EVALUATING QUASI-SIMULTANEOUS AND CONTOUR WELDING FOR USE WITH THE CLEARWELD™ PROCESS

Michelle M. Burrell and Nicole M. Woosman – GENTEX Corporation, Carbondale, PA 18407-0315, USA

Abstract

The Clearweld™ process is a form of through transmission laser welding that enables welding of two clear substrates with minimal effect on the appearance. Aesthetics are especially critical in the medical and packaging industries. The Clearweld™ process can also weld colored or opaque substrates, and reduces the number of color limitations imposed in traditional through transmission laser welding.

Single beam contour and quasi-simultaneous welding methods were evaluated for use with the Clearweld™ process to aid users in the selection of beam delivery methods. The welding speed, laser power, and clamping pressures were varied in order to determine the effect on weld strength, amount of collapse, residual color, and weld time. Studies were focused on PETG.

Introduction

Through transmission laser welding (TTLW) uses laser energy to produce heat necessary to weld thermoplastics. The top substrate must be transmissive to the laser energy. The bottom substrate, or the weld interface, contains a laser absorbing material. In traditional TTLW, the laser absorbing material is carbon black. The laser beam transmits through the top substrate, is absorbed at the interface by the absorbing material, which then converts the laser energy into heat melting the two substrates together.

Advantages of TTLW include the ability to weld without contact with the substrates, no vibration which can damage delicate features, and does not generate particulates. The disadvantage with traditional TTLW is the use of carbon restricts the bottom substrate to being colored and generally opaque.

Background

Clearweld™ is a TTLW process that provides designers with a tool to laser weld clear, colored or opaque thermoplastics. The process is especially suitable for medical and electronic applications because in addition to the benefits of traditional TTLW, both substrates can be laser transmissive, for example, water white.

Clearweld™ was developed by TWI in conjunction with Gentex Corporation [1]. The principle is similar to traditional TTLW; however, the Clearweld™ process involves the use of specialized materials systems applied at the joint interface or within the bottom substrate. One form of the material systems is a liquid solution comprised of a near-infrared absorbing dye dissolved in a variety of solvents. The solvents act only as a carrier of the dye in order to apply the dye evenly to the desired location. After the solution is applied, the solvents are allowed to evaporate leaving only a thin layer of the dye on the surface. The dyes have a slight green tint prior to welding. The coloration enables the user to verify application of the dyes. The dyes degrade upon exposure to the laser energy and become nearly colorless to colorless. The dyes are designed for maximum absorption in the wavelength range of 940 to 1064nm which allows the use of diode and Nd:YAG lasers.

Clearweld™ Welding Parameters

The critical welding parameters for the Clearweld™ process include clamping pressure, laser power, beam size, welding speed, and amount of absorber material. Previous studies evaluated the effect of one welding parameter [2], or focused on maximizing the weld strengths for various thermoplastics [3, 4]. The purpose of this study was to evaluate several welding parameters and define the parameters suitable for PETG.

Laser Beam Delivery Methods

There are various methods for delivering the laser beam to the joint interface. Contour welding uses a single laser beam that is moved across the part. Scanning or quasi-simultaneous welding utilizes a series of mirrors attached to a galvanometer motor to reflect the beam in the appropriate shape. The beam scans the part rapidly, up to many times per second. Because the beam moves rapidly, the entire weld interface is heated almost simultaneously. Curtain welding consists of a wide beam larger than 5mm. The beam is either a single beam that is elongated by a lens or a series of laser beams fixed in a line. Similarly, simultaneous welding uses a beam focused by a lens or a
series of laser beams that is designed to match the shape of the component being welded.

This experimental study was designed to evaluate contour welding and quasi-simultaneous for use with the Clearweld™ process.

**Experiment**

**Material**

The material tested was PETG\(^a\). The test samples were based on the AWS [5] ultrasonic welding test specimen where two mating beams were welded together. The specimens will be referred to as I-beams.

**Laser System**

A scanning laser system\(^b\) was utilized for the Clearweld™ process. The laser was a high-power diode laser with the following parameters:

- Wavelength: 940 ± 10 nm.
- Maximum output power: 300 W continuous.
- Beam size: 2.0 mm x 2.0 mm
- Maximum speed: 10,000 mm/sec

**Welding Procedure**

Clearweld™ material system LD130B was liquid dispensed\(^c\) on to the top surface of the bottom beam. The material system completely dried prior to clamping the two mating beams together. Samples were welded using a single beam contour method and a quasi-simultaneous method to compare weld strengths and collapse. The laser beam transmitted through the top mating beam and absorbed by the material system at the interface between the two mating beams. The laser power, welding speed, and clamping pressure were varied to determine the conditions producing the highest strengths, maximum collapse, fastest welding speeds, and minimum residual color; see Table 1 for welding conditions. The beam size and amount of material system applied were constant.

Weld strengths are reported as the peak load divided by the area of the sample after welding. The weld flash was not removed for tensile testing.

---

\(^a\) Eastar GN007 PETG copolyester with mold release, provided by Eastman Chemical Company.

\(^b\) Laserline, DioScan 300

\(^c\) EFD Inc. valve 740V-ss

**Energy Density - Definition**

Energy density was used to compare results under various welding conditions. The energy density was calculated as follows:

\[
\text{Energy Density} = \frac{\text{(Laser Power)} \times \text{ (Number of Passes)}}{\text{(Beam size)} \times \text{(Welding Speed)}},
\]

where laser power is in Watts, beam size in mm, welding speed in mm/sec, and energy density is J/mm\(^2\). The number of passes is the number of times the laser beam scanned across the weld specimen in the quasi-simultaneous method.

**Results and Discussion**

**Quasi-Simultaneous vs. Single Beam Contour**

Figure 1 shows the amount of collapse for all welding conditions. The amount of collapse linearly increases at low energy density and becomes level at high energy density. Quasi-simultaneous welding produced less collapse than the single beam, but was most evident at low energy densities where quasi-simultaneous generated 0.2mm less collapse than single beam contour.

Figure 2 shows a comparison of strengths for quasi-simultaneous versus single beam contour welded. The weld strengths for single beam contour welding were higher than quasi-simultaneous welding. A weld strength greater than 32MPa was considered high because, in general, samples yielded in the parent material prior to weld failure above 32MPa. The Clearweld™ material system was applied only on to the surface of one part, which results in a thin region of melted material. The quasi-simultaneous method scans the weld interface quickly to essentially heat the entire interface at once. However, because only a small region is melted in the Clearweld™ process, the region cools rapidly. As a result, there is insufficient time for the heat to conduct to the other substrate and melt the two plastics together to form a strong weld. A large amount of collapse was produced with quasi-simultaneous, but the majority of the collapse may be occurring only in the substrate with the material system.

The main advantage of the quasi-simultaneous process was little to no residual color in the weld. Quasi-simultaneous progressively welds the entire weld interface where as single beam contour heats one spot at a time. During welding with a single beam contour, material was forced out of the interface, which also caused some of the Clearweld™ material system to squeeze out. This resulted in residual color in the flash. Quasi-simultaneous gradually caused collapse, which enabled the Clearweld™
system to remain at the weld interface. Each successive pass of the laser beam degraded more of the material system, thereby eliminating coloration in the weld and weld flash. Less residual color is possible with contour welding by matching the welding parameters with the material system. For example, applying a lower amount of material system and increasing the laser power results in low to no residual color.

**Single Beam Contour Weld Parameters**

The effect of welding parameters on weld strengths were studied for single beam contour welding. The results are shown in Figure 3. The energy density had no effect on strengths for samples welded at a mid range power and speed (57-150W, and 16.2-32.1 mm/sec). Strengths were above 32 MPa at all energy densities. High strengths were achieved at 300W for energy densities greater than 4.6 J/mm². Welding at a slow speed, 4.28 mm/sec required an energy density greater than 8.0 J/mm² to obtain high strengths.

The difference between the strengths may be due to the ability of molecular chains to flow from one substrate into the other. To obtain weld strengths equal to that of the parent material, the number of molecular chains and alignment must mimic that of the parent. Molecular chains from both substrates must flow into one another. At the mid range power and speed (57-150W and 16.1-32.1 mm/sec), the amount of chain movement was sufficient to produce high strengths. The amount of collapse was 0.24 mm for 150W, 32.1 mm/sec and 0.30 mm for 75W, 16.1 mm/sec. For the samples welded at 300W, the amount of collapse was 0.13 mm at 65.2 mm/sec and 0.21 mm at 42.9 mm/sec. The weld strengths were 27.6 MPa and 33.1 MPa, at 65.2 mm/sec and 42.9 mm/sec, respectively. A high weld strength of 34.1 MPa was achieved at 32.1 mm/sec where the amount of collapse was 0.30 mm. Therefore, at speeds of 65.2 mm/sec and 42.9 mm/sec the collapse was not large enough to produce sufficient flow of molecular chains from one substrate to the other. The data is summarized in Table 2.

Low strengths were also obtained for samples welded at 4.28 mm/sec and power less than 70W. The cause of low strengths may be due to insufficient flow of molecular chains, but in this case, the molecular chain flow was impeded. When the laser was stopped half way in the I-beam, bubbles were observed in the region 10 to 18 mm behind the spot where the beam stopped. The region that welded initially did not have bubbles. The area that was not exposed to the laser beam prevented the region directly behind the stopped beam from collapsing, allowing the bubbles to remain intact. Upon further heating, melting causes the material to collapse and therefore the bubbles to collapse. Samples welded completely across the entire length did not have bubbles. Figure 4 shows images of two specimens welded at the same energy density, 2.3 J/mm². Specimen 4(a) was welded at 20W, 4.28 mm/sec, and specimen 4(b) was welded at 300W, 65.2 mm/sec. Specimen 4(a) has significantly larger bubbles than 4(b). Due to the slow welding speed of 4(a), the bubbles were able to grow to a large size before collapsing. The large bubbles impede flow of molecular chains from one substrate to the other. The small bubbles in specimen 4(b) allowed for sufficient flow to produce a mediocre strength. The strength of the 20W, 4.28 mm/sec was 18.9 MPa and 300W, 65.2 mm/sec was 27.6 MPa. At 70W and higher, there was sufficient amount of collapse to produce weld strengths greater than 33.0 MPa. However, at lower powers, less than 70W, there was insufficient collapse to overcome the large bubbles.

Specimens 4(b) and 4(c) were welded at 300W and 65.2 mm/sec. The clamping pressure was 4.5 MPa for 4(b) and 9.1 MPa for 4(c). The higher clamping pressure either prevented bubbles from forming or collapsed the bubbles quicker. As a result, the sample welded at 9.1 MPa had a higher strength, 34.8 MPa versus 27.6 MPa. High pressure should only be used at 65.2 mm/sec. The strengths degraded at slower speeds, 28.7 MPa at 42.9 mm/sec and 37.5 MPa at 26.0 mm/sec. A significant advantage of using the high pressure was to obtain a fast welding time of only 0.78 sec while achieving a high strength. The fastest time achieved with quasi-simultaneous was 0.76 sec but the strength was only 28.9 MPa.

**Concluding Remarks**

Fast welding speeds are achievable with contour welding. Higher strengths were achieved with single beam contour welding than quasi-simultaneous. A maximum collapse of 0.63 mm to 0.67 mm was achieved with both methods under the conditions evaluated. Collapse was detrimental only at 300W, pressure of 9.1 MPa, and weld speed less than 65.2 mm/sec.

**Acknowledgements**

The authors would like to thank Kevin Black of the Gentex Quality Test Lab for performing the tensile strength tests. The authors would also like to thank Eastman Chemical Company, especially Tony Pifer, for providing the test specimens. Bill Cawley, thank you for your assistance with liquid dispensing and TWI personnel for their valuable inputs.
References

5. AWS G1.2M/G1.2:1999 “Specification for Standardized Ultrasonic Test Specimen for Thermoplastics.”

Key Words

Thermoplastics, laser, Clearweld, Eastar, PETG.

Table 1. Welding conditions evaluated using the Clearweld process.

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Weld Speed (mm/sec)</th>
<th>Number of Passes</th>
<th>Clamping Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,30,40, 50,60,70, 80,90</td>
<td>4.28</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>75,115, 150,187, 225,265, 300</td>
<td>16.1</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>150</td>
<td>7.1,10.7,16.1, 18.5,32.1</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>300</td>
<td>16.1, 18.5, 21.4, 25.7, 32.1, 42.9, 65.2</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>300</td>
<td>32.1, 42.9, 65.2</td>
<td>1</td>
<td>9.1</td>
</tr>
<tr>
<td>Quasi-Simultaneous</td>
<td>Varied Power (4.28mm/sec)</td>
<td>Varied Speed (300W)</td>
<td>Varied Speed (300W)</td>
</tr>
</tbody>
</table>

Table 2. Summary of collapse data in comparison to weld strengths.

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Speed (mm/sec)</th>
<th>Clamp Pressure (MPa)</th>
<th>Collapse (mm)</th>
<th>Weld Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>65.2</td>
<td>4.5</td>
<td>0.13</td>
<td>27.6</td>
</tr>
<tr>
<td>300</td>
<td>42.9</td>
<td>4.5</td>
<td>0.21</td>
<td>33.1</td>
</tr>
<tr>
<td>150</td>
<td>32.1</td>
<td>4.5</td>
<td>0.24</td>
<td>33.9</td>
</tr>
<tr>
<td>300</td>
<td>32.1</td>
<td>4.5</td>
<td>0.30</td>
<td>34.1</td>
</tr>
<tr>
<td>75</td>
<td>16.1</td>
<td>4.5</td>
<td>0.30</td>
<td>36.5</td>
</tr>
<tr>
<td>20</td>
<td>4.28</td>
<td>4.5</td>
<td>0.33</td>
<td>18.9</td>
</tr>
<tr>
<td>70</td>
<td>4.28</td>
<td>4.5</td>
<td>0.57</td>
<td>33.4</td>
</tr>
<tr>
<td>300</td>
<td>65.2</td>
<td>9.1</td>
<td>0.23</td>
<td>34.8</td>
</tr>
<tr>
<td>300</td>
<td>42.9</td>
<td>9.1</td>
<td>0.32</td>
<td>28.7</td>
</tr>
<tr>
<td>300</td>
<td>32.1</td>
<td>9.1</td>
<td>0.4</td>
<td>26.0</td>
</tr>
</tbody>
</table>

Figure 1. Amount of collapse for various welding conditions.

Figure 2. Comparison of strengths for quasi-simultaneous to single beam contour welding.
Figure 3. Weld strengths for single beam contour welding.

Figure 4. Images of welds stopped half way. Samples welded at the same energy density of 2.3J/mm²: (a) 20W, 4.28mm/sec, 4.5MPa, (b) 300W, 65.2mm/sec, 4.5MPa, and (c) 300W, 65.2mm/sec, 9.1MPa.