THE INFLUENCE OF CARBON FIBRES ON THE TEMPERATURE DISTRIBUTION DURING THE LASER TRANSMISSION WELDING PROCESS

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Abstract

In the following, the effect of heat conduction along carbon fibres within the frame of laser transmission welding process is investigated. Therefore the heat conduction in unidirectional continuous carbon fibre reinforced polyphenylene sulfide (CF PPS UD) was examined without and with a laser transparent partner. The experiments were performed with a Nd:YAG and a diode laser. For the evaluation, the temperature was monitored with a thermo camera and a pyrometer. Furthermore, optical micrographs of the weld seam were prepared to determine the weld seam shape depending on the fibre direction. Additionally, the influence of the welding technique, contour and quasi-simultaneous welding, on the weld seam width was determined.

1. Introduction

Today, parts based on fibre reinforced thermoplastics are used in many different applications in the aerospace, automotive or sports sector. For some applications these parts have to be joined. There exist different joining techniques for these materials e.g. vibration or hot plate welding. Furthermore, thermoplastic components can be joined by laser transmission welding. This application utilizes the partial transparency of the thermoplastic material. Thermoplastic materials containing the additive carbon black or carbon fibres are laser absorbing. At the laser transmission welding process the laser beam passes the laser transparent part and generates heat in the laser absorbing material. Due to heat conduction, the laser transparent part melts too and a welding connection is realized. This welding technique can be divided into contour, quasi-simultaneous, simultaneous and mask welding. During the contour welding the laser beam is guided only once over the work piece and all the energy that is needed for the melting of the material is brought into the material at once. At the quasi-simultaneous welding the laser beam passes the welding area a couple of times at high speed. In this case the heat is slowly developed in the complete weld seam [1, 2].

The existence of fibre reinforcements in the thermoplastics has an influence on the welding process. Grewell et al. determined the dependency between short glass fibre content and the transmissivity of the material. Due to the increasing fibre content the possibility for the laser beam to pass the material without being scattered decreases [3]. Carbon fibres in the laser absorbing piece have a high effect on the welding result due to the different heat conductivities of matrix material and carbon fibres (Table 1).

Material	C-Faser HT (T300)	C-Faser ST (T800)	C-Faser HM (M46J)	C-Faser HM (M60J)	Polyphenylene sulfide (PPS)
Heat conductivity	4.9 W/mK	10 W/mK	49.8 W/mK	74.8 W/mK	0.19 W/mK

Table 1. Characteristics of carbon fibres and polyphenylene sulfide [4, 5]

The heat conduction in a unidirectional carbon fibre reinforced materials (CFRP UD) can be described as a combination of the heat conductivity of the fibre and the matrix material. The heat conductivity for the matrix material is for every direction the same. The heat conductivity along the carbon fibres is higher than perpendicular. The heat conduction along to the carbon fibre direction can be described as:

$$\lambda_p = \lambda_{pf} * \varphi + \lambda_m * (1 - \varphi) \tag{1}$$

with λ_p is the complete heat conductivity of the UD CFRP in fibre direction, λ_{pf} is the heat conductivity along the fibre, λ_m is the heat conductivity of the matrix material and φ is relative fibre volumetric content.

Perpendicular to the fibre direction, the heat conduction can be described as:

$$\lambda_n = \frac{\lambda_{nf}+\lambda_m+(\lambda_{nf}-\lambda_m)*\varphi}{\lambda_{nf}+\lambda_m-(\lambda_{nf}-\lambda_m)*\varphi} * \lambda_m \tag{2}$$

where λ_n is the complete heat conductivity of the UD CFRP perpendicular to the fibre direction and λ_{nf} is the heat conductivity perpendicular the fibre [4].

Jaeschke et al. investigated the absorption behavior and heat distribution of a carbon fibre composite material during the laser transmission process. They pointed out that the absorption occurs on the fibre reinforcement. Furthermore, the development of the weld seam depends on the upper fibre orientation and the presence of a matrix reservoir [6, 7].

2. Experimental Set-up

For the experiments two set-ups were used. The first set-up is used for bead on plate welding investigations. The experiments were preformed with a Nd:YAG laser, which emits at a wavelength of $\lambda = 1064$ nm. The scanner consists of two galvanometer mirrors, which are guiding the laser beam across the surfrace (Figure 1). The temperature measurment occours with a thermo camera.

The second experimental series was performed with a diode laser emitting of a wavelength of $\lambda = 940$ nm, providing a maximum power of P = 300 W. In these experiments glass fibre reinforced PPS (GF PPS) was welded on short and continuous reinforced PPS. The temperature in the weld seam was measured by a pyrometer. For the experiments test samples were pressed together against a glass plate at a pressure of p = 2 bar. The glass plate was d = 7 mm thick and the laser beam had to pass the glass plate before the laser beam got in contact with the thermoplastics.

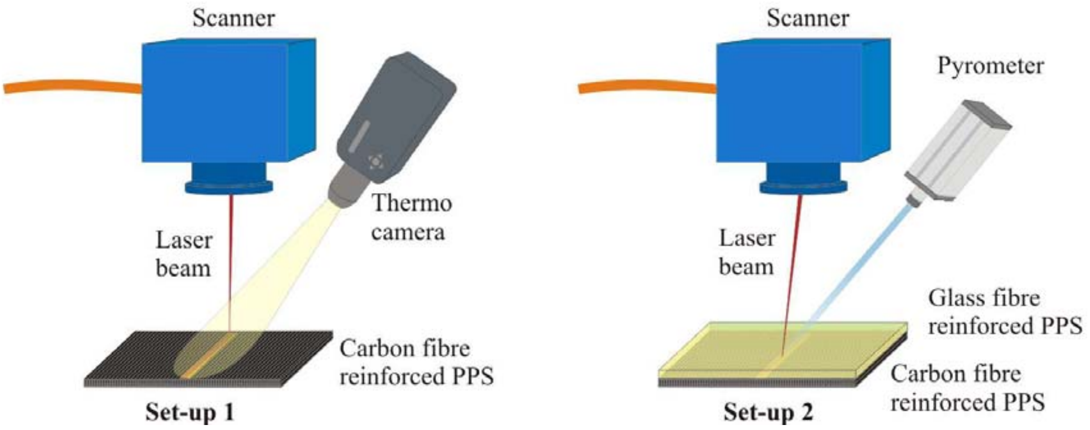

Figure 1. Experimental set-ups for the investigations on the heat conduction in fibre reinforced materials

3. Material Characterization

The heat conduction was investigated with CFRP containing a PPS matrix, which is known for its high thermal, mechanical and chemical resistance. The melting temperature is T = 285°C. The reinforcements for the laser absorbing (LA) part are CF PPS UD, short glass fibre (PPF GF) and carbon fibres (PPS CF) containing carbon black (Table 2.). The laser transmitting (LT) part consists of PPS with glass fibre fabric reinforcement (GF PPS).

Short Name	Reinforcement Additive	Thick-ness
GF PPS	glass fibre fabric	1.0 mm
CF PPS	carbon fibre, unidirectional	2.4 mm
PPS GF c.b.	short glass fibres 40% vol., carbon black	2.0 mm
PPS CF c.b.	short carbon fibres 40% vol., carbon black	2.0 mm

Table 2. Classification of materials.

4. Results and Discussion

In a first step the temperature field in CF PPS UD was explored by a thermo camera while the laser beam and piece stayed unmoved. Thereby a single hot point is applied in the CF PPS UD. The material was heated up until the limit of temperature range (T_{max} = 290°C) of the thermo camera was reached. Figure 2a shows the heat distribution at the end of the heating-up phase. At his point, the maximum measured temperature along the carbon fibres (Y-direction) creates a wider plateau than for the temperature distribution perpendicular to the fibres (X-direction). This is due to the higher heat conductivity along the fibres as described in equations 1 and 2. In Figure 2b the heat distribution at t = 0.3 s after the laser was shut off is depicted. For the direction perpendicular to the fibres the temperature declines fast from its maximum to the left and right. The graph for the measurement along the fibres is wider than for the other fibre orientation, i.e. the temperature decreases slower until it reaches its lowest point. This denotes the material along the Y-axis stays longer molten, which affects the weld seam quality.

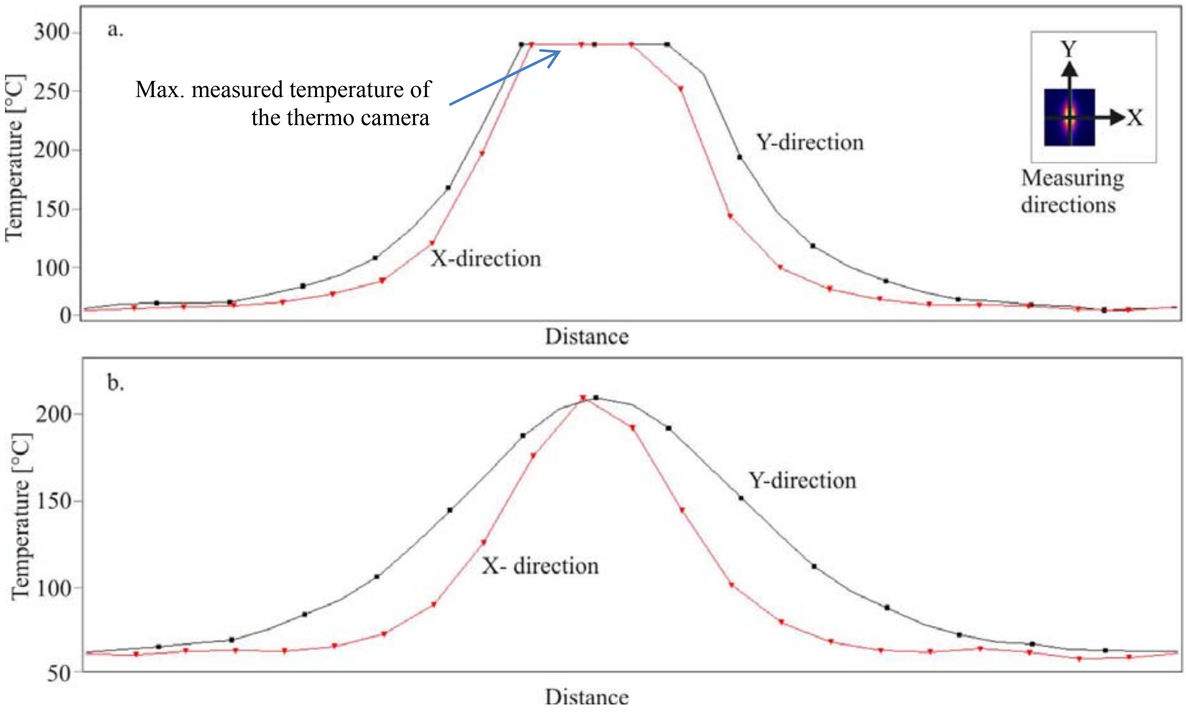

Figure 2. The thermo camera software depicts diagrams of the temperature distribution along the X and Y-orientation of the carbon fibres during bead on plate welding of a single dot: a. at the end of the heating phase; b. 0.3s after the laser was turned off

In a fabric the fibres are typically orientated in an angle of 0° and 90° to the laser beam movement direction, within a weld seam different temperature fields are introduced, which are responsible for melting the thermoplastic and for the generating of a weld seam width.

Futhermore, the influence of the welding technique on the weld seam width was examined. Therefore, bead on plate welding experiments were performed with contour and quasi-simultaneous welding with an angle of 0° and 90° between the fibre direction and the laser beam movement (Figure 3).

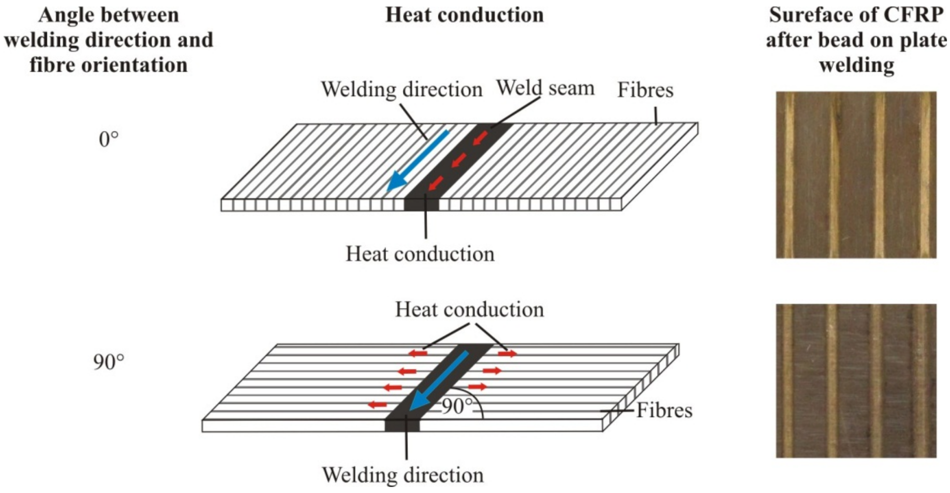

Figure 3. Influence of the angle between fibre orientation and welding direction

For a comparison of both welding procedures, the applied energy was calculated with:

$$E_s \; Energy \; Per \; Unit \; Length \; [\frac{J}{mm}] = n * \frac{Laser \; Power \; [W]}{Welding \; Speed \; [\frac{m}{s}]}, \tag{3}$$

where n describes the number how often the laser beam passes the work piece. The weld seam width was determined by a binocular microscope. For contour welding, the difference between the average weld seam width of welding under an angle 0° (CF PPS UD 0°) and 90° (CF PPS UD 90°) to the laser beam movement and the fibre direction increases with increasing E_s (Figure 4).

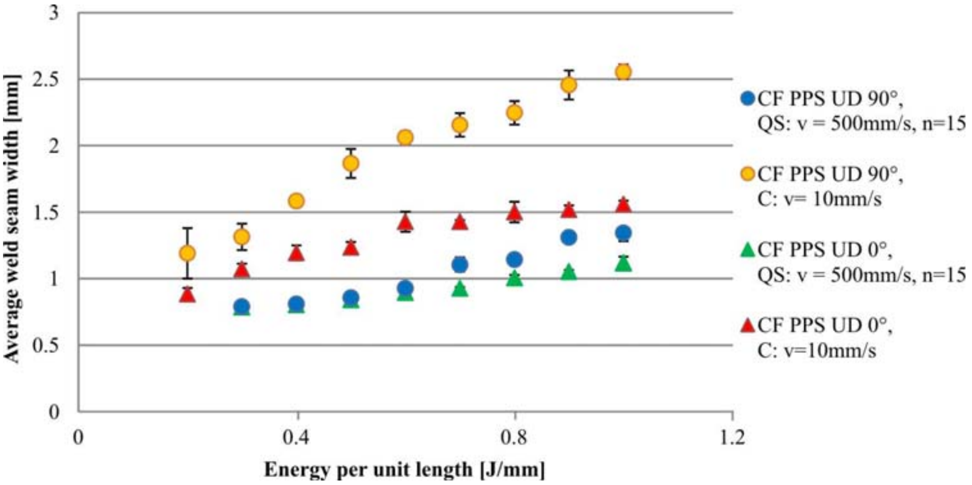

Figure 4: The average width of bead on plate weld seams is influenced by the contour (C) and quasi-simultaneous (QS) welding and the angle between laser beam movement and fibre direction

This indicates that the heat conduction has a higher effect at high E_s. A similar tendency is observed for the quasi-simultaneous welding, but the differences are not as high as for contour welding. At low energies per unit length the weld seam for both fibre directions have almost the same width. Furthermore, this implies for 90° that the developed heat is not high enough to melt larger amounts of the thermoplastic material. This can be due to the high and fast heat conduction. The heat is guided out of the welding area, thereby decreasing the heat, that will melt the thermoplastic and increasing the amount of heat, which will warm up the composite without effecting it. At $E_S = 1$ J/mm the weld seam for the fibre orientation of 90° to the laser movement is about 1.6 times higher than for the 0° fibre direction. During the quasi-simultaneous welding the heat is generated slowly in the CFRP compared to the contour welding. Therefore, there is more time so the heat can conduct out of the welding area, which leads to a loss of heat to melt the matrix material and so to smaller weld seam widths. For example, the weld seams width at $E_S = 1$ J/mm for contour welding is about 1.7 times higher than for quasi-simultaneous welding at an angle of 90° between laser beam movement and fibre orientation.

The investigations with a laser transmitting part were conducted with the experimental set-up 2. At the laser transmission welding the laser beam has to pass the upper thermoplastic part. So the transmissivity of the GF PPS is affecting the welding process. In figure 5 the transmissivity of the GF PPS is exemplary depicted for two different samples. The curves of both pieces have the same development. The GF PPS has at a wavelength of $\lambda = 940$ nm a transmissivity of $t = 9.06$ %, which is a low value caused by the high glass fibre content. Due to the glass fibres the laser beam is scattered in the laser transmitting piece and it is necessary to apply the heat slowly to avoid a burning of the upper material.

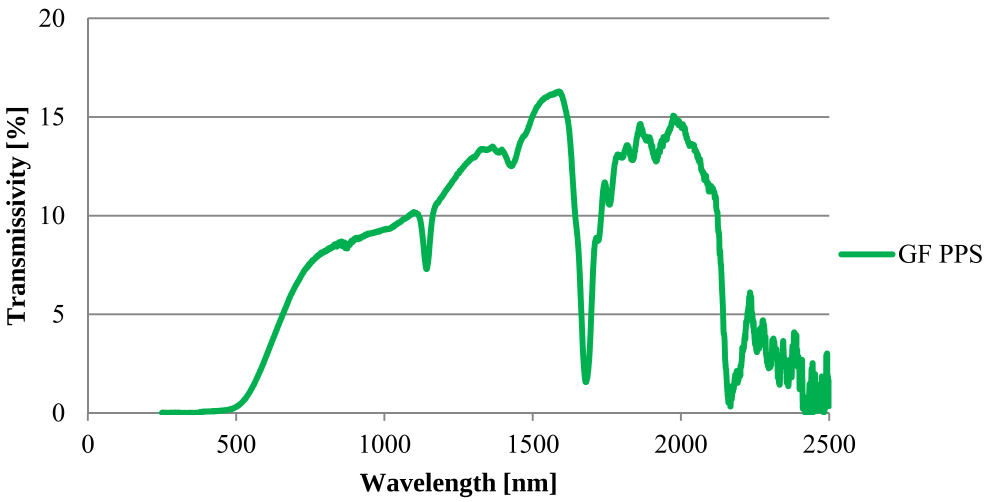

Figure 5. Transmissivity spectrum of GF PPS for different wavelengths

The temperature measurement was performed using a pyrometer providing a measurement range of T = 100-400°C at a spectral range of λ = 1.8- 2.4 µm. The output is given as a voltage. The pyrometer detects the temperature in the weld seam. The measurement is affected by the laser transparent part and by the glass plate. For example, the temperature measurement through the glass plate is about 5% lower than the actual value.

The experiments to demined the effect of the fibre orientation on the weld seam geometry were performed with a constant welding speed v = 5000 mm/s and a constant laser power of P = 130 W. A new energy per unit length was created by adapting the repetition rate. Optical micrographs were prepared to evaluate the weld seam. The laser absorbing material was PPS GF, PPS CF and CF PPS UD. In the following only the absorbing part will be named, because the laser transmitting material GF PPS stays for all combinations constant
Figure 6 describes the average result of the pyrometer measurement with the standard deviation for different repetition rates, i.e. for different energies per unit length. The short glass and carbon fibre reinforced LA material was weldable with lower repetition rates like n = 550, than CF PPS UD.

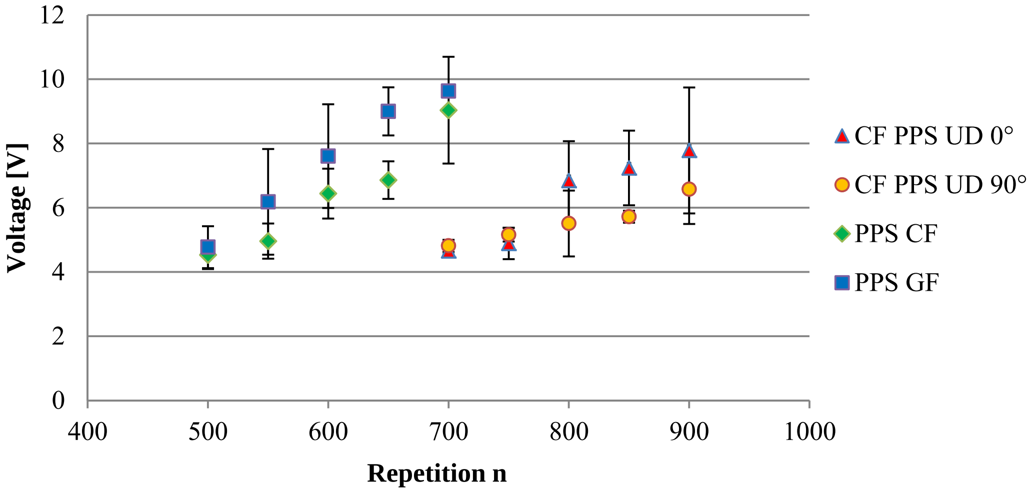

Figure 6. Influence of the repetition rate, on the average weld seam temperature, e.g. average voltage

A 1.4 times higher energy per unit length is needed to create a weld seam in CF PPS UD than in the short fibre reinforced PPS. Furthermore, even the PPS CF shows a lower heat development than the PPS GF, i.e. short carbon fibres effect the heat development. For a repetition rate of n = 700, optical micrographs show that degradation occurs in the weld seam of the PPS CF and PPS GF samples. At this point, the pyrometer measurement reveals a higher value compared to the CF PPS UD at the same energy per unit length. At this energy input the CF PPS UD 0° develops a small weld seam width and for CF PPS UD 90° no weld seam could be detected. For repetition rates over n = 800 the pyrometer detected a higher temperature for CF PPS UD 0° than for CF PPS UD 90°. For the laser welding of CF PPS UD 0° the laser beam moves parallel to the fibre orientation and the developed heat stays in the weld seam. This is the reason for a smaller weld seam width than for the CF PPS UD 90° (Figure 7). For this case the heat conducts out of the weld seam and the maximum temperature is lower than for CF PPS UD 0°. For both fibre directions the weld seam width increases with increasing repetition rates.

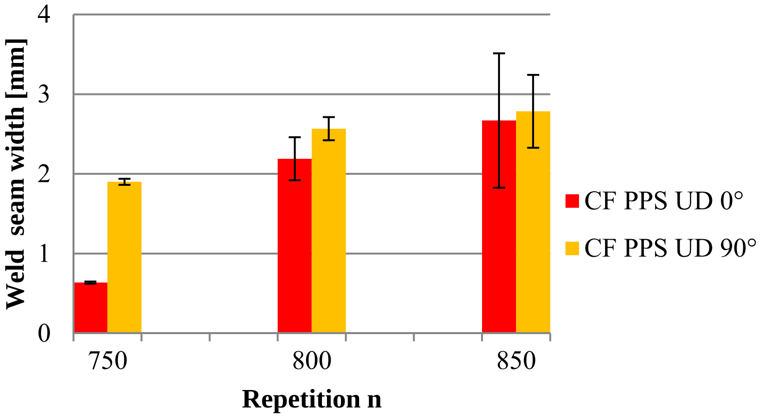

Figure 7. Average weld seam width of CF PPS UD 0°/90° depending on the repletion rate at the quasi-simultaneous welding process with a constant welding speed of v = 5000 mm/s and laser power P = 130 W

5. Conclusions

In this paper the influence of continuous carbon fibres on the heat conduction during the laser transmission welding process was investigated. Therefore bead on plate welding with CF PPS UD 0° and 90° were performed using contour and quasi-simultaneous welding. At the quasi-simultaneous welding more heat conducts out of the welding area and which will not be part of the melting of the matrix material. This leads to smaller weld seam widths. Futhermore, the influence of the carbon fibres on the temperature development and the weld seam width was examined by quasi-simultaneous welding of GF PPS onto four different laser absorbing materials. For the PPS CF and PPS GF a lower repetition rate, e.g. energy per unit length, is necessary to create a weld seam than for CF PPS UD. For example, for CF PPS UD the energy input has to be over 1.4 times higher to create a load bearing weld seam than for the short fibre reinforced PPS. The temperature during the welding of CF PPS UD 90° is lower than for CF PPS 0° with the same laser parameters due to the heat conduction along the carbon fibres and out of the welding area. Also, the heat conduction out of the welding area leads to wider weld seams.

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