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Laser welding of thermoplastics – Improving the weld strength of short glass fiber reinforced thermoplastics

Gereon Bussmann[a*], Andreas Schollmayer[a], Mattias Ölscher[a],
Marcus Scholl[a], Ulrich Russek[a]

[a]Rheinische Fachhochschule Köln gGmbH, Vogelsanger Str. 295, 50825 Köln, Germany

Abstract

Laser welding of short fiber reinforced thermoplastics is well-established in industrial production.
However, until now only the polymer matrices within the joining plane experience a connection; the glass fibers do not participate in the joining. Therefore, the achievable weld seam strength is limited to bulk strength, not to the much higher short fiber reinforced polymer strength. As a consequence weld seam areas have to be large enough to withstand expected forces / tensions. Additionally, larger weld areas asking for appropriate design, higher laser power and longer processing time.
By applying adapted irradiation methods, a movement of short glass fibers from one into the other joining part has been achieved while increasing weld seam strength by about 30 %.

Keywords: Laser welding of thermoplastics, short fiber reinforced thermoplastics, weld strength improvement

1. Introduction

The consumption of polymers in 2017 is estimated to be 348 million tons. The main areas of application in Europe are the packaging industry (40 %), the building industry (20 %), the automotive (10 %) and the electrical (6 %) industry (Plastics Europe, 2018). Primary forming such as injection molding is constrained when producing parts do have complex geometries. Therefore, these parts must be joined.

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* Corresponding author. Tel.: +49 221 54687 896; fax: +49 221 54687 889.
E-mail address: bussmann@rfh-koeln.de.

In general, there are two reasons to join polymers:

- Producing a complex component from a single piece is not possible due to manufacturing restrictions,
- Joining can help to avoid highly elaborate and complex molding processes. (Russek, 2009)

The joining of materials can be generated by various technical processes. In the following, the f bonding welding processes and laser transmission welding in particular will be presented. All welding processes have in common that the parts to be joined are heated above the melting temperature and brought together or they are heated when they are already in contact. The energy to heat the parts is made available for example by friction, heating elements or radiation. Conventional welding processes heat the parts and bring them together by a feed motion. The molten polymers are squeezed together, part of the material is pressed out of the joint – which often produces welding beats – and a material bond is created.

Another possible solution for joining polymers is the laser transmission welding. Laser energy is passed through a laser transparent part and converted into thermal energy, near the surface of a laser absorbing part. A characterizing figure for the absorption depth is the optical penetration depth δ_{opt}, representing the depth when only about 37 % ($\triangleq$ 1 / e) of the irradiated laser energy is left. Due to direct contact between the two parts the laser transparent part is also heated and plasticized through thermal conduction. Laser transmission welding is a well-established process, allowing a contactless connection between two parts while maintaining their geometry, generating small heat-affected zones (HAZ) and avoiding the formation of welding beads. The application of energy is highly defined in its location (≥ 100 µm) as well as in the duration (≥ ms). This ensures almost no mechanical or thermal load to the parts being joint and their surroundings. In addition no particles, gases or acoustic pollution are created. In order to make the process accessible for many technical applications there are different methods of irradiation strategies available. The most industrially used irradiation strategies are contour welding and quasi-simultaneous welding. Another irradiation strategy which is of importance for the present study is the TWIST® method. These different irradiation methods differ mainly because of the interaction time between the laser energy and the polymer. These are denoted in this paper as traditional irradiation methods. (Kagan, 2002) (Russek, 2006)

Contour welding is based on a once-only single radiation along the seam contour. Any desired seam contours can be realized by a relative movement between the laser beam and the workpiece. This relative movement can be realized by a multiple axis system, a robot to which the laser processing head is attached or a scanner system. With longer weld seams, solidification of already plasticized zones can occur before the remaining seam has been traversed, which may produce failure of the weld seam.

When **quasi-simultaneous welding** is used, the laser beam is moved with a high frequency over the weld seam. While during contour welding, every point of the seam experiences interaction with the laser only once, with quasi-simultaneous welding interaction takes place more than once at short time intervals. This method is usually executed with scanner systems which can move the laser beam at high speeds (up to 10 m / s). The multiple traversing of the weld seam contour creates an almost simultaneous plasticization of the entire seam contour, which can be used to work with a joining path (similar to the feed motion mentioned for the conventional welding techniques).

The **TWIST® method** (**T**ransmission **W**elding by an **I**ncremental **S**canning **T**echnique) uses two superimposed movements of the laser beam. The movement along the weld seam is similar to the one with contour welding, but there is an additional movement of the laser beam which serves to optimize the time required for thermal transport, allowing sufficient diffusion to generate the weld seam.

Besides the irradiation method, the laser power density distribution (PDD) is one of the key process parameters (others are for example wavelength, laser power or clamping technology). The power density distribution in the interaction plane has a significant influence on the temperature distribution in the joining area.

While different welding processes are successfully used in a wide field of applications, the demand for a higher strength of the weld seam is common. In particular this is important for short glass fiber reinforced thermoplastics, which offer higher mechanical properties than unreinforced thermoplastics. Short glass fibers are responsible for the high mechanical properties. However, the strengthening effect of short glass fibers is most successful when they are oriented parallel to the direction of an applied force.

Depending on fiber filling degree, fiber material, fiber diameter, average fiber length, fiber length distribution and other parameters the bulk strength can be up to 400 % higher than the bulk strength of the unreinforced polymer (Campus, 2019).

The objective of welding processes should be to join these reinforced thermoplastics in a way that the glass fibers are part of the joint, while transferring the bulk material strength into the weld seam.

Approaching this issue IGF, 2017 used innovative concepts for hot plate welding, infrared welding and vibration welding to increase the weld seam strength. Due to the feed motion that is used with this processes the welded materials shear off. As a result the short glass fibers in the material are oriented parallel to the welding contact area and perpendicular to the force direction of the welded test specimen. Therefore, the strengthening effect of the glass fibers is nonexistent in the weld seam. To improve this a device was built (IGF, 20018) that allows a so-called diffusion welding without any feed motion and welding time up to one hour. This method does not produce higher weld strengths.

As with the described welding processes laser transmission welding also only allows up until now to join the polymer matrices of the parts and not the reinforcing short glass fibers. The reinforcing properties of the short glass fiber have no effect in the weld seam, which leads to significantly lower weld strength than the bulk strength of the reinforced polymer.

The approach which is presented in the following uses some unique advantages of laser transmission welding to arrange the short glass fibers in a way that they contribute to the weld seam strength. The idea is to irradiate the parts in order to achieve an intrinsic movement within the interaction area. The result of this movement is a reorientation of the short glass fibers

- from the absorbing into the transparent part (if both parts are reinforced also in the opposite direction),
- perpendicular to the contact area (and therefore parallel to an applied force).

The result of this movement is that no preferred direction for the orientation of the short glass fibers is given. Fig. 1 shows the ideal situation of how the short glass fibers are located before and after the welding process for an unreinforced-reinforced material combination. Presented experiments are carried out with different combinations of joining partner materials, different irradiation methods and different process parameters. By now, in all executed welding experiments short process times, which are a significant parameter in industrial processing, are not considered. In further investigations this process parameter will be taken into account.

Fig. 1. Objective of the experiments: Location and orientation of short glass fibers before and after the laser transmission welding.

2. Experimental environment

2.1. Laser welding system

The welding experiments are carried out with a diode laser which features an emitting wavelength of 980 nm (LIMO Lissotschenko Mikrooptik GmbH, Dortmund, Germany). The laser beam is radiated onto the specimen with a galvanometer scanner (Raylase AG, Wessling, Germany) using an F-Theta lens with a plane field of work of 115 x 115 mm. The used gaussian power density distribution has a diameter of 1.4 mm in the focal plane. The seam length of 20 mm is chosen that on the one hand the energy input is as constant as possible and on the other hand the seam and not the transparent joining partner is destroyed during the subsequent lap shear test.

2.2. Tested materials and combination for welding study

The flat material is confectioned to the dimensions 40 x 60 mm, which are suitable for both the tensile shear test and the subsequent evaluation. The transparent and the absorbing parts are 2 mm thick. The specimen are positioned with an overlap of 20 x 40 mm. In order to ensure a uniform joining pressure over the entire overlapping surface of the joining partners, they are pressed with 2 N / mm² against a (laser beam) transparent quartz glass pane. The seam area is shaded with a mask so that acceleration and switch-on/off delays of the laser beam have no influence on constant energy input.

All tested materials are different types of polyamide 6. They are combined in such manner that different aspects of the materials come into play (e. g. viscosity, glass fiber content, optical penetration depth).
A table with the properties of interest is given in Tab. 1.

Table 1. Tested materials and significant properties for the present investigation.

material name	glass fiber content [wt.-%]	transmission, reflection, absorption @ 980 nm [%]	δ_{opt} [µm]	tensile strength [N / mm²]	viscosity number [cm³ / g]
Durethan B30S (transparent)	0	64.2 / 26.6 / 9.2	–	36.68 ± 0.54	134
Ultramid B3EG3 (transparent)	15	76.1 / 13.8 / 10.1	–	63.71 ± 0.31	140
Durethan BKV30 XWPHV (absorbing)	30	–	85.6	91.18 ± 1.92	195
Durethan BKV30 H2.0EF (absorbing)	30	–	90.7	120.52 ± 1.54	–

The optical properties for both transparent materials are well suited for laser transmission welding. The optical penetration depth for both absorbing parts are similar. The optical penetration depth is higher than for most laser transmission welding applications but is chosen to allow a pronounced melting pool.

These materials are combined in different ways to examine which adaption (compare section 2.4) is most promising for different materials combinations. The respective combinations which have been tested are shown in Tab. 2. The approach is to join unreinforced transparent parts with reinforced absorbing parts as well as reinforced transparent parts with reinforced absorbing parts.

Table 2. Material combinations for presented study.

Combination designation	Laser transparent part (glass fiber content)	Laser absorbing part (glass fiber content)
A	Durethan B30S (0 wt.-%)	Durethan BKV30XWPHV (30 wt.-%)
B	Durethan B30S (0 wt.-%)	Durethan BKV30H2.0EF (30 wt.-%)
E	Ultramid B3EG3 (15 wt.-%)	Durethan BKV30XWPHV (30 wt.-%)
H	Ultramid B3EG3 (15 wt.-%)	Durethan BKV30H2.0EF (30 wt.-%)

2.3. Evaluation methods

To evaluate the results of the welding experiment three different evaluation methods are used.

The first method is to measure the lap shear strength of the welded specimen. Due to its geometry (flat) the strength test cannot be performed with a uniform direction of force. To obtain a significant amount of data for each parameter set seven welded specimen are tested. For each specimen the force at break is documented and the weld area is measured which allows to calculate the lap shear strength. To analyze the results of the non-traditional irradiation methods, experiments are carried out to compare them to the “best possible” joints for the respective material combination. These comparative experiments are conducted through the contour and quasi-simultaneous method with process times of 0.4 seconds.

The second and third part of the investigation are imaging techniques. For every laser parameter set thin sections are prepared which can be analyzed via transmitting light microscopy. This allows to investigate if short glass fibers of the reinforced part have been moved to the unreinforced part. In case of the combinations E and H this evaluation does not work since both joining partners are reinforced. For these combinations the lap shear strength is pivotal. By using polymerized light, the morphology of the weld seam can also be evaluated and potential decomposition phenomena can be detected.

For combinations that appear to show an intermixing of short glass fibers (high lap shear strength, short glass fiber transport shown in thin sections) computed tomography scans are conducted. While the microscopic evaluation shows a thin section out of the entire weld seam, a computed tomography scan can give an overview about the glass fiber movement along the entire weld seam.

2.4. Adaption of irradiation method and power density distribution

In order to induce a movement into the weld pool the traditional irradiation methods are extended or combined. In the following the irradiation methods that created the best results are presented.

The first approach is to provide the molten polymers more time to intermix by irradiating the specimen for a long time (up to 20 sec.) with a quasi-simultaneous irradiation method with frequencies of up to 60 Hz. The combination of long process times, low laser energies and high frequencies produces a state in which the whole weld seam is plasticized and gets new energy / heat impulses with each passage of the laser beam. The temperature gradients that are created may cause an intrinsic movement of the polymer which can also transport the short glass fibers from one part to the other and vice versa.

The second approach is to combine the quasi-simultaneous method with the TWIST® method. This – in theory – creates a similar state as with the first approach but generates more complex temperature gradients that are not only parallel to the forward feed motion but also perpendicular to it.

Another (third) approach is to combine these irradiation methods with an adaptation of the laser power density distribution. This adaptation is realized by masking the laser beam before it impinges the transparent specimen. The dimensions of this mask are shown in Fig. 2. Besides the effect of masking the power density distribution the mask has the same purpose as the mask described in section 2.1.

Timpe et. al., 2016 show that different power density distributions result in different weld seam strengths along the cross section of the heat affected zone. The usage of a super-gaussian distribution or a top-hat-distribution can create a higher ratio of weld seam strength per length unit of the cross section. The masking of the power density distribution which is used in the present study is an approach to create a power density distribution which resembles a top-hat-distribution.

This creates a different geometry of the interaction area in which the polymers are molten. The flat ends tend to not develop which creates a more rectangular area. Therefore, the short glass fibers have more space in which they can move. As a result, the subsequently prepared thin sections show a more rectangular heat affected zone. Since heat conduction plays a dominant role in the shaping of the heat affected zone, the more rectangular geometry still has curvatures. Since the edges of the power density distribution are ’cut off’ the weld seam area becomes smaller, but is chosen to be big enough to allow the short glass fibers to move.

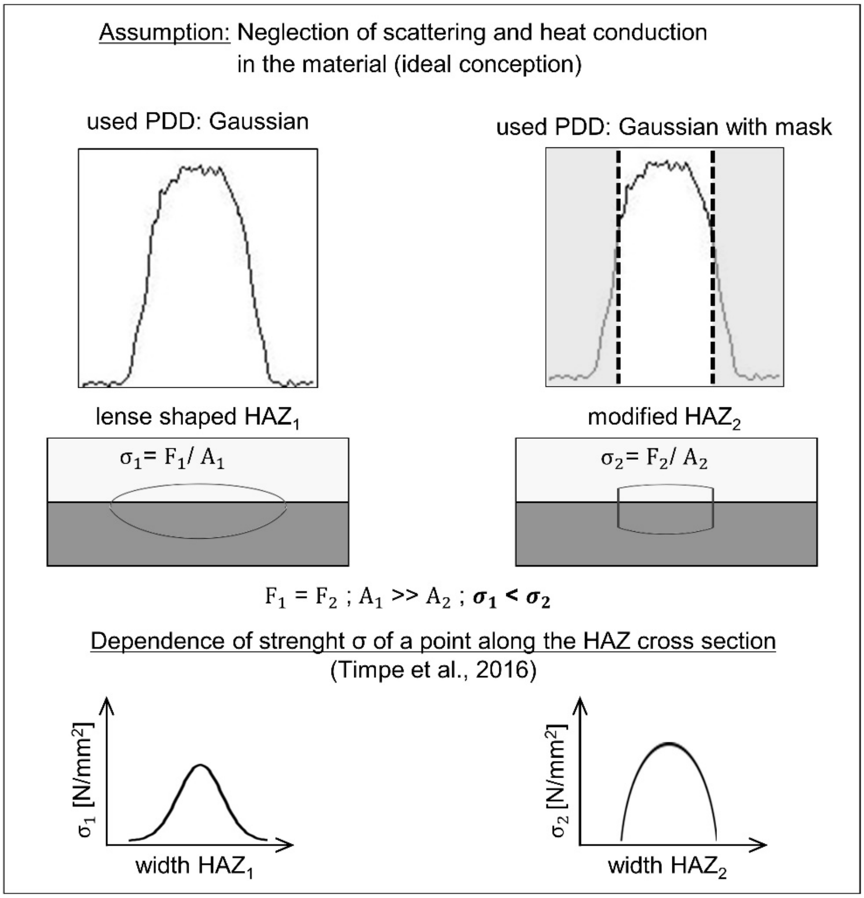

Fig. 2. Creation of an adjusted heat affected zone (HAZ) by modification of used laser power density distribution (PDD) by a mask.

3. Results and discussion

3.1. Lap shear strength

In the following the results of the lap shear strength test are presented. The declared objective to create a higher weld seam strength is achieved for all material combinations. As a comparative figure the maximum attained weld strength with the contour method is chosen, since this method creates slightly higher weld seam strength as the traditional quasi-simultaneous method with the same process time. Fig. 3 presents the maximum attained increase in weld seam strength.

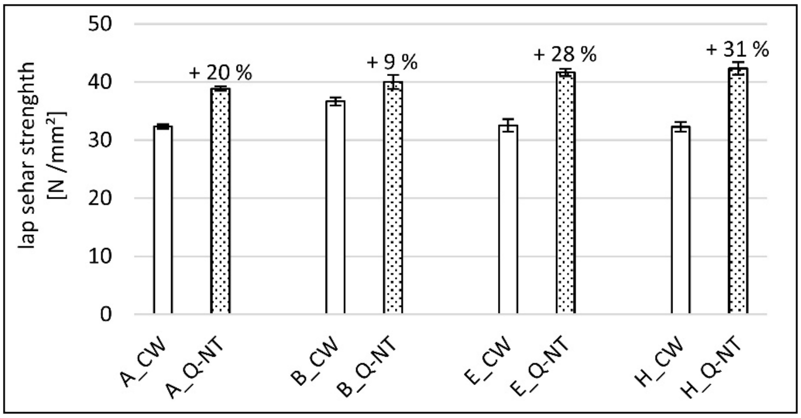

Fig. 3. Maximum lap shear strength with adapted irradiation method.

Designation:

A, B, E, H: material combination,
CW: contour welding,
Q-NT: non-traditional quasi-simultaneous welding.

For all material combinations a non-traditional quasi-simultaneous irradiation method with a long process time attains the highest increase of lap shear strength. For material combination ‘A’ a radiation method with a process time of 7.2 seconds results in an increase of lap shear strength of 20 %. The increase of 9 % for material combination ‘B’ is achieved with a process time of 8 seconds. The attained lap shear strength for combination ‘B’ (41.66 ± 1.23 N / mm²) is even about 14 % higher than the bulk strength of the unreinforced Durethan B30S (36.68 ± 0.54 N / mm²), which implies a participation of the short glass fibers. For the combination ‘E’ and ‘H’, which combine two reinforced welding partners an increase of 28 % (E) and 31 % (H) is created with radiation times of 12 (E) and 18 (H) seconds.

The results for the lap shear strength for the modification of the laser power density distribution by masking part of the laser beam are shown in Fig. 4. The axis designation is the same as in the previous Fig. 3 with the addition of an M which represents the use of the mask.

For the material combination ‘E’ an irradiation method that combined the quasi-simultaneous and the TWIST® method creates the highest lap shear strength. It is achieved with a process time of 18 seconds. For the material combinations ‘A’, ‘B’ and ‘H’ the non-traditional quasi-simultaneous irradiation method created the best results. For combination ‘A’ a process time of 10 seconds creates an increase of lap shear strength of 21 %. An increase of 14 % is realized by an irradiation with a process time of 8 seconds. For material combination ‘H’ a process time of 18 seconds results in an increase of lap shear strength of 30 %.

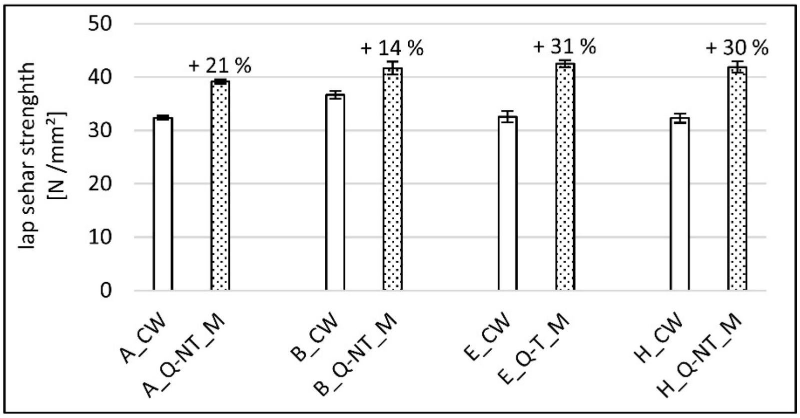

Fig. 4. Lap shear strength with adapted irradiation method and masked power density distribution.

Designation:

A, B, E, H: material combination,

CW: contour welding,

Q-NT: non-traditional quasi-simultaneous welding,

Q-T: combination of non-traditional quasi-simultaneous welding and TWIST® welding,

M: use of mask to modify power density distribution.

3.2. Microscopy and computed tomography scan

Fig. 5 shows a heat affected zone of the material combination with the non-traditional quasi-simultaneous method. The thin section was taken out of the middle of the weld seam. Especially in the magnified view (Fig. 5b) it seems that the short glass fibers are present in the transparent part. It also seems that these short glass fibers are no longer enclosed by the polymer matrix of the absorbing part. This indicates that they have been detached from the polymer matrix and have been moved in the planned manner into the transparent part.

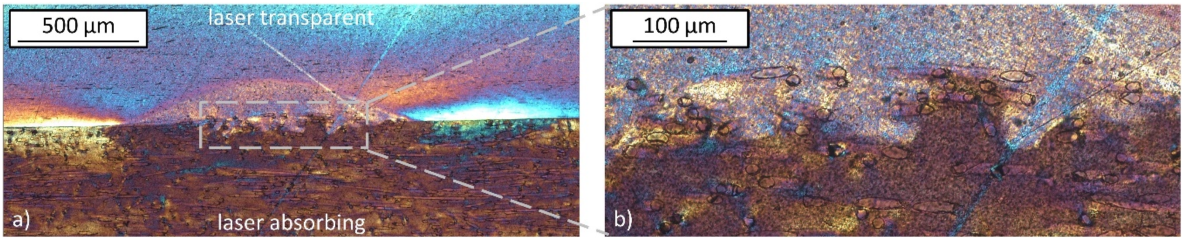

Fig. 5. Thin section of heat affected zone which shows short glass fiber transport from absorbing part to transparent part (B_QSW_NT)

a) complete HAZ with visible intermixing of transparent and absorbing part.

b) magnified view with short glass fiber within transparent part.

Since the short glass fibers seem to have moved from one joining part into the other and the gain of lap shear strength is significant this specimen is scanned with computed tomography to get a better understanding of the intermixing of the polymers and the short glass fibers, respectively.

Fig. 6 shows the same weld seam which is depicted in Fig. 5 in a computed tomography scan. The upper picture (Fig. 6a) shows a three-dimensional view which resembles the presentation in Fig. 5 but in a slightly different angle so that the short glass fibers along the weld seam can be seen.

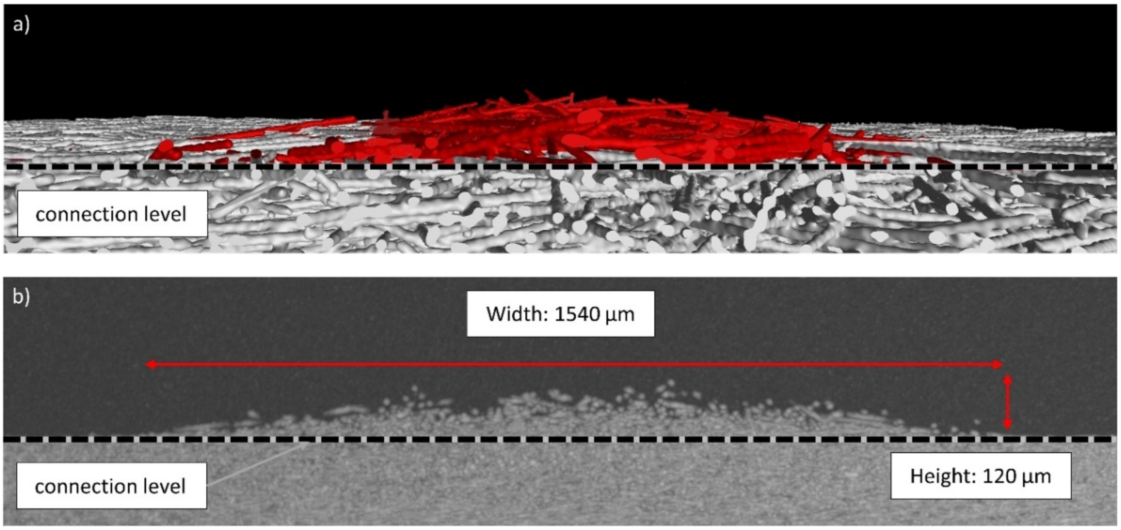

Fig. 6. Computed tomography scan which shows short glass fiber transport from absorbing part to transparent part (B_QSW_NT).

The picture only shows the short glass fibers as white fibers, whereas the polymer matrix is not represented. The red colored short glass fibers are identified to lay above the connection level of the joined parts. These fibers have been moved from the absorbing to the transparent part. The orientation of the fibers is partially perpendicular to the connection level which resembles the direction of force in a subsequently strength test. Fig. 6b shows a projection of all short glass fibers along an 8 mm range in the middle of the weld seam.

This method integrates every signal along the range. The width of the area in which the short glass fibers have been transferred into the transparent part corresponds with the diameter of the laser power density distribution. The detected maximal height of the short glass fiber transport into the transparent part is about 120 µm.

3.3. Discussion

The declared objective to move short glass fibers from one welding part into the other is successfully realized. Contrary to previous assumptions the material viscosity has no significant influence on the process. It can be assumed, that this intermixing is causing the achieved increase of lap shear strength in comparison to traditional contour welding. If – in an industrial application – the attained weld seam strength is higher than required, the weld seam width can be reduced.

Although some of the conducted experiments used process times up to 18 seconds, almost none of the specimen showed sink marks on the opposite side to the weld seam. How many or to which height (into the transparent part) the short glass fibers must move to increase the weld seam strength cannot be answered, yet. The height of the movement corresponds to the process time, which also correlates with the length and geometry of the weld seam. For every material combination and weld seam should be optimal process parameters combinations available to create the described movement of short glass fibers and thus increase of weld seam strength with minimized process times. For the combination B_Q_NT a reduction of process time from 8 to 0.9 seconds ($t_{contour}$ = 0.4 seconds) has been realized while the increase of weld seam strength dropped from 32 % to 21 %.

4. Conclusion

Laser transmission welding is a well-established process for joining reinforced thermoplastics. Until now the strengthening properties of these thermoplastics could not be transferred into the weld seam area, because short glass fibers could not be moved in a way to participate in the force transmission. The present study shows that non-traditional irradiation methods and a modification of the laser power density distribution can increase the weld seam strength by up to about 30 % in comparison to traditional contour welding. As a reason for an increase in weld seam strength a movement of the short glass fibers is identified. Transmission microscopy and computed tomography scans show a short glass fiber movement from a reinforced absorbing part into an unreinforced transparent part of about 120 µm. The position of these fibers indicates that they can participate in the force transmission. This allows to create weld seams with higher strength or to reduce the weld seam width while maintaining a strength that meets the requirements.

Further research will be performed to get a better understanding of the physical processes that motivate the short glass fiber movement. Also, a reduction of process time and other methods to modify the laser power density distribution will be investigated.

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References

Plastic Europe, 2017. Plastics -The Facts 2017.
URL (06.05.2019): https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf.

Russek, U. A., 2009. Laser Welding of Polymers – Fundamentals, influences, applications, p. 37 ff.

Kagan, V. A., 2002. Innovations in Laser Welding of Thermoplastics: This Advanced Technology is Ready to be Commercialized, SAE International, Detroit, Michigan, United States.

Russek, U. A., 2006. Prozesstechnische Aspekte des Laserdurchstrahlschweißens von Thermoplasten, Dissertation, RWTH Aachen, Aachen, Germany.

Campus. Campus® - a material information system for the plastics industy. Mai 2019.
URL (06.05.2019): https://www.campusplastics.com.

IGF, 2017. Final report, IGF-Nr. 18.702 N. Wirksame Faserverstärkung in der Schweißnaht beim Schweißen von faserverstärkten Kunststoffen, Schweißen und verwandte Verfahren e.V. of DVS, Paderborn, Germany.

Timpe, N., Stuch, J., Scholl, M., Russek, U.A., 2016. Laser welding of polymers: Phenomenological model for a quick and reliable process quality estimation considering beam shape influences. High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications V. San Francisco, California, United States.