fracture surfaces of samples welded with 0.06 mm and 0.25 mm-thick EDs were analyzed and are shown in Figure 9.

<table>
<thead>
<tr>
<th>ED thickness [mm]</th>
<th>Vibration time [ms]</th>
<th>Maximum power [%]</th>
<th>Energy [J]</th>
<th>LSS [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>475 ± 0</td>
<td>72 ± 11</td>
<td>798 ± 120</td>
<td>32.9 ± 2.2</td>
</tr>
<tr>
<td>0.25</td>
<td>566 ± 47</td>
<td>66 ± 2</td>
<td>942 ± 82</td>
<td>37.3 ± 0.9</td>
</tr>
<tr>
<td>0.50</td>
<td>604 ± 39</td>
<td>68 ± 3</td>
<td>1031 ± 28</td>
<td>36.5 ± 1.8</td>
</tr>
</tbody>
</table>

Table 2: Vibration time, maximum power, energy and LSS for all ED thicknesses at the optimum travel value. Power is a percentage of the maximum available power (3000 W).

In both cases, broken fibre bundles are present on the fracture surfaces. This demonstrates that the adhesion developed at the interface by the diffusion of the polymer chains extends into the substrates [4]. However, for 0.06 mm-thick energy directors, there are clear signs of resin degradation, as evidenced by the brown colour on the surface of the fibres. Figure 10 shows a high-resolution picture of a small area on the fracture surface. Numerous voids, resin flakes and a darker resin colour are observed, which are believed to be indicative of thermal degradation of PEI [8, 9]. It is suggested that 0.06 mm-thick energy directors are not as efficient as 0.25 mm and 0.50 mm EDs to achieve
preferential heat generation at the weld line. Due to the lower thickness, strain and viscoelastic heating created during the vibration phase are reduced [6]. As seen in Figure 7 (a), the first layer of the adherend started to be affected by heat generated at the interface at 450 ms, when the ED was almost completely melted. In the case of 0.25 mm-thick ED, the first ply of the composite specimen is only affected to the same extent well after the onset of the flow of the ED [7]. This indicates that for a thinner energy director, more heat is generated in the bulk adherend. Consequently, heat transfer from the weld line to the composite is less effective and overheating, as observed in Figure 10, can occur more easily. 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 mm and 0.50 mm energy directors.

In addition, while samples welded with 0.06 mm EDs showed the lowest vibration time and energy to reach the optimum weld quality (Table 2), it can only be achieved through time-control, not travel, which was demonstrated to lead to significant scatter in strength [4]. Therefore, based on the findings presented in this section, it is preferable to use thicker energy directors (i.e. 0.25 mm) to obtain consistent weld quality.

Figure 9: Fracture surfaces of samples welded at optimum travel distance for 0.06 mm (a) and 0.25 mm (b) energy directors. The welding parameters were 500 N force and 82.6 μm vibration amplitude.

Figure 10: Stereomicroscope image showing voids and resin degradation on the fracture surface of samples welded with 0.06 mm-thick energy director, 500 N welding force and 82.6 μm vibration amplitude.
4 CONCLUSIONS

In this paper, a detailed experimental examination of the influence of the thickness of flat energy directors on the USW process for thermoplastic composites was presented. Three thicknesses were investigated: 0.06 mm, 0.25 mm and 0.50 mm. Power and displacement curves for both 0.25 mm and 0.50 mm-thick EDs showed a similar behaviour with a clear definition of the five stages of the process. It was therefore possible to identify the optimum travel value for best weld quality based on stage 4.

However, power and displacement data for 0.06 mm-thick ED did not clearly show the five phases and the location of the optimum. Consequently, an investigation of samples welded without consolidation at different vibration times and travel values in the welding process had to be performed to assess the extent of the heat affected zone. It was confirmed through optical microscopy that delamination is present under the first ply of the adherend at the onset of the downward displacement of the sonotrode, at 450 ms. Based on LSS results, it was determined that a vibration time of 475 ms led to the best weld quality.

The output parameters of specimens welded at the optimum conditions for all thicknesses were compared. On average, vibration time and energy increased with thickness, which is consistent with the resin volume that needs to be melted. Lap shear strength was similar for 0.25 mm and 0.50 mm EDs, but slightly lower for 0.06 mm. Analysis of the fracture surfaces revealed the presence of resin flakes and voids. These observations suggest that thin energy directors are not as efficient as thicker EDs (i.e. 0.25 mm) to achieve preferential heat generation at the weld line. Therefore, it is recommended to use thicker energy directors (i.e. 0.25 mm) to be able to easily determine the optimum travel value and to obtain consistent weld quality without thermal degradation.

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