LASER HEAT CONDUCTION WELDING OF INLINE CLEANED ENDLESS CARBON FIBRE REINFORCED THERMOPLASTICS

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Abstract

In the following, laser transmission welding was transferred to heat conduction welding for joining endless carbon fiber reinforced thermoplastics (CFRTP). The purpose of the investigation was to demonstrate the laser weldability of this material combination. In these investigations, lap shear samples were welded using a carbon fiber fabric and a non-crimped fabric in a PEKK matrix and a carbon fiber fabric with a PPS matrix. The influence of surface contaminations and the effect of the removal technique on the lap shear strength were investigated. These investigations generate the basic knowledge to transfer this new CFRTP-CFRTP welding technique for real parts.

1. Introduction

Presently, fiber reinforced materials are used to save weight and to maintain high mechanical properties. This is the reason why these materials can be found in different industries such as automotive, sports and aerospace. An example from the aerospace industry is the aircraft A 350 XWB from Airbus, which consists of 53 % composites [1]. Carbon and glass fibers are often used as reinforcement. These fibers can be short and have mainly a randomly orientated in the matrix or the fibers can be continuous and be bounded as a fabric or tape. The most common matrix material is epoxy thermoset, which has the advantage of a high temperature resistance and low moisture pick up. Recently, thermoplastics have gained importance as a matrix material due to their high impact strength, thermoformability and weldability [2]. Therefore, welding can be applied in addition to adhesive bonding and riveting for joining fiber reinforced thermoplastics. Typical welding techniques are ultrasonic, resistance and induction welding [3].

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Another process is laser transmission welding, which is desirable to industry for its consistency and therefore the possibility of automation. Laser transmission welding has one main limitation: one of the joining members has to be partially transparent for near infrared laser radiation. Short and continuous glass fiber reinforced thermoplastics show sufficient optical transparency up to a certain material thickness [4]. However carbon fiber reinforced thermoplastics (CFRTP) can not be joined by this welding technique due to high absorption of the carbon fibers for the laser wavelength. In order to overcome this limitation, the laser transmission welding was transferred to heat conduction welding by the Laser Zenrtum Hannover e.V. for the first time. For this welding technique, two CFRTP parts are placed in overlap configuration. The surface of the upper part is heated up by laser radiation and due to heat conduction between both parts, the matrix material of the lower part also becomes molten. After the material cools down, a reliable weld seam can be achieved.

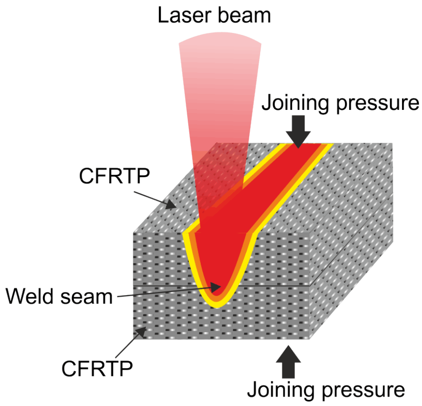

Figure 1. Schematic diagram of heat conduction welding of CFRTP to CFRTP.

The weld seam is influenced by the layup of the material, the applied welding parameters as well as possible surface contaminations. Due to the manufacturing processes of CFRTP parts, the surface can contain contaminations like release agents or accumulated additives, which affect the weld seam development. These contaminations have to be taken into account for the joining process development. To remove surface contaminations, different techniques can be applied. The most common techniques in the aircraft and wind-power industry is by mechanical activation using a combination of solvent cleaning and manual grinding. This technique is easy to use, but the risk of inconsistent quality and material deterioration due to exposer and damage to the fibers is high because the use of manual labor can be inconsistent. More attractive are inline compatible automated processes which prevent a fiber release and have a reliable and quality controlled cleaning process. For that purpose CO_2-snow cleaning and also atmospheric pressure plasma (APP) cleaning and activation are highly attractive [5]. This is because during CO_2-Snow cleaning liquid CO_2 is expanded from high pressure to an atmosphere which leads to the formation of small CO_2 snow crystals which are accelerated by compressed air to the substrate surface. Here the particles can lead to a removal of contamination due to the combination of thermal effects and the sublimation of the CO_2. In the case of the APP processes the use of highly reactive radicals which are generated inside the plasma leads to the removal of organic and fluor organic contaminations and also the formation of highly reactive and hydrophilic functional groups on the surface of the treated polymer material [6].

2. Experimental Set-up

The experiments were conducted with a diode laser emitting at a wavelength of $\lambda = 940$ nm. The maximum output power of this laser was $P_{max} = 300$ W. The laser radiation was guided by an optical fiber to the welding optic. This welding optic contained homogenizing lenses in order to obtain a homogeneous energy distribution in the focal point, also known as the top head profile. The samples were placed in overlap configuration in a clamping device in order to keep the samples in place and to ensure a constant clamping pressure. The clamping device was mounted to an axis-system. For the

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welding process the samples and the clamping device were moved with a constant speed relative to the welding optic. Therefore, the laser beam passes the weld seam just once, which is known as contour welding. The applied laser energy per unit length E_s can be calculated by:

$$E_s\ [J/mm] = \frac{P\ [W]}{v\ [mm/s]} \tag{1}$$

with the laser power P and the welding speed v.

For the determination of the process window pretests were conducted with the laser power kept constant and a varied welding speed. The lower limit of the welding speed was set, when decomposition of the matrix material on the surface of the upper part became visible. Afterwards, for each welding parameter set three lap shear samples were welded and tested afterwards.
For the removal of surface contaminations as reference process solvent cleaning with manual grinding with sandpaper has been used. In case of the CO_2-snow cleaning trials an industrial ring-line with automated CO_2 flow control in combination with a commercial blasting nozzle with 9 mm diameter has been used with a blasting angle of 45°. For the atmospheric pressure plasma (APP) treatment a rotational nozzle type RD1004 from Plasmatreat company has been used with compressed air as process gas.

3. Material Characterization

For the experiments, CFRTP consisting of a Polyphenylene sulfide (PPS) and Polyetherketoneketone (PEKK) matrix was used. Both matrix materials are semi-crystalline, which makes the materials resistant to solvents and are often used for aerospace applications. The used laminates consist of carbon fiber fabric or tape (Table 1). The glass transition temperature for the CF PPS Fab laminate is T_g = 90°C and its melting temperature is T_P = 280°C. For the CF PEKK Fab and CF PEKK UD the glass transition temperature is T_g = 160°C and their processing temperature T_P = 370-400°C. [7, 8] The laminates were cut with a diamond saw into samples with a dimension of d = 25 mm x 55 mm and were placed with a resulting overlap area of a = 25 mm x 20mm.

Table 1. Classification of materials.

Acronym	**Fiber**	**Matrix**	**Set-up**	**Thickness**
CF PPS Fab	Harness satin weave	Polyphenylene sulfide	[0/90]2s	1.20 mm
CF PEKK Fab	Harness satin weave	Polyetherketoneketone	[0/90]2s	1.25 mm
CF PEKK UD	Unitape	Polyetherketoneketone	[0/90]2s	1.10 mm

4. Results and Discussion

During the welding process, the generated process heat in the upper part conducts through the material and reaches the lower part, which also gets molten. During the welding, the process heat is also conducted along the carbon fibers. Therefore, depending on the fiber orientation the process heat spreads out perpendicular to the weld seam direction. The heat conduction perpendicular to the weld seam has a high influence on the weld seam width and therefore the weld seam area. Due to this heat conduction, part of the process heat leaves the welding area and less energy is available to melt the

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material at the interface. In Figure 2, the weld seam strength and the weld seam area for varying energy per unit lengths using CF PPS Fab is depicted.

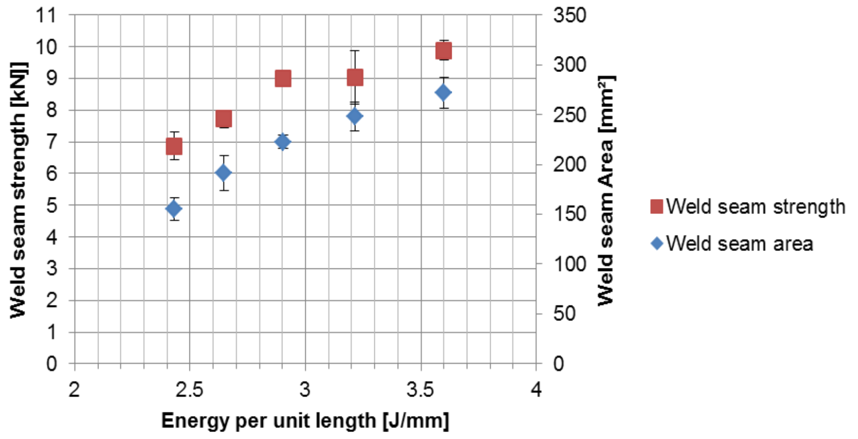

Figure 2. Average weld seam strength and average weld seam area progression for increasing energy per unit length for CF PPS Fab.

The weld seam strength as well as the weld seam area are increasing with increasing energy. At high energy levels the curve progressions are starting to be constant. The leveling of the weld seam area progression is probably due to a changing ratio between generated surface heat and heat loss due to heat conduction out of the weld seam. Furthermore, at high energies the weld seam temperature is increasing, which results in overheating of the matrix material. The leveling of the weld seam strength progression can also be due to a combination of the weld seam area not increasing as much and overheating of the matrix material, which results in cavities in the load transmission area. This dependency is affecting the shear strength, which is the ratio between the tensile force and the weld seam area. For E_s = 2.4 J/mm the lap shear strength is σ = 44.4 N/mm^2 and for E_s = 3.6 J/mm the lap shear strength decreases to σ = 36.4 N/mm^2.

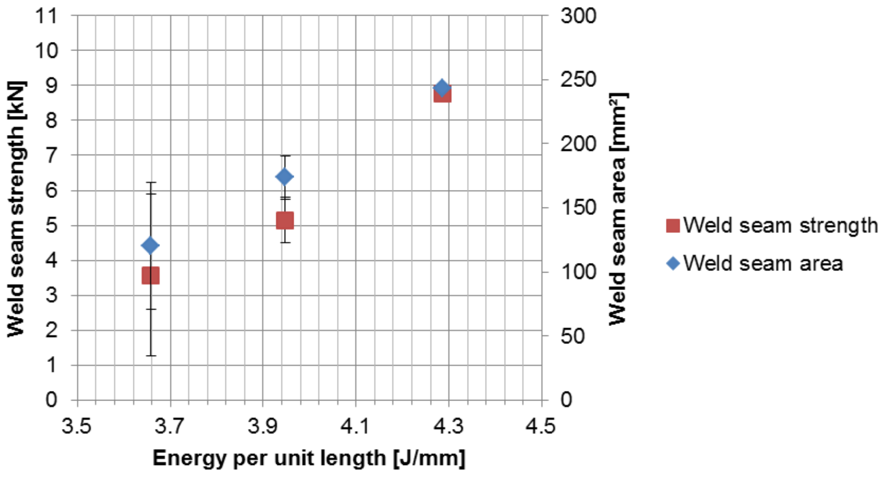

Figure 3. Average weld seam strength and average weld seam area progression for increasing energy per unit length of CF PEKK Fab.

For the welding of CF PEKK Fab as well as CF PEKK UD a higher energy per unit length is needed than for welding of CF PPS Fab, which is due to the different melting points of the materials (Figures 3 and 5). Furthermore, the investigated process window for CF PEKK Fab is smaller compared to CF

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PPS Fab. In Figure 3, an increasing weld seam strength and area for CF PEKK Fab for increasing energy per unit lengths is depicted. In this graph no levelling effects are observable. This could be due to the maximum amount of applied energy, which is too low to generate decomposition effects of the matrix material resulting in an unaffected weld seam strength. In Figure 4, pictures of optical micrographs for low and high energy per unit lengths E_s are observable.

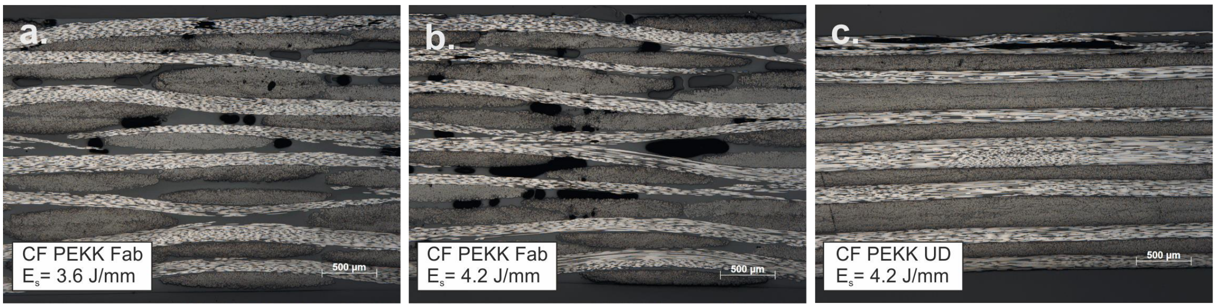

Figure 4. Optical micrographs of cross sections perpendicular to the weld seam orientation for welded CF PEKK Fab and CF PEKK UD.

It is observed that the number of cavities increase at higher energy levels, but the cavities are distributed mainly in the whole upper part and less in the connection area between both parts (Figures 4a and 4b). Therefore, the effect of decomposition on the weld seam strength is limited.

If industrial produced parts have to be welded, the surface can be contaminated due to previous manufacturing steps. In order to determine the influence of surface contaminations on the weld seam strength CF PEKK UD was welded once with an untreated surface and once with a grinded surface without contaminations. In Figure 5, the weld seam strength for the two different surface prepared samples are depicted. The untreated CF PEKK UD results in lower weld seam strengths than the sandpapered ones. The maximum weld seam strength for CF PEKK UD is lower than for CF PEKK Fab for same energy per unit length (Figure 6). Comparison of the optical micrographs show, that the CF PEKK UD has no cavities in the matrix material (Figure 4c). The CF PEKK Fab contains cavities, which is an indication that the processing temperature is too high. This leads to the assumption, that the processing temperatures in the CF PEKK UD are lower than in the CF PEKK Fab due to the different fiber set-up and amount of matrix material.

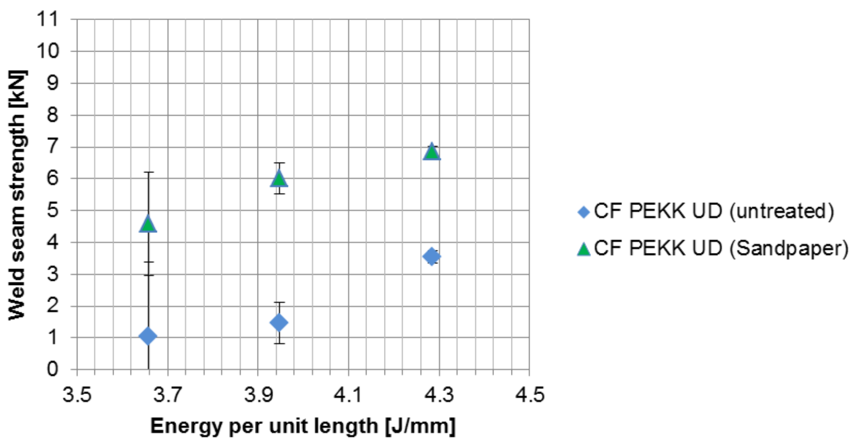

Figure 5. Average weld seam strength for untreated and sandpapered CF PEKK UD.

However, applying sandpaper for surface treatment has the disadvantage that part of the matrix material is removed, which is needed for the weld seam to connect the parts. In order to avoid the matrix material removal different cleaning methods are tested. These methods were CO_2 and ADP with different parameters (Table 2).

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Table 2. Parameter for surface preparation.

Process	Pressure	Distance	Speed	No. Cycles
CO_2-1	8bar	18mm	20m/min	1
CO_2-2	6bar	18mm	20m/min	1
ADP1	1bar	4mm	10m/min	5
ADP2	1bar	4mm	10m/min	1

The samples with different cleaned surfaces were welded with $E_s = 4.28$ J/mm. The CO_2 surface treatment with two different parameters did not lead to a remarkable increase of the average weld seam strength compared to the untreated reference samples. However, the variation of the seam strength, shown by the error bars, has been significantly reduced (Figure 6). While the plasma process with the lower intensity (ADP2) leads to weld seam strengths below the manual activated test samples (sandpaper), the parameter ADP1 generates the highest average weld seam strength, again with a very low strength variation.

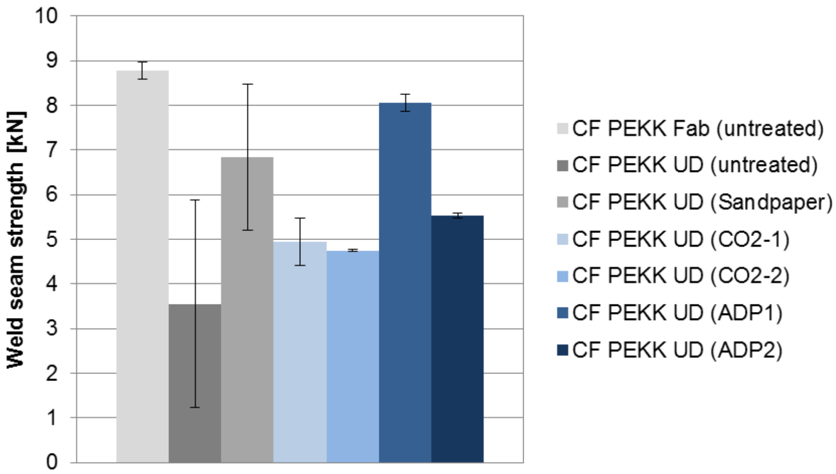

Figure 6. Average weld seam strength for CF PEKK Fab and different pretreated CF PEKK UD.

5. Conclusions

In this paper, the first results of welding CFRTP to CFRTP using laser radiation under consideration of surface contaminations are presented. In these investigations CF PPS Fab was welded to itself and maximum lap shear strength of $\sigma = 44.4$ N/mm^2 was obtained. Furthermore, the laser weldability of CF PEKK Fab and CF PEKK UD was demonstrated. These materials are more challanging to weld because in order to have a strong weld seam the processing temperature $T_P = 370$-400°C has to be reached in the connection area without damaging the upper joining member. The maximum seam strength for CF PEKK Fab was F = 9.9 kN, which is higher than the maximum obtained seam strength for CF PEKK UD (F = 8.1 kN). Furthermore, it was demonstrated, that a surface treatment can enhance the weld seam strength. The results of mechanical activation, CO_2-snow cleaning and APP

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treatment showed the high potential of the inline compatible and automated methods, to improve the reliability and quality of the laser heat conduction welding.

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