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Temperature monitoring independent of laser-beam-position during laser transmission welding of fibre reinforced thermoplastics

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Abstract

The heterogeneous heat conductivity in carbon fibre reinforced plastics (CFRP) critically influences process temperature during welding and increases the necessity for temperature control to secure weld quality. While infrared cameras are a powerful tool for monitoring process temperature they have a low temporal resolution and they are comparatively expensive. A potential alternative is sought by utilisation of a dynamically movable pyrometer measuring spot.

In this work, heat development during bead-on-plate laser welding on carbon fibre reinforced polyphenylenesulfide (PPS) is investigated. The pyrometer spot is capable of measuring temperatures locally independent of the processing laser spot. Thus, temperatures are monitored at a high temporal resolution during welding in front of, behind, and aside the current weld area.

Results of this investigation give rise to expectations that a dynamic pyrometer spot allows for precise temperature measurements at critical points of complex weld geometries such as curved weld seams. This will set up the basis for an automatic laser welding control, which will be capable of adjusting the laser welding power according to required temperatures for a supreme weld quality.

Keywords: laser transmission welding; composites; temperature monitoring; dynamic pyrometer spot

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1. Motivation / State of the Art

Increasing utilisation of CFRP for structural parts in the aviation and automotive industry has led to growing research activities not only in production and design of these composites but also in machining as well as process automation strategies. Besides conventional tools laser technology has proven that it is capable to deliver significant advantages when cutting and joining CFRP (Dittmar et al., 2012).

Laser based joining processes like laser transmission welding (LTW) are applicable only if thermoplastic composites are involved, as they rely on the material's ability to meld and solidify (Dequine et al., 2013). Compared to other joining processes like riveting or adhesive bonding LTW is a well-adapted technique for the unique characteristics of fibre reinforced thermoplastics (van Wijngaarden et al., 2014).

In order for LTW to progress to a wide industrial application, support technologies need to be developed or improved to reach a higher level of automation. A critical criterion during LTW is the process temperature which is the reason why process monitoring and temperature control are fundamental parts in automation of LTW. Especially at the LTW of thermoplastics to CFRP, the process heat in the weld seam is conducted along the carbon fibres, which highly affects the weld seam geometry and the seam strength (Jaeschke, 2012).

Usually temperature monitoring is conducted by utilisation of on-axis pyrometers at contour welding, which allows adjusting the laser power during the contour welding processes. Contour welding is a slow welding technique compared to for example quasi-simultaneous welding, in which the complete process energy is applied almost instantly (Jaeschke, 2012). For welding of composites, having a low transparency for the laser wavelength, the process energy has to be applied slowly, which can be conducted by quasi-simultaneous welding or welding with an oscillating laser beam. Investigations have been performed regarding pyrometer based temperature detection for scanner based processes. Therefore, the pyrometer measuring section was guided through the scanner optic, parallel to the laser beam. These investigations have shown that temperature detection through a scanner optic is possible, but an automated process control is limited due to the high deflection speeds (Wippo et al., 2012).

However, if temperature monitoring of critical parts of the weld seam geometry can be performed independently of the current laser beam's position for scanner based welding processes, it will be possible to adjust the laser power according to the detected temperature increase. This also applies when trying to counter the influence of fibre orientation and resulting heat conductivity on process temperature during LTW. Precise monitoring of the temperature in front of the laser beam can be used to automatically control the laser output power and secure a supreme weld quality.

In order to show the fundamental possibility of this approach, the heat development on carbon fibre reinforced PPS during LTW was investigated. During the experiments the temperature was monitored by a pyrometer in different positions relative to the actual laser beam position.

Nomenclature			
A	welding spot dimension	P_L	laser output power
d_L	laser beam diameter	θ	pyrometer measuring angle
d_p	pyrometer measuring spot diameter	T	relative temperature
f	pyrometer detection frequency	T_G	glass transition temperature
λ	wavelength	T_M	melting temperature
$O_{a,b}$	pyrometer position off-set	v_a	axis velocity

2. Experimental

The investigation was performed on carbon fibre reinforced PPS (CF-PPS) with satin-woven fibres. PPS has got a glass transition temperature of $T_G = 90$ °C and melting temperature of $T_M = 280$ °C. The experimental setup involved of a $\lambda = 940$ nm diode laser emitting a maximum laser output power of $P_L = 300$ W continuous wave. The laser beam was focused through a welding head and had a diameter of $d_L = 2$ mm.

The samples were fixed on a linear x-y-axis table and moved relative to the beam position at an axis velocity of $v_a = 5$ mm/s.

Monitoring of the temperature was performed by the pyrometer HI18 of Sensortherm GmbH, which has got a detection range of $\lambda = 1.65 - 2.40$ µm and a maximum detection frequency of $f = 50$ kHz. Pyrometer measurements were taken at angles of $\theta = 5 - 70$ ° relative to the surface. The pyrometer measuring spot had a diameter of $d_p = 2$ mm.

During the experiments bead-on-plate welding was performed, which is a standard method to investigate the heat conduction and development in the absorbing partner of an LTW joint without having to consider secondary effects resulting from the laser transparent joining partner.

This investigation focused on two aspects of pyrometer measurements. In a first experiment the influence of the pyrometer measuring angle on the measured temperature was examined for welds parallel and perpendicular to the surface's main fibre orientation. These experiments were performed with a laser power of $P_L = 31$ W. The pyrometer spot was focused at the area in the weld seam with the highest temperatures. In the second part, the influence of a local displacement of the pyrometer measuring spot on the temperature measurements was investigated. Therefore, the pyrometer spot was positioned in front of, behind, and to the left side of the laser beam at two different off-sets $O_a = 1$mm and $O_b = 2$mm. Figure 1 shows a schematic of the laser beam and the position of the pyrometer measuring spot. These temperatures were measured at an angle of about $\theta = 70°$ to the surface. The bead-on-plate welding was performed with a laser output power of $P_L = 12$ W.

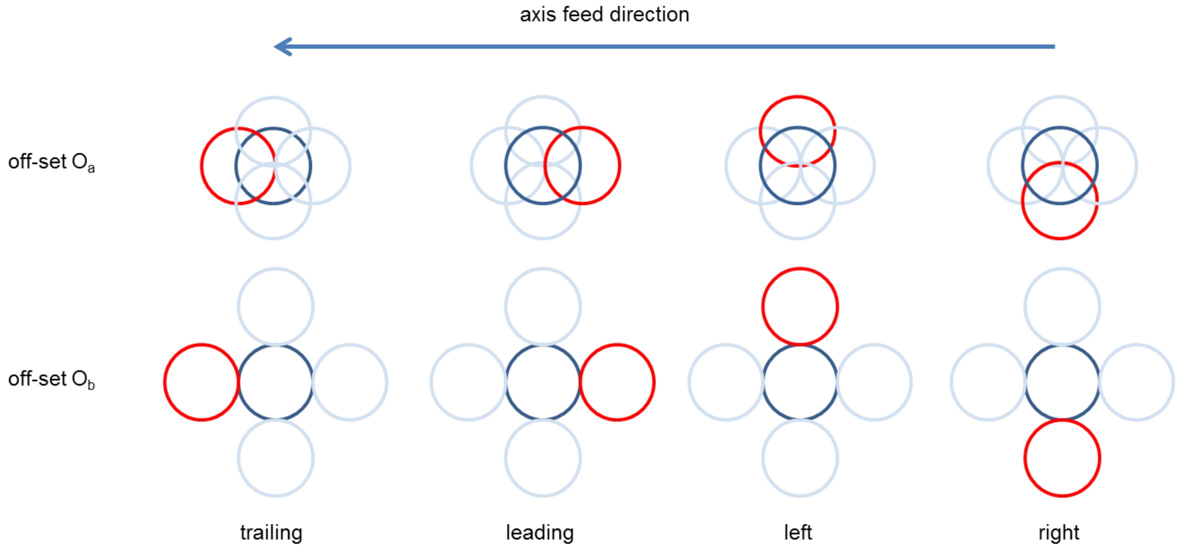

Fig. 1. Schematic position of pyrometer measuring spot (red) relative to laser beam's position (dark blue)

3. Results

The investigation of the influence of the pyrometer measuring angle on the detected temperature showed a distinct difference for bead-on-plate welds for CF-PPS when processed parallel or perpendicular to the main fibre orientation. For the evaluation the maximum temperatures during the welding process were taken into account. At angles of θ = 40 - 70 ° the temperature signal was of similar level, whereas it was decreasing towards smaller angles, cf. figure 2.

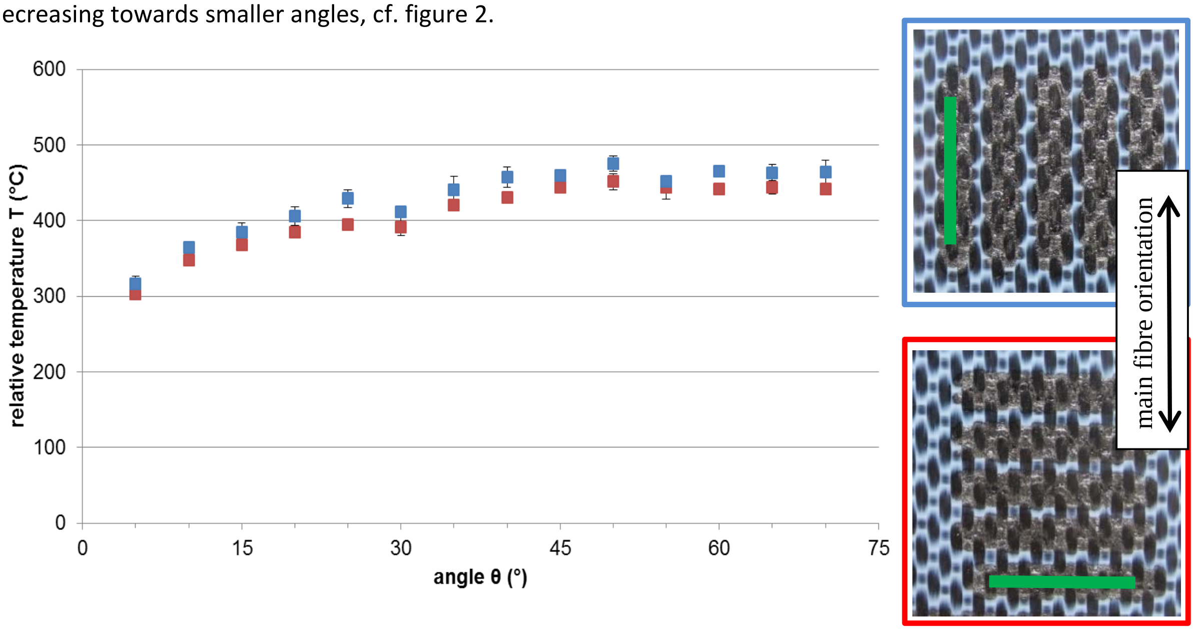

Fig. 2. Relative temperature signal dependent on pyrometer measuring angle for satin-woven CF-PPS processed parallel (blue) and perpendicular (red) to the main fibre orientation during bead-on-plate welding (green). Maximum values are depicted

At small angles only a small amount of thermal radiation is detected by the pyrometer resulting in a difference to the actual temperature measured at higher angles of approx. ΔT = 150 °C for both in line and perpendicular to the main fibre orientation. The detected temperature signal for parallel processing was higher than for perpendicular weld seams at the respective angle, which is due to the different formation of the carbon fibres on the surface and their respective heat conductivity. These effects have to be taken into account for the development of an automated process control for scanner based welding processes.

The investigation of the process temperature offside the laser beam location showed significant differences in the intensity of the measurement signal and in the resulting temperature progress. The intensity varied both with the distance towards the laser beam's position as well as with the relative position of the pyrometer's measurement spot. The following figure 3 shows graphs of the temperature development when the pyrometer spot was in a trailing or leading position relative to the laser beam at two different off-sets O_a = 1 mm and O_b = 2 mm.

It can be seen in the graph of the trailing signal that the signal's intensity is only slightly lower when comparing the two off-sets, which is due to the heat accumulation within the CF-PPS. Also the peak temperatures of the two signals are of similar values with approx. T = 260 °C. For both high and low temperatures small relative peaks are detected, resulting from the changing orientation of carbon fibre rovings at the surface and their influence on overall heat conductivity.

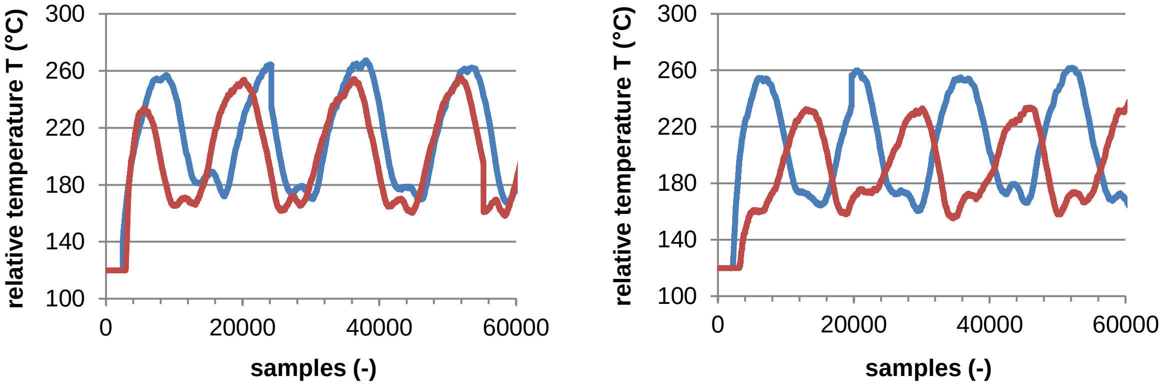

Fig. 3. Relative temperature signal for trailing (left) and leading (right) pyrometer at off-sets O_a = 1 mm (blue) and O_b = 2 mm (red)

While there is only a small deviation for the trailing signals, the two leading signals differ significantly. Not only is the peak temperature a bit lower than for the trailing signal (approx. T = 250 °C), but the relative temperature of the bigger off-set O_b is also less than for O_a by ΔT = 30 °C. As with the trailing signals the formation of signal maxima and minima results from the carbon fibres' orientation. The shift of these local extremes results from the experimental setup. As only one pyrometer was used during the experiments, measurements of the different positions and off-sets were performed separately on different parts of the sample material. Thus, some bead-on-plate welds started on carbon fibres oriented in weld direction, whereas others started on PPS-matrix depots or fibres oriented perpendicular towards the weld direction.

Figure 4 shows the graphs for measured temperature adjacent to the laser's line of movement. The detected peak temperatures are of similar value of about T = 250 °C. The off-set does not lead to a significantly lower signal, because within the very small time frame of the temperature measurements, the heat conductivity almost instantly heats up the carbon fibre rovings running perpendicular to the weld direction.

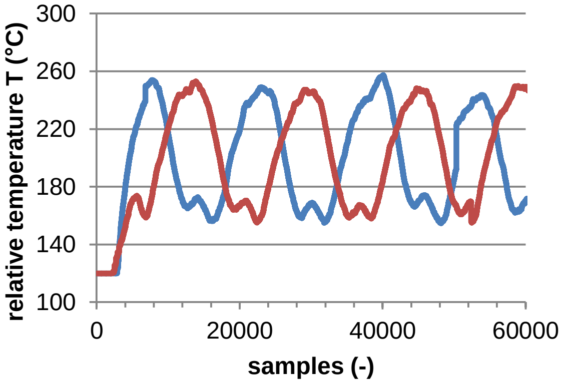

Fig. 4. Relative temperature signal for pyrometer spot placed adjacent to movement direction at O_a = 1 mm (blue) and O_b = 2 mm (red)

4. Conclusion

During the presented investigation temperature measurements on satin-woven CF-PPS were conducted utilising a pyrometer. Two aspects of measuring with a pyrometer were experimentally evaluated, the angle of detection and a local displacement of the measuring spot in relation to the laser beam's position.

Results showed that an angle of detection of $\theta < 45$ ° lead to a decrease in the measured temperature of up to $\Delta T = 150$ °C. Angles wider than $\theta = 45$ ° did not show significant changes in the detected temperature. Utilising a locally displaced pyrometer measuring spot, it was possible to identify signal patterns resulting from the carbon fibre reinforced surface. The signal maxima relate to carbon fibre rovings on the surface whereas the signal minima belong to the PPS matrix. The measurements also showed that the pyrometer is not only capable of identifying PPS-matrix depots and carbon fibres while performing bead-on-plate welding, but the measurements were accurate enough to detect these surface features also at larger local displacements of $O_b = 2$ mm. Therefore, a leading pyrometer measuring spot can be used to set up an automatic control of the laser power to change the process temperature in order to keep a constant weld seam width independent of changing fibre orientation at the surface.

This investigation was performed with a pyrometer spot fixed to a certain position in the weld seam. Thus, in order to keep the off-sets constant, measurements were only possible for straight weld seams. If the pyrometer measuring spot is combined with a galvanometer scanner, cf. figure 5, it will be possible to adjust the measuring spot's position during LTW creating a dynamic pyrometer spot. This development of a combined scanning head is part of the current project A'Quilaco and will allow the temperature monitoring not only of straight weld seams, but also of curved weld seams or sharp corners. The detection angle is constantly changing during scanner movement of the pyrometer spot, so it is required to know the deviation between actual and measured temperature in relation to θ and to take the resulting offset of the accuracy of the measurement into account. This will be part of future investigations as well as the development of an automatic control of the laser output power based on the surface temperature in the frame of the A´Quilaco Project. When added to the dynamic pyrometer spot this technique is deemed to significantly advance LTW automation.

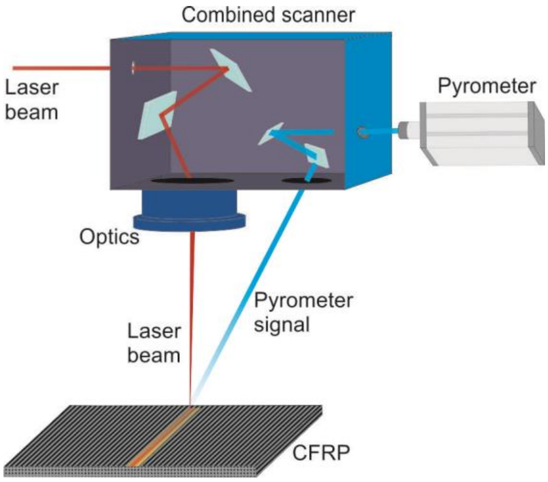

Fig. 5. Schematic drawing of a combined scanner for a flexible positioning of the pyrometer spot relative to the laser focus

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