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Residual stresses and crack formation in laser welding of amorphous polymers

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Abstract

Residual stresses in welded parts can limit the mechanical performance and reliability of the components. In polymers, especially in amorphous thermoplastics, tensile residual stresses in the presence of certain media can lead to environmental stress cracking, which can result in catastrophic failure of the connection. In this work the mechanisms of stress generation in welding of plastics is compared to metallic materials and methods for evaluating residual stresses are discussed in terms of suitability to polymer materials. The application of solvents in liquid and vapor phase is shown to be a useful tool for intentionally inducing stress cracking in laser-welded parts to evaluate and compare residual stress levels and orientations in the weld zones. Appropriate process parameters are examined for reducing welding stresses.

Keywords: laser transmission welding; polymers; residual stresses; environmental stress cracking;

1. Introduction

Inhomogeneous cooling, changes in the pressure history and suppressed relaxation processes generally lead to the formation of residual stresses during manufacturing of components made from polymer materials, Jansen and Titomanlio, 1996. Welding operations, especially laser welding, lead to high heating and cooling rates and therefore thermal expansion and subsequent contraction of the material, Sooriyapiragasam and Hopmann, 2016. Since the heat input is highly localized and the interaction time is usually short, shrinkage of the material is constrained by the surrounding cold material and stress relaxation

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is limited. In laser transmission welding, where the weld seam is generated at the interface of an overlap joint between two components, these constraints are not only limited to the sides of the material but also to the top and bottom of the weld seam. Therefore, a multiaxial residual stress state is expected around the weld seam, Magnier 2018. Furthermore, usually an external clamping force is applied to the parts to avoid insulating air gaps between the components. These stresses superpose to residual stresses, which might remain from the manufacturing processes of the components, and therefore complex residual stress states will be present in welded polymer parts.

Residual stresses can be evaluated using optical, mechanical or scattering techniques. Compared to metallic or crystalline materials, several restrictions have to be taken into account when using these techniques for residual stress measurements in polymers. X-ray scattering techniques can only be applied to the crystalline phase in semi-crystalline polymers. The amorphous phase can possess different residual stress distributions than adjacent crystallites, rendering a macroscopic evaluation of the entire stress distribution inside the material impossible, Magnier 2018. Mechanical methods are based on the removal of parts of the material and measurement of the resulting distortion of the part due to the rearrangement of the internal stress equilibrium. From the measured distortion it is possible to gather information on the initial stress distribution inside the removed material. Two of the most common of these techniques are the layer removal and the incremental hole drilling method. In the layer removal method a flat specimen is prepared with strain gauges on the one side. Material is removed layer by layer from the opposite side for example by grinding, milling or etching. The curvature of the component can be used to calculate the initial stresses inside these layers. This technique allows for the evaluation of the integral stresses parallel to the layer plane, but features no information about the local stress distribution inside this plane or perpendicular to it. The incremental hole drilling technique uses the distortion of material around a blind hole while the depth of this hole is increased step by step. This method enables the stress evaluation in a relatively small region equivalent to the hole diameter of typically 1 - 4 mm. However, since the strains can only be measured at the surface of the part, the sensitivity of the methods decreases with increasing hole depths. Using mechanical methods special care has to be taken to avoid the generation of new residual stresses during the process of material removal, making these methods labor-intensive, Nau et al., 2011. Furthermore, strain measurements with strain gauges are very sensitive to temperature fluctuations, with the necessary precautions further increasing the experimental efforts, Magnier 2018. A convenient method for the evaluation of residual stresses in birefringent transparent materials is photoelastic stress analysis. Materials like polycarbonate show different refractive indices based on the state of stress at a specific location. Polarized light passing through the component therefore experiences different phase retardation, which can be analyzed using a polariscope. Based on the resulting interference pattern the difference between the two principal stresses in the component can be examined. However, it is not possible to assess the absolute values of residual stresses or three-dimensional stress fields.

Due to the aforementioned limitations of quantitative measurement techniques, in this work a qualitative analysis of residual stresses is performed to investigate basic relationships between the processing parameters and the resulting residual stresses in laser welding of thermoplastics. The process of environmental stress cracking in polymers in presence of certain media can be used to locate regions of high tensile stresses, since cracks will form perpendicular to them when the material is exposed to a crack-initiating medium, compare for example Al-Saidi et al, 2003. The amount and length of cracks as well as the time scale of their formation can provide some insight into the residual stress levels. The influence of the stress-releasing agent and the form of application on the formation of cracks in the weld seam area is investigated. While residual stress in metal welding have been studied intensively for decades, see for example Rappe, 1974 or Macherauch and Hauk, 1987, residual stresses in welding of polymers are less intensively investigated, especially regarding laser welding. In some recent investigations by

Sooriyapiragasam and Hopmann, 2016 and Magnier, 2018, experimental and simulative approaches for the determination of residual stresses in laser welding of plastics were performed. In these studies analogies are drawn between the shrinkage stress distributions in metal welding, as shown in Fig. 1, and the stress distribution in laser welded polymers. While possible deviations due to the different geometrical constraints are considered in Magnier, 2018, the transferability of the mechanisms based on different material properties have not been investigated further.

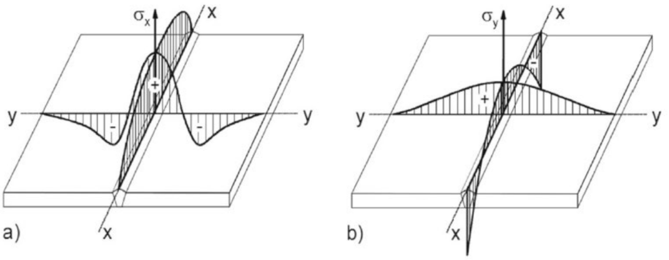

Fig. 1. Typical residual stress profile in butt-welding of steel sheets. Longitudinal stresses (a) and transversal residual stresses (b), based on Rappe, 1974.

Longitudinal residual stresses parallel to metal welds arise from the longitudinal contraction of the weld as it cools down, Radaj, 1992. For balancing reasons these stresses are zero at the ends of the weld and reach a constant value in between for sufficiently long welds. These longitudinal stresses are equilibrated by compressive stresses in the adjacent zones as shown in Fig. 1 a. Tensile longitudinal stresses at the edge of the weld seam would lead to an in-plane bending deformation inside the sheet. The weld seam suppresses this deformation, leading to a transversal residual stress state as shown in Fig. 1 b. Apart from these shrinkage stresses, typically quenching and phase transformation processes as defined by Wohlfahrt and Macherauch, 1977 are considered as the two dominant additional sources of residual stresses in metal welds.

The basic mechanism of stress generation by partly suppressed shrinkage during the cooling phase should be comparable in welding of plastics and metals. Phase transformation stresses will not be comparable due to the different transformation mechanisms but can be easily neglected at least for amorphous polymers. Quenching stresses, resulting from inhomogeneous cooling however could have a significant influence on the residual stresses in laser welding of polymers. Due to the rapid heating of the weld zone and the comparatively slow heat conduction, a steep temperature gradient develops. The temperature gradient mechanism, commonly applied to laser bending or laser powder bed fusion processes, compare Kruth et al., 2004 can be transferred to the transmission welding process. The surrounding material around the weld seam restricts thermal expansion of the heated material, leading to elastic and plastic compressive strains. Since the yield stress is lowered due to the high temperatures, significant plastic compression can be expected. During cooling, the compressed material shrinks more than the surrounding material. Depending on the mechanical constraints and the joint geometry, this leads to additional residual stresses and deformations, which are directly influenced by the thermal gradients and therefore by the processing conditions.

To investigate the transferability of the residual stress generation mechanisms known from metallic components to welding processes in polymer materials, a two-stage experimental approach based on stress analysis by environmental stress cracking is used. In a first step, butt welding of polycarbonate sheets using a 2 µm thulium laser, which is in parts directly absorbed by the transparent material, is used to generate a weld geometry and temperature distribution which is as close as possible to a typical weld in sheet metal. By this, material-dependent deviations, originating for example from the viscoelastic deformation behavior, stress relaxation or the broader softening temperature range could be identified. In a second step, laser transmission welding experiments are carried out to examine the influence of the processing parameters on the residual stress levels and their distribution.

2. Experimental

2.1. Welding

Extruded sheets of clear polycarbonate (PC, Covestro Makrolon GP099 clear) with a thickness of 2.0 mm are butt-welded using a single mode thulium-fiber laser (IFL30, Futonics Laser GmbH) with a wavelength of 1998 nm and a maximum output power of 30 W. Additionally, T-joints between the transparent PC and a black colored polycarbonate / acrylonitrile butadiene styrene - Blend (PC/ABS, Sabic Cycoloy XCY620S) with a thickness of 2.6 mm are created by transmission welding. The sheets are cut to pieces of 25 x 50 mm and the longer faces are ground flat using 220 grit silicon carbide sandpaper to ensure close contact between the joining partners. An external clamping pressure of approximately 2 MPa is applied to the joint face in the T-joint configuration using a pneumatic clamping device. For overlap welding, both the thulium laser and a more commonly used fiber coupled diode laser (Compact Evolution, DILAS Diodenlaser GmbH) with a wavelength of 980 nm and a maximum output power of 110 W are used in the welding experiments. The Laser beams are collimated and focused to the joining plane using a flying optics setup mounted on a linear stage, enabling variable feed rates. By adjusting the distance of the focusing lenses to the joining plane both beams are focused to a $1/e^2$-beam diameter of 4.2 ± 0.05 mm.

2.2. Characterization

Xylene (mixture of isomers, 98%) and a commercially available mixture of solvents and colorants, specifically designed for the analysis of environmental stress-cracking (Crack Knacker PS-2, Kunststoff Institut Lüdenscheid) are used to initiate cracks in the welded samples. Both liquids are applied to the weld zone using a small brush. Crack Knacker PS-2 is washed from the parts after 24 hours using tap water, leaving colorants inside the generated cracks. The applied xylene evaporates from the surface within several seconds. For comparison, xylene is also applied in vapor phase to a different set of samples by placing the samples in a sealed desiccator for 24 hours, filled with air and 50 ml of liquid xylene. The samples are mounted to a fixture about 40 mm above the liquid to avoid direct contact between the solvent and the polymer. Instead, parts of the solvent vaporize and can diffuse into the samples without excessive surface damage or swelling as observed when directly applying the liquid to the samples. All experiments are carried out at room temperature to avoid accelerated stress relaxation. The resulting cracks are examined using an optical stereo microscope (Stereo Discovery.V12, Carl Zeiss). The weld seam area can be observed directly through the transparent PC part.

3. Results

3.1. Comparison of crack initiating media:

Xylene vapor and liquid Crack Knacker PS-2 are used successfully to generate stress cracks in laser weld seams in a T-joint configuration. Both media lead to similar crack patterns as shown exemplarily in Fig. 2 a and b. In both welds, straight cracks perpendicular to the feeding direction, indicated by white arrows, can be observed within the weld seam. Liquid xylene in contrast leads to almost instantaneous swelling, crazing and cracking in the area where the solvent is applied, see Fig. 2 c. While some cracks originating from the edge of the weld are observable with liquid xylene as well, the weld seam itself is unaffected.

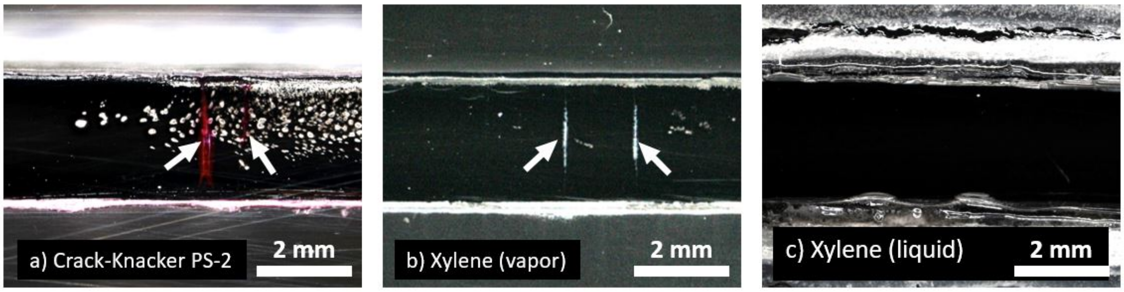

Fig. 2. Top view of weld seams created with a laser power of 6,6 W, 980 nm and a feed rate of 10 mm/s; Crack initiating media: (a) Crack-Knacker PS-2, washed after 24h; (b) Xylene vapor, 24h exposure; (c) liquid xylene, single application.

For the investigation of residual stresses in welds seams, a long enough diffusion time of the medium is necessary to allow it to reach the regions of highest tensile stresses. In T-Joint configurations, this can be achieved by moderately strong solvents in liquid phase or by stronger solvents in low concentrations in vapor phase. In overlap joints, where the welds seam is protected from direct access of the medium, application of a medium in vapor phase can be necessary to initiate stress cracking, as previously shown in Schkutow and Frick, 2018. Application of liquid xylene was not successful due to excessive surface damage and short interaction times due to the rapid vaporization of the liquid and is therefore discarded in the following.

3.2. Butt welding

The application of a laser wavelength of 1998 nm enables laser welding of transparent PC without absorbing additives due to the intrinsic absorption properties of the material. Despite this, absorption is still relatively low, with about 16 % of the incident radiation being absorbed over the material thickness of 2 mm. This leads to relatively evenly distributed heating of the material at the joint interface. The low absorption efficiency necessitates a low feed rate of 2 mm/s and therefore even with the low thermal conductivity of the PC material sufficient heat transfer from the center of the weld to the adjacent material is ensured, leading to a qualitatively comparable thermal field as in welding of sheet metal. Fig. 3 shows a tow view of the weld after 24 hours of exposure to xylene vapor. Multiple parallel cracks have formed perpendicular to the feed direction. Furthermore, a single, longitudinal crack has formed in the middle of the weld seam. The resulting cracks show the expected distribution of tensile residual stresses arising from suppressed shrinkage of the material in the weld seam. The observed crack distribution agrees well with expected homogeneous level and distribution of longitudinal tensile stresses along the weld. The longitudinal crack along the centerline of the weld also coincides with the expected maximum of tensile transversal residual stresses. However, the analysis of the crack pattern alone does not allow for a comparison of the relative magnitude of the longitudinal and transversal stresses. Despite the obvious differences in the material behavior, the mechanism of shrinkage stress generation in butt welding of polymers and metals are transferable and the residual stress state can be assumed to agree well with the theoretical considerations summarized in Chapter 1.

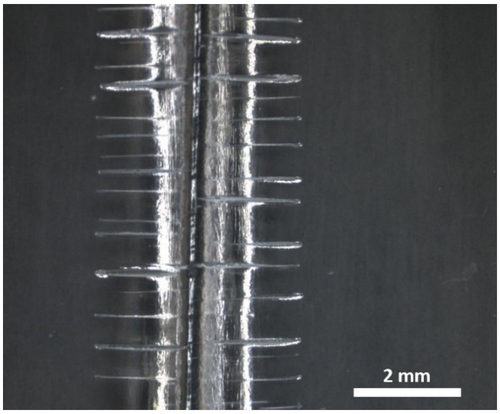

Fig. 3. Top view of butt-welded polycarbonate, laser power 27 W, feed rate 2 mm/s after 24 h exposure to xylene vapor.

3.3. Influence of line energy

To get more insight into the crack generation and the relative magnitude of longitudinal and transversal residual stresses, the laser line energy is increased by raising the laser power for a constant feed rate in transmission welding. With increasing laser power crack generation starts perpendicular to the feed direction, indicating stronger residual stresses in the direction of the weld seam. At higher line energies, additional cracks in longitudinal direction are generated and the overall amount and length of cracks increases.

Fig. 4 shows weld seams created with laser powers between 5,8 W and 8,6 W for a feed rate of 10 mm/s. At the lowest laser power, which resulted in a visually good weld seam, no cracks show up even after 24 hours of solvent exposure, see Fig. 4 a. With increasing heat input, cracks perpendicular to the weld seam are created first, indicating tensile stresses parallel to the feed direction. These stresses can be traced back to the longitudinal shrinking of the weld during the cooling process after the passage of the laser beam and agree with the expected longitudinal stress distribution shown in Fig. 1a . When the laser power is increased further, additionally to the cracks perpendicular to the feed direction, cracks are generated parallel to the weld seam as indicated by the arrows in Fig. 4 c. These can presumably be traced back both to the transversal tensile stresses resulting from the longitudinal shrinkage as shown in Fig. 1 b, and to the volumetric contraction of the inhomogeneously compressed material according to the temperature gradient mechanism.

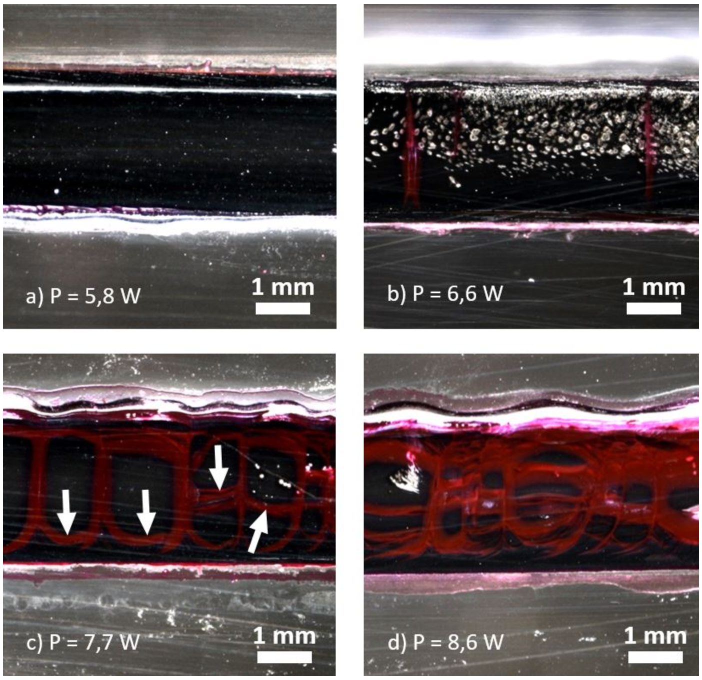

Fig. 4. Top view of weld seams created with a laser power of 5,8 W (a), 6,6 W (b), 7,7 W (c) and 8,6 W (d), laser wavelength 980 nm, feed rate 10 mm/s, crack initiating medium: Crack-Knacker PS-2;

3.4. Influence of thermal gradients

Since the absorption properties of polymers are wavelength-dependent, it is possible to some extent to modify the temperature distribution in the joining zone by using a different laser wavelength. While approximately 16 % of the 1998 nm radiation of the thulium laser is absorbed within the transparent PC part, less than 1 % of the radiation of the 980 nm diode laser is absorbed there. Furthermore, the optical

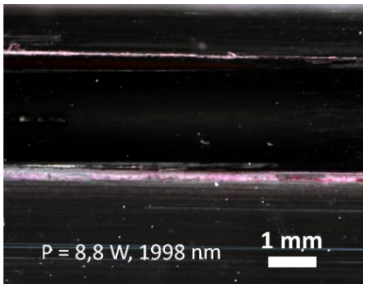

Fig. 5. Top view of weld seam created with a laser power of 8,8 W, laser wavelength 1998 nm, feed rate 10 mm/s, crack initiating medium: Crack-Knacker PS-2;

penetration depth within carbon black filled, absorbing polymers is also wavelength dependent, as shown for example in example by Schkutow and Frick, 2016 and Geißler et al. 2018. The increased absorption in the transparent part and the increased penetration depth in the absorbent part lead to a reduced peak temperature and less pronounced temperature gradients. Fig. 5 shows the top view of a weld seam created with a laser power of 8,8 W and a laser wavelength of 1998 nm after 24 h of solvent exposure. All other parameters are identical to the previous experiments with the diode laser, making it directly comparable to results shown in Fig. 4. Despite the highest applied laser power of 8,8 W and therefore the highest line energy, the weld shows no sign of crack formation. A reduction of the temperature gradients during the welding process therefore clearly leads to a reduction of the tensile residual stress level.

4. Summary

Residual stresses in laser-welded thermoplastics can be investigated using solvents in liquid or vapor phase to initiate environmental stress cracking. Stress generation in welding of amorphous thermoplastics can be described by the shrinkage and quenching mechanisms known from welds in metallic materials. Tensile residual stress levels can be reduced by applying lower laser line energies and appropriate laser wavelengths, which can lead to reduced temperature gradients due to the wavelength dependent absorption properties.

Acknowledgements

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