SIMULTANEOUS SUB SECOND LASER WELDING OF POLYMERS WITH DIFRACTIVE OPTICS

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Abstract

The paper presents a novel method for simultaneous transmission welding of polymers using a high power multimode fiber laser. The method utilizes a diffractive optical element which shapes the focused laser beam into the desired weld shape. This kind of optical device enables the use of high power multimode fiber laser which again gives a possibility to use sub-second welding times.

Weld quality was assessed in terms of strength (pull test) and visual appearance. The diffractive optics provides an even power distribution and only small part of power is lost on the zeroth order.

Design of diffractive element gives flexibility with the weld shapes and sizes but the drawback is that these parameters cannot be modified after the production of the element. Using the optics would be more advantageous if multiple parts could be welded at one shot because the part changing time will be a lot longer than the welding time. Results show good weld quality, superior welding speed and high weld strength compared to quasi-simultaneous laser welding of the same material.

Introduction

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Introduction

Various polymers are used in different industrial fields, for example automotive, electronics and medical device industry, and have applications from side to side. Polymers have good material properties and are a cost-effective alternative for other materials because of their low material and manufacturing costs. Manufacturing of polymer parts is often mass-production where the joining method of parts must also be a very fast process. Laser welding of polymers is a very suitable and flexible joining method for mass-production.

Laser transmission welding of polymers has been used for couple of decades already and many different process variations have been seen. All of these different processes are well suited to some areas of welding applications but have drawbacks on others. That is why industry is still seeking for a novel method to enable different welding geometries with really fast welding cycle time. Traditional simultaneous welding [1] is carried out with a set of diode bars and optics which are used to generate the welding path on the sample. Because diode bars and optics take some space, really small parts are difficult to weld and also complex, not simple line shaped, geometries need special setups which often make the investment too large. Using multiple diode bars is also problematic on the overlapping areas where too much or too little power might be resulting. These setups can be tuned to produce good welds after all. Anyway, the disadvantages of this welding method are evident.

Quasi-simultaneous [2], TWIST [3] and contour welding [4] on the other hand give freedom to generate the weld path according to a user computer file. Quasi-simultaneous welding works nicely for small parts but speed and accuracy of the scanner sets limits to the length and complexity of the weld. If the length of the weld is long, the scanning speed must be high enough so that the material does not cool off too much between consecutive passes. Contour welding is the basic welding method but with some polymers the welding parameter window might be quite narrow which could cause the material to be destroyed easily. The TWIST-method smoothens the heat input against contour welding and weld width can be modified from the program. Welding speed with contour and TWIST-welding is not as fast as with quasi-simultaneous welding. Mask welding [5] is an ingenious method but
needs an accurate mask and part positioning but it has its applications also in the industry.

In 2003 Lizotte [6, 7] showed a paper about using DOE’s and HOE’s (Diffractive and holographic optical elements) for a novel welding method. The method uses diffractive optics which enables welding of free geometries according to specified optical element. Typically the special optics are quite high in cost due to complex processing stages that are needed to fabricate the optics from e.g. fused silica. After fabrication the optical element is good only for the specified geometry and it cannot be modified. Only with different optical setups (focusing) the size of the geometry can be modified. This also changes the power distribution through the geometry because the created shape actually consists of multiple small spots which shape the specified geometry. So, when changing the overall size, also the spot sizes will change and the weld width too will change accordingly. A small drawback on using the diffractive optical element (DOE) is the zeroth order which is always present. If this cannot be designed to be a part of the geometry it can be taken out with a mask. Design and fabrication of the element has a big effect on the outcome of the geometry and efficiency of the element.

Grewell et al [8, 9, 10] have reported laser welding of polymers with DOE’s as beam-shaping elements. Grewell made his PhD thesis [11] on: ”Modeling of molecular healing for micro-laser welding of plastics with diffractive optical elements as spatial light modulators” in 2006. This thesis enlightens the topic quite well. There are couple of patents on this subject, for example one by Kawamoto et al [12], but their status might be a little controversial due to previously published data.

Since this method of using DOE seems to be promising but has drawbacks due to the non-flexibility of the optical component, the future might be in using the spatial light modulators (SLM) [13]. SLM can be computer controlled and refreshed up to 150 times in a second. These components need to be developed more because their power handling capabilities are at the moment too restricted.

This paper reviews the first experiments made with 5 kW fiber laser in transmission welding of Makrolon 2405 polycarbonate with sub-second welding times. Tensile tests are carried out to see what the actual strength of the welds is with different welding times. Short comparisons against previous tensile testing results from quasi-simultaneous welding is also made [14].

Experimental

The experimental part of this paper consists from two different sets of tests. In both of these tests, the welded material, part geometry and laser wavelength remained relatively the same. The first set of testing used a setup with single-mode fiber laser utilizing scanner optics, while the second relied on high power multimode fiber laser and used the DOE for beam shaping.

Test part and fixturing

The test parts used in the welding tests can be seen on the figure below. The weld shape was a circle with a nominal diameter of 30 mm. This shape was chosen because of the simple construction and the ease of tensile testing with this type of part.

Figure 1. Transmissive (1.) and absorbing (2.) parts for the testing.

Setup for the quasi-simultaneous welding tests

In the quasi-simultaneous welding tests the setup consists from a SPI 100 W fiber laser; a beam shaper (MolTech GmbH pi-shaper) with a 5-axis mount; and Arges Fiber Rhino scan head. The pi-shaper helps to create stronger welds especially with lower scanning speeds by altering the beam spatial profile closer to a top-hat mode. The welding setup (Figure 2) has a nominal focal length of 825 mm but due to the beam shaper the working distance is 1000 mm at focus. The optical properties of the pi-shaper change the working distance from the nominal focal length. This change could be compensated by adjusting the divergence slightly in the pi-shaper.
Setup for the simultaneous welding tests

The laser source used in this research was a 5 kW IPG YLR-5000-S multi-mode fiber laser (Figure 3). The beam was focused using a Precitec YWS50 welding head with ILV DC-Scanner. The scanner was not operated during testing.

The laser beam quality was analyzed using a Primes Focus Monitor focus measurement device. The beam was measured through the cutting head to get the most reliable and actual result. The beam quality of the laser can be seen in the figure below (Figure 4). The analyses showed the beam parameter product of 4.6 mm*mrad for this setup.

The diffractive element was located below the focusing lens to attain the suitable beam size for the element itself. The size of the weld was adjusted with the position of the optical element. Figure 5 shows the setup for the welding tests. The welding fixture was a machined aluminum unit which was suited for the test part. The clamping device utilizes a high force pneumatic cylinder, which gives a maximum clamping force of nearly 3000 Newtons.

The multi-part optical system had high power losses, which concluded to only about 40% of the total available 5 kW that was in the welding itself. Most of the losses were created by the welding head setup and the diffractive optical element. Other losses come from the glass part on the welding fixture and the transmissive (upper) welding part.

The theoretical maximum transmission for the element used was 69%, due to the simple design and
manufacturing methods used and because of the lack of anti-reflection coatings. Some amount of the laser power is lost in the zeroth order of the diffracted shape. The power that the DOE creates to the zeroth order was simply guided away from the work piece.

Process parameters for the quasi-simultaneous welding tests

The process parameters for the quasi-simultaneous tests are listed on Table 1. The focal length of the f-theta optic was 825 mm, was actual working distance is chosen to be 1000 mm. Spot size was measured to be \(\approx 380\mu m\) in diameter.

Table 1. Welding parameters of the quasi simultaneous welding tests.

<table>
<thead>
<tr>
<th>Power</th>
<th>14–100 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of scans</td>
<td>5, 10, 30, 50, 100</td>
</tr>
<tr>
<td>Welding times</td>
<td>1.0, 0.5, 0.2, 0.1, 0.05, 0.01, 0.002 s</td>
</tr>
<tr>
<td>Scanning speed</td>
<td>0.5–24 m/s</td>
</tr>
<tr>
<td>Focal length</td>
<td>825 mm</td>
</tr>
</tbody>
</table>

Process parameters for the simultaneous welding tests

The main parameters used in this experiment can be seen in the table below (Table 2.). The listed powers are nominal laser powers, the actual powers on the work piece are significantly lower.

Table 2. Welding parameters of the simultaneous welding tests

<table>
<thead>
<tr>
<th>Power</th>
<th>50–5000 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding times</td>
<td>1.0, 0.5, 0.2, 0.1, 0.05, 0.01, 0.002 s</td>
</tr>
<tr>
<td>Focal length of collimation</td>
<td>150 mm</td>
</tr>
<tr>
<td>Focal length of focusing optics</td>
<td>300 mm</td>
</tr>
</tbody>
</table>

Visual examination

The welded parts were examined visually during the welding experiments to determine the extent of destruction in the polycarbonate. This type of damage is visible as light coloring or bubbles in the normally dark weld material.

The weld quality was estimated and the weld dimensions were measured using an Olympus light Microscope.

Tensile strength testing

The tensile strength of the welded parts was tested with a plunger system that measured the maximum load bearing capacity of the part. The weld strength was calculated from this value and the cross-sectional size of the weld (weld width * weld ring circumference). This method has been proven to give accurate results and it simulates the strength of real-life welded polymer parts well. The tests were done with three samples with same parameters to eliminate errors and examine the repeatability of the process.

Results and Discussion

Quasi-simultaneous welding tests

The figures 7 and 8 show the weld widths and weld strengths that were acquired from the tests with quasi-simultaneous process. From figures we can see typical behavior when using quasi-simultaneous process for
plastic welding. Strength of the welds is far away for material strength.

![Weld widths](image1)

Figure 7. Weld widths from quasi-simultaneous welding tests. [15]

![Weld strength](image2)

Figure 8. Weld strengths from the quasi-simultaneous welding tests. [15]

**Simultaneous welding tests**

From Figure 9 we can see how the weld strength is affected by the different welding times. Welds were done so that first welds were made with as low power as possible and then power was raised gradually as many times as needed to achieve visible destruction of the weld. This can be seen well from Figure 9 where the strength curves first start to raise and then lower when power is raised beyond a certain point. This is natural because after the weld is destroyed the weld loses its strength.

![Weld Strength](image3)

Figure 9. Weld strengths from the simultaneous welding tests.

Designed weld width on the DOE is 200 µm which is quite small when long welding times are used. Design was made to be close to the spot size that was used on the quasi-simultaneous welding setup without beam shaper. With 1.0 second welding time weld widths are as much as 1.48 mm which is a lot more than the designed width. This means that the heat will be conducted quite far away from the area where the beam hits the material. With shortest times, the process is so fast that even when the weld starts to be destroyed it still has good strength properties. Because with 1.0 and 0.5 second welding times the heat was transferred to the whole width of the material, the sides of the weld are not so strong as the middle part of the weld. That is one reason why the weld strengths are lower in these welds than in narrower welds with shorter welding times. At 2 ms welding time there was not enough power from the laser to be inputted to the sample and this is why the weld strength was not as high as with the others.

Variation of the weld strength may be caused by the problems with the injection moulding of the parts. The upper parts had problems in the moulding because the polycarbonate did not flow well enough in all samples. Also some residues were left inside upper part in some cases. One error source might be also the surface quality of the welded parts (Figure 10), which can cause some irregularity in the welding. The surface textures are relatively rough, which can create a slight air gap between the parts. If the parts have an air gap, there is a possibility that the absorbing material is destroyed without any heat conducting to the upper part. In the transmissive part, the flow direction of the molten material can also be seen.
From the Figure 11 we can see a relatively linear behaviour on welding time and laser power versus weld widths. If we compare these results to our previous work on quasi-simultaneous welding results we can see a lot wider welds and also a lot higher strength values. This confirms the simultaneous welding methods advantage: Longer simultaneous welding time is enough for the melted materials to be properly mixed.

The base material strength with this polycarbonate is ~65 N/mm² [14] which is really close to best welds. From the figures (Figure 12 and Figure 13) we can see two tensile tested samples. From both samples we can see that the base material has given in which means that the weld has to be at least close to base material strength.

If we compare these strength values to the previous tests with quasi-simultaneous welding (figures 7 and 8) on the same material, we can see that the strength on the previous welds was only about half of the strength compared to current welds with the same laser power (0.5 seconds and 90W) [16]. Weld widths are close to each other depending on the number of scans on quasi-simultaneous welding.

Visual appearance of the welds is good on all welding times except 2 ms. This extremely short welding time would have needed to have more power. At too high powers it can be noted that weld centreline starts to have bubble like formation (Figure 14). This may be because the design width of the weld is perhaps too narrow. The heat does not have time to conduct to the surrounding material and therefore bubbles are created. If heat would be spread to a larger area it could make better welds on larger parameter window. It could also
be so that it would require a lot more average power on short welding times.

Figure 14. Example of an acceptable (A.) and a destroyed (B.) weld.

Conclusions

The tests indicated that extremely high weld strengths can be achieved with simultaneous welding process using a DOE. In best cases, the weld strengths were as high as the material strength itself.

When looking at our current results and the previous results with quasi-simultaneous welding we can see a clear advantage on simultaneous welding with diffractive optics due to the increased strength in weld. Also with one second welding time one would only need a 100 W fiber laser to perform this type of simultaneous welding. Of course if weld length would increase it would mean that higher average powers are needed, but also the challenges with quasi-simultaneous welding are increased due to the need for higher scanning speeds.

The use of 5 kW fiber laser enabled us to use as low as 2 ms welding times with still good weld strength and appearance. This really is sub-second welding and would mean that welding does not have to be anymore faster. With these welding times the fixture and part handling aspects play a big role if really high production rates are wanted.

Even tough a large amount of power was lost in different optical components this still gives good efficiency. Although efficiency of DOE is only ~70% it is standard efficiency for this kind of DOE. For future purposes a spatial light modulator (SLM) would be needed for the approximation of correct weld size for each part to be welded. This must be done in order to get the correct DOE for the welded part because manufacturing of high power DOE is quite expensive. Using a SLM with low power the welding can be tested beforehand with a relatively low cost.

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References


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