THE INFLUENCE OF MOISTURE CONTENT ON THE WELD SEAM QUALITY FOR LASER WELDED THERMOPLASTIC COMPOSITES

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ABSTRACT

Today, fiber reinforced materials are present in many industrial applications to implement lightweight solutions. These materials are used for example in automotive, aerospace and medical sectors. In the last couple of years, fiber reinforced materials with a thermoplastic matrix have gained importance due to their thermo formability and good recyclability. Besides the joining of these materials by mechanical fasteners, they can also be joined by welding in order to generate complex parts. A new welding method for composites is laser transmission welding. This welding technique has high potential for excellent reproducibility, high flexibility, and automation.

The weld seam quality of several kinds of thermoplastics can be affected by the moisture content of the matrix material. During laser transmission welding, both parts are heated up at the interface. Due to the process heat, moisture in the composite evaporates and can cause pores in the connection area. The authors investigated the influence of the moisture content on the weld seam quality of endless glass fiber reinforced polyetherimide (GF PEI) welded to GF PEI containing carbon black. Before welding, the material was conditioned in three different ways to generate “dry”, “wet” and “room humid” samples. With the materials, lap shear samples were produced with different welding parameters. The lap shear strength results were correlated to the moisture content and the utilized welding parameters. Furthermore, cross sections were prepared to determine the amount of pores in the joining zone and correlated to the lap shear strength results.

1 INTRODUCTION

Endless fiber reinforced composites (FRP) have a great potential in lightweight construction for many applications, for example in the aircraft sector and in various industries such as marine and automotive [1, 2, 3]. FRP have the potential for significant weight reduction compared to metallic materials. The current trends for producing composite parts consisting of FRP, which focus on economic and ecological issues, requires the use of thermoplastic FRPs combined with adapted machining techniques [4, 5]. Thermoplastic composites (TPC) offer several benefits such as unlimited
and uncritical storage times, quick forming process availability and weldability compared to thermoset systems [6, 7]. Today, different welding techniques such as resistance welding, ultrasonic welding, vibration welding or induction welding, can be applied to join TPC structures to complex parts. Another newer welding technique for composites is laser transmission welding, which has a high potential for excellent reproducibility, high flexibility, and automation. Laser transmission welding is based on the optical characteristics of TPC. The laser radiation passes the transparent joining member (LT-part) until it reaches the absorbing joining member (LA-part), where the radiation converts into process heat (Figure 1). Due to heat conduction between the parts, the transparent part gets molten, too. To support the heat conduction, both parts are clamped together [8, 9].

The laser transmission welding process is affected by the kind of TPC. For example, glass fiber reinforced TPC are semi-transparent for near-infrared laser radiation. The transparency depends, among other things, on the kind of matrix material, the amount of glass fibers and the material thickness [8]. TPC containing carbon fibers (CFRP) or the additive carbon black are absorbing for near-infrared laser radiation. Carbon fibers are good heat conductors, thus the process heat is mainly conducted along the carbon fibers. The orientation of the carbon fibers in the weld seam dictates the resulting weld seam geometry. For example, at glass fiber reinforced thermoplastic containing carbon black in the matrix material, the absorption of the laser radiation is more homogeneous than for CFRP due to the missing predominant heat conduction direction [8].

Figure 1: Principle of a laser transmission welding process.

The laser transmission welding can be divided into four main categories based on the way the laser radiation is applied: contour, quasi-simultaneous, simultaneous and mask welding. The most commonly used welding techniques to join composites are contour and quasi-simultaneous welding. For contour welding the laser beam passes the joining area just once. This laser welding method is used to generate long weld seams, but has the drawback of a low gap bridge capability. For quasi-simultaneous welding the laser beam is guided over the welding area several times with a higher speed compared to the contour welding. For both laser welding types, the applied energy per length $E_s$ is calculated by:

$$E_s = \frac{P}{v} \times n \quad (1)$$

with the laser power $P$, welding speed $v$ and the number of repetitions $n$ [10, 11].

The weld seam quality for different welding procedures depends, among other things, on the hygroscopic characteristics of the matrix material. Investigations reported the influence of the moisture content of unreinforced or short glass fiber reinforced thermoplastic on the weld seam for ultrasonic, hot gas string-bead, vibration and hot-tool welding [12, 13, 14]. Hopmann et al. have shown that the weld strength decreases with increasing moisture content for ultrasonic welding of polyamide [12]. Similar observations were made by Fischer et al. on hot gas string-bead welding of chlorinated
polyvinyl chloride. They determined that the number of pores in the joining area increase with increasing moisture content, which was dedicated to the degassing of moisture out of the material during the welding process [13]. Kagan et al. also reported that the lap shear strength decreases with increasing moisture content for laser welded unreinforced and short glass fiber reinforced polyamide [15].

Another thermoplastic, which absorbs much moisture is polyetherimide (PEI). Unreinforced PEI picks up 0.25 % water after 24 h. The maximum moisture absorption is listed as 1.25% [16]. For a glass fiber fabric reinforced PEI with a matrix content by volume of 50 %, the moisture pick up is listed as 0.35 % [17]. Staehr et al. reported that increasing moisture content results into an increasing heat affected zone for laser based cutting of carbon fiber fabric reinforced PEI. This was attributed to the vaporization of water during the cutting process, similar to the welding case [18].

Besides the carbon fiber reinforced PEI, also glass fiber fabric reinforced PEI (GF PEI) is an industrial established material for high performance application. So, it is of interest to determine the influence of moisture on the weld seam characteristic. Therefore the authors have conducted laser transmission welding tests to determine effects of the moisture content on the weld strength.

2 EXPERIMENTAL

For the experiments, TenCate Cetex® laminates consisting of GF PEI were used (Table 1). The joining member GF3 PEI have a transmissivity of about $T_{\text{gl}} = 50.2 \%$ and the ones of GF6 PEI have a transmissivity of $T_{\text{gl}} = 29.9 \%$ for the used laser wavelength. The absorbing part consists of 4 layers glass fiber fabric in a PEI matrix containing the additive carbon black. The material was cut into 20 mm x 50 mm samples, which were welded in overlap configuration.

<table>
<thead>
<tr>
<th>LTW Type</th>
<th>Short Name</th>
<th>Reinforcement / Additive</th>
<th>Number of layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT</td>
<td>GF3 PEI</td>
<td>Glass fabric; 50% vol.</td>
<td>3</td>
</tr>
<tr>
<td>LT</td>
<td>GF6 PEI</td>
<td>Glass fabric; 50% vol.</td>
<td>6</td>
</tr>
<tr>
<td>LA</td>
<td>GF PEI c.b.</td>
<td>Glass fabric; 50% vol. Carbon black</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 1: Classification of materials used.

Three different sets of conditioned material were prepared. All materials were dried at $T = 120^\circ\text{C}$ for $t = 48$ h, which is similar to the material drying step before thermoforming. Then, one set of material was placed for 18 days into distilled water in order to generate samples with high moisture content. These samples are classified as “wet” samples. Another set of samples were stored at room temperature and an air humidity of 39 % for 18 days and classified as “AH”. This should give a reference for a new produced part, which is stored for several days until the joining process takes place. The last set of samples were welded directly after the drying process and classified as “dry” samples. They give a reference for part welded directly after production.

The experiments were conducted with a diode laser emitting at a wavelength of $\lambda = 940$ nm in continuous wave operation mode. The maximum output power of the laser is $P = 300$ W. The laser beam was guided over the joining members by a scanner optic consisting of two mirrors, which allows a flexible and fast movement of the laser beam. The focal diameter was $d_{\text{foc}} = 2$ mm. In order to apply a clamping pressure both joining members were pressed together between a pneumatic cylinder and a glass plate. The glass plate was highly transparent for the applied laser radiation.

All experiments were conducted by quasi-simultaneous welding with a laser power of $P = 80$ W at two different welding speeds, $v = 250$ mm/s and $v = 500$ mm/s. To generate different energies per length the number of repetitions were varied. The welded lap shear samples were stored for two weeks at air humidity of 39% before testing them for their maximum strength. Furthermore cross sections were prepared in order to analyze the weld seam for pores.
3 RESULTS AND DISCUSSION

3.1 Moisture absorption

For the conditioning of the material, all samples were dried. Afterwards, five samples of each material type and conditioning kind (AH and wet) were weighed with a high-accuracy weighing machine. This procedure was repeated over the next 18 days during the conditioning process. The moisture content $M_{\%}$ of the material was calculated by:

$$M_{\%} = \frac{m_n - m_{dry}}{m_{dry}} \times 100$$  \hspace{1cm} (2)

with $m_n$ for the weight of the material after $n$ hours of conditioning and $m_{dry}$ for the weight directly after drying of the material [18]. The measured moisture contents of the materials are shown in Figure 2.

The water is absorbed over the surface. Due to the part’s geometry, the surface area over which the water is absorbed is just slightly higher for the GF6 PEI compared to GF3 PEI. Thus, the ratio between surface area and $m_{dry}$ is lower for GF6 PEI than for GF3 PEI. This could explain why the detected percentage moisture pick up of the GF3 PEI is higher than for the GF6 PEI.

The moisture content for the GF PEI c.b., which consists of 4 layers glass fiber fabric, is distinct higher than for GF3 PEI for the wet conditioning type. The ratio between surface/weight is for GF PEI c.b. lower than for CF3 PEI. So, the higher moisture pick up could be caused by the modified matrix material, which contains the additive carbon black.

3.2 Weld seam quality

Figure 3 depicts the average strength curves of lap shear samples consisting of GF3 PEI and GF PEI c.b. welded with a speed of $v = 250$ mm/s for varying numbers of repetitions. The curve progression for the dry material combinations corresponds to a standard strength curve progression tested with unreinforced material for different energies per length $E_s$. The curve increases until a maximum at 13 repetitions is reached. This is, for example, due to an increase of the weld seam width based on heat conduction in the material (Figure 4). If more energy is applied, the matrix starts to overheat, which causes degeneration of the thermoplastic and causes the generation of pores. This leads to a strength loss of the weld seam.

For the curve progression of the AH and wet type of material, a decrease in strength could not be detected in the chosen parameter range, which might be found at higher numbers of repetitions.
Figure 3: Average weld seam strength for laser welded GF3 PEI with $v = 250 \text{ mm/s}$ and $P = 80 \text{ W}$.

A comparison between the three conditioning types shows that the dry samples have higher strengths at low repetitions, followed by the AH and then wet sample strengths. A possible explanation is that part of the applied energy goes into vaporizing the moisture in the AH and wet samples. This reduces the amount of energy for the actual welding process and leads to a reduced weld seam width compared to the dry material (Figure 4). Furthermore, small pores are generated, which can also affect the weld strength. At a medium number of repetitions, the average strengths are fairly similar for all three conditioning types.

Figure 4: Average weld seam width of laser welded GF3 PEI with $v = 250 \text{ mm/s}$ and $P = 80 \text{ W}$.

At high number of repetitions, weld strength of the dry samples decreases due to overheating of the matrix material, but the strength of the wet and AH still increases. As shown in Figure 4, for all conditioning types the average weld seam width stays similar for all types and increases with the number of repetitions. As described before, part of the applied laser energy evaporates the moisture in the matrix material and this might prevent it from overheating. Due to the vaporizing, more pores are generated. Figure 5 shows micrographic pictures of cross sections for all three conditioning types. All cross-sections were visually examined. Due to the varying amount of pores observed for each laser parameter set, the samples with the most pores for each laser parameter set were picked. For the wet and AH samples, it was observed that the pores were generated not just in the interface between the parts, but also in wider area around the connection area. Many pores are located around and between the fiber bundles and have no direct connection to the interface of the materials, where the weld seam is located. For the dry samples pores occurred mainly in the interface between both parts. These various damage manifestations can cause the difference in the weld seam strengths. Furthermore, it
was observed that, mostly the area of pores is located in the absorbing part. This could be due to the higher moisture content measured in the GF PEI c.b. (q.v. 3.1).

![Figure 5: Microscopic pictures of cross section for different conditioning types.](image)

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Figure 6 depicts the average strength curves of lap shear samples for GF PEI c.b. with GF3 PEI as well as GF6 PEI, for dry and wet material. These material combinations were welded with a speed of $v = 500$ mm/s for varying numbers of repetitions. Due to the higher speed compared to the previous experiments, a higher number of repetition was needed in order to generate a weld seams. Furthermore, the actual welding process took a longer time span. The laser beam was guided for every welding repetition back to the same starting point. Due to the higher number of welding repetitions, there was also a longer break time. In this time, the material in the weld seam could cool down due to heat conduction and convection. The curve progressions for the dry and wet material for GF3 PEI with GF PEI c.b. show the same trends as in Figure 3. It was observed that more energy was needed to generate a weld seam in wet material than in dry material at low energies per unit length. Thus, it was not possible to generate a weld seam in the wet material at 15 repetitions.

![Figure 6: Average weld seam strength for laser welded GF PEI with $v = 250$ mm/s and $P = 80$ W.](image)

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The strength curves of the material combination GF6 PEI with GF PEI c.b. show a larger standard deviation than for the material combination with the thinner transparent part, which can be caused by a higher scattering of the laser radiation in the transparent part. For this material combination the difference between the average strength of wet and dry samples is larger than for the material combinations with GF3 PEI. This has to be investigated in more detail in order to determine the
occurring effects. Because of the large standard deviation, the number of samples per parameter set has to be increased. Furthermore, investigations focusing on different welding speeds can deliver the bases to understand the thermal effects while welding wet and dry GF6 PEI.

4 CONCLUSIONS AND OUTLOOK

In this paper, the influence of the moisture content in GF PEI on the weld seam strength was shown. The weld seam strength was higher for the wet conditioned samples at high energies per unit length than for dry material. This could be due to a loss of energy, because of the vaporization of the moisture, and so preventing the material from overheating. The generated pores by the vaporization process were located in an area around the interface of the materials. Thus, the pores did not have a high effect on the seam strength.

These results are different from what is reported by other investigations [15] regarding the influence of moisture on laser generated weld seams. The difference could be due to the glass fiber length in the GF PEI used. For the investigations here presented, the glass fiber length was endless, and so the generated pores were located between the fibers and fiber bundles, and had no direct matrix connection to the interface of the materials.

Furthermore, the effects on laser welded GF6 PEI have to be further investigated in order to evaluate the high difference in strength between the wet and the dry materials.

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