Laser Transmission Welding of Absorber-free Thermoplastics Using Dynamic Beam Superposition

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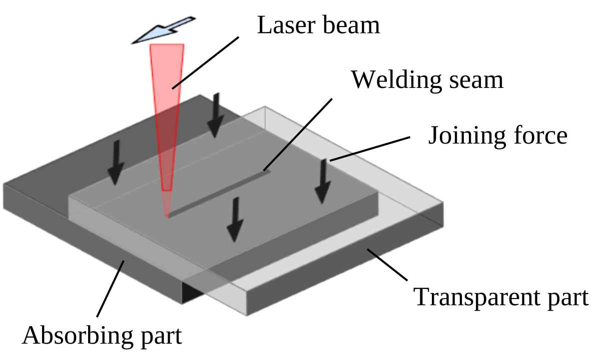
ABSTRACT

So far, the main approach to weld absorber-free thermoplastics is exploiting their intrinsic absorption by choosing a proper wavelength of the laser. In order to melt the joining partners spatially restricted at the interface usually optics with a high numerical aperture are used. However, practice shows that the heat affected zone (HAZ) extends over a large area along the beam axis regardless of the optics used. Without clamping or convective cooling thermally induced expansion of the material can cause blowholes or deformation of the irradiated surface. To reduce the thermal stress on the part surface a dynamic beam superposition is investigated with the laser beam performing a precession movement.

Keywords: Absorber-free, transparent thermoplastics, intrinsic absorption, adapted wavelength, high numerical aperture, beam superposition

1. INTRODUCTION

For many years laser transmission welding of thermoplastics has successfully been used in several industrial applications. Especially when small parts or parts with integrated electronics need to be joined, laser transmission welding is the process of choice as classical joining techniques like hot plate/ ultrasonic welding or adhesive bonding reach their limit [1]. Joining by the means of laser radiation offers the advantage of a contactless and defined energy input keeping the thermal and mechanical stress on the joining partners low. Furthermore, no particles are released during processing making the process ideal for applications with stringent requirements on the cleanliness as often found in the medical sector. However, the need to adapt the optical properties of the joining partners was the major drawback of the process so far.
As thermoplastics are transparent in the wavelength range of traditional lasers (800-1100 nm) (Figure 1, right) the absorbance of one of the joining partners has to be enhanced in order to generate process heat. With one part being transparent and the other absorbing, the laser beam is able to reach the interface where its electromagnetic energy is converted into heat (Figure 1, left). The heat distributes via heat conduction and fuses the joining partners at their interface.



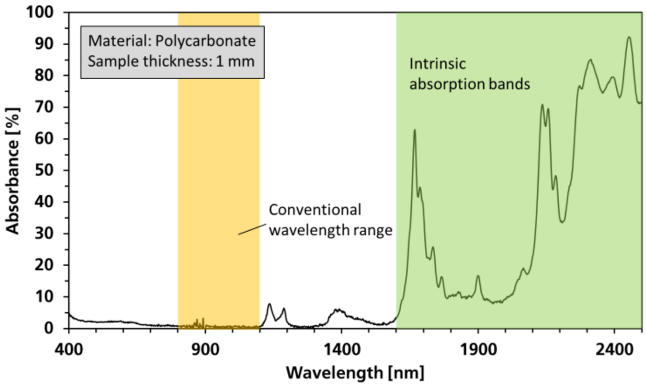


Figure 1: Principle of laser transmission welding (left), absorption spectrum of polycarbonate (right)

Among the absorbance enhancing additives carbon black is most commonly used due to its low costs and favorable absorption properties over a large wavelength range. Unfortunately, the absorption of carbon black also covers the visible range giving the bulk material a dark shade. Therefore, near-infrared (NIR) absorbers were developed which mainly absorb outside the visible spectrum, thus barely affecting the natural color of the polymer. However, their lack of inherent color is offset by higher prices which can considerably increase the production costs especially for large scale parts with the absorber being incorporated into the bulk material. To minimize the costs and the influence of absorbers they can be selectively applied at the interface of the joining partners instead [2].
However, in some applications absorbers are inadmissible as they may affect functionality or biological compatibility of the product [3]. To bypass the use of absorbers, the absorption bands of thermoplastics can be exploited by matching the emission wavelength of the laser (Figure 1, right) [5]. The main challenge in laser transmission welding without absorbers is to melt the joining partners spatially restricted at their interface. A vertically extended HAZ which is usual in current approaches indicates a high thermal load and can lead to deformation of the welded part or even burning on the irradiated surface. Therefore, an approach using dynamic beam superposition is considered in this paper.

2. ABSORBER-FREE LASER WELDING

2.1 Fundamentals

Exposing a thermoplastic part to laser radiation a small part (~4-5 %) of the incident radiation (**I_0**) is reflected (**R**) at the surface with the angle of incidence (Figure 2). The remaining part enters the material and is attenuated according to the law of Lambert-Beer (1) with C_{ex} being the extinction coefficient and z the space coordinate.

$$I(z) = (1 - R) \cdot I_0 \cdot e^{-C_{ex} \cdot z} \tag{1}$$

There are two factors contributing to the attenuation of the beam, absorption and scattering, which occur separately or jointly, depending on the material itself and its additives. The absorbed fraction of the radiation is transformed into heat whereas scattered radiation is deflected out of its original direction leaving the material as forward (**T'**) or backwards (**R'**) directed scattering. The part which is neither absorbed nor scattered passes through the material as directed transmission (**T**).

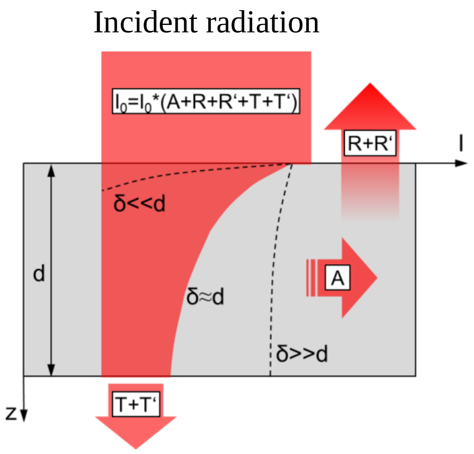


Figure 2: Interaction between laser radiation and a polymer (left)

For undoped amorphous thermoplastics as considered in the following scattering can be neglected, hence the radiation is only attenuated by absorption. The optical penetration depth **δ** is another measure for the absorption which is the reciprocal of the extinction coefficient. It indicates the distance from the surface at which the intensity of the entering beam has dropped to 1/e % (Figure 2). A too high optical penetration depth means that only a small portion of the radiation is absorbed and thus can be used for the process. In case the depth is too low, most of the radiation is absorbed in the near-surface layers of the upper part without reaching the joining plane.

2.2 Energy deposition

As mentioned earlier, in conventional transmission welding the upper part shows no substantial absorption (δ>>d) whereas the underlying part absorbs the entire radiation near the surface (δ<<d). The place of energy input is thus determined by the transition between the optical properties. In absorber-free laser welding, both joining partners have equal optical properties (δ≈d) thus evenly absorbing the radiation according to (1). Thereby, higher located layers are exposed to higher intensities which initiates melting from top to bottom. In order to start melting between both joining partners the highest intensity must be located in the joining area.
To elevate the intensity in the joining area beyond the surface intensity one approach is to use optics with a high numerical aperture (Figure 3). The numerical aperture (NA) of optics is defined as

$$NA = n \cdot \sin\varphi \tag{2}$$

with n being the refractive index of the surrounding medium (for atmosphere n~1) and φ the half opening angle of the beam. A high NA strongly increases the intensity along the beam axis, thereby counteracting the decrease of intensity due to absorption.

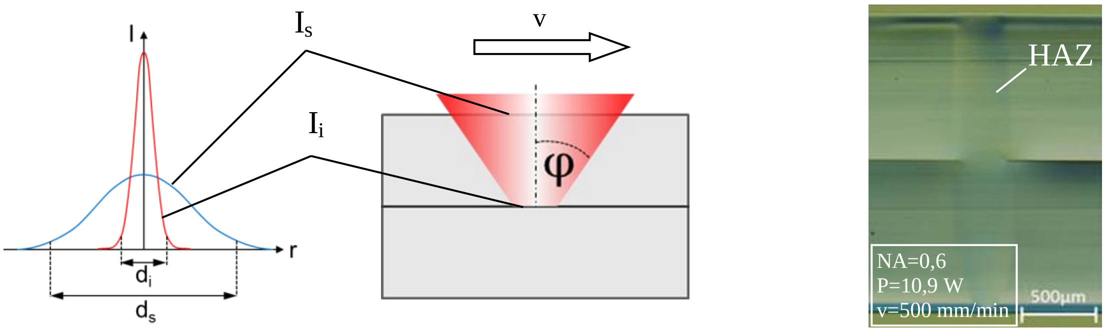


Figure 3: Surface/interface intensity distribution using optics with high NA (left), cross-section of a weld seam (right)

However, as the beam is usually moving along the welding contour (with the feed rate **v**) the interaction time $\mathbf{t_{s,i}}$ between the material and the radiation has to be considered. On the surface the beam diameter $\mathbf{d_s}$ is larger than at the interface $\mathbf{d_i}$, thus exposing any point in the beam path longer to radiation. The time of exposure is related to the diameter as follows:

$$t_{s,i} = \frac{d_{s,i}}{v} \tag{3}$$

Therefore, the interaction time relativizes the intensity differences between the surface and the interface which is also observed in welding trials [5]. Instead of being spatially restricted the HAZ usually extends over a large range along the beam axis regardless of the NA (Figure 3, right).
Another approach to achieve a spatially limited HAZ is using multiple tilted beams which cross each other in one point. In the crossing point, the intensities of the individual beams add up whereas on the surface the intensity is distributed over several beams.
In [6] trials with a 4-beam-setup were carried out and compared to the single beam approach with a high NA. It was found that the extension of the HAZ can be minimized by using the 4-beam-setup. The results suggest that the extension of the HAZ can be further minimized by increasing the number of beams.

3. DYNAMIC BEAM SUPERPOSITION

3.1 Principle

The basic idea of beam superposition is distributing the intensity on the irradiated surface over a large area thereby decreasing the thermal load. In the crossing point of the beams, which is ideally located at the interface the intensities add up. Hence, the more beams are superimposed the more the individual beam intensities decrease. The ideal case thus would be an infinite number of beams arranged in a circle at an incline angle crossing in one point. However, more beams also increase the complexity of the setup and its adjustment.

An infinite number of circular arranged beams results in an annular intensity distribution on the surface of the upper joining partner. One option to simulate such a beam arrangement is using optical elements to shape the beam. By the means of an axicon a collimated beam can be transformed into an annular beam which is then collimated and focused onto the joining plane [7].

Another way is illustrated in Figure 4. Using a scanner the laser beam performs a circular movement along the inner side of a copper ring which is coaxially positioned below. The inner surface of the ring is polished to ensure high reflectance and low scattering.

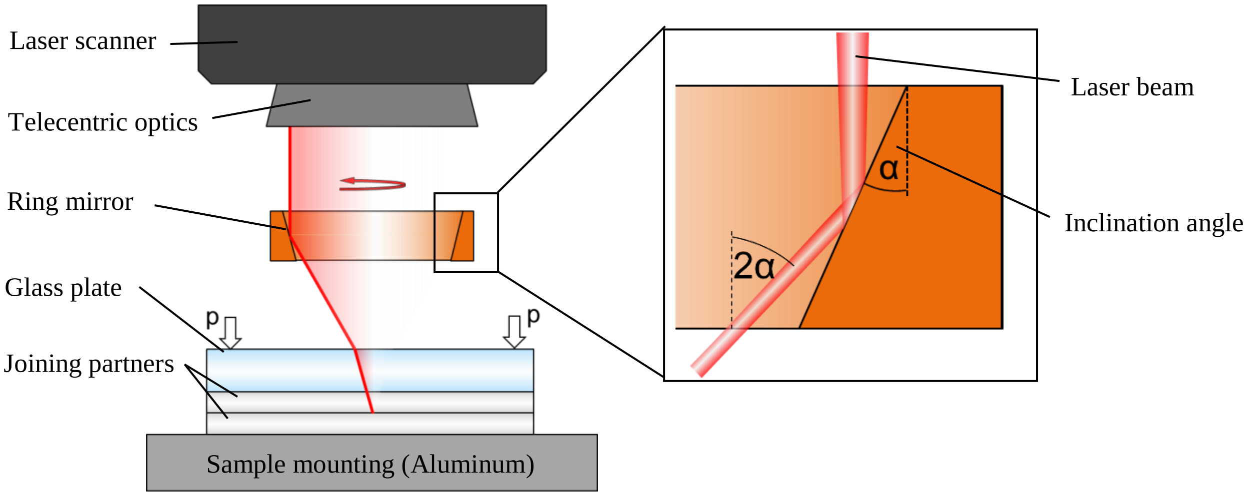


Figure 4: Principle of dynamic beam superposition

For the trials carried out a scanner with a telecentric optics was used which lets the beam fall vertically onto the copper ring. Its inner diameter tapers downwards to allow the beam hitting the inside area. Following the law which states that the angle of reflection is equal to the angle of incidence, the beam is deflected at an angle twice as high as the inclination angle of the ring's inner surface **α**.

Applying high speeds the inner side of the ring is quasi-simultaneously irradiated similar to the approach used in quasi-simultaneous welding [8]. The reflected sub-beams cross in one point generating a pseudo superposition.

3.2 Experimental setup

In the trials Polycarbonate (PC) was investigated which is an amorphous thermoplastic. To exploit its intrinsic absorption a scanner based fiber laser was used emitting at 1940 nm (Figure 1, right). A detailed overview of the laser system and material properties can be obtained from the following table.

One of the main aspects investigated in trials is the incidence angle of the beam. Therefore, three ring mirrors with a diameter of 50 mm were experimented with that differ in the inclination angle. The material the ring mirrors are made of is copper which reflects 97 % of the incident radiation at 1940 nm wavelength.

Welding system	
Beam source / Emission wavelength	TLM-120 (IPG Photonics) / 1940nm
Scanner	Intellicube 10 (Scanlab)
Optics	S4LFT1900/159 (Sill) telecentric
Beam characterisitcs	
Focal diameter (without superposition)	144 µm
Divergence angle φ	1,6°
Rayleigh length	2,5 mm
Sample properties	
Material	Polycarbonate (Makrolon® GP clear 099)
Thickness	1 mm
Absorption coefficient (1940 nm)	0,1 mm^{-1}

Table 1: Properties of laser system and material used in experiments

As mentioned above the angle of incidence (**2α**) is twice the inclination angle (Figure 4). However, as the crossing point of the sub-beams is placed between the joining partners the circulating beam has to pass through the glass plate of the fixture and the upper part before reaching the crossing point (Figure 5). At the interfaces refraction has to be taken into account as it changes the incidence angle of the beam. In accordance to Snellius' Law

$$n_1 \cdot \sin(\alpha_1) = n_2 \cdot \sin(\alpha_2) \tag{4}$$

the actual incidence angles (2α*) are calculated (Table 2) with the refraction indices shown in Figure 5.

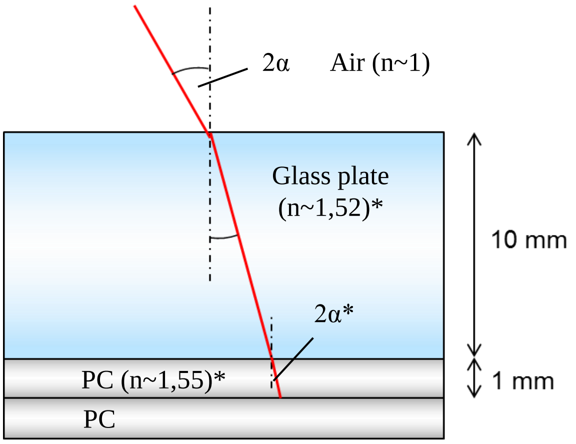


Figure 5: Refraction along the beam path

Inclination angle α	Beam incidence angle 2α (2α*)
15°	30° (18,8°)
20°	40° (24,5°)
25°	50° (29,61°)

*Refraction indices of PC and glass plate at 1940 nm were calculated from reflection measurements using Fresnel's formula for perpendicular beam incidence

Table 2: Angles of beam incidence

To ensure a quasi-simultaneous irradiation of the ring mirror the angular frequency of the beam circulation is set to 1000 Hz for all ring geometries investigated. The beam guidance along the welding contour is performed by a x-y stage where the clamping device is mounted on.

In the run-up to the trials the positions of the ring mirror and the crossing point of the beam superposition were adjusted properly. To make sure the sub-beams meet in one point the ring mirror and the scanner must be coplanar and coaxial. Additionally, the focal position of the circulating beam should be also in the crossing point which is determined by the distance between the scanner and the ring mirror.

To place the crossing point onto the joining plane a black foil is put between the joining partners. Through its high absorption and contrast the seam is clearly visible. The width of the seam changes with the position of the crossing point which is gradually varied. The crossing point is assumed to be placed correctly when the detected width is smallest.

3.3 Experimental results

First, trials were undertaken using the ring mirror with 15° inclination angle which leads to an incidence angle of 18,8° (Table 2). In Figure 6 the development of the HAZ in dependence of laser power at a constant feed rate is depicted. Compared to a weld produced with the same system but without beam superposition (Figure 6, right) it can be stated that the presented approach allows for a more spatially restricted HAZ. Without superposition both joining partners melt over their entire cross section which originates from the small divergence angle of the beam (1,6°). As the resulting intensity gradient along the beam axis is too small the joining partners melt downwards from the irradiated surface (see Figure 2). Applying dynamic beam superposition the HAZ has an oval shape which turns into a more rectangular shape with increasing power (Figure 6, left). What is striking is that a second HAZ starts to form within the first HAZ when the energy input has reached a certain level. Without superposition this phenomenon has never been observed before and remains to be clarified.

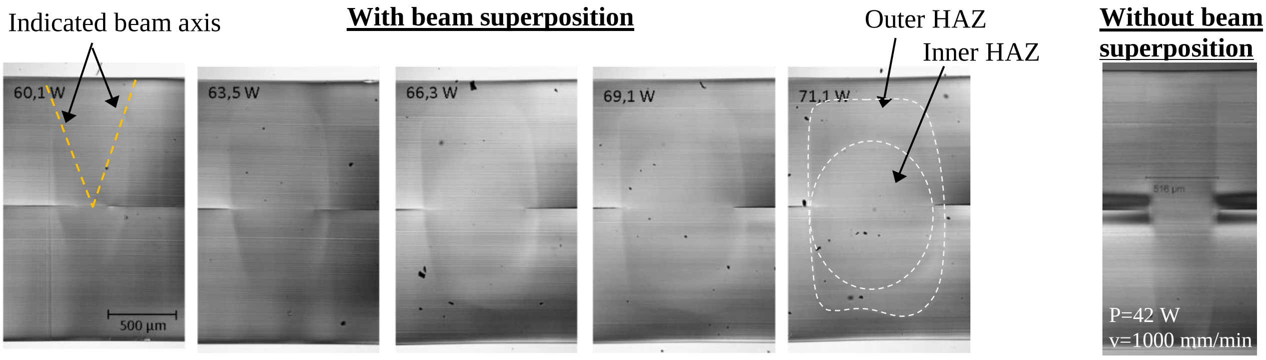


Figure 6: Development of the HAZ in dependence of laser power at 875 mm/min (left), HAZ without beam superposition (right)

The formation of the HAZ (Figure 6, left) shows that the upper part of the HAZ is more pronounced at the point both parts start to fuse. With increasing power the upper height (**H_1**) of the HAZ slightly rises stagnating at about 800 µm (Figure 7a). Assuming that the HAZ encloses the area molten during processing, a layer of approximately 200 µm remains solid. Consequently, the superposition provides a lower thermal load on the irradiated surface compared to classic contour welding. The lower HAZ part (**H_2**) is considerably smaller at the beginning but grows faster compared to the upper part. It also stagnates at about 800 µm in the considered power range. Higher laser powers led to burning within the material and were therefore not examined.

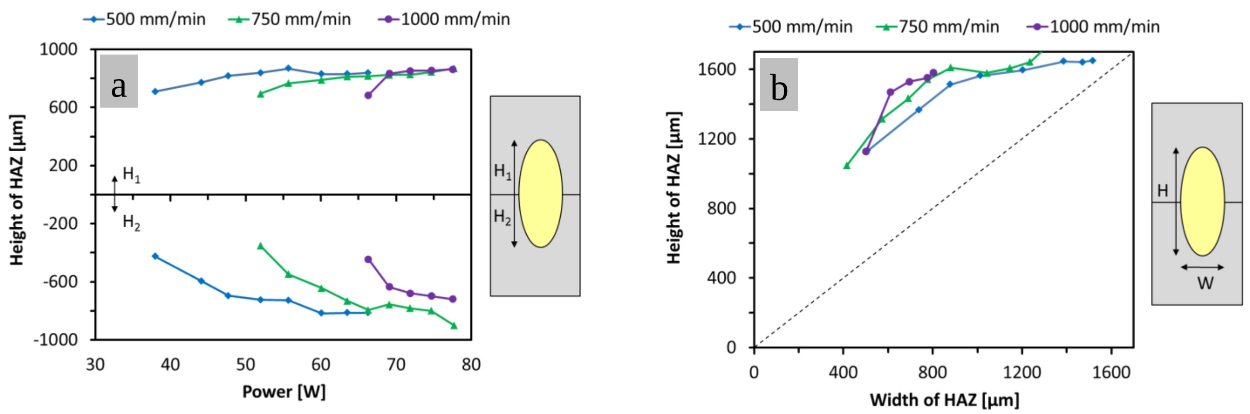


Figure 7: a) HAZ height in dependence of power and feed rate, b) ratio between height and width of HAZ (inclination angle 15°)

Another aspect investigated is the development of the HAZ width and height in relation to each other. As the vertical extent of the HAZ normally exceeds the horizontal extent, a ratio of 1 is striven for which is indicated by the diagonal line in Figure 7b. The slopes of the curves show that both, width and height have the same ratio unless the height starts to stagnate. As the curves are close together it is hard to predict how the feed rate affects the ratio of width and height of the HAZ. However, best ratios are provided by lower feed rates and the according powers.
The influence of the beam incidence angle was examined next. On the one hand the radius and the length of the circular beam path respectively increase with the incidence angle. To ensure a constant angular frequency (1000 Hz) the beam speed must be increased with the incidence angle as well which reduced the interaction time (see Equation 3). However, the distance in the upper part from the entry point to the crossing point also increases with the incidence angle. Thus, a greater part of the radiation is absorbed before reaching the crossing point.
In Figure 8 the welding results obtained with the different ring geometries are compared. The laser power used for the comparison is 63,5 W.
From the results it can be stated that in terms of vertical extent of the HAZ best results are achieved with an inclination angle of 15°.

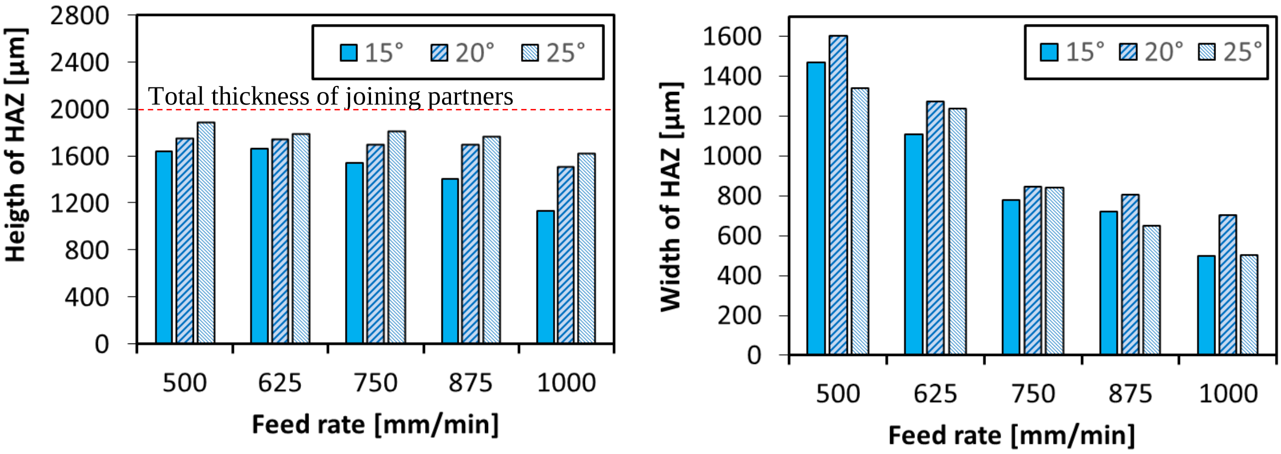


Figure 8: Influence of incidence angle on HAZ height and width for different feed rates at 63,5 W laser power

In the entire feed rate range investigated the ring geometries with 20° and 25° inclination angle show no significant decrease in the height of the HAZ as it is the case for 15°. Taking the width of the HAZ into account the largest widths are achieved with an inclination angle of 20°. The joining efficiency (which is defined by the joint area at the interface per unit laser energy) [9] is therefore highest with 20° inclination angle.

4. SUMMARY & OUTLOOK

It can be concluded that using dynamic beam superposition allows for welding with a spatially restricted HAZ. However, it was found that at the point the joining partners fuse the HAZ is already relatively large which indicates that a large material volume exceeds the melting temperature at the same time. Considering the size of the circulating beam a possible explanation could be scattering through the surface of the copper ring. As the copper rings were turned and polished the surface roughness might be too high. Thereby, the beam is widened which leads to lower intensity gradients and thus a larger HAZ at the interface. Another thing contributing to the size of the HAZ is the curvature of the inner surface which focuses the incident beam in one plane thus generating a second focus (comparable to astigmatism). Measurements of the caustic of the reflected beam show that the two focal points are 8-9 mm apart.
The described effects prevent a precise energy input which is indicated by the large HAZ sizes observed in the trials. In the upcoming trials ring mirrors with better surface qualities will be tested in order to reduce scattering and the HAZ size respectively. A further approach to reduce the HAZ size will be using ring mirrors with a larger diameter thereby minimizing the focusing effect of the rings curvature.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] Poprawe, R.: Lasertechnik II-Anwendungen der Lasertechnik, lecture script, RWTH Aachen University, 2003

[2] Hoffmann, W.-M.: Laserdurchstrahlschweißen unpigmentierter Kunststoffe, Doctoral Thesis, RWTH Aachen University, 33-41 (2008)

[3] Boehm, A.-J.: Laser transmission welding of plastics in medical device manufacturing-How to choose the right laser additive, Proceedings of the 2nd International Conference on Joining Plastics, Paper 22, 1-4, London (2006)

[4] Roesner, A., Abels, P., Olowinsky, A., Matsuo, N., Hino, A., "Absorber-free laser beam welding of transparent thermoplastics", Proceedings of the 27th International Congress on Applications of Lasers & Electro Optics, Paper M303, 105-111 (2008)

[5] Mamuschkin, V., Olowinsky A., Britten, S.-W., Engelmann, C.: Investigations on Laser Transmission Welding of Absorber-free Thermoplastics, Proc. SPIE 8906, Laser-based Micro- and Nanoprocessing VIII, San Francisco (2014)

[6] Polster, S.: Laserdurchstrahlschweißen transparenter Polymerbauteile, Doctoral Thesis, Friedrich-Alexander-Universität Erlangen-Nürnberg, 127-136 (2009)

[7] Poggel, M., Gillner, A.: Verfahren zum Fügen von wenigstens zwei aus thermoplastischem Material bestehenden Fügepartnern mittels Laserstrahlung, patent specification, DE 10 2006 008 776 B4, (2011)

[8] Boglea, A.-L.: Laser transmission welding of thermoplastics using local laser beam modulation, Doctoral Thesis, RWTH Aachen University, 16-20 (2013)

[9] Miyamoto, I., Horn, A., Gottmann, J., Wortmann, D., Yoshino, F.: Fusion welding of glass using femtosecond laser pulses with high-repitition rates, Journal of Laser/Nanoengineering Vol.2, No. 1, 2007