Ultrasonic welding of thermoplastic composite coupons for mechanical characterization of welded joints through single lap shear testing

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TITLE:

Ultrasonic welding of thermoplastic composite coupons for mechanical characterization of welded joints through single lap shear testing

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SHORT ABSTRACT:
A straightforward procedure for ultrasonic welding of thermoplastic composite coupons for basic mechanical testing is described. Key characteristics of this ultrasonic welding process are the use of flat energy directors for simplified process preparation and the use of process data for the fast definition of optimum processing conditions.

LONG ABSTRACT:
This paper presents a novel straightforward method for ultrasonic welding of thermoplastic-composite coupons in optimum processing conditions. The ultrasonic welding process described in this paper is based on three main pillars. Firstly, flat energy directors are used for preferential heat generation at the joining interface during the welding process. A flat energy director is a neat thermoplastic resin film that is placed between the parts to be joined prior to the welding process and heats up preferentially owing to its lower compressive stiffness relative to the composite substrates. Consequently, flat energy directors provide a simple solution that does not require molding of resin protrusions on the surfaces of the composite substrates, as opposed to ultrasonic welding of unreinforced plastics. Secondly, the process data provided by the ultrasonic welder is used to rapidly define the optimum welding parameters for any thermoplastic composite material combination. Thirdly, displacement control is used in the welding process to ensure consistent quality of the welded joints.

According to this method, thermoplastic-composite flat coupons are individually welded in a single lap configuration. Mechanical testing of the welded coupons allows determining the apparent lap shear strength of the joints, which is one of the properties most commonly used to quantify the strength of thermoplastic composite welded joints.

INTRODUCTION:

Thermoplastic composites (TPC) have the ability to be welded, which contributes to their cost-effective manufacturing. Welding requires local heating under pressure to soften or melt the thermoplastic resin of the joining surfaces and to allow for intimate contact and subsequent inter-diffusion of thermoplastic polymer chains across the welding interface. Once molecular inter-diffusion is achieved, cooling down under pressure consolidates the welded joint. Several welding techniques are applicable to thermoplastic composites which differ mainly in the source of heat[1], however, the main "adhesion" mechanism, i.e. molecular entanglement, remains unchanged. Ultrasonic welding offers very short welding times (in the order of a few seconds), easy automation and it is virtually independent of the type of reinforcement in the thermoplastic composite substrates. Moreover, it offers the possibility for in situ monitoring[2,3], which can be used for in line quality assurance or for fast definition of processing windows[4]. Ultrasonic welding of thermoplastic composites is mostly a spot welding process, however successful welding of longer seams through sequential ultrasonic welding has been reported in literature[5]. As opposed to resistance or induction welding, ultrasonic welding has not been industrially applied for structural joints between thermoplastic composite parts so far. Nevertheless, significant effort is currently being devoted to further development of structural ultrasonic welding of thermoplastic composites for aircraft applications.

In ultrasonic welding, the parts to be joined are subjected to a combination of static force and high-frequency low-amplitude mechanical vibrations transverse to the welding interface, which results in heat generation through surface and viscoelastic heating. Preferential heating at the welding interface is promoted through the use of resin protrusions on the surfaces to be welded which undergo higher cyclic strain, and thus higher viscoelastic heating, than the substrates[6]. Force and vibration are exerted onto the parts to be welded through a sonotrode connected to a press and to an ultrasonic train consisting of piezo electric converter and booster. Depending on the distance between the point where the sonotrode contacts the part to be joined and the welding interface, a distinction can be made between near-field and far-field ultrasonic welding. Near-field welding (less than 6 mm between sonotrode and welding interface) is applicable to a wider range of materials whilst the applicability of far-field welding to a specific thermoplastic material is highly dependent on the ability of the material to conduct sound waves[6].

The ultrasonic welding process can be divided into three main phases. Firstly, a force build-up phase, during which the sonotrode gradually increases the force on the parts to be welded until a certain trigger force is reached. No vibration is applied during this phase. Secondly, a vibration phase, which starts once the trigger force is reached. In this phase the sonotrode vibrates at the prescribed amplitude for a certain amount of time generating the heat needed for the welding process. Microprocessor controlled ultrasonic welders provide several options to control the duration of the vibration phase, among them time (i.e. direct control), displacement or energy (indirect control). The force applied during this phase, i.e. welding force, can be kept constant and equal to the trigger force or can be gradually varied during application of the vibration. Thirdly, a solidification phase, during which the welded parts are allowed to cool down under a certain solidification force for a certain amount of time. No vibration is applied during this last stage.

Welding force, vibration amplitude, vibration frequency and duration of the vibration phase (either directly or indirectly controlled through energy or displacement) are the welding parameters that control heat generation. Force, amplitude and duration are user-defined parameters, while frequency is fixed for each ultrasonic welder. Solidification force and solidification time, also welding parameters, do not intervene in the heating process but affect the consolidation and, together with the rest of parameters, the final quality of the welded joints.

This paper presents a novel straightforward method for near-field ultrasonic welding of individual TPC coupons in a single lap configuration for subsequent mechanical, single lap shear (LSS), testing following ASTM (American Society for Testing and Materials) D 1002 standard. Mechanical testing of the welded coupons allows determining the apparent lap shear strength of the joints, which is one of the properties most commonly used to quantify the strength of thermoplastic composite welded joints[7]. The welding method described in this paper is based on three main pillars. Firstly, loose flat energy directors are used for preferential heat generation at the joining interface[8,9] during the welding process. Secondly, the process data provided by the ultrasonic welder is used to rapidly define the optimum duration of the vibration phase for a specific force/amplitude combination [2,4]. Thirdly, the duration of the vibration phase is indirectly controlled through the displacement of the sonotrode in order to ensure consistent quality of the welded joints[4]. This welding method offers the following main novelties and advantages with regards to state-of-the-art welding procedures for thermoplastic composites: (a) simplified sample preparation enabled by the use of loose flat energy directors instead of traditional moulded energy directors[3], and (b) fast and cost-efficient definition of processing parameters based on in-situ process monitoring as opposed to common trial and error approaches. Although the method described in this paper is geared towards obtaining a very specific and simple welding geometry it can serve as a basis to define a procedure for the welding of actual parts. A main difference in that case results from constrained flow of the energy director as opposed to unrestricted flow at the four edges of the overlap in single lap coupons.

PROTOCOL:

1. Specimen cutting and preparation for ultrasonic welding

1.1) Cut rectangular samples measuring 25.4 mm x 101.6 mm from a larger thermoplastic composite laminate using a cutting technique that prevents delamination of the edges of the samples (e.g. diamond-saw or water-jet cutting).

Note: The dimensions of the samples are based on ASTM D 1002 standard.

1.1.1) Since strength of the welded joints depends on the fiber orientation on the surfaces to be welded[10], take care to cut all the samples in the same orientation.

1.2) After cutting, dry samples in an oven as per the manufacturer's recommendations in case the thermoplastic resin tends to absorb moisture (e.g. 6 hours at 135 °C for six-layer carbon fiber reinforced polyetherimide, CF/PEI, samples).

1.3) Cut flat energy directors made out of neat thermoplastic film (same resin as the matrix in the composite) to size (approximately 26 mm x 26 mm) with a thickness of at least 0.25 mm. If necessary, dry the energy director following manufacturer's recommendations (e.g. 1 hour at 135 °C for PEI energy director).

1.4) Before welding, inspect specimens one by one for delaminated corners and discard if necessary. Clean them using a degreaser and a cotton cloth. Clean the flat energy directors following the same procedure.

2. Ultrasonic welding of single lap shear coupons

Note: A micro-processor controlled ultrasonic welder able to weld at constant amplitude is used in this step. The welder outputs process data, such as dissipated power and displacement of the sonotrode versus time to data acquisition software in a computer. A custom-built jig designed and manufactured to accurately position and clamp single lap shear samples during ultrasonic welding is used in this step (see Figure 1).

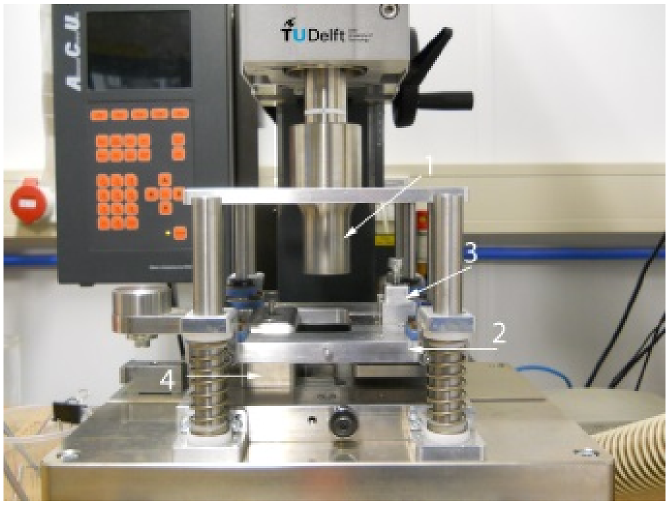


Figure 1: Ultrasonic welder and custom-built welding setup used in this study. 1: sonotrode, 2: sliding platform, 3: clamp for the upper specimen (attached to 2), and 4: clamp for the lower specimen (Reprinted from reference 4 with permission from Elsevier).

2.1) Fill out a logbook sheet before each welding experiment.

2.1.1) Take note of the following parameters: room temperature and humidity, welding setup reference, sonotrode type, sample number and materials, width and thickness of top and bottom samples, and thickness of the energy director.

2.2) Turn on the ultrasonic welder and computer. Start the data acquisition software and open a new session.

2.3) If not already in place, change the sonotrode to a cylindrical sonotrode with a diameter of 40 mm so that its bottom surface completely covers the welding area.

Note: A different shape of sonotrode can be used, but its bottom surface should not be smaller than the welding area.

2.4) Position and fixate specimens and energy director into the welding jig (see Figure 1).

2.4.1) Attach a flat energy director to the bottom specimen with adhesive tape so that it covers a slightly larger area than the area to be welded (12.7 mm x 25.4 mm).

2.4.2) Place the bottom sample into the jig and clamp it by tightening the top screw.

2.4.3) Tape the other end of the energy director to the base of the setup so that it stays in place during the process.

2.4.4) Place the upper sample into the clamp, align it and tighten the top screw.

2.4.5) Position the clamp for the top sample into the sliding platform and tighten both screws.

2.4.6) Before proceeding further, tighten all four screws once more.

2.5) Determine the optimum duration of the vibration phase based on the displacement of the sonotrode to achieve the highest weld strength, as described in steps 2.5.1) to 2.5.8).

Note: An optimum duration of the vibration phase is determined for each desired combination of welding force and vibration amplitude.

2.5.1) Set the ultrasonic welder to differential displacement-control mode.

2.5.2) Input welding force and vibration amplitude into the ultrasonic welder (for example, 300 N and 86.2 μm).

Note: For this ultrasonic welder, 86.2 μm corresponds to the peak-to-peak vibration amplitude.

In the machine settings, it is expressed as half this value, 43.1 μm.

2.5.3) Input the sonotrode displacement, or travel, at the end of the vibration phase as a value equal to the initial thickness of the energy director (for example, 0.25 mm).

2.5.4) Input solidification force and time into the ultrasonic welder (for example, 1000 N and 4000 ms).

2.5.5) When ready, put on soundproof headphones and start the ultrasonic welding process.

2.5.6) After the completion of the process, take note of the following output parameters: welding distance, maximum power, vibration time and energy. Remove the coupon from the welding setup and write its identification number on both ends with a paint marker.

2.5.7) Export the welding data (power and displacement of the sonotrode) to a spreadsheet and plot the power and displacement versus time curves during the vibration phase of the process.

Note: The displacement curve should plot the downward displacement of the sonotrode relative to its position at the onset of the vibration phase.

2.5.8) Identify the displacement in the middle of the power plateau (stage 4) as shown on Figure 2 (in this case, 0.10 mm).

Note: This particular displacement value is the optimum travel that controls the duration of the vibration phase and will be used in every subsequent weld for the same welding force and amplitude.

[Place Figure 2 here]

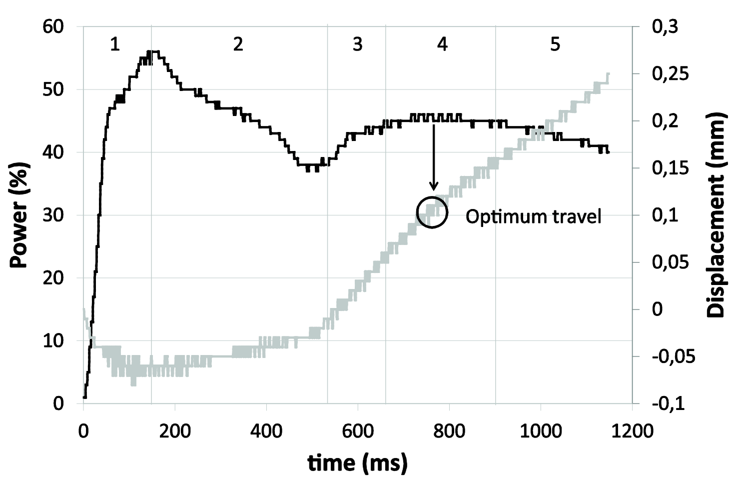


Figure 2: Power (black) and displacement (grey) curves for the ultrasonic welding process indicating optimum travel value. The vibration phase of the ultrasonic welding can be divided in 5 stages. Optimum travel value is located within stage 4. Study case: carbon fiber reinforced polyetherimide -PEI substrates, 0.25 mm-thick flat PEI energy director, 300 N welding force, 86.2 µm vibration amplitude, 0.25 mm travel. (Reprinted from reference 4 with permission from Elsevier)

2.6) Weld coupons at the optimum travel value for the given welding force and amplitude combination.

2.6.1) Repeat steps 2.1) to 2.5.6) for each weld. In step 2.5.3), use the optimum travel determined in step 2.5.8) for the corresponding welding force and amplitude combination.

Note: All LSS tests are carried out following ASTM D 1002 on a universal testing machine with a crosshead speed of 1.3 mm/min.

3) Single lap shear strength (LSS) testing of welded coupons

3.1) Measure and take note of the width of the overlap for each welded coupon.

3.2) Turn on the universal testing machine and open the testing procedure for LSS on the computer.

3.3) In the testing interface, enter the sample number and dimensions of the overlap. Set the force to 0 and the grip-to-grip separation to its initial position (for example, 60 mm).

3.4) Position the sample in the grips of the testing machine as shown on Figure 3.

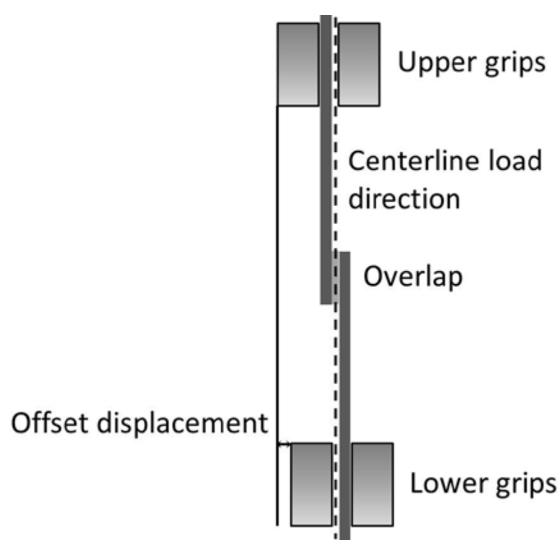


Figure 3: Schematic view of the clamping in the Zwick/Roell 250 kN universal testing machine (not to scale). The offset displacement between the top and lower grips allows aligning the load direction with the center weld line to minimize bending during the lap shear strength test.

3.5) Start the testing procedure from the computer by clicking the “Start” button.

3.6) After the sample breaks, remove it from the grips and secure both parts together with tape.

3.7) Repeat steps 3.3) to 3.6) for all other samples.

3.8) When the tests are completed, export the data to a spreadsheet and calculate the average LSS value, according to the procedure described in the standard, for each welding force and amplitude combination.

REPRESENTATIVE RESULTS:

Carbon fiber reinforced polyetherimide (CF/PEI) samples were welded following the method described in this paper. The samples were obtained from a composite laminate made out of five-harness satin fabric CF/PEI, with $(0/90)_{3S}$ stacking sequence and 1.92 mm nominal thickness. Samples were cut from this laminate so that the main apparent orientation of the fibers was parallel to their longest side. Flat PEI energy directors with 0.25 mm thickness were used. Both the composite samples and the energy directors were dried in an oven at 135 °C for 6 and 1 hour, respectively, as indicated by the manufacturer. Using power and displacement curves obtained for 0.25 mm travel, an optimum travel value around 0.10 mm, i.e. 40% of the initial thickness of the energy director, was obtained for the CF/PEI samples welded under 300 N welding force and 86.2 µm peak-to-peak vibration amplitude (see Figure 2). Samples welded under these welding parameters (300 N welding force, 86.2 µm amplitude and 0.10 mm travel) and solidification force and time of 1000 N and 4 s, respectively, yielded 37.3±1.6 MPa (average ± standard deviation of five samples) apparent lap shear strength. Power curves obtained for each one of these samples as well as a representative cross-section micrograph and fracture surface are shown in Figures 4 and 5, respectively.

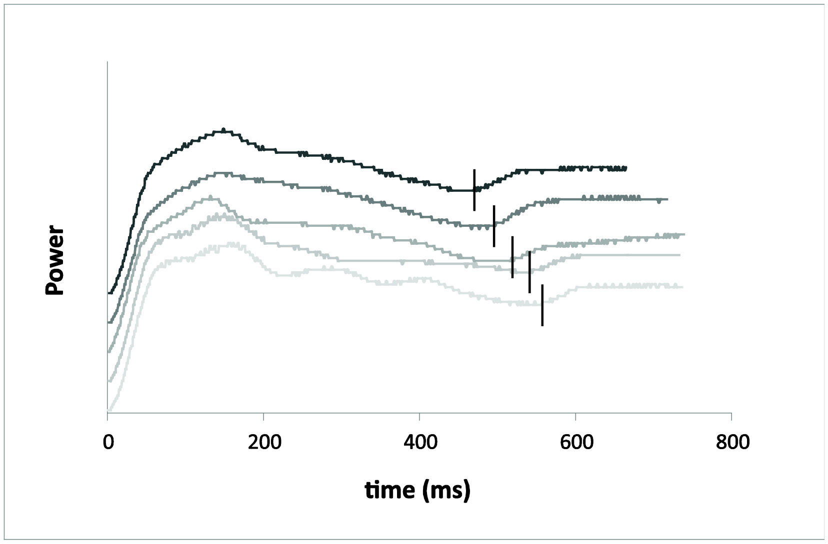
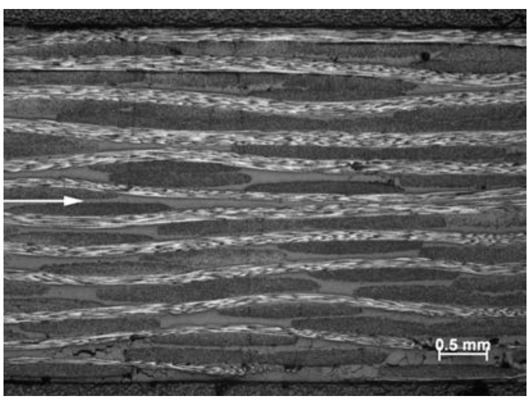


Figure 4: Power curves for CF/PEI coupons welded under optimum travel. The power curves (shifted vertically for clarity) show consistent ending of the welding process at stage 4. Vertical lines indicate the onset of stage 3. Study case: CF/PEI substrates, 0.25 mm-thick flat PEI energy director, 300 N welding force, 86.2 µm vibration amplitude, 0.10 mm travel.



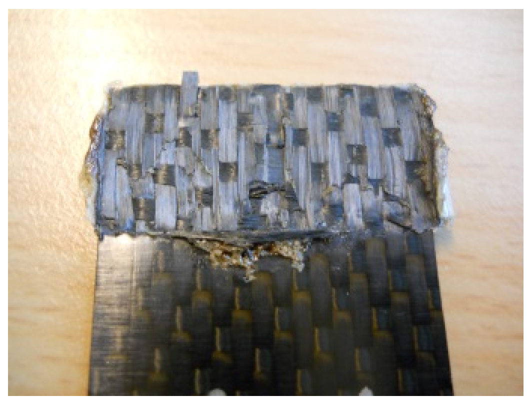


Figure 5: Typical cross-section micrograph (left) and fracture surface (right) for CF/PEI coupon welded under optimum travel. Welded joints resemble a thicker composite laminate with no visible differences between the weld line (indicated by arrow) and the substrates. After lap shear testing, fracture surfaces show significant fiber tearing. Study case: CF/PEI substrates, 0.25 mm-thick flat PEI energy director, 300 N welding force, 86.2 µm vibration amplitude, 0.10 mm travel. (Reprinted from reference 4 with permission from Elsevier)

In order to check the validity of the approach presented in this paper to determine the optimum travel for a certain force/amplitude combination, samples were welded at different travel values, below and above the optimum travel, and subsequently tested. The rest of the welding parameters used for the welding of these samples were, as in the previous case, 300 N welding force, 86.2 µm amplitude, 1000 N solidification force and 4 s solidification time. Figure 6 shows the apparent lap shear strength as a function of the travel (represented as a percentage of the initial thickness of the energy director).

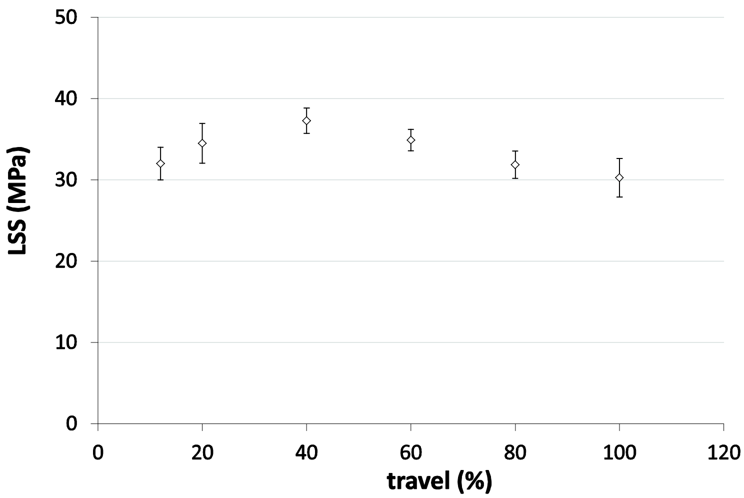


Figure 6: Apparent lap shear strength of CF/PEI coupons welded under different travel values. Travel is represented here relative to the thickness of the energy director. Study case: CF/PEI substrates, 0.25 mm-thick flat PEI energy director, 300 N welding force, 86.2 µm vibration amplitude, variable travel. (Reprinted from reference 4 with permission from Elsevier)

Finally, displacement-controlled welding was compared to other possibilities offered by the ultrasonic welder such as time- or energy-controlled welding. With this purpose, the lap shear strength values depicted in Figure 4 were plotted as a function of the vibration time (Figure 7) and of the welding energy (Figure 8). Vibration time and energy values for all the samples welded in this study were provided by the ultrasonic welder as an output of the welding process.

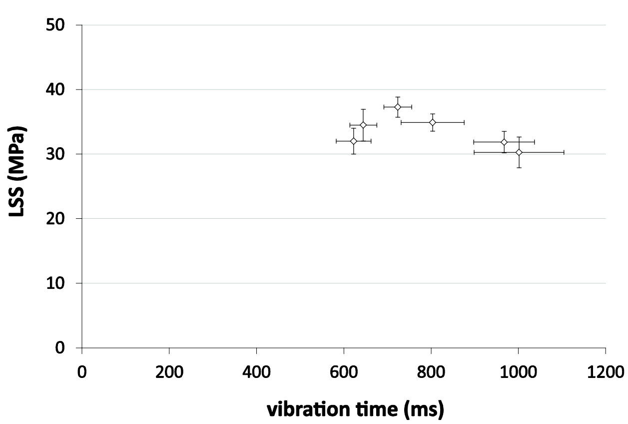


Figure 7: Apparent lap shear strength of CF/PEI coupons versus vibration time. Obtained by using vibration times of samples used to plot Figure 6. Study case: CF/PEI substrates, 0.25 mm-thick flat PEI energy director, 300 N welding force, 86.2 µm vibration amplitude, variable travel. (Adapted from reference 4 with permission from Elsevier)

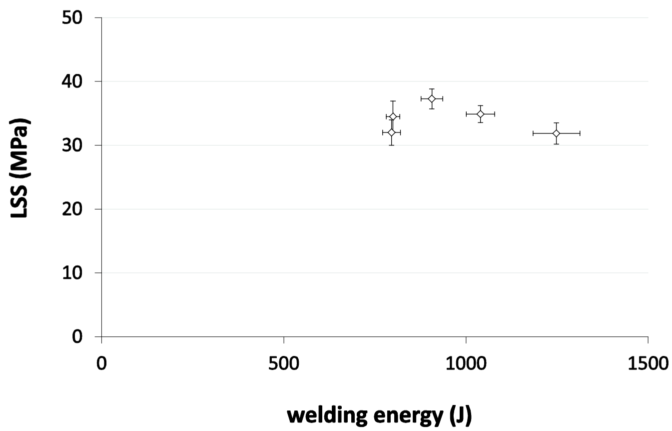


Figure 8: Apparent lap shear strength of CF/PEI coupons versus welding energy. Obtained by using welding energy values of samples used to plot Figure 6. Study case: CF/PEI substrates, 0.25 mm-thick flat PEI energy director, 300 N welding force, 86.2 µm vibration amplitude, variable travel. (Adapted from reference 4 with permission from Elsevier)

DISCUSSION:

The results presented in the previous section indicate the appropriateness of the straightforward method proposed in this paper for ultrasonic welding of thermoplastic composite single lap coupons for the purpose of mechanical testing. The following paragraphs discuss how the results validate the three main pillars of the method, i.e. use of flat loose energy directors, use of process feedback to define optimum duration of the vibration and use of displacement control, as well as the applicability and limitations of the technique.

With regards to the first pillar, flat energy directors are shown to allow successful welding of the TPC coupons. In ultrasonic welding of unreinforced plastics, energy directors in the form of resin protrusions with a smaller cross-sectional area than that of the joining overlap are required to generate higher cyclic strains and hence, preferential viscoelastic heat generation at the welding interface[6]. However, in ultrasonic welding of TPCs, flat energy directors with the same cross–sectional area as the welding overlap do successfully result in preferential viscoelastic heating at the welding interface owing to the lower compressive stiffness of the flat energy director and thus higher cyclic strains during the welding process. The heat generated at the interface melts the energy director and is transferred to the substrates. Under the effect of the welding force, the molten energy director is squeezed out of the welding overlap until the prescribed travel is reached. Optimum travel values result in fully welded overlaps and cross sections that resemble a thicker laminate since the thickness of the weld line is similar to that of the resin-rich areas in the substrates (see Figure 5).. It should be noted that, when using flat energy directors, optimization of the energy director is not needed in order to achieve fully welded overlaps[8], as opposed to more traditional energy director solutions, in which the size, shape and spacing between energy directors need to be optimized to achieve full coverage of the intended welding area[10,11]. Likewise, as compared to solutions such as triangular energy directors traditionally used for ultrasonic welding of TPCs[3], flat energy directors have been shown to result in similar weld strength values while not having a significant negative impact on other important output of the process such as maximum power, energy or welding time[8].

With regards to the second pillar, for a certain combination of welding force and amplitude, it is possible to define optimum travel values, i.e. travel values that lead to maximum strength, based on the power and displacement curves provided by the ultrasonic welder. Essentially, the different events in the power and displacement curves during the vibration phase of the welding process can be related to the physical changes occurring in the energy director and the TPC substrates during heating[2]. Accordingly, and as shown in Figure 2, the vibration phase of the welding process can be divided into the following 5 stages[2]:

Stage 1, characterized by continuous increase of the dissipated power until a maximum is reached and small retraction of the sonotrode to accommodate the vibration. In stage 1 heating of the energy director without any observable physical changes at the welding interface occurs. Stage 2, characterized by power decrease and no significant displacement of the sonotrode. In stage 2 the flat energy director starts to locally melt as a hot-spot nucleation and growth process. Stage 3, characterized by power increase and downward displacement of the sonotrode. In stage 3 the complete energy director is molten and starts to flow under the effect of the welding force. Stage 4, characterized by a power plateau and downward displacement of the sonotrode. In stage 4 the matrix in the uppermost layers of the composite substrates starts to locally melt along with the squeeze flow of the energy director. Stage 5, characterized by declining power and downward displacement of the sonotrode. In stage 5 melting of the matrix in the substrates is predominant.

The highest weld strength occurs during stage 4 since melting of the matrix in the uppermost layers of the composite substrates enables diffusion of polymer chains across the welding interface and hence molecular entanglement between the two substrates. This molecular entanglement develops a strong connection which results in fiber tearing during single lap testing, as seen in Figure 5. Beyond this optimum stage, excessive melting of the matrix in the composite substrates results in significant fiber distortion at the welding interface, which is believed to cause a drop in the weld strength[4]. The results presented in Figure 6, which correspond to a specific combination of welding force and amplitude of vibration, support this discussion. It must be noted that different force/amplitude combination would result in different output from the welding process in terms of maximum power and energy consumed as well as duration of the vibration phase[2]. Nevertheless, the method for determining the optimum travel value is independent of the chosen force/amplitude combination[4].

With regards to the third pillar, displacement-controlled welding resulted in relatively low scatter in the apparent lap shear strength of joints welded in the optimum conditions. This is believed to result from the fact that all the samples were consistently welded in the same stage (i.e. stage 4) within the vibration phase of the process) as shown in Figure 4. Figure 7 indicates that if time had been used as the controlling parameter for the welding process, a higher scatter in the strength values could have been expected due to the significant overlapping in the vibration times for different travel values. According to Figure 8 and to results presented in literature[12], energy is a better option than time as the controlling parameter. However, the welding energy is highly dependent on thickness of the substrates and nature of the welding jig and therefore the optimum energy value changes significantly when any of those two variables change[4]. Contrarily, displacement of the sonotrode is directly related to the squeeze flow of the energy director and matrix at the welding interface and thus can be expected to be less sensitive to changes in any of the above-mentioned variables[4].

The novel method described in this paper allows straightforward near-field ultrasonic welding of thermoplastic composite coupons for single lap shear testing. The results presented refer to welding of CF/PEI composites but the same method has been successfully applied to other reinforced thermoplastic composites such as CF/polyphenyplene sulfide (PPS)[8]. As described in the paper, the method is directly applicable to the welding of a very specific geometry, however, in the case a different welding geometry is considered, there are three critical points that need to be taken into account. Firstly, increasing of the contact area between the parts to be welded has a direct impact on the maximum power dissipated during the welding process. Consequently, the maximum area that can be welded in one shot is limited by the maximum power delivered by the ultrasonic welder. Secondly, the method described in this paper considers unrestricted flow of the molten energy director out of the four edges of the welding overlap. A different welding configuration might, however restrict the polymer flow. This can be expected to have an impact on the evolution of the displacement of the sonotrode during the welding process and to probably impose limitations to displacement-controlled welding. Thirdly, if the thickness of the parts is such that the distance from the sonotrode to the welding interface is higher than 6 mm, specific considerations of far-field ultrasonic welding should be accounted for. Nevertheless, the method presented in this paper can be considered as a basis for the development of ultrasonic welding procedures for the assembling of actual thermoplastic composite structures. The main novelties and advantages of this method are simplified processing due to the usage of loose flat energy directors and the usage of the data provided by the welder to quickly define the optimum duration of the vibration for different combinations of force and amplitude. As compared to current trial-and-error procedures, the definition of process parameters based on process data has the potential to offer significant savings in the effort and time needed to develop welding processes for specific applications.

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DISCLOSURES:

The authors declare that they have no competing financial interest.

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