European Conference on Multifunctional Structures
EMuS 2020
Dr. J. Kos, Prof. X. Martinez and Dr. H. Schippers (Eds)

INFLUENCE OF THE ANGLE BETWEEN ADHERENDS ON ULTRASONIC WELDING OF THERMOPLASTIC COMPOSITES

EMUS 2020

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Key words: Misalignment, Manufacturing, Joining, Tolerances, Strength

Abstract. Research on ultrasonic welding of composites has focused mostly on studying parameters that are inputs for the process or material-related parameters, but almost no attention has been given on the effect of manufacturing tolerances. In this work, we investigated how an angle between adherends impacts the welding process and the weld quality. By increasing the angle between top and bottom adherends, it was found that the duration of the process increased while the power consumed, the weld uniformity and the weld strength decreased. However, by increasing the clamping distance, which increased the compliance of the adherends and hence their ability to deform under the applied welding force, the effect of the misalignment on both the welding process and weld quality could be substantially reduced.

1 INTRODUCTION

Ultrasonic welding is a fusion bonding method that uses high-frequency low-amplitude vibrations to generate heat in the interface to be bonded. It is well known how processing parameters such as welding force and amplitude of vibration affect the process [1,2], but almost no attention has been given to the influence that manufacturing tolerances can have on it, such as a misalignment between adherends, which could cause uneven heating of the overlap [5], potentially leading to a heterogeneous melting of the overlap area and impacting the final quality of the joint. Although the need of parallelism between adherends is usually mentioned [3,4], no further investigation has been found in literature until this point. Understanding the influence of a misalignment between the adherends is essential to allow the industrialization of this process, such as for its use on the Multifunctional Fuselage Demonstrator of the Clean Sky 2 project [6].

In this work, we investigate the influence that an angle between adherends may have on the ultrasonic welding process. A clamping jig composed by two metal bars as clamps and flat energy directors (ED) were used. The distance from the clamps to the sonotrode and the thickness of the base under the top adherend were varied in order to obtain a variety of angles between adherends, which was quantified using side-view pictures of the welds. The effects on the welding process were assessed by analysing the consumed power and the vertical displacement of the sonotrode during welding. Single-lap shear strength tests and fracture surfaces were used to evaluate the homogeneity and quality of the welds.

2 METHODOLOGY

The material used to manufacture the specimens was Toray Cetex® TC1200 carbon 5-harness satin fabric reinforced polyetheretherketone (C/PEEK) from TenCate Advanced Composites (the Netherlands) *(T300JB 3K Carbon 280gsm FAW 5HS Woven Fabric Reinforced Laminate 42% RC).* The laminate stacking sequence was $[(0/90)_3]_s$, consolidated in a hot platen press at 385°C and 10bar for 30min, resulting in a final nominal thickness of 1.9mm. Single lap shear coupons of 25.4mm x 101.6mm were cut with a water-cooled diamond blade from the consolidated laminates. The apparent main orientation of fibers was kept parallel to the longitudinal direction of these coupons. A 0.25mm thick flat film of pure PEEK was used as ED.

The specimens were welded with a 20kHz Herrmann Ultraschall ultrasonic welder machine with 1:2 booster and 1:1.7 sonotrode. Amplitude of vibration was 86.2µm peak-to-peak. The static welding force was 500N and consolidation force was 500N for 4s. Displacement control was used, i.e. the duration of the vibration was defined by the downward displacement of the sonotrode. The consumed power and vertical displacement of the sonotrode during the vibration phase were given by the welding machine as outputs at the end of the process. The in-situ monitoring method described by Villegas [1] was used to define the onset of flow and the optimum displacements. Figure 1 shows the jig used to hold the samples during the welding process. The distance between sonotrode and top clamp (*clamping distance,* CD) was either 5mm or 50mm and five supporting base thicknesses (BT) were tested. The nomenclature CD (mm)/BT (mm) is used when mentioning the different clamping configurations. Pictures perpendicular to the center of the overlap were taken with a high resolution camera. ImageJ was used to measure the angle between top and bottom adherends (Figure 2).

Single-lap shear strength (LSS) tests were performed with a Zwick/Roell 250kN universal testing machine and a cross-head speed of 1.3mm/min. Naked-eye fractographic analysis was performed after testing. When needed, cross section microscopic analysis of as-welded samples was performed using a Keyence VH-100UR digital microscope.

3 RESULTS

Varying CD and BT resulted in a misalignment between top and bottom adherends, which was quantified as the angle between the top and bottom adherends after the sonotrode applied the static force of 500N (Figure 3). For the shorter CD (5mm), one can see that the angles are higher and the rate in which the angles increase with decreasing BT is higher than for 50mm CD.

Typical power curves stopped at the onset of the ED squeeze flow are shown in Figure 4. When decreasing BT, a general increase in the time required for the ED to start flowing (*time to flow*) and a decrease in the maximum consumed power (*power peak*) occurred. These two effects are more pronounced for 5mm CD. Decreasing BT from 2.15 to 1.25mm increased the time to flow more than 10 times and decreased the power peak more than 75% for 5mm CD. However, a change in BT from 2.15mm to 0.00mm increased time to flow only 5 times and caused a 50% decrease in the power peak for 50mm CD.

The cross-sectional micrograph in Figure 5 corresponds to the onset of the flow of the 1.25/5 configuration. One can see that the state of the weld and of the adherends is highly non uniform from edge to edge of the welding overlap. At one edge, intact ED is seen while at the opposite edge the ED cannot be identified anymore and severe squeeze flow and porosity can be seen in the adherends. The transition between those two opposite edges shows a gradual increase in the number of voids in both adherends.

Finally, Table 1 shows the fracture surfaces and the results of the LSS tests for welds made with 50mm CD and different BT. Decreasing BT from 1.90mm to 1.50mm led to a decrease in LSS of 5%, while further decreasing BT to 0mm decreased LSS by 16%. All fracture surfaces were fairly uniform. Both the optimum sonotrode displacement and the corresponding vibration time were affected by the angle, which consistently increased with decreasing BT.

Table 1: Fracture surfaces, single-lap shear strength test results, optimum displacement (d_{opt}) and total duration of the process for welds with 50mm CD and different BT.

Fracture surfaces			
Case	1.90/50	1.50/50	0.00/50
Angle [°]	0.20 ± 0.08	0.58 ± 0.02	2.00 ± 0.04
LSS [MPa]	50.81 ± 2.25	48.04 ± 1.48	42.56 ± 1.76
d_{opt} [mm]	0.10	0.07	0.03
Time [ms]	994.33 ± 28.43	857.00 ±1.41	2206 ± 259.93

4 DISCUSSION

Figure 6 plots time to flow and power peak versus angle. A general trend is observed, where time to flow increases and power peak decreases with increasing angle. However the fitting seems to be sensitive to the CD. This is believed to be a result of the fact that the angle measured outside of the overlap does not take into account the effect of the CD on the deformation of the adherend within the overlap. Indeed, the portion of the top adherend that is under the sonotrode will deflect (δ) according to Equation 1, where P is the applied force (500N), l is the arm length (i.e. CD), E the Young's modulus and I the second moment of area:

$$\delta = \frac{Pl^3}{3(EI)} \tag{1}$$

The misalignment between top and bottom adherends is believed to result in part of the amplitude of vibration being invested in closing the angle between top adherend and ED that remains after the welding force is applied. This loss in the amplitude will decrease the cyclic strain the ED is subjected to during the welding process. Decreasing the cyclic strain results in lower friction and viscoelastic heating rates [7,8], which will consequently increase the time required to take the ED to its melting temperature (time to flow) and decrease the power consumed by the process. However, according to Equation 1, a larger deflection will occur for longer CD, resulting in the top adherend having a higher compliance and, hence, better conforming to the ED and bottom adherend. Thus, a case with longer CD will potentially present higher intimate contact and a smaller angle between top adherend and ED, which leads to a smaller portion of the amplitude of vibration invested in closing the remaining angle. The fact that both the 1.90/5 and the 0.00/50 configurations featured similar time to flow and power peak despite significant different angles (0.95° and 2.00°, respectively, see Figure 6) supports this reasoning. It is believed that under the static force applied by the sonotrode, the top adherend in the 0.00/50 configuration deflects more than the adherend in the 1.90/5 configuration, compensating for the initial larger angle and resulting in a similar remaining angle.

Additionally, the micrograph in Figure 5 shows highly non-uniform heating within the overlap at 5mm CD. At the onset of the flow, one edge showed signs of overheating while the opposite edge had intact ED. Thus, one can expect that optimum welds cannot be achieved for such cases. Contrarily, the fracture surfaces corresponding to different BT at 50mm CD (Table 1) presented an uniform aspect. Neither unwelded areas nor fibre distortions and voids could be observed on the fracture surfaces. Accordingly, the welds featured high single-lap shear strength values. These results seem to indicate that increasing CD not only reduces the impact of an angle between adherends on the process, but also on the weld uniformity and strength.

5 CONCLUSIONS

In this paper, the influence of the angle between adherends on ultrasonic welding of CF/PEEK adherends with flat energy directors (ED) was investigated. The position of the top clamp and the thickness of the supporting base in the welding jig were varied in order to obtain a wide range of angles. The main observations were that with increasing angle the time needed for the ED to start flowing increased while the maximum consumed power and the uniformity at the weld interface decreased. Apart from the angle, the clamping distance had an effect on these results since it influences the compliance of the top adherend and consequently the actual amplitude transmitted to the ED and which is invested in heat generation. A clamping distance of 50mm was enough to diminish the misalignment effects, providing high weld strength and uniform weld quality even under significant adherends misalignment, which shows that ultrasonic welding is a promising method for aerospace applications such as in the Multifunctional Fuselage Demonstrator from Clean Sky 2 project.

ACKNOWLEDGEMENT

The work presented in this paper is carried out as part of a project, which has received funding from the Clean Sky 2 Joint Undertaking (JU) under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 776455.

DISCLAIMER

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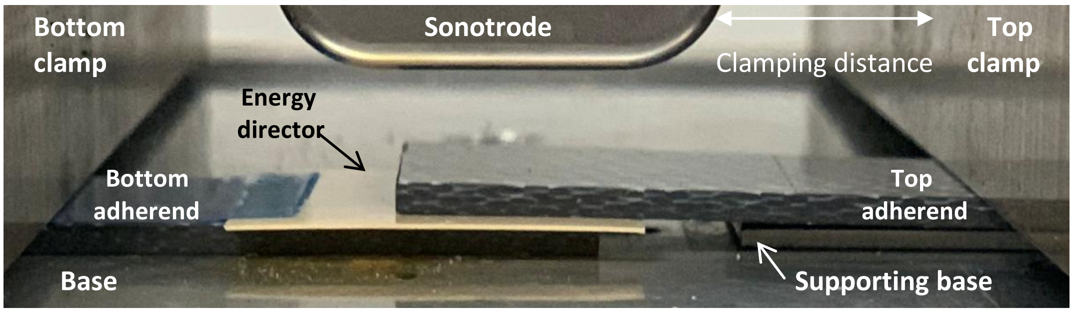

Figure 1: Setup of static ultrasonic welding process.

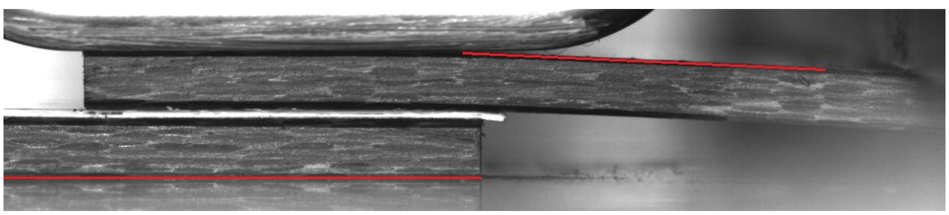

Figure 2: Side view of overlap with sonotrode applying the static force. Red lines indicate the two arms that compose the angle to be measured.

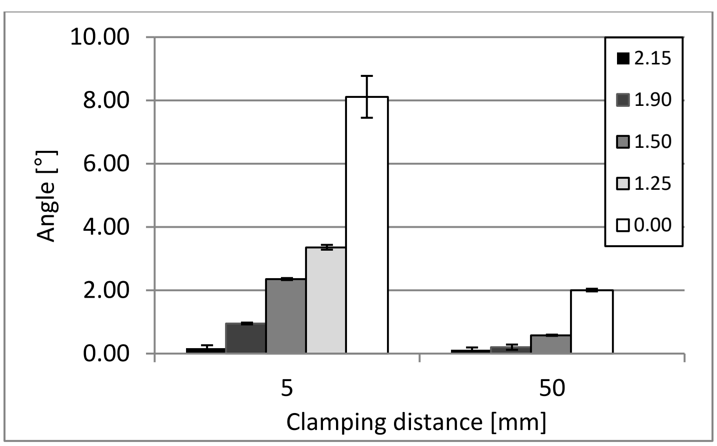

Figure 3: Angle between adherends versus clamping distance for different thicknesses of supporting base (2.15mm, 1.90mm, 1.50mm, 1.25mm, and 0.00mm) with 500N welding force being applied.

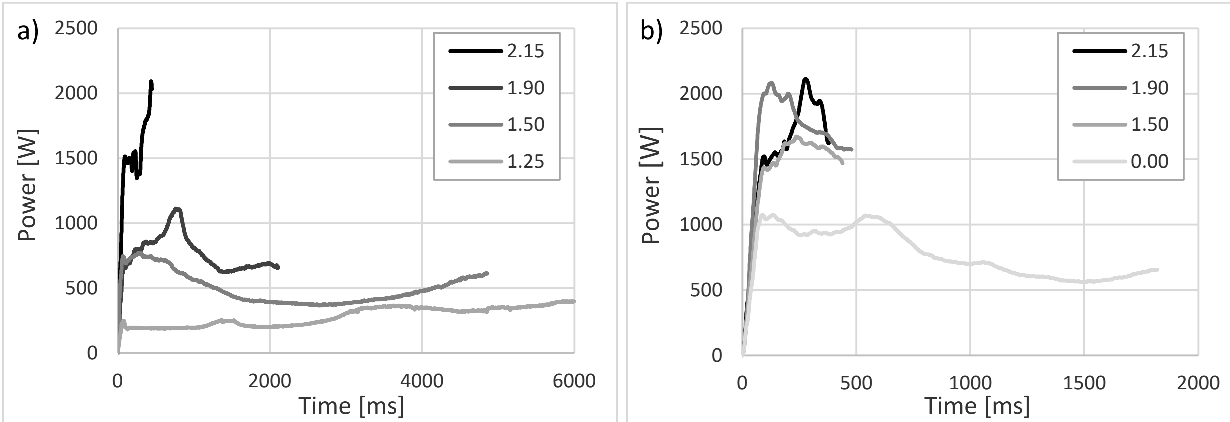

Figure 4: Power consumed until onset of flow for different supporting bases thicknesses and clamping distance of a) 5mm and b) 50mm.

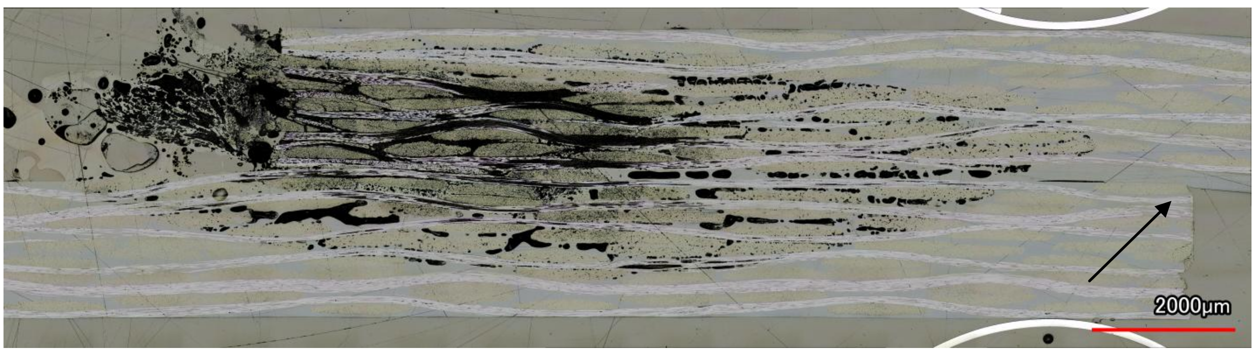

Figure 5: Cross-section microscopy of weld representative of case 1.25/5 stopped at the onset of flow (0.03mm). Black arrow indicates intact ED.

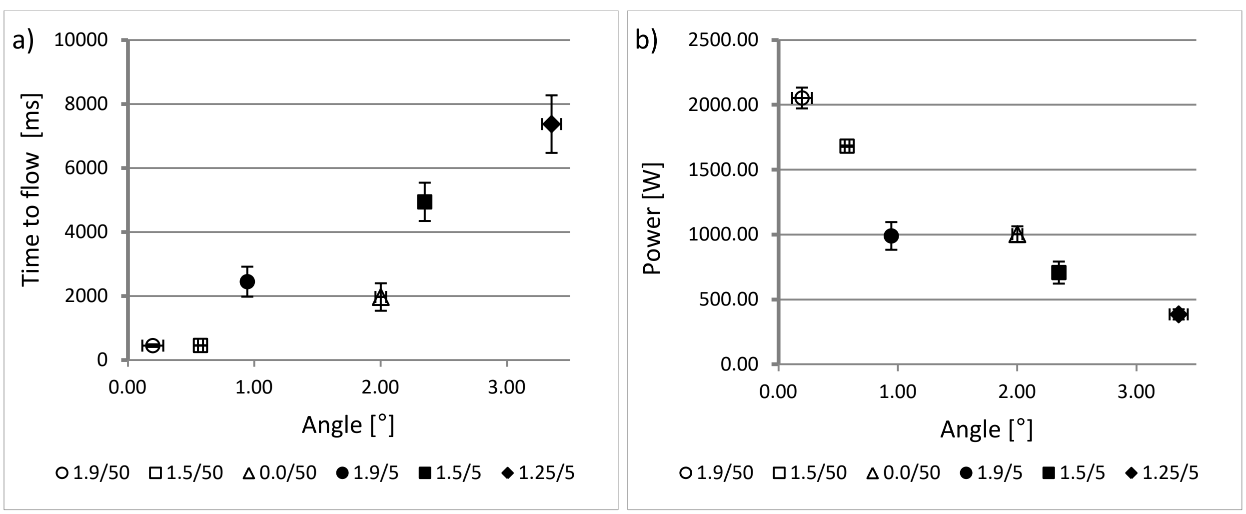

Figure 6: a) Time to flow and b) Power peak versus angle between adherends.