IMPROVING WELD UNIFORMITY IN CONTINUOUS ULTRASONIC WELDING OF THERMOPLASTIC COMPOSITES

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Abstract
Continuous ultrasonic welding (CUW) is an innovative high-speed joining method for thermoplastic composites. Currently, thin flat energy directors (EDs) are used to focus the heat generation at the weld line. The resulting fracture surfaces exhibit large areas of intact ED, resulting in a non-uniform weld, and significantly lowering the strength. The goal of this study is to improve the weld uniformity of continuous ultrasonically welded joints. In the first part of this paper we found that a 0.20 mm-thick woven mesh ED significantly improved the weld uniformity and strength in comparison to a 0.08 mm thick flat ED. The second part the paper focuses on understanding why the mesh gives this improved weld uniformity by analyzing the feedback data from the welder and by performing a microscopy analysis of the weld line at different moments during the static welding process. It was found that at the beginning of the welding process the mesh filaments expand within the open areas of the mesh while flattening; the mesh is being pre-formed in between the adherends. This pre-forming most likely created a good uniform intimate contact between the ED and adherends, which most likely resulted in a uniform heat generation and therefore created a uniform weld line. Because energy directing meshes make it possible to create uniform weld lines, they are expected to play an important role in the future for the continuous ultrasonic welding of thermoplastic composites.

1 Introduction

Ultrasonic welding is a favourable joining method for thermoplastic composites [1]. It is characterized by very short cycle times, high joint strength, low energy consumption and the potential to be automated [1–7]. During the welding process a sonotrode presses down on the stack to be welded with a welding force, while exerting high frequency an low amplitude vibrations. These vibrations heat up the interface via viscoelastic heating and surface friction [8]. An energy director (ED) is used at the interface to focus the heat generation. The low stiffness of the ED compared to the adherends introduces high cyclic strains in the ED causing it to heat up quicker than the adherends [9]. A typical solution is to use a flat resin film made from the

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same matrix material as the adherends [2,3,7,10]. In order to obtain high a strength weld with a flat ED, the welding process typically involves squeeze out of the ED going hand-in-hand with the downward displacement of the sonotrode [2,3,5,7,10].

Ultrasonic welding of thermoplastic composited is so far only known as a spot welding technique. Continuous ultrasonic welding is typically used in industry to create continuous seams in fabrics and flexible materials. For most aerospace applications a continuous weld line is preferred over a discontinuous row of welded spots. Recently, our research has shown that ultrasonic welding can be used to make continuous seams in thermoplastic composites [11]. A thin 0.08 mm-thick flat ED was proposed by Senders et al. to minimize the squeeze flow of the energy director. In order to have squeeze flow during continuous ultrasonic welding, the top adherend must be flexible enough to allow the downward displacement of the sonotrode accommodating the temporary thickness difference at the weld stack. They expected that the stiff adherends and the un-molten ED ahead of the sonotrode would not allow the sonotrode to travel downwards, therefore they expected no squeeze flow to occur [11]. The squeeze flow was minimized, but the weld lines obtained in their research contained areas with intact ED resulting in non-uniformly welded joint area.

In this paper we aimed at improving the weld uniformity of continuous ultrasonically welded joints. In the first part of this paper, the use of an energy directing 0.20 mm-thick mesh is investigated for continuous ultrasonic welding in comparison to the 0.08 mm-thick flat ED. The second part of the paper is performed using static welding, and focuses on understanding why the mesh improves the uniformity of the welded area by analyzing the feedback curves from the welding machine and performing cross-sectional microscopy.

2 Experimental procedures

2.1 Materials

The thermoplastic composite laminates are made from carbon fibre powder-coated semi-preg fabric (five harness satin weave) reinforced CF/PPS. The product code of the material is CF 0286 127 Tef4 43% (TenCate Advanced Composites, the Netherlands). The laminates are stacked according to $[0/90]_{3s}$ sequence, and consolidated in a hot platen press for 20 min at $320°C$ and 1 MPa pressure. For the continuous welding process 220 mm-long by 101.6 mm-wide plates were cut from the laminates. For the static welding process 25.4 mm by 101.6 mm coupons were cut from the laminates. Two different energy directors were used in this study: a 0.08 mm-thick and a 0.20 mm-thick mesh. The 0.08 mm-thick flat film was supplied by TenCate and has the product name Rayotec S 080 PPS film 1280 mm. The 0.20 mm-thick mesh was supplied by PVF FmbH, Germany. The product code of the mesh is PPS100. The mesh has a filament diameter of 100 μm. The two ED's are listed in Table 1 together with their resin volume for an area of 12.7 mm by 25.4 mm. The table shows that the 0.08 mm-thick film and the 0.20 mm-thick mesh contain almost a similar amount of material.

Table 1: Overview of energy directors, their thickness and resin volume for a 12.7 mm by 25.4 mm overlap.

ED type	**Thickness** $[mm]$	**Resin volume** $[mm^3]$
Flat film	0.08	25.8
Mesh	0.20	22.6

2.2 Continuous ultrasonic welding procedure

The 220 mm-long plates were welded in a 12.7 mm-overlap single lap shear configuration shown in Figure 1c. The in-house built continuous ultrasonic welding machine is shown in Figure 1. The converter (C20-10), booster and sonotrode were obtained from Rinco Ultrasonics, Switzerland. The maximum continuous output power of the machine is 1200 W. During the welding process, the welding train shown in Figure 1a moves over the weld line with 45 mm/s pneumatically compressing the welding stack with a constant welding force of 500 N and applying 20 kHz ultrasonic vibrations with an amplitude of 82.5 μm. In Figure 1b it can be seen that the plates are kept in place by bar clamps, while the sonotrode moves over the weld line. In 1c the orientation of the sonotrode is shown.

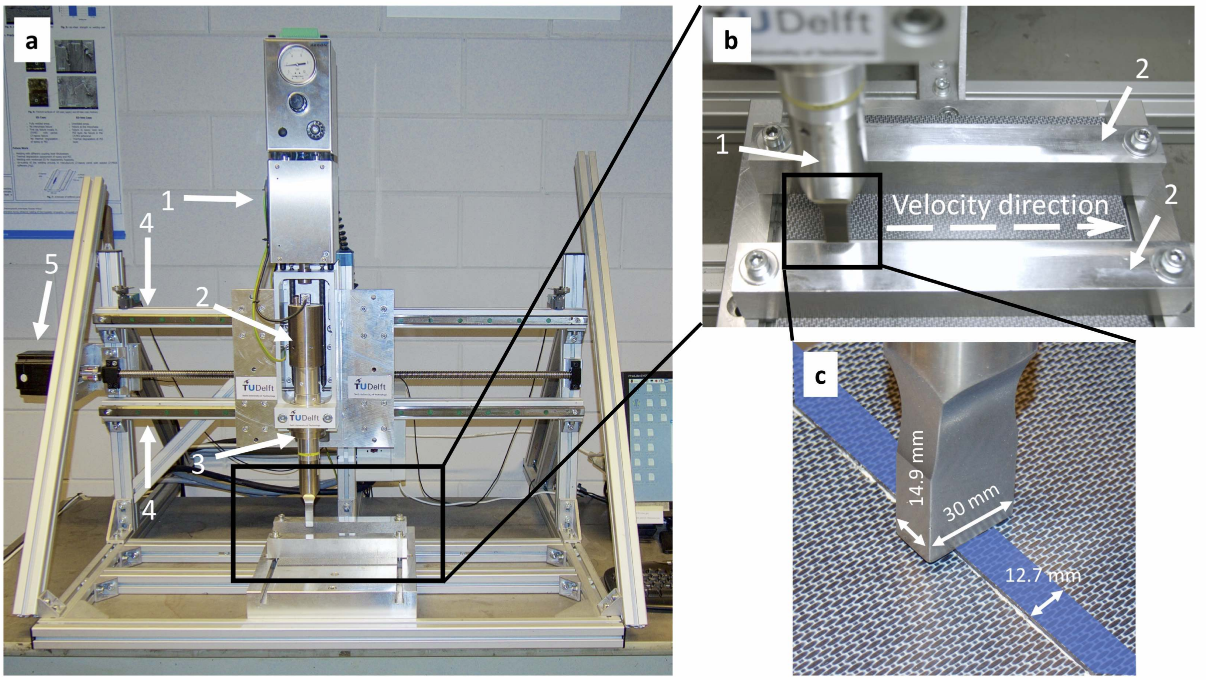
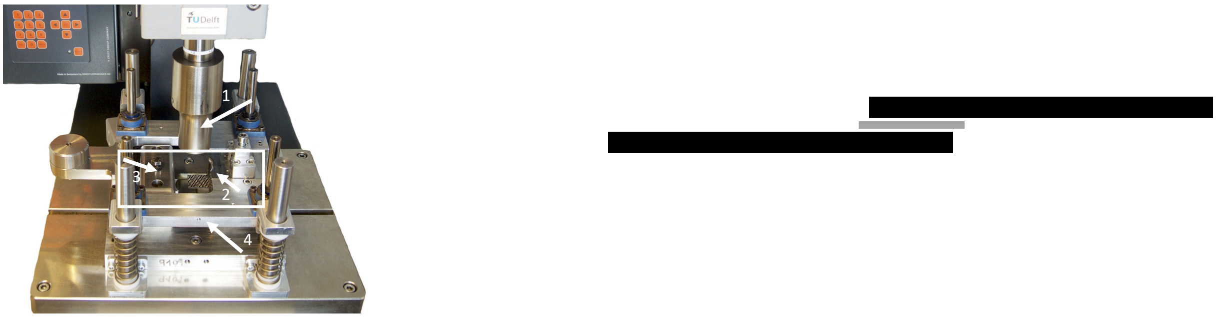


Figure 1: (a) Overview of setup used for continuous ultrasonic welding (1. pneumatic press, 2. converter, 3. booster, 4. rails for moving the stack, and 6. stepper motor). (b) 1. Sonotrode with indicated welding direction, and 2. bar clamps. (c) Close-up of weld line (blue area) and sonotrode with indicated dimensions.

2.3 Static ultrasonic welding process

For the analysis of the deformation behaviour of the mesh, a Rinco Dynamic 3000 static 20 kHz ultrasonic welding machine with a circular 40 mm-diameter sonotrode was used. The welding set-up shown in Figure 2a is used to weld the single lap shear coupons with an overlap of 12.7 mm shown in Figure 2b. The spring supported platform allows the upper coupon to freely move vertically during the welding process, reducing the bending of the coupon. To obtain the full power and displacement curves, welds were made for a duration 550 ms. The weld settings are 500 N welding force, a vibrational amplitude of 86.5 μm and a consolidation force of 1000 N during 4000 ms. For the analysis of the deformation behaviour of the energy directing mesh additional welds were made. The welding process was stopped at different moments during the welding process.



(a) (b)

Figure 2: (a) In-house built welding jig and ultrasonic welding machine, (1) sonotrode, (2) upper coupon clamp, (3) lower coupon clamp, and (4) spring-supported platform for the upper clamp. The white box shows the location and orientation of the lap shear coupons schematically shown in (b). (b) CF/PPS coupons (black) and ED (grey).

2.4 Mechanical testing and cross-sectional characterization

After the continuous ultrasonic welding, the plates were cut into thirteen 14 mm-wide lap shear coupons discarding the two edges at the start and the end of the weld, resulted into eleven LSS coupons. The lap shear coupons cut from the continuously welded plates were mechanically tested with a Zwick/Roell 250 kN universal testing machine with hydraulic grips at a cross-head speed of 1.3 mm/min according to ASTM D 1002. The welds made with the static machine to analyse the deformation behaviour of the mesh were cut in the middle of the joint and analysed with cross-sectional microscopy with a Keyence VH-Z100UR digital microscope. The same microscope was used to obtain top view images of the mesh before and at the beginning the welding process. At the beginning of the welding process at 80 ms, no strength was generated yet, therefore the top adherend could easily be removed from the ED to take microscopy images.

3 Results

3.1 Energy director types in continuous ultrasonic welding

Figure 3 shows the fracture surfaces after single lap shear testing of the weld lines made with the two different energy directors considered in this study: a 0.08 mm-thick flat film (a), and a 0.20 mm-thick mesh (b). For the 0.08 -thick flat film, it can be seen that large areas with intact ED are present in the weld line. The areas surrounding the intact ED show a significant amount of voids. This is in agreement with the findings from Senders et al. [11]. For the 0.20 mm-thick mesh, no intact mesh could be identified anymore in the weld line. All the fracture surfaces of the entire weld line show a consistent appearance, but resin rich areas containing voids were seen at the edges indicated with black arrows in Figure 3b.

In Table 2 the single lap shear strength results are shown for the plates welded with the two different energy directors. The 0.08 mm-thick flat film shows the lowest strength with 18.8 MPa, which is most likely due to the presence of large parts of intact ED. For the 0.20 mm-thick mesh the strength is much higher with 33.7 MPa and the standard deviation low with only ± 2.4 MPa.

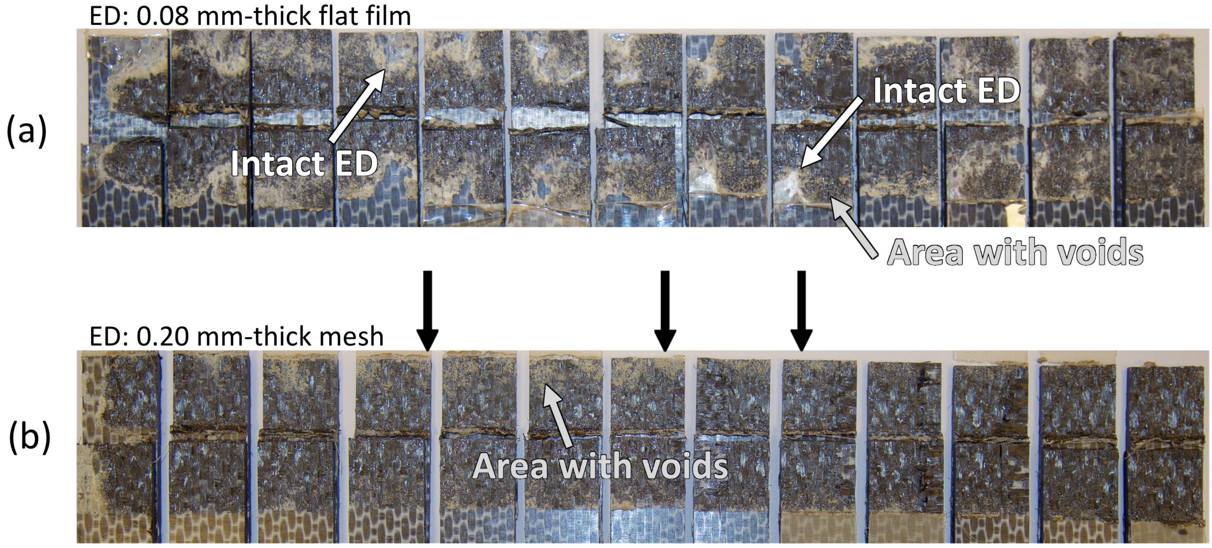


Figure 3: Representative fracture surfaces obtained after lap shear testing of 220 mm-long laminates continuously welded with two different types of energy directors: (a) 0.08 mm-thick flat film, and (b) a 0.20 mm-thick mesh. The white arrows indicate intact ED. The grey arrows indicate areas with voids. Welded with 45 mm/s with 500 N welding force and an vibrational amplitude of 82.5 μm

Table 2: Single lap shear strength results for continuously welded plates for the two different energy director types.

ED type	**LSS [MPa]**	**Standard deviation [MPa] (n=11)**
0.08 mm-thick flat film	18.8	± 6.2
0.20 mm-thick mesh	33.7	± 2.4

3.2 Mesh behaviour at the weld interface

In order to understand why the mesh has a beneficial behavior in comparison to flat EDs, the mesh deformation is studied in this section. In Figure 4 three representative full power and displacement curves are shown for static welds made with 0.20 mm-thick energy directing mesh. In the same figure a top view is shown of the mesh before welding (A at 0 ms) and at the beginning of the process (B at 80 ms). A cross-sectional micro-graph is presented in C (at 150 ms). Looking at the power and displacement curves, the following can be observed: from the start of the welding process until approximately 120 ms an increasing displacement can be seen together with a rapid increase in power. After approximately 120 ms a displacement plateau is reached at a displacement of 0.06 mm during which the mesh continues to heat up as seen by the increase in dissipated power [2]. At the end of the displacement plateau the power reaches a maximum, after which it decreases with increasing displacement. When looking at the the top view microscopy image in Figure 4 at moment A it can be seen that the mesh is fully intact. After 80 ms of welding at moment B, the top view microscopy image shows that the mesh is clearly deformed. This deformation is most likely plastic deformation. The mesh filaments deformed most at the locations where the filaments cross each other, which is visible by the oval shaped areas at the filament crossings. At moment C, at the beginning of the plateau, the cross-sectional micro-graph shows that the mesh follows the contour of the adherends and the open areas of the mesh are becoming smaller.

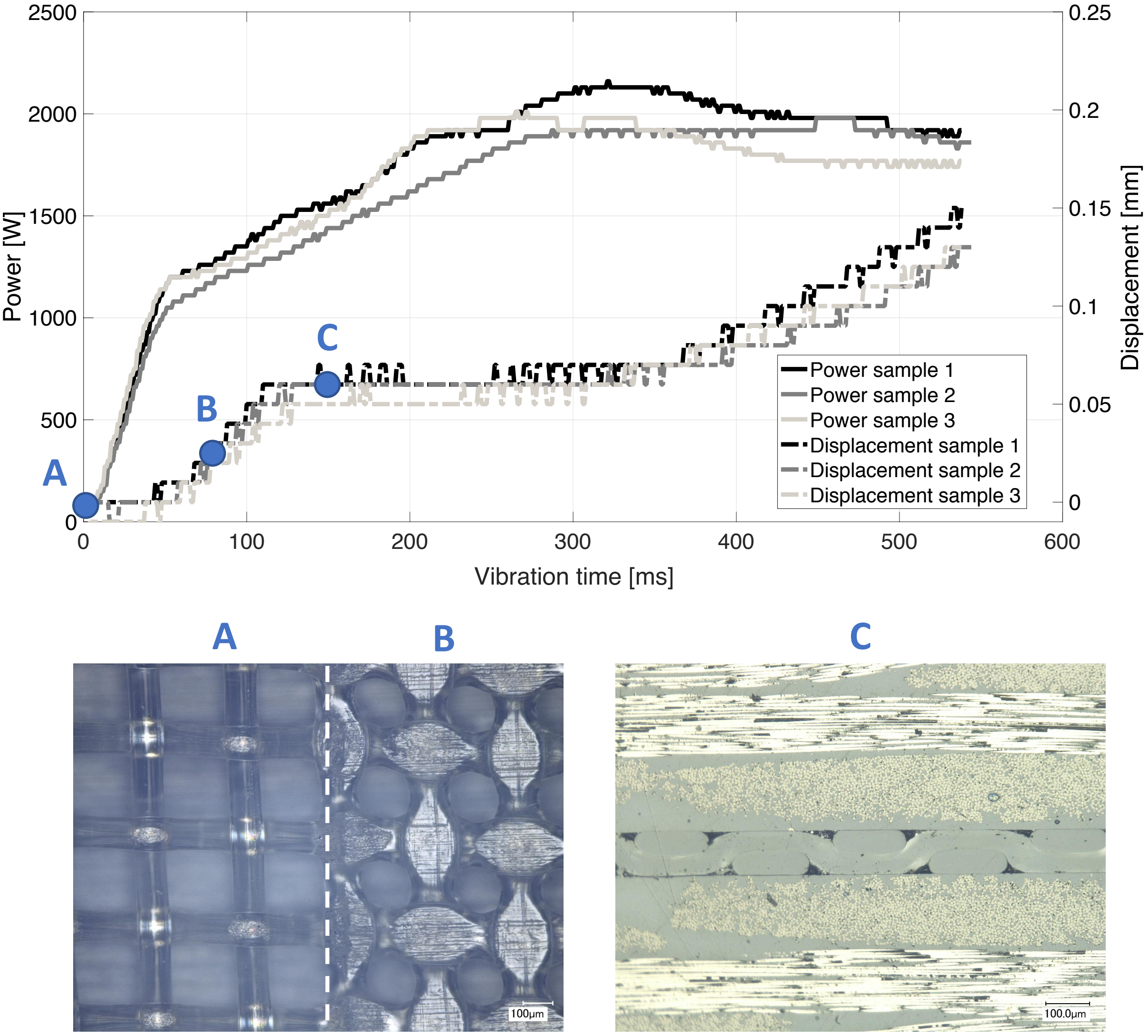


Figure 4: Representative power and displacement curves together with the top view of the 0.20 mm-thick mesh ED at A (0 ms) and B (80 ms), and a cross-sectional micrograph of the weld line at C (120 ms).

4 Discussion

We observed that utilizing a 0.20 mm-thick mesh as an energy director resulted in an improved weld uniformity in continuous ultrasonic welding in comparison to the use of 0.08 mm-thick flat film. The strength also increased by almost 80 %. The goal of this study is to understand why the mesh improved the weld uniformity. In Figure 4 the top view microscopy image at moment A shows open areas of 154 μm between the mesh filaments. These large open areas make it possible for the filaments to easily expand and deform during the welding process. The mesh comes in contact with the adherends at the filament crossings, resulting in small contact areas uniformly distributed all over the weld shown in Figure 4 at moment B. The softening and expansion of the mesh is initiated at the contact areas under the high cyclic strains induced by the mechanical vibrations of the welder. The initial small contact areas result in high static and dynamic welding pressures during the welding process. The expansion and flattening of the mesh can be seen in the displacement curve by the increase in displacement from 0.00 mm to approximately 0.06 mm. During the displacement from the start until approximately

120 ms the mesh is effectively pre-formed in between the two adherends. At moment C in Figure 4 it can be seen that the expanded mesh follows the contour of the adherends. This pre-forming of the mesh most likely results in a very good intimate contact between the ED and the adherends. From the moment the displacement plateau is reached, the power and displacement curves are very similar to the curves found for thin films [10,11], which indicates that from this moment the mesh starts behaving like a thin film, but with the added benefit that the ED and the adherends have an improved intimate contact. This improved uniform intimate contact most likely results in a more uniform heat generation, and therefore gives an improved weld uniformity.

5 Conclusion

This study focused on improving the weld uniformity in continuous ultrasonic welding of thermoplastic composites. A new energy director, a 0.20 mm-thick mesh was introduced in comparison to the current state-of-the-art 0.08 mm-thick flat ED. In the first part of this paper, the resulting fracture surfaces and lap shear strength values of the weld lines were analysed and compared. The second part of the paper aimed at understanding why the 0.20 mm-thick mesh gave a better weld uniformity. In order to understand the behaviour of the mesh during the welding process, static welds were performed. The feedback data from the welder was analysed, and cross-sectional micro-graphs were taken at different stages of the welding process. The main observations from are the following:

- The 0.20 mm-thick mesh energy director significantly improved the weld uniformity of a continuous weld in comparison to the 0.08 mm-thick flat energy director. An average lap shear strength of 33.7 ± 2.4 MPa was obtained for the 0.20 mm-thick mesh compared to 18.8 ± 6.2 for the 0.08 mm-thick flat film.
- The filament crossings within the mesh, uniformly present in the weld line, come in contact with the adherends first. At the beginning of the welding process the mesh filaments expand and flatten under the high cyclic strains imposed by the welder, called pre-forming. The pre-formed mesh has a uniform intimate contact with the adherends. This uniform intimate contact most likely ensured a more uniform heat generation all over the weld line, resulting in an more uniformly welded area.

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