Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 83 (2016) 1064 – 1072

Physics Procedia

9th International Conference on Photonic Technologies - LANE 2016

The influence of laser welding processes on the weld seam quality of thermoplastic composites with high moisture content

V. Wippo[a],*, Y. Winter[a], P. Jaeschke[a], O. Suttmann[a], L. Overmeyer[a]

[a]*Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany*

Abstract

Presently, fiber reinforced materials are used for many industrial applications. Laser transmission welding (LTW) is a suitable method to join these materials. For multiple thermoplastics, the weld seam quality is affected by the amount of moisture content in the joining members. For LTW, heat is applied to the welding members and water in the composite changes phase from liquid to gas. Increasing the gas content can lead to detrimental cavities in the weld seam.
Therefore, experiments were performed to investigate the influence of the laser focal geometry on the generation of cavities. Different focal geometries lead to different levels of process heat generation which affects the amount of vaporization. The experiments were conducted with endless glass fiber reinforced polyetherimide and endless carbon fiber reinforced polyetherimide. These samples were tested for their weld seam strength and the results were correlated to the moisture content and laser beam geometry.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: laser transmission welding; contour welding; thermoplastic; glass fiber; moisture

---

1. Introduction

Fiber reinforced plastics are often used in order to save weight when large masses are moved. Carbon and glass fibers are often used as reinforcements. The European market development shows for the year 2015, that glass fiber reinforced polymers (GFRP) are mainly used in the transportation (35%) and construction (34%) industry. The transportation industry includes the automotive, aerospace, railed vehicles as well as marine engineering industries. In all sectors it is necessary to join simple parts to more complex parts.

Glass fibers are known for their durability, high strength, resistance to heat and resistance to temperature. In the last couple years thermoset resins have often been replaced by thermoplastic resins. Thermoplastics have the

---

* Corresponding author. Tel.: +49-511-2877-384 ; fax: +49-511-2877-100 .
E-mail address: v.wippo@lzh.de

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2016.08.112

advantages of high damage tolerance, recyclability and thermoforming by fusion of the thermoplastic [1, 2]. Also, thermoplastic composites can be joined by welding, for example resistance, induction, ultrasonic and laser transmission welding. Welding has the advantage that the reinforcement fibres are not interrupted, as it would be needed for riveting, and no extensive surface preparation is needed as it is for adhesive bonding [3, 4].

For laser transmission welding one of the joining members has to be transparent for near infrared laser radiation. So the applied radiation can pass the upper part and is absorbed by the lower part. GFRP becomes absorbing when the matrix material contains carbon black. The absorbed radiation is converted into heat, which melts the matrix material. Due to heat conduction the transparent joining member also becomes molten. In order to support the heat conduction between the parts a clamping pressure has to be applied.

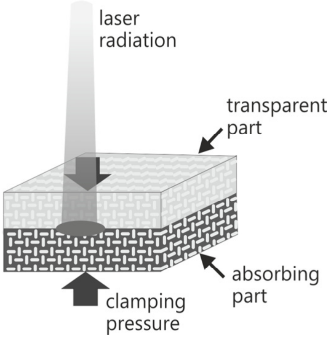

Fig. 1. Principle of a laser transmission welding process.

The laser transmission welding can be divided into four basic techniques: contour, quasi-simultaneous, simultaneous and mask welding. For contour welding the laser beam is guided over the weld seam once by a relative movement between welding head and work piece. This welding technique can be applied to generate long and three dimensional weld seams. During quasi-simultaneous welding the laser beam is guided by mirrors in a scanner optic several times over the work piece with a high speed. The advantage of this welding method is its high gap bridge capability, but the maximum weld seam length is limited by the scanner optic [4, 5]. The weld seam quality is affected by the welding technique combined with the applied clamping pressure as well as the material itself. The transparency of the upper part depends on the kind of matrix material and its reinforcements. Glass fibers for example scatter the radiation so less radiation will reach the welding zone compared to unreinforced materials. This has to be taken into account by process design [6]. Furthermore, the matrix material can influence the weld seam quality by its moisture content. Polyamide and polyetherimide (PEI) absorb moisture from their surroundings. For example, the material brand ULTEM 1000, which is an unreinforced PEI, obtains a moisture content of around 0.25 % within 24 hours at 23°C. The maximum moisture absorption is 1.25% [7].

The influence of moisture on the weld seam quality was investigated for different welding techniques and mainly for unreinforced and short fiber reinforced thermoplastics. Fischer et al. explored that the number of cavities in the weld seam increase with increasing moisture content for hot air welded polyvinyl chloride. Furthermore, they found out that increasing the welding temperature and reducing the welding speed, reduces the number of cavities by enhanced degassing [8]. Hopmann et al. have studied the influence of moisture on ultra-sonic welded polyamide 6 with the results that moisture decreases the seam strength but enhances the homogeneity of the weld seam morphology [9]. Another study was conducted by Kagan et al. focusing on laser welding of polyamide. They investigated that there is no difference in the influence of moisture for unreinforced and short glass fiber reinforced polyamide [10]. Wippo et al. investigated the effect of moisture in glass and carbon fiber fabric reinforced PEI for quasi-simultaneous welding. In these investigations, a three layer glass fiber fabric reinforced PEI (GF3 PEI) as well as a four layer glass fiber fabric reinforced PEI containing carbon black (GF PEI cb) was used. The materials were conditioned for 18 days in distilled water ("wet") and at air humidity ("AH"). The weight of the first dried material increased after conditioning therefore the GF3 PEI wet samples obtained a moisture content of $M_{\%,wet} =$ 0.42 %

(wet) and the air humidity samples were observed to have a lower moisture content $M_{\%,AH} = 0.15$ % (AH). The moisture content of GF PEI cb was $M_{\%,wet} = 0.46$ % (wet) and $M_{\%,AH} = 0.16$ %. Differences in the welding speed, laser power, number of repetitions, and overall welding process time, resulted in different results for dried and moisture containing material. They found out that moisture can have a positive effect on the seam strength by avoiding overheating of the matrix material. Furthermore, the cavities do not always have a direct connection to the interface between the parts due to the fiber bundles of the fabric and therefore this lack of connection reduced the influence on the seam strength [11]. Further investigations with a carbon fiber fabric reinforced PEI as an absorbing member have shown, that a high welding speed combined with a high number of repetitions result in a statistical convergence between dry and wet samples. [12] Therefore it was shown that the conditioning type has an influence on the weld seam strength depending on the welding parameters [11, 12]. Composite parts are often large and therefore contour welding would be the chosen welding method to join them. Therefore, the authors investigated the influence of moisture content on contour welded fabric reinforced PEI. Also, in these experiments the laser beam geometry was varied in order to obtain different time frames in which the thermoplastic material stays molten with the goal to enhance degassing of the moisture.

2. Experimental Set-up

For the experiments, glass fiber fabric reinforced PEI (CETEX) from Tencate Advanced Composites BV was used (Table1). The material has a glass transition temperature of $T_g = 210°C$ and a melting temperature of $T_m = 310°C$. The maximum moisture pick up of the composite is listed as 0.35% [13] and the matrix material itself is listed with maximum moisture absorption of 1.25% [7]. In order to determine the influence of moisture on the weld seam quality, all materials were conditioned. In a first step, the material was dried at T = 120°C for 48 hours. Samples welded directly after drying were defined as “dry”. Then samples were placed into distilled water for a different number of days. These samples were classified as “wet”. Also, samples were stored at room temperature at air humidity. These samples were classified as “AH” for air humidity. Therefore, the conditioning was conducted related to Wippo et al. [11, 12] in order to obtain materials which can have an influence on the weld seam quality due to the conditioning type.

Table 1. Classification of materials used.

Acronym	**Fiber**	**Matrix**	**Additive**	**Thickness**
GF2 PEI	5 Harness satin weave	polyetherimide	-	0.5 mm
GF4 PEI c.b.	5 Harness satin weave	polyetherimide	Carbon black	1.0 mm

The laser transparent part consisted of 2 layers fabric and had a transmissivity of 54.94% at a wavelength of $\lambda = 940$ nm. The material was cut into samples with a geometry of a x b = 25 x 55 mm² and were placed in overlap configuration for welding.

The welding was conducted with two different diode lasers emitting at $\lambda = 940$ nm. The maximum output power of one laser was $P_1 = 300$ W and was connected to a scanner optic generating a focal point with a diameter of d = 2mm (Fig. 2a). The second laser had a maximum output power of $P_2 = 1200$ W and was connected by an optical fiber to a homogenized optic generating a focal point with the dimension of a x b = 10 x 20 mm² (Fig.2b).

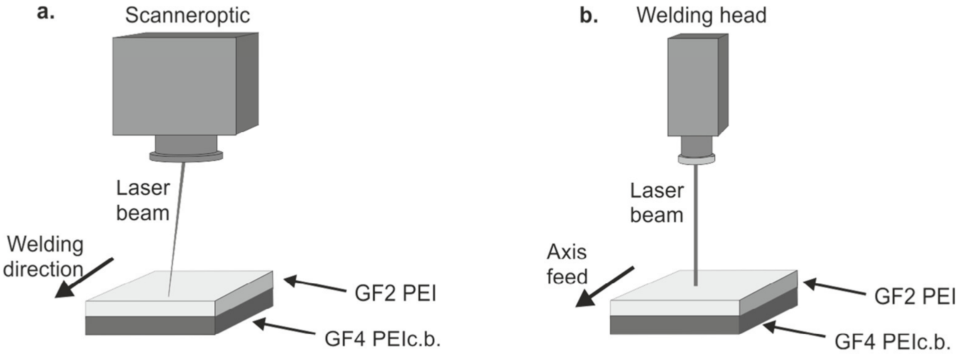

Fig. 2. Experimental set-up.

All experiments were conducted by contour welding with a welding speed of v = 2.5 m/min and v = 5 m/min, respectively. Pre-tests were performed in order to determine the laser power needed to join materials. The minimum laser power was defined, when a continuous weld seam was generated. The maximum power was set when visible damage of the matrix material occurred due to process temperatures that were too high.

3. Results and Discussion

First, samples were conditioned in distilled water for 13 days and then compared to the dry samples. In order to determine the influence of the laser power on the lap shear strength and the weld seam area, different laser powers were applied at a welding speed of v = 2.5 m/min and a focal point diameter of d = 2 mm. Figure 3a depicts the average seam strength of dry and wet samples.

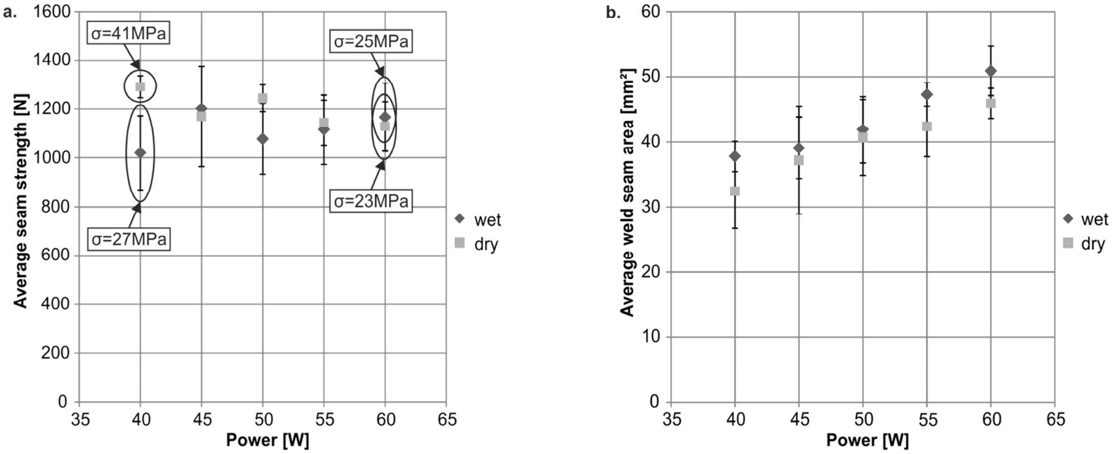

Fig. 3. Average seam strength and weld seam area for wet and dry lap shear samples welded with a speed of v = 2.5 m/min and a focal point diameter of d = 2 mm.

It can be seen, that the seam strength of the dry samples at a laser power of P = 40 W is higher than the seam strength of the wet samples. During the welding of the wet samples, part of the applied laser energy vaporizes the moisture in the material and does not contribute to the actual welding process causing lower temperatures in the weld seam corresponding to [12]. This can affect the duration of the liquid phase within the weld seam and so the seam strength [14].

Figure 3b shows that the weld seam area for the wet samples is higher than the area of the dry samples at P = 40 W. This can be based on scattering effects due to the cavities generated by the vaporizing moisture. Therefore, the radiation is absorbed over a larger area, which can affect the weld seam temperature and the timeframe that the thermoplastic stays in the liquid phase after the laser beam has moved on. It is known that the weld seam strength significantly depends on the time frame of the liquid phase [14]. Another possibility is that the weld seam area was enlarged by vaporized moisture leaving the material and heating up the surrounding areas, but no evidence for this was observed.

With increasing power the seam strength slightly decreases for the dry samples. This can be due to overheating of the matrix material in the weld seam, which leads to the generation of cavities and weakens the weld seam. This effect is known for laser transmission welding for unreinforced and endless glass fiber reinforced thermoplastics [4, 15] The seam strength of the wet samples increases with increasing power. The moisture in the material starts to vaporize during the welding process, so part of the process heat is lost for the actual welding process. This effect has a higher influence for low laser powers. For the dry and wet samples the weld seam area increases with increasing power. The off-set between dry and wet samples stays almost constant for varying laser powers. The seam strength relating to the weld seam area results in different lap shear strengths σ for the dry and wet samples depending on the laser power as given in the graph a. For the lowest laser power the difference between the lap shear strength between wet and dry samples is σ = 14 MPa, which is high compared to the results with the highest laser power (σ = 2 MPa). Furthermore, the shear strength decreases with increasing laser power for the wet and dry samples due to a higher increase of the weld seam area compared to the seam strength. In order to clarify the fundamental effects due to the conditioning and the chosen welding parameters, the seam strength and the weld seam area are separately examined and not the shear strength, which is just the ratio of seam strength and weld seam area. Furthermore, for industrial applications, the weld seam area is given by the design of the parts; therefore for a defined weld seam area it is the reachable weld seam strength, which is of high relevance.

During the welding pre-test with the large spot of a x b = 10 x 20 mm², the produced lap shear samples broke in the laser transparent part and not in the weld seam. Therefore, an influence of the conditioning type and the laser power, respectively, could not be determined. Next, part of the laser beam was covered in order to generate a focal point with the dimension of a x b = 5 x 20 mm². Lap shear samples welded with this reduced focal point width broke in the weld seam and this allows a determination of a difference between the conditioning type and the laser power. Figure 4 shows the seam strength (Fig.4a) and weld seam area (Fig.4b) of lap shear samples welded with 2.5 m/min and varying laser powers. Again, the wet samples were conditioned for 13 days in distilled water.

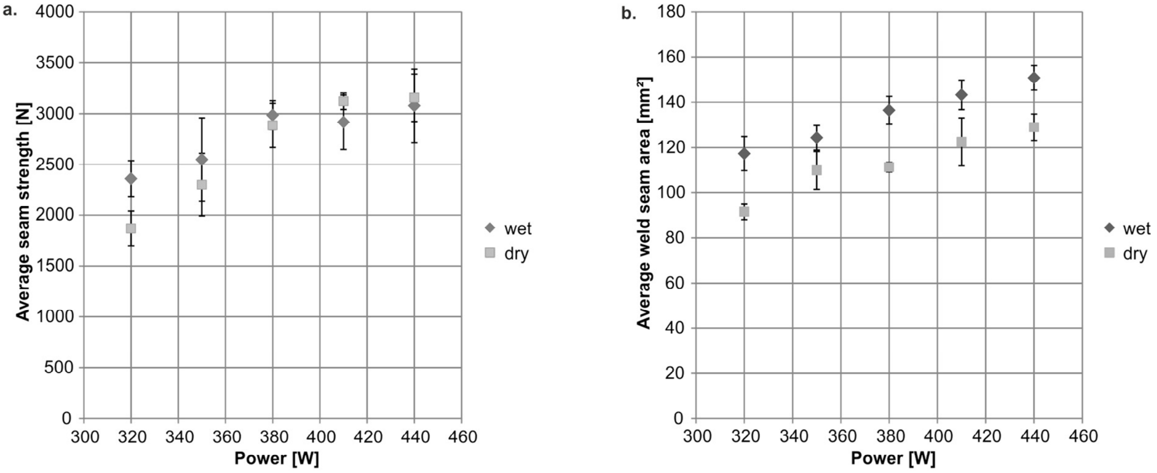

Fig. 4. Average seam strength and weld seam area for wet and dry lap shear samples welded with a speed of v = 2.5 m/min and a focal point geometry of a x b = 5 x 20 mm².

The seam strength for the wet samples is higher than for the dry samples at low laser powers. This can be due to overheating of the dry material, causing cavities in the connection area. In the wet material part of the laser energy vaporizes the moisture and so less energy is available for the actual welding process as it was also described by Wippo et al. [11, 12]. Furthermore, the weld seam area for the wet samples is larger than for the dry samples. This is the same effect observed for the results of the lap shear samples welded with a focal point diameter of d = 2 mm. The laser radiation was scattered in the laser transparent part due to cavities generated by vaporizing moisture.

Thus, the irradiated area of the absorbing part increases and so the amount of radiation per area reaching the absorbing part decreases. With increasing laser powers the wet and the dry samples obtain similar seam strengths, while the off-set of the weld seam area stayed almost constant.

With the basic condition of having a later part design allowing the maximum weld seam area and maximum weld seam width, these parameters could be used in order to obtain constant seam strength independent of the conditioning type. In a detailed investigation, samples with different conditioning time frames and conditioning types (AH, wet) were welded with the same parameters of v = 2.5 m/min and P = 410 W. Figure 5 shows the seam strength of the wet and AH samples. These results are fluctuating around F = 3000 N and are independent of the conditioning days.

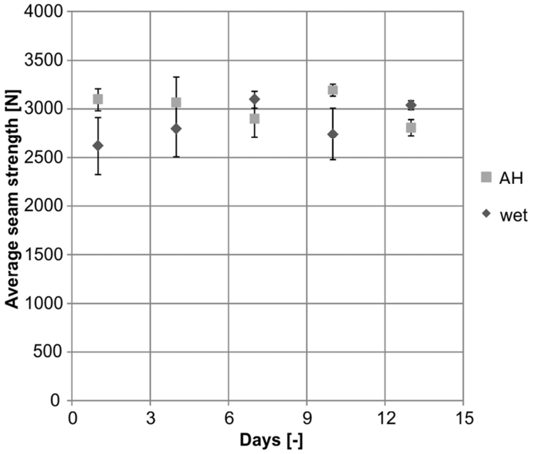

Fig. 5. Average seam strength for wet and AH overlap samples welded after different number of conditioning days (speed v = 2.5 m/min, laser power P = 410 W, focal point geometry a x b = 5 x 20 mm²).

For more detailed information about the influence of the conditioning process, samples with 7 and 13 days of conditioning were prepared in order to evaluate seam strength results of figure 5. Therefore, a welding speed of v = 2.5 m/min and a laser power of P = 410 W was chosen. Thus, optical micrographs of cross sections were prepared for wet and AH samples as well as for dry samples as reference (Fig. 6). The cavities generated during the welding process are located around the weld seam. For the dry samples the cavities are found closer to the interface between both parts as for the AH and wet samples. The main influences on the weld seam strength have the cavities directly in the interface where the load transmission takes place. The cavities further away from the interface often have no direct connection to the interface because of the glass fibre bundles and have a smaller effect on the seam strength. Overall, it has to be stated, that for the chosen welding parameters, the optical appearance of the weld seams are similar as it is for the seam strengths. The optical appearance cannot be clearly assigned to either overheating of the matrix material, vaporizing of moisture or a combination of both effects.

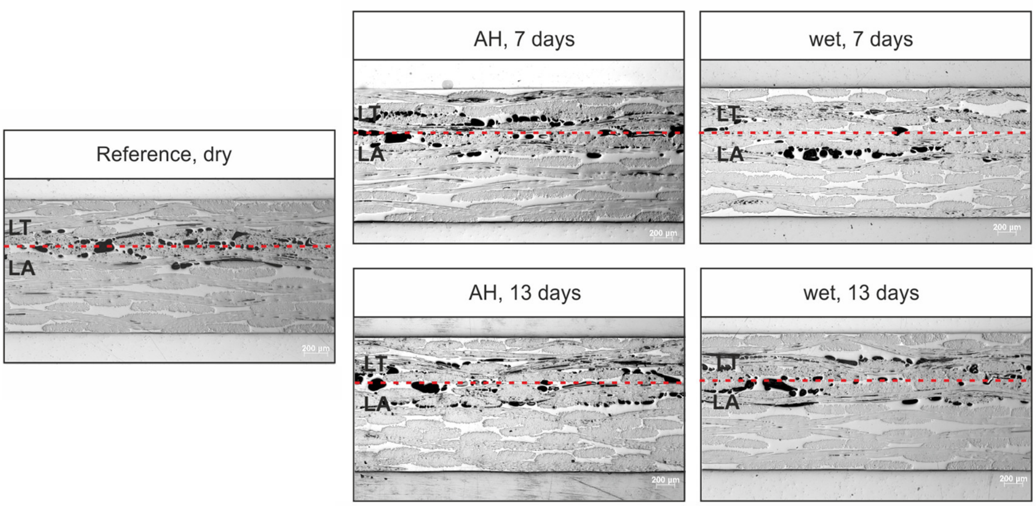

Fig. 6. Optical micrographs of cross sections for dry, wet and AH samples welded with a speed of v = 2.5 m/min and a laser power of P = 410 W with a focal point geometry of a x b = 5 x 20 mm².

In order to determine the influence of the welding speed on the weld seam quality of dry samples and for samples soaked for 13 days in distilled water the welding speed was increased to v = 5 m/min for contour welding with a focal point dimension of a x b = 5 x 20 mm². Due to the increase in speed, the average seam strength was lower than for the samples welded with lower speed (Fig. 7a, Fig.4a). Based on the higher welding speed, the weld seam is in the liquid phase for a shorter time frame. So the polymer molecules have less time to interact with each other, which reduces the weld seam strength. Furthermore, the time frame is reduced during which the moisture is vaporized and can diffuse out of the material. This might be the reason, that the seam strength of the wet and dry samples show an almost constant off-set in the average seam strength and do not converge like the samples welded with a speed of v = 2.5 m/min that were found to be independent of the focal point geometry (Fig. 7a) and so a constant influence of the conditioning type is visible.

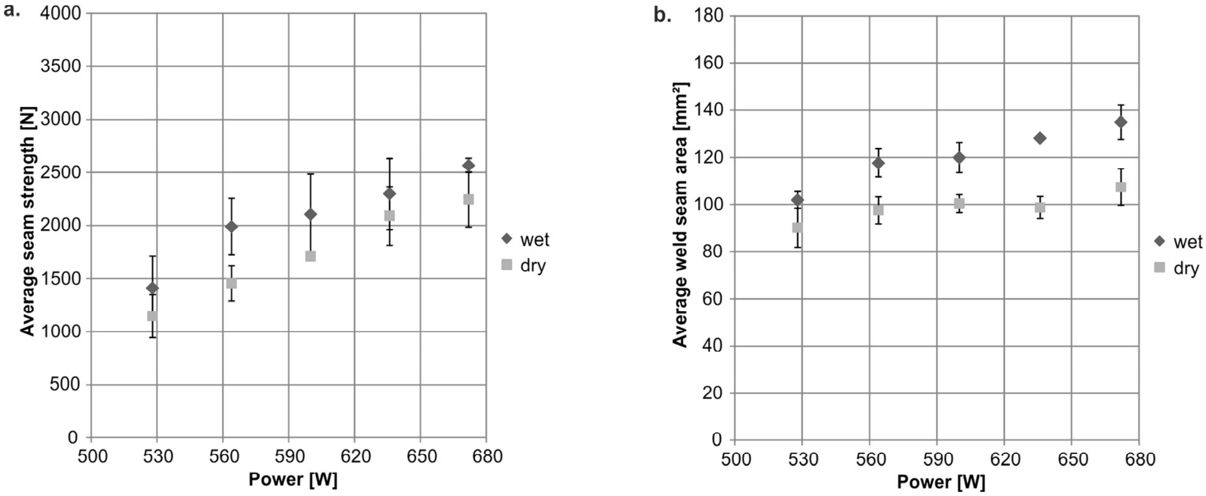

Fig. 7. Average seam strength and weld seam area for wet and dry lap shear samples welded with a speed of v = 5 m/min and a focal point geometry of a x b = 5 x 20 mm².

Furthermore, the weld seam area increases for the wet and dry samples in a similar way as for the slower welded samples (Fig. 7b, Fig. 4b). The average off-set ΔA were calculated by

$$\Delta A = \frac{|A_{w1}-A_{d1}|+|A_{w2}-A_{d2}|+\cdots+|A_{wn}-A_{dn}|}{n} \tag{1}$$

with average weld seam area A_{wn} for the wet samples and average weld seam area A_{dn} for the dry samples.

The average off-set for the samples welded with the large focal geometry are $\Delta A_{5m/min} = 21.7$ mm² for v = 5 m/min and $\Delta A_{2.5m/min} = 21.6$ mm² for v = 2.5 m/min. For the small focal point with a diameter of d = 2 mm the off-set is $\Delta A_{2.5m/min} = 3.6$ mm² for v = 2.5 m/min. This leads to the deduction that the off-set is mainly influenced by the focal geometry and its energy distribution and less effected by the welding speed.

4. Conclusion

The influence of moisture in glass fiber fabric reinforced polyetherimide on the weld seam quality of laser transmission welded samples was investigated. For these investigations two different focal geometries were applied as well as different welding parameters. The seam strength of wet and dry samples converge for high laser powers at a welding speed of v = 2.5 m/min independent of the focal point geometry. These parameters would always generate a weld seam with the same strength independent of the conditioning type of the material, which is of interest for the production of real parts with varying storage times. Noticeable is that the weld seam area for wet samples are larger than for the dry samples, which would have to be taken into account for the part design. The average off-set between wet and dry samples is $\Delta A_{2.5m/min} = 21.6$ mm² for welding with a large (a x b = 5 x 20 mm²) and $\Delta A_{2.5m/min} = 3.6$ mm² for welding with a focal point with a diameter of d = 2 mm. If the welding speed is increased to v = 5 m/min the off-set in the weld seam area stays almost constant $\Delta A_{5m/min} = 21.7$ mm² while using the large focal geometry. This leads to the deduction that the off-set is mainly influenced by the focal geometry and its energy distribution and less effected by the welding speed.

Acknowledgements

The authors would like to thank the Federal Ministry for Economic Affairs and Energy (BMWI) for funding these investigations within the project KASI (FKZ: 20K1306J) of the German federal aeronautical research program.

References

[1] Witten, E., T. Kraus, M. Kuehnel, 2015.Composites-Marktbericht 2015 - The Global CFRP-Market. In Carbon Composites & AVK.
[2] http://www.marketsandmarkets.com/Market-Reports/glass-fiber-reinforced-plastic-composites-market-142751329.html Status:08.02.2016.
[3] Fernandez Villegas, I., Moser, L., Yousefpour, A., Mitschang, P., Bersee, H. EN, 2012. Process and performance evaluation of ultrasonic, induction and resistance welding of advanced thermoplastic composites. In Journal of Thermoplastic Composite Materials 26(8) pp. 1007–1024.
[4] Jaeschke, P., 2012. Laserdurchstrahlschweißen kontinuierlich kohlenstofffaserverstärkter Kunststoffe und thermoplastischer Polymere. Dissertation. Leibniz Universität Hannover.
[5] T. Frick, 2007. Untersuchung der prozessbestimmenden Strahl-Stoff-Wechselwirkungen beim Laserschweißen von Kunststoffen. Bamberg: Meisenbach.
[6] V. A. Kagan, R. G. Bray, W. P. Kuhn, 2002. Laser transmission welding of semi-crystalline thermoplastics - Part I: Optical characterization of nylon based plastics. In Journal of Reinforced Plastics and Composites 21, 1101-1122.
[7] H. Domininghaus, 2012. Kunststoffe: Eigenschaften und Anwendungen. Verlag: Springer, pp.1024-1025.
[8] F. Fischer, U. Albrecht, D. Weiler, F. Kraetz, 2011. Investigations into the hygroscopic property of chlorinated polyvinyl chloride (PVC-C) as well as into its effects on the joining technology. In Joining plastics 1/11, pp40-45.
[9] C. Hopmann and A. van Aaken, 2012. Investigations into reliable process configuration in the case of the ultrasonic welding of hygroscopic thermoplastics using the example of polyamides. In Joining plastics 3-4/12, pp. 208-213.
[10] V.A. Kagan, S.A. Kocheny, J. E. Macur, 2005. Moisture effects on the mechanical performance of laser-welded polyamide. In Journal of reinforced plastics and composites, Vol. 24 No 11, pp. 1213-1223.

[11] V.Wippo, P. Jaeschke, O. Suttmann, L. Overmeyer, 2015. The influence of moisture content on the weld seam quality for laser welded thermoplastic composites. In: Proceedings of 20th International Conference on Composite Materials. Copenhagen.

[12] V. Wippo, J. Mangold, P. Jaeschke, O. Suttmann, L. Overmeyer, 2015. Influence of moisture content in fiber reinforced polyetherimide on laser weld seam. In: Proceedings of the 34nd International Congress on Applications of Lasers & Electro‑Optics ICALEO, Atlanta.

[13] TenCate Cetex: http://www.composites.nl/documents/TCAC_MD_PEI_LAM.pdf (29.03.2016).

[14] P. Jaeschke, D. Herzog, H. Haferkamp, 2009. Influence of the beam forming and the intensity distribution on the process limits in the process of laser transmission welding. In: Joining Plastics (1).

[15] T. Frick, 2001. Untersuchung der prozessbestiprozess Strahl-Stoff-Wechselwirkungen beim Laserschweißen von Kunststoffen. Meisenbach Verlag Bamberg.