LASER TRANSMISSION WELDING OF THERMOPLASTIC POLYURETHANES: A ROBUST PROCESS WITH HIGH RELIABILITY

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ABSTRACT

This paper introduces the laser transmission welding process as an advantageous joining technique and investigates its characteristics for welding thermoplastic polyurethanes (TPU). Laser power, feed rate, and clamping pressure are all variable parameters that influence the weld seam quality, and have been described and analyzed in detail in this paper. This process has been shown to be characterized by a wide processing parameter field and exhibits excellent monitoring and automation capability. Material strain property modifications were realized by adding endless glass fiber reinforcements in the welding area.

1 INTRODUCTION

Thermoplastic Polyurethanes (TPU) bridge the gap between rubber and solid thermoplastic materials, combining the meltability of thermoplastics with the elastic properties of rubbers. In addition, the recyclability, chemical resistance and wear resistance of TPUs have made them a widely used material in the construction, automotive, electronics, medical, sports and leisure industries. Due to expanding industrial applications the demand of TPU has continuously increased in recent years and is expected to further follow this trend in the years to come [1]. Typical efficient and high volume production methods, such as injection molding, are able to cover an extensive range of geometries, but once the production method becomes inadequate for the part for reasons such as complexity or scalability, the production step must then also include a joining process. If such a joining step is needed, a key determinant for the efficiency and reliability of production, is how optimized the joining technique is. Although the welding of TPU materials is mentioned in various sources, they mostly refer to joining techniques such as fusion bonding, hot knife, hot plate, ultrasonic, high frequency, heat impulse or friction welding [2]. The few sources that mention laser welding are mostly applied for foils or films and do not go into detail with regards to the description of the welding process or results [3]. In comparison to the other joining techniques of thermoplastics, laser transmission welding offers the specific benefits of being a highly flexible process, working in absence of tool wear and vibrational loading, having a well-defined and localized heat input, and its suitability to integrate monitoring and control options [4].

The working principle of laser transmission welding relies on the partial optical transparency of the thermoplastic material in the range of near infrared radiation (see Figure 1). The joining of two overlapping components involves the laser radiation passing through a natural, non-absorbing thermoplastic (laser transparent part, LT) until it can be absorbed by the adjoined part, usually containing carbon black or another absorbing additive. The heat generated by the absorbed radiation is conducted to the overlapped interface, locally melting both parts and in the process producing the weld seam. In order to ensure homogeneous heat conduction in the interface between the parts, a uniform clamping pressure has to be applied along the whole weld seam [5]. Among various strategies that exist for laser transmission welding, contour and quasi-simultaneous welding are often used. In contour welding, the weld seam is generated by a single pass of the laser beam on a defined contour. This technique is preferably used to generate long weld seams. Quasi-simultaneous welding describes a strategy in which the laser beam is deflected by moving mirrors in a scanner optic. The beam is redirected and scanned rapidly over the entire joining region at once, allowing the process energy input and heat generation to develop slowly. In order to apply sufficient energy for the joining process, during quasi-simultaneous welding the laser beam passes the contour several times (multiple passes).

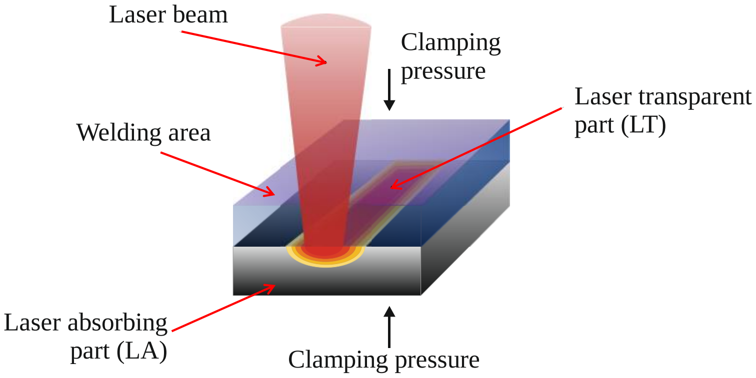


Figure 1. Laser transmission welding principle.

In order to better establish laser based welding of TPU materials in industry, the published content detailing processing characteristics, setup and results needs to be made more comprehensive and explicit. This present work gives an overview of the subjects mentioned and demonstrates the capabilities of this process.

2 EXPERIMENTAL SET-UP

The TPU material used in the experiments was an Elastollan® 1185A compound produced by BASF. Since laser transmission welding processes require both a laser transparent (LT) material and laser absorbing (LA) partner, the material featured in these experiments consisted of a natural (transparent) TPU component coupled with a carbon black (c.b.) masterbatch (absorbing) mate. The material thickness was 1.9 mm

All investigations were performed with a diode laser emitting at a wavelength of λ = 940 nm with a maximum power of P_L = 300 W. The laser beam was guided by an optical fiber to a homogenizing optic, generating a rectangular focal point geometry between A = 10x10…10x20 mm². The specifications are summarized in Table 1.

Table 1. Laser machine and focussing optics parameter.

Parameter	Value
Maximum laser power P_L (W)	300
Laser wavelength λ (nm)	940
Focal geometry homogenizing optics A (mm²)	10x10 to 10x20

Following preliminary trials, the use of standard optics which provide a circular spot geometry, were forgone for the use of homogenizing optics to obtain a homogeneous energy distribution and thus homogenized temperature distribution within the weld seam. By doing so, it allows for the generation of a wider weld seam, with enhanced gap bridging capabilities. A qualitative comparison between the weld seam generated from standard optics with that of the homogenized optics is given in Figure 2 b).

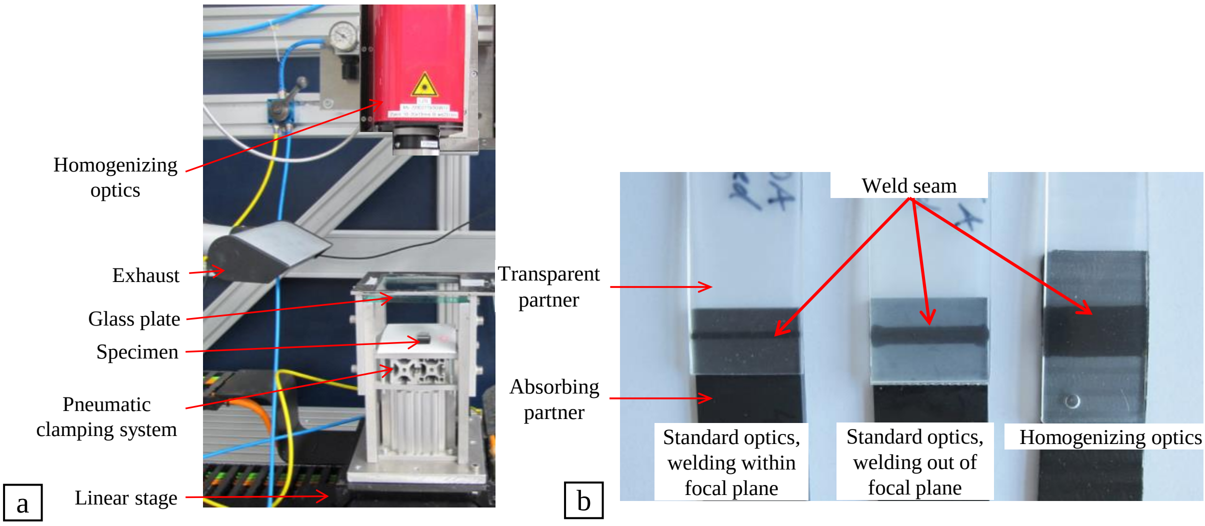


Figure 2. (a) Experimental setup with homogenizer optics and (b) weld seam geometry for different optics and focal plane settings.

In addition to the laser source and homogenizing optics, the experimental setup also featured an exhaust used to remove process potential emissions. Adequate clamping pressure for proper heat transfer between mated parts was achieved through the use of a pneumatic clamping against a transparent glass plate. As a result, the beam also had to pass through the glass plate before reaching the test parts. A linear stage system was used to regulate and control the feed rate and so welding speed. The setup is shown in Figure 2 a).

For the experiments the laser power was set to P_L = [100 / 200] W. For these power levels, the feed rate was varied in the range of v = 500…10000 mm/min to determine the best resulting weld strength as well as the limitations of the welding process. In order to identify the effect of the clamping pressure the pressure level was set to p = [1 / 2 / 3] bar. The focal geometry of the homogenizer optic was kept constant at A = 10x10 mm². The parameters are summarized in Table 2.

Table 2. Experimental parameters.

Parameter	Value
Laser power P_L (W)	100 / 200
Feed rate / welding speed v (mm/min)	500…10000
Focal geometry homogenizer A (mm²)	10x10
Clamping pressure p (bar)	1 / 2 / 3

The temperatures were detected by a high speed pyrometer HI18 by Sensortherm GmbH providing a measurement frequency of f = 50 kHz which is fast enough for a continuous and reliable temperature detection even at high welding speeds. The temperature measurement range is T = 120…520 °C measuring at a spectral range of λ = 1.65…2.1 µm.

3 EXPERIMENTAL RESULTS

One of the preliminary steps necessary in a laser transmission welding process is the evaluation and measurement of the spectral transmission for the source material. This gives insight into the materials compatibility with the lasers wavelength with regard to laser radiation absorption and transmission. The results for the natural TPU and the c.b. TPU are given in Figure 3, showing a very high transmission of 90% for the natural, laser transparent TPU and no transmission for the c.b. TPU. This combination can be described as ideal for transmission welding processes. However, it was already shown in [6] that even materials with low transmissivities down to ~20% can be welded by adapted parameters.

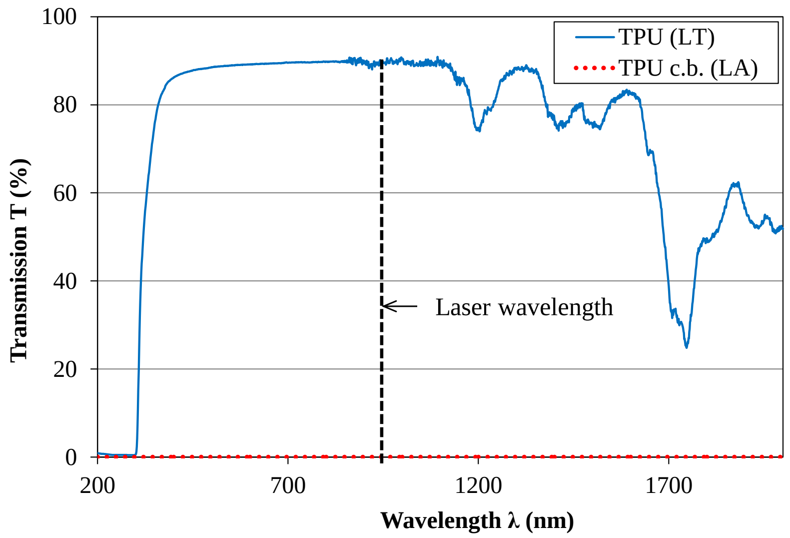


Figure 3. Optical transmission measurement.

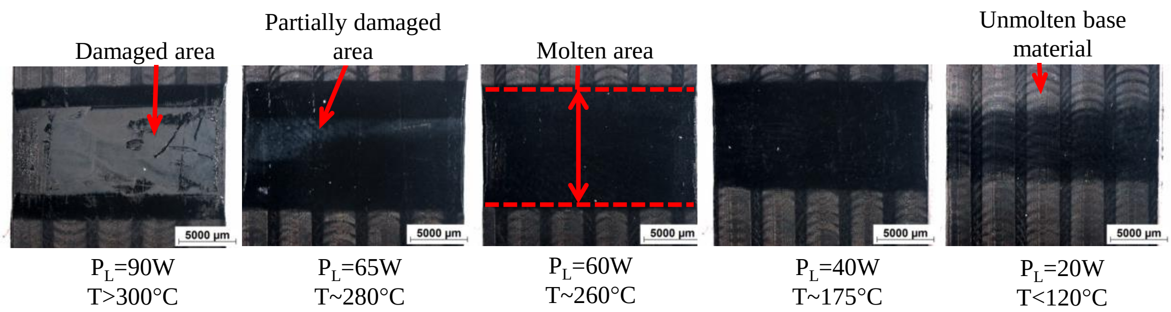


Figure 4. Bead-on-plate weld results with corresponding laser power and temperature measurements.

In a next step, bead-on-plate welding without the transparent partner was performed for varying laser power at a constant feed rate of v = 3500 mm/min in order to evaluate the bead appearance and to determine ideal temperature ranges. The surface temperatures were synchronously measured with a pyrometer. The images shown in Figure 4 are captioned, identifying the various regions visually indicative of weld quality. Good results with molten material areas in the range of the spot geometry were obtained for temperature levels between T = 175…260 °C (corresponding laser power P_L = 40…60 W). The manufacturer's material specifications state that the TPU will likely begin to degrade at T ~ 230 °C; but since the degradation process is a time dependent process and the duration during welding for which the material will be at such elevated temperatures is short, the degrading effect to the mechanical properties of the material are likely to be minimal. Above this temperature, at T ~ 280 °C, the material starts to undergo visual degradation, with colour changes at the surface becoming apparent. Beginning at T > 300 °C, it can be seen that the degraded region extends to cover the entirety of the welded region. At temperatures below T = 175 °C, the weld seam width starts to decrease, beginning at the outer borders of the spot geometry, until the material is not molten even in the center area of the spot (T < 120 °C). The temperature range found gives a reference for later monitoring and control solutions, although as the following laser welding and temperature measurements were performed through both the transparent TPU material as well as the glass plate used in the clamping system, thermal radiation damping must be considered. In addition, the laser power needs to be adjusted accordingly to account for both the partial radiation absorption of the glass plate in the clamping configuration, as well as for the heat transfer at the interface between the welding partners. Therefore, in a next step different parameters were varied in order to generate strong weld seams. Test specimens were produced to evaluate the toughness of the welded specimens.

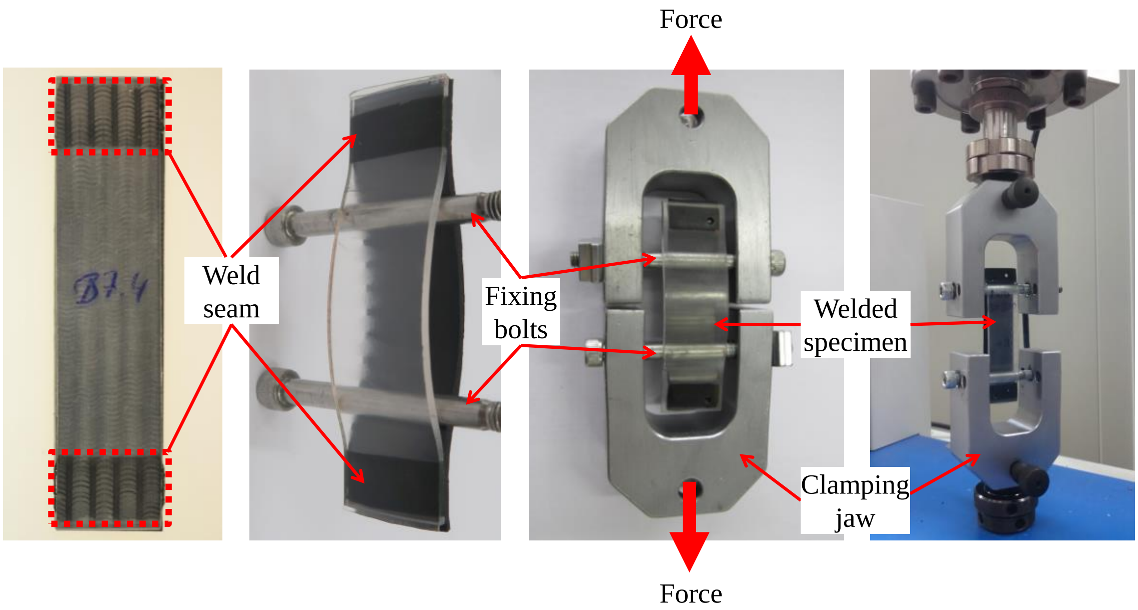


Figure 5. Tensile testing specimen and setup.

For evaluation purposes a non-standard test method was used. The specimen dimensions were kept constant at 75x20 mm², overlapping on their full geometry. As shown in Figure 5, a weld seam was applied on both ends of the specimen. This closed geometry was clamped by two fixing bolts in clamping jaws. By applying a tensile force, the weld seam is exposed to a stress similar to a peel test on both welded ends synchronously. The maximum force recorded was divided by the weld seam (specimen) width. The measurements were performed with 5 specimens and an average value und standard deviation was calculated for the evaluation.

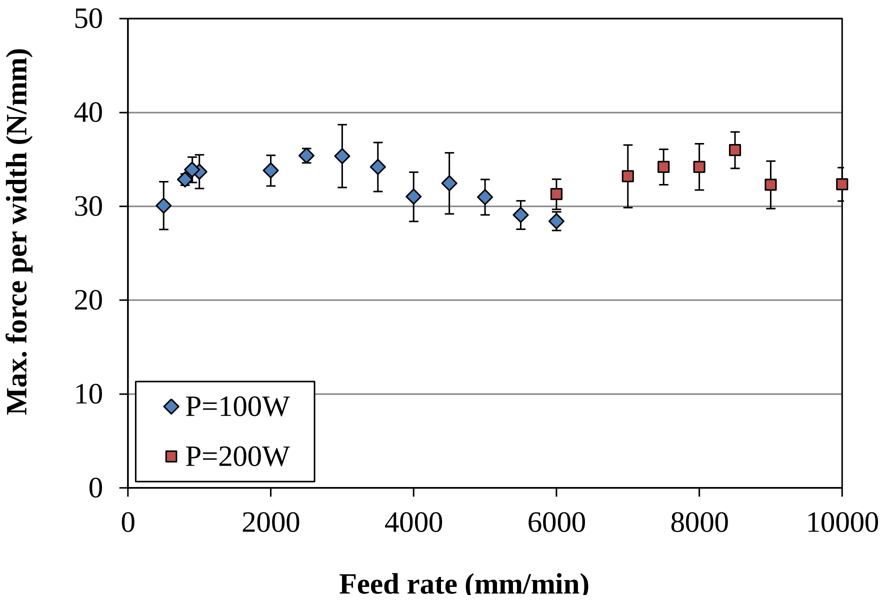
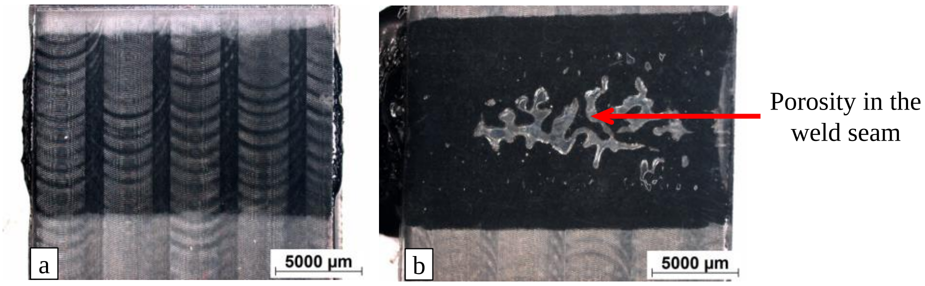


Figure 6. Maximum force obtained for varying laser power and feed rate at a constant spot size of A = 10x10 mm² and clamping pressure of p = 3 bar.

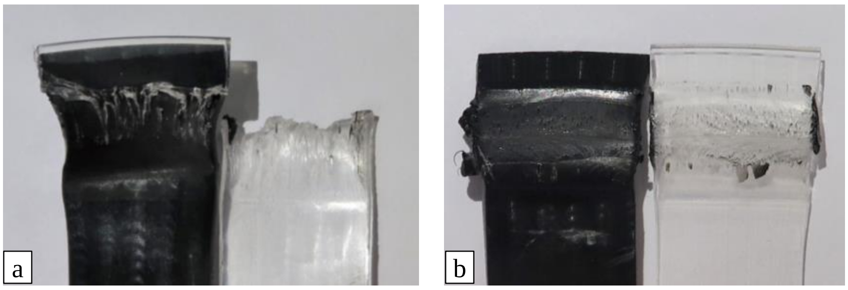
Tensile test results were obtained from trials performed with a laser power of both P_L = 100 W and P_L = 200 W over a range of feed rates, keeping both the spot size and clamping pressure constant at A = 10x10 mm² and p = 3 bar respectively, as shown in Figure 6. For both laser power levels, a feed rate range with maximum strength values can be observed. At a laser power of P_L = 100 W and within the feed rate range of v = 1000…4500 mm/min, comparable results for the weld seam strength were obtained, varying less than 9% between the highest and lowest mean strength value and having overlapping error bars. Operating the laser power at P_L = 200 W, the feed rate was varied between v = 6000…10000 mm/min leading to comparable weld seam strengths over the entire range of tested feed rates. Optimal feed rates can be assumed in the range of v = 2500…3500 mm/min at a laser power of P_L = 100 W and in the range of v = 7000…9000 mm/min at a laser power of P_L = 200 W. At a laser power of P_L = 100 W, it was observed that once the feed rate adjusted outside the optimal range, the heat input was not sufficient to generate an adequate joint. Conversely, if the feed rate falls considerably below the optimal range, the heat generation will lead to degradation and porosity in the weld seem (see Figure 7), with a resultant decrease in the recorded strength values.



P_L = 100W
v = 2000mm/min
T ~ 245°C

P_L = 100W
v = 500mm/min
T > 330°C

Figure 7. Exemplary weld seam appearance for an ideal welding parameter set (a) and a parameter set leading to overheating (b).



P_L = 200W
v = 7500mm/min

P_L = 100W
v = 800mm/min

Figure 8. Exemplary fracture appearance for an ideal welding parameter set (a) and a parameter set leading to overheating (b).

The samples highlighted in Figure 8 contrast the difference in fracture between that of a good parameter set and that of one that underwent overheating and the associated degradation. It can be seen that the fracture occurred predominantly in the base material for the samples welded with optimal parameters, where the fracture occurred at the welding partners' interface for the samples which overheated.

Through synchronous temperature measurements with high speed pyrometers, it not only allows the temperature in the weld seem to be monitored and controlled to the ideal temperature, but also presents the ability to detect real time temperature changes occurring due to gaps or defects in the welding path. This capability was demonstrated by creating an artificial gap in the weld seam of 0.5x0.5 mm^2 filled with a copper wire to simulate a contamination. As shown in Figure 9 a distinct local temperature drop was observed when passing the gap. The temperature drop occurs due to the reduced absorption and the enhanced thermal conductivity of the copper wire. Other defects or contaminating materials would lead to different temperature profile changes, but once a reference profile is defined, any changes can be detected. This observation can be used as a basis for simultaneous process monitoring in industrial application.

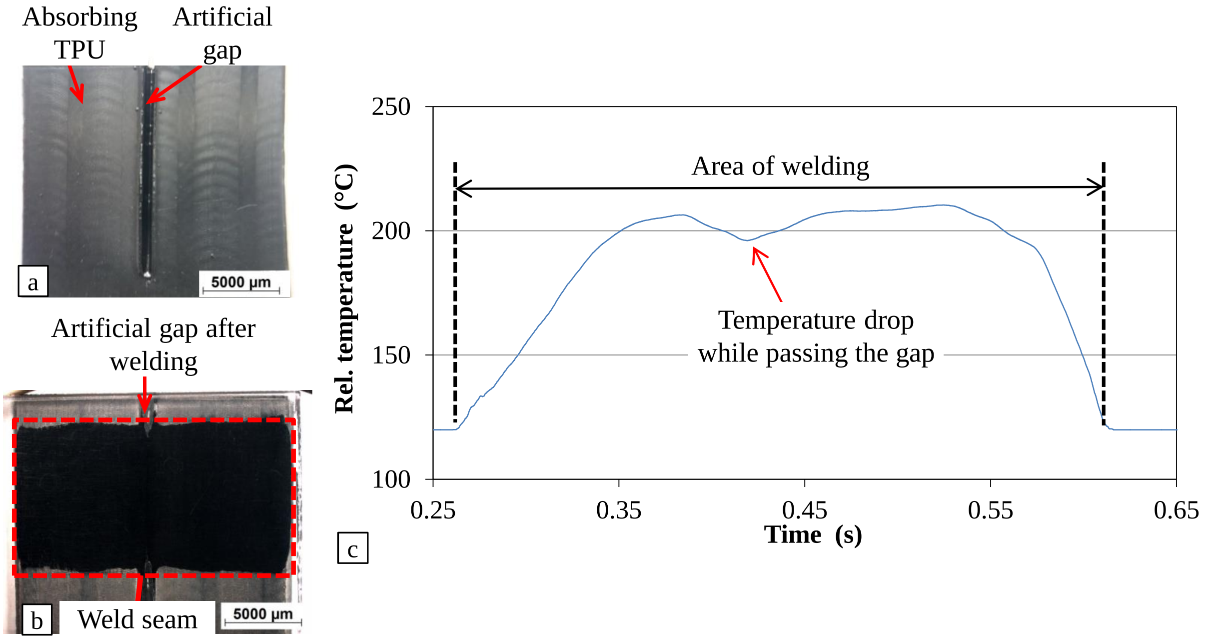


Figure 9. Defect simulation; (a) artificial gap before welding, (b) gap after welding, (c) temperature profile during welding, passing an artificial gap.

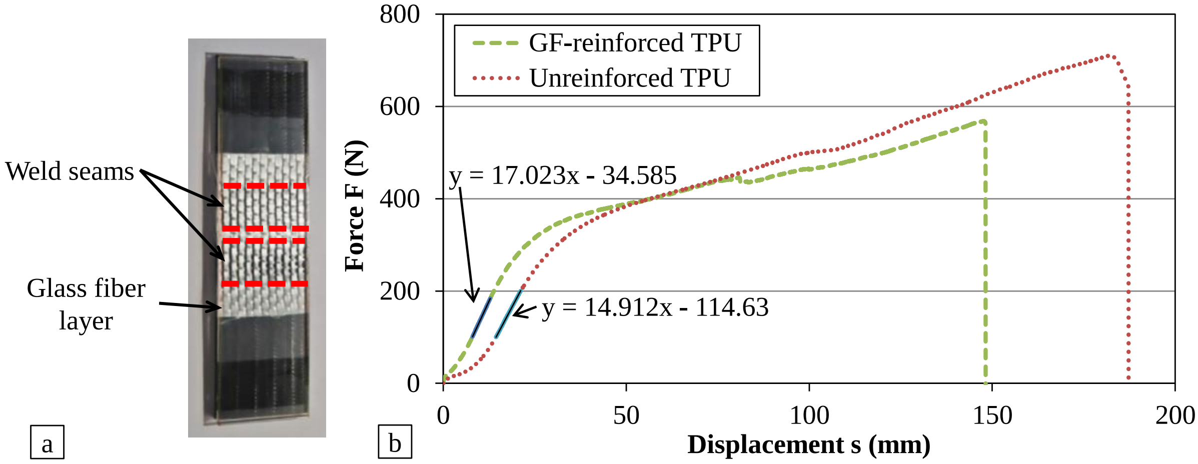


Figure 10. (a) Glass fiber reinforced specimen and (b) force-displacement curve for tensile testing of reinforced and unreinforced specimens

The TPU material can also be partially reinforced by (weaved) endless glass fiber (GF) layers directly added in the welding zone as shown on the specimen in Figure 10 a) on which two additional weld seams were generated in the center of the specimen. When doing so, the welding parameters have to be adjusted to slower welding speeds of v = 20 mm/min to ensure a sufficient generation of molten material. By simultaneously applying the clamping pressure a full impregnation of the glass fiber layer with the molten material is achieved and once reaching the transparent welding partner a weld seam is generated.

By tensile testing reinforced specimens according to the procedure described previously it was shown, that with this technique the strain behavior can be modified compared to unreinforced specimens (see Figure 10 b). Mainly in the beginning of the specimen's displacement higher force values are obtained until the adhesion in the reinforced area fails and the specimen's displacement curve compares to that of an unreinforced specimen.

Compared to injection molded short fiber reinforced TPU parts, the laser welding technique allows for the production of parts with an integrated locally restricted elastic behavior which is useful for specific industrial applications e.g. squeeze valves.

4 CONCLUSION

In this paper a laser transmission welding process for TPU materials was presented, characterized by its wide process parameter range, its robustness and by its process monitoring potential. The TPU material used in the experiments was an Elastollan® 1185A compound. Since laser transmission welding processes require a laser transparent material partner and a laser absorbing partner, natural (laser transparent) TPU coupled with a black masterbatch (laser absorbing) containing compound were selected for use in the experiments. The clamping pressure needed for a proper heat transfer between the two overlapping parts was applied by pneumatic clamping. Tensile testing was performed on the welded samples to characterize the welding strength.

The results revealed a wide processing parameter range for the feed rate wherein sufficient weld seam strengths were achieved. Sufficient weld seam strengths where achieved with feed rates as high as v = 10000 mm/min, operating at a laser power of P_L = 200 W.

The pyrometer temperature measurement showed good capabilities in terms of a synchronous temperature monitoring in order to sustain ideal welding temperatures as well as for defect monitoring by recording deviations e.g. local temperature drops. This observation can be used as a basis for simultaneous process monitoring in industrial applications. Combined with the wide process parameter range, a robust and highly reliable welding process is provided. By adding endless glass fiber reinforcements in the welding area the material strain properties were modified which could be a useful industrial application if locally varying strain is required.

ACKNOWLEDGEMENTS

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