Welding of Infrared Transmissive Thermoplastic Polymers using Diode Laser Systems

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Abstract

Clearweld™ technology is a tool, which is readily employed for transmission laser welding of thermoplastic polymers using near infrared diode lasers. This process is accomplished through the use of specialized material systems uniquely chosen and targeted to absorb the laser light at the intended laser weld joint in order to rapidly effectuate a weld. Data will be presented showing actual weld strengths, critical process parameters, and quantification of residual stresses in a variety of thermoplastic materials.

Keywords: polymer joining, plastics welding, laser transmission welding, laser materials processing, laser materials processing, Clearweld

1 Introduction

Transmission laser welding involves the use of high-density electromagnetic energy produced by a laser source to create thermal energy at the joint interface necessary for weld formation. Plastics in their natural state do not absorb near-infrared (NIR) light; therefore energy from lasers operating in the NIR efficiently transmits through plastics. To successfully use lasers for joining polymer, this laser energy must be properly harnessed to create the heating and intermolecular diffusion critical for weld formation. Controlling factors in the process are the power of the laser, the size of the laser beam, welding speed and the absorptive properties of the material at the interface. Typically carbon black pigment is used as an additive to enhance absorption of the bottom substrate.

First used in the mid-1980s for welding automotive components, laser welding offers a number of distinct advantages compared with other plastics joining techniques. Because laser welding does not involve vibration, mechanical damage to a part or generate particulates are avoided, making the process especially suitable for medical and electronics applications. Resulting weld strengths are comparable or superior to other joining techniques, such as hot plate and ultrasonic, without visible markings or weld flash. Laser welding accommodates preassembly and high weld speeds, permits 3-D contour joint lines and facilitates rapid changeover to different products. In addition, process parameters can be controlled precisely, and low heat input reduces the risk of thermal damage.

The principal disadvantage of laser welding has been the need to use carbon black as an absorbent, posing a limitation in applications where appearance and color are important.

2 The Clearweld™ Process

A significant process advancement has been developed that offers all the advantages of conventional laser welding without the use of opaque materials or the addition of unwanted color. The process can be used to join a wide range of rigid and flexible plastics, both clear and colored, making the process ideal for assembling electronic, medical, automotive and consumer products, as well as packaging. The process uses near-infrared (NIR) absorbing material systems to convert laser energy into heat. A thin layer of these materials applied at the interface of two pieces of plastic to be joined absorbs the light, acting as a focal point for the laser. Localized heating of the substrates occurs at the joint interface, producing clean, optically clear joints with no particulates or visible color.

Called Clearweld™, the process was invented by TWI, an U.K.-based industrial research and development organization that specializes in materials joining, and has been developed for commercial use by Gentex Corporation, a privately owned technology company. Gentex has developed a series of materials capable of powerful absorption in the near-IR spectrum, while remaining virtually colorless.
Clearweld incorporates these absorbents in unique material systems designed for use in a variety of production processes.

3 Critical processing parameters

A number of critical processing parameters must be followed to ensure successful welding of a joint. These include intimate contact, heat generation, and proper material application and will each be covered in more detail in the following paragraphs.

An important factor when using laser transmission welding is intimate contact between the surfaces to be joined to ensure sufficient melt flow to produce a strong bond. To obtain intimate contact of the substrates at the weld interface, a certain amount of clamping pressure is required for most joints (the notable exception being an interference fit, as clamping may not be necessary). The amount of pressure depends upon the materials being joined, the specific joint design chosen, and the quality of the surface conditions at the weld interface. Surfaces typically have asperities (bumps, valleys and inconsistencies) which prevent close contact. As the surfaces heat and expand, the clamping pressure helps to flatten the surface, removes entrapped air to impart even contact along the interface, and facilitates diffusion of the polymers necessary to create a strong weld. As with other welding methods, having a clean surface free of contaminants is important for assuring uniform weld performance.

Also critical to the welding process is heat generation. Diode lasers have been selected to provide the coherent electromagnetic energy necessary for generating heat. The typical wavelengths employed range from 940nm to 1064nm. Neodymium: YAG lasers operating at 1064nm have been proven to work with the Clearweld process; however extensive research has not be yet done with this wavelength. Diode lasers were chosen for their efficiency, smaller size, and minimal maintenance requirements. However, one critical requirement is that the laser output matches the wavelengths at which the material system is designed to absorb.

Diode lasers can be used in a number of different ways in the Clearweld process. The choice and configuration of equipment for a given application will depend on a number of factors, including the size, shape and material of the components being welded, required cycle times, and the desired strength and weld width.

There are various methods for applying the laser energy to the part including single beam-contour, curtain, scanning, and simultaneous/array. With a single beam laser system, the equipment generally operates as a single-pass process, with either the laser fixed and the part moving or the part fixed and the laser moving. This process is usually accomplished using numerically controlled (NC) tables to move the parts around and expose the parts to the proper amount of laser energy. A two axis or rotary table can handle a majority of applications but additional axles can be added if needed. Single beam method will work for just about any method, but speed is limited by the motion control system.

Curtain welding involves creating a beam of light at least the width of the required weld width. The part is moved under the laser curtain and a weld occurs only where the Clearweld material system has been printed. Curtain welding is very simple to accomplish and works well with complex printed surfaces; however, curtain welding is not the most efficient method due to laser energy being applied to unneeded sections. Welding times and power requirements tend to be higher with this method as well.

Another equipment configuration is a scanning laser system, whereby mirrors are programmed to move the laser beam (via galvanometer motors) around the joint line of the fixed component. The beam moves very quickly scanning the joint many times per second. Both the part and laser remain fixed during the process.

This equipment has the added advantage of easily altering the weld line profile by simply loading a different program into the scanning unit, but maximum part sizes are presently a limiting factor.

In the simultaneous/fixed diode array, the laser diodes are mounted in a frame designed to match the shape of the component being welded. This usually requires the need for multiple diodes forming an array. The process operates with the entire joint being irradiated for a given time. This is the best method for applying the laser energy uniformly as the whole part is exposed simultaneously; however, its ability to handle significantly different part configurations is often compromised.

The Clearweld process depends upon accurate and repeatable application of the NIR absorbing layer at the localized joint interface. The effectiveness of these material systems depends upon their compatibility with specific process parameters. These systems are custom-formulated, taking into account substrate materials, part design and process requirements, and are tested and certified for use with specific delivery methods. Certified methods of application are liquid dispensing and spray.

Liquid dispensing involves the use of commercially available syringe dispensers where the liquid flows through a needle tip and a valve controller is utilized to regulate flow for more precise application. The dispenser is normally attached to a numerically controlled (NC) table allowing the dispenser to accurately trace the outline of the part to be coated. The Clearweld material systems are designed to work with needle dispensers from EFD Inc., a division of the Nordson Corporation. The amount of material dispensed is controlled by the following factors:

- The length of time the valve is open
- The fluid reservoir pressure
- The needle stroke
- The dispensing tip size used
- The viscosity of the Clearweld material system being dispensed
Spray systems can also be utilized to apply Clearweld material systems. In this method of application, the solution is stored in a reservoir. A low pressure is applied to the reservoir and forces the solution to an air cap on a spray gun. Atomizing air is introduced into the air cap to disperse the solution from the nozzle as droplets. This system has the advantages of ease of operation and the ability to cover a large area in a single pass. Many spray guns are commercially available. Some care must be taken in selection of a particular system to avoid any solvent compatibility issues as well as clogging of the nozzle tip.

Once the part design, clamping system, laser and dispensing system have been identified, the key to ensuring a successful process implementation is optimization of laser power, weld speed and absorption of the custom material system. Fine-tuning these parameters can help to improve resulting weld strengths.

4 Achievable Weld Strengths

The Clearweld process was utilized to weld various polymers in a butt joint configuration. Samples were cut into pieces 25mmx100mmx3mm. The absorber material system was applied to the 25mmx3mm edge as shown in Fig. 1.

![Absorber Material](image)

**Fig.1: Welding joint configuration**

After the solvent evaporated, two substrates were placed in a clamping device such that the final welded joint was 25mmx200mmx3mm.

A scanning laser system (Laserline, DioScan 300) was utilized for welding the samples. 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

The welding parameters depended on the polymer. In order to determine the maximum attainable strengths, only the speed was varied. The parameters held constant were the power (between 100W and 300W), the pressure (between 3.4-4.6MPa), beam size (2mmx2mm), and absorber material system.

The maximum welding strengths obtained for the various polymers evaluated are shown in Tab. 1.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Weld Strength MPa</th>
<th>Weld Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS, natural</td>
<td>36.5</td>
<td>0.87</td>
</tr>
<tr>
<td>Acetal Copolymer</td>
<td>51.6</td>
<td>0.79</td>
</tr>
<tr>
<td>Acrylic/PVC</td>
<td>No weld</td>
<td>-</td>
</tr>
<tr>
<td>HDPE</td>
<td>27.7</td>
<td>1.0</td>
</tr>
<tr>
<td>LDPE</td>
<td>10.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Nylon 6,6</td>
<td>35.9</td>
<td>0.45</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>49.6</td>
<td>0.76</td>
</tr>
<tr>
<td>PEI</td>
<td>23.7</td>
<td>0.31</td>
</tr>
<tr>
<td>PETG</td>
<td>51.0</td>
<td>0.98</td>
</tr>
<tr>
<td>PMMA</td>
<td>56.6</td>
<td>0.82</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>28.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Polystyrene, HIPS</td>
<td>No weld</td>
<td>-</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>51.7</td>
<td>0.73</td>
</tr>
<tr>
<td>PTFE</td>
<td>No weld</td>
<td>-</td>
</tr>
<tr>
<td>PTFE, mechanical grade</td>
<td>No weld</td>
<td>-</td>
</tr>
<tr>
<td>Rigid PVC</td>
<td>49.8</td>
<td>0.96</td>
</tr>
<tr>
<td>PVDF</td>
<td>42.3</td>
<td>0.78</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>20.3</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Acrylic/PVC and Polystyrene could not be welded due to low transmission, 0.55 and 1.2%, respectively. The two PTFE samples did not weld despite having sufficient transmission. The absorber degraded, however the plastic did not melt. The weld efficiencies for Nylon 6,6, PEI, and UHMWPE were low, less than 0.50. Nylon 6,6 and PEI are high melting temperature thermoplastics. Due to the absorber being only on the surface of the substrate, the region of melting may not have penetrated deep enough to obtain high weld strengths. For these materials, the absorber may need to penetrate deeper into the plastic and at a higher concentration. Applying a higher concentration only at the interface may help slightly, however too much absorber will act as a barrier between the two substrates. The high melt viscosity of UHMWPE impeded welding.

The test samples were not ideal for obtaining the highest strengths possible using the Clearweld process. The weld surfaces were machined, imparting some surface roughness and possibly residual stresses. Extruded sheets have some molecular orientation of the polymer chains. The extruded direction was not taken into consideration when cutting the samples. Higher strengths may be obtained with injection molded samples.

The Clearweld process has also been shown to effectively weld other thermoplastics, for example, polyurethane, cyclic-olefin copolymer, cyclic-olefin polymer, PEEK, clear polystyrene, CPVC, transparent Noryl, polyester. The thermoplastics may be rigid, films, or foams, etc.
5 Residual Stresses

Residual stresses in polycarbonate Clearwelded butt-joints were measured using photoelasticity [1] and verified by the solvent testing technique [2]. Samples were prepared and welded using the technique described in the previous section. Fig. 2 shows a comparison of the residual stresses in Clearweld joints to other welding techniques.

Fig. 2: Comparison of residual stresses

Despite the very high heating and cooling rates, the residual stresses in Clearwelded joints are slightly lower than in conventional TTIR welds and substantially lower than in ultrasonic and vibration welds [3].

Fig. 3 shows that at constant welding speed of 14.8 mm/sec, the residual stresses increased with an increase in laser power.

Fig. 3: Residual stress at various laser powers

This can be explained by the fact that an increase in power allows greater absorption of energy by the absorbers and thereby results in higher temperatures and temperature rise rates. Therefore, temperature gradients during cooling should increase with increasing power resulting in higher residual stress levels. Notice the good agreement between the GE solvent test estimates and the photoelasticity measurements.

Fig. 4 shows that increasing the scan speed results in a small increase in maximum residual stress levels.

Fig. 4: Effect of weld speed on residual stress

The Clearweld process produces a small amount of material collapse, or deformation, due to localized heating. A comparison of the heat affected zone generated by the Clearweld process to hot plate welding is shown in Fig. 5.

Fig. 5: Heat Affected Zone of Hot Plate (left photo) vs Clearweld (right photo)

Tab. 3 shows examples of the amount of deformation obtained during welding.

Tab. 3: Amount of material deformation resulting from the Clearweld process

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Amount of Deformation mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE</td>
<td>0.41</td>
</tr>
<tr>
<td>PETG</td>
<td>0.18</td>
</tr>
<tr>
<td>PMMA</td>
<td>0.28</td>
</tr>
<tr>
<td>PP</td>
<td>0.080</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>0.23</td>
</tr>
<tr>
<td>PVDF</td>
<td>0.070</td>
</tr>
<tr>
<td>PEI</td>
<td>0.060</td>
</tr>
</tbody>
</table>

The small amount of material deformation may also contribute to the low residual stresses of Clearwelded materials compared to other welding techniques.
6 Conclusions

High weld strengths can be obtained using the Clearweld process to joint plastics. In some plastics, weld strengths equal to the parent material were achieved. The technology is applicable to a diverse range of thermoplastics. Despite the name “Clearweld”, translucent and opaque materials with sufficient transmission in the infrared-region are weldable.

Residual stresses present in Clearweld joints are lower compared to other fast welding techniques. As a result of lower stresses, Clearwelded joints may be able to withstand higher exposure limits to solvents, have longer fatigue life and higher fracture toughness.

7 Nomenclature

ABS – acrylonitrile-butadiene-styrene
Acetal – POM, polyoxymethylene
Acrylic – PMMA, polymethyl methacrylate
HDPE – high density polyethylene
LDPE – low density polyethylene
PEI – polyetherimide
PETG – polyethylene terephthalate with cyclohexanedimethanol (CHDM)
PTFE – polytetrafluoroethylene
PVC – polyvinyl chloride
PVDF – polyvinylidene fluorride

8 Bibliography

