A Study of the Effect of Weld Parameters on Strengths of Clearwelded^{TM} Thermoplastics

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Abstract

Clearweld is a unique through transmission laser welding technique that allows for welding of two clear or two near-infrared transparent substrates. The process yields a nearly colorless weld when joining clear substrates. The resulting welds are also free from flash with minimal residual stresses. Applications of the Clearweld process can be found throughout the plastics welding industry including medical, automotive and electronics.

An investigation was performed on the effect of welding parameters on joint strengths. The Clearweld process was utilized to weld thermoplastics in a butt joint configuration. Welds were produced at various laser powers, weld speeds, and clamp pressures. In addition, welds strengths were compared for samples generated by simple contour welding and quasi-simultaneous welding. Acrylic and polypropylene Clearwelded samples were examined.

Introduction

Through-transmission laser welding (TTLW) of thermoplastics involves the use of laser energy to produce the heat necessary to generate a weld. Traditionally this is accomplished by using an additive in one of the substrates to absorb the laser energy. Plastics, in their natural state, transmit near-infrared laser energy. Therefore, one substrate must remain in its natural state, while the second substrate is altered, typically by adding carbon black, in order to make it absorbent to the laser energy. The laser light transmits through the top substrate until it reaches the bottom substrate where it is absorbed. Under favorable welding parameters, this heating conducts into the top substrate allowing the two materials to melt and flow together forming a weld. The main advantages of laser welding are that it does not involve vibration, is non-contact, does not impart mechanical damage, and does not generate particulates. The main disadvantage is the use of carbon in one of the substrates that virtually rules out using this process for any application in which aesthetics and lack of color are important.

Clearweld is a new form of TTLW that became commercially available in early 2002 [1]. The process is a new tool for designers who wish to join clear, colored or opaque thermoplastics and achieve high integrity welds without many limitations. The process is especially suitable for medical and electronics applications because it maintains all of the common benefits of laser welding, but with the added benefit that both substrates can be laser transmissive. This allows for the possibility of laser welding without the use of opaque materials or the addition of unwanted color.

Clearweld was developed by TWI in conjunction with Gentex Corporation. The principle is similar to that of conventional TTLW, however the Clearweld process involves the use of specialized material systems applied at the joint interface of a part or within the bottom substrate to act as a focal point for the laser. It absorbs the laser light, and through an exothermic reaction, converts the energy to heat and effectuates a weld. These material systems are comprised of near-infrared absorbing dyes dissolved in a variety of solvents. The solvents are used only as a transport medium to get the material to the desired weld location. Once delivered, the solvent evaporates very quickly, leaving a thin coating of the near-infrared absorbing material at the interface. The material system has a slight green tint before welding which allows it to be seen during application; however after laser exposure under optimized parameters, the dye degrades and the color is eliminated. The material systems are designed for maximum absorption in the wavelength range of 940-1064nm which allows the use of commercially available diode and Nd:YAG lasers. Other wavelengths, including the visible region [2], have also been shown to be effective in the Clearweld process.

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.

An important factor when using laser transmission welding is intimate contact between the surfaces to be joined. This ensures sufficient melt flow to produce a strong weld. 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, the quality of the surface conditions at the weld interface, and the final strength requirements. Surfaces typically have irregularities (bumps, valleys, etc.) which prevent close contact. As the surfaces heat and expand, the clamping pressure helps to flatten the surface, which removes entrapped air to impart even contact along the interface. This facilitates diffusion of the polymers necessary to create a strong weld. As with other welding methods, having a clean surface free of contaminates is important for assuring uniform weld performance (contaminants can interfere with both uniform material deposition as well as interact with the laser beam to cause unnecessary burning).

Also critical to the welding process is heat generation. An essential requirement is that the laser output matches the wavelengths at which the material system is designed to absorb. The Clearweld material systems have a maximum absorption range between 940nm to 1064nm. Both diode and Nd:YAG lasers can be used with the Clearweld process. A diode laser was selected to provide the coherent electromagnetic energy for this paper due to its efficiency, smaller size, and minimal maintenance requirements.

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

Curtain welding involves creating a beam of light at least as wide as 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 sections that will not be welded. 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 can scan around the part once, or more commonly it can scan the joint very quickly, up to many times per second. Both the part and laser remain fixed during the process. This equipment has the added advantage of easily changing the weld line profile by simply loading a different program into the scanning unit. Maximum part sizes are presently a limiting factor due to the fact that the beam can only travel in a specified area.

In the simultaneous/fixed diode array, the laser diodes are mounted in a frame designed specifically 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, each new part would require its own custom tooling.

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, taking into account substrate materials, part design and process requirements. They are tested and certified for use with specific delivery methods. Certified methods of application are liquid dispensing and spray. The NIR absorber may also be dispersed throughout the bottom substrate.

Liquid dispensing involves the use of commercially available needle valve dispensers. In this method, 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:

-length of time the valve is open
-fluid reservoir pressure
-needle stroke
-dispensing tip size
-viscosity of material

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 material system. Fine-tuning these parameters can help to improve resulting weld strengths and aesthetics.

Experiment

Materials

The plastics evaluated were polypropylene and acrylic. Samples were cut into 25 mm by 100 mm pieces. The 25 mm edges were milled for smoother and parallel surfaces. Two samples were welded along the 25mm in a butt joint configuration to produce a 25mm by 200mm tensile sample.

Clearweld Material System

A methoxy-propanol based ink, LD110B, was utilized with polypropylene to generate the weld. Acrylic was welded using an ethanol-based ink LD140B. The inks were selected based on previous experiments to determine the compatibility between substrate. The inks were applied using a liquid dispensing valve[1].

Laser System

A scanning laser system[2] 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

Clamping System

Figure 1 shows the clamping system used to Clearweld the butt welds.

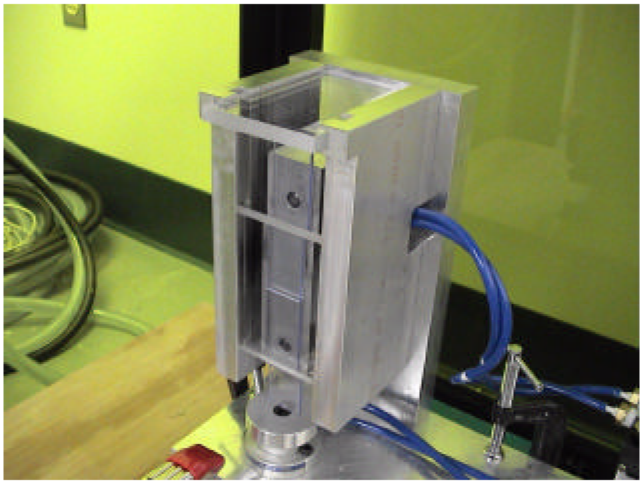

Figure 1. Clamping system for Clearwelded butt joints.

The clamp consisted of two air cylinders. One air cylinder applied pressure perpendicular to the sample in order to keep the two pieces aligned. The sample was placed between a piece of 10 mm piece of borosilicate glass and an aluminum plate. The air cylinder moved the aluminum plate to hold the sample between the glass and plate with a force between 61-89 N. The second air cylinder applied pressure parallel to the sample, perpendicular to the weld

[1] EFD, 740V-ss

[2] Laserline, DioScan 300

interface. The top of the clamp was a 10 mm piece of PMMA. The maximum force applied at the weld interface was 356 N. The top plate was PMMA instead of glass to avoid shattering of the glass due to the applied pressure. The front clamping plate could not be PMMA due to burning of the edge. The transmissions of PMMA and borosilicate glass are comparable in the 930-950 nm range, 91.3% and 91.4%, respectively.

Welding Procedure

After the ink containing the absorber was applied and allowed to dry, the two substrates were brought under pressure using the clamping system. The clamping pressure was constant at 4.1 MPa for polypropylene. The pressure was varied at 4.5 MPa, 3.9 MPa, and 3.3 MPA for acrylic. The beam was 2mm at the focal point and focused at the weld interface. The power and welding speed were varied. For the quasi-simultaneous welding of acrylic, the number of times the beam was rastered across the weld interface was varied in order to change the energy density applied to the weld. The angle of the weld interface with respect to the beam path varied depending on the transmissive properties of the plastics welded; see Figure 2. For acrylic, the angle was 90° to the beam path, i.e., the beam passed through 100 mm of material. Polypropylene was welded with the angle 45° to the beam path to allow sufficient energy to reach the weld interface. Clamping pressure was removed immediately after welding.

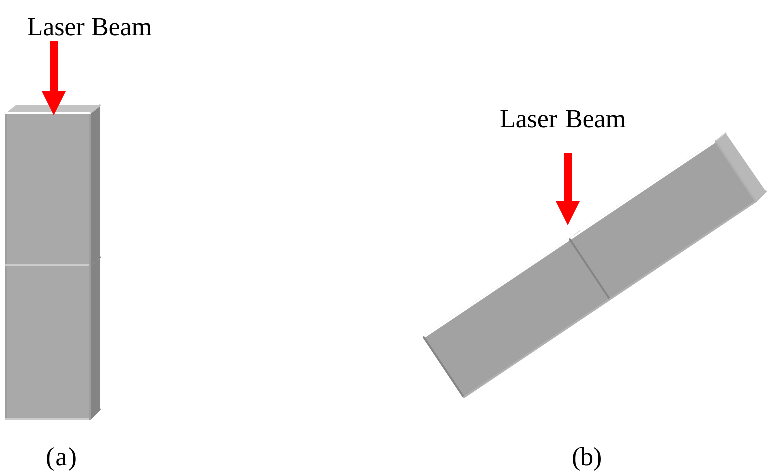

Figure 2. Orientation of Acrylic (a) and polypropylene (b) with respect to the laser beam.

Results and Discussion

Figure 3 shows the effect of varying the weld speed and power for polypropylene.

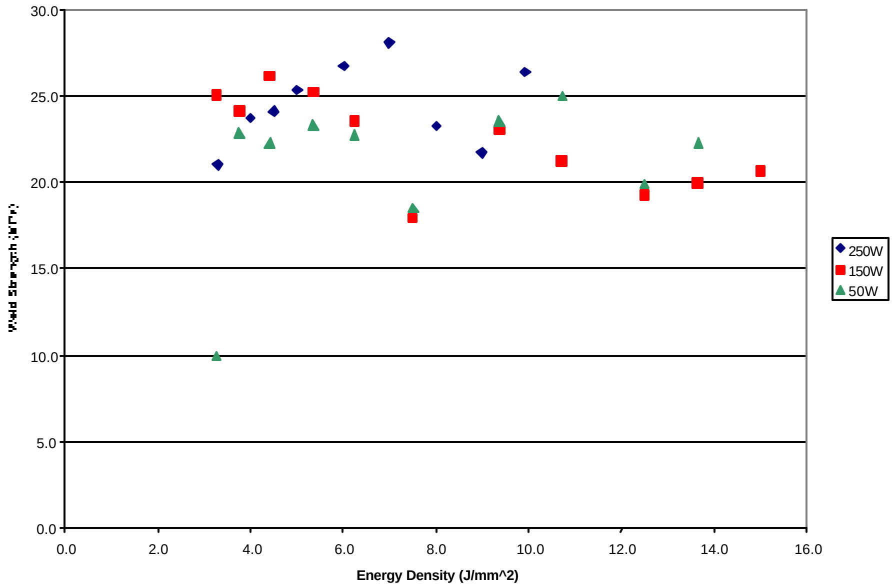

Figure 3. Effect of welding parameters on polypropylene.

As the weld speed increased (energy density decreased), the strengths increased until a peak was reached. At the mid-range speeds, the strength decreased. The strengths increased to a second peak at fast speeds (low energy density). The highest strength was achieved at the highest power of 250W. At 250W, the weld strength was more sensitive to changes in the weld speed. The weld strength did not vary significantly at 150W or 50W at fast speeds.

The reasoning for the variation in weld strengths has not been confirmed. However, studies on infrared welding [3] suggest that the tensile strength increased with melt layer thickness until an optimum was reached. The strength proceeded to decrease due to surface decomposition of the polymer caused by rapid increase in surface temperature. As the melt layer increased, the decomposition products were pushed out of the way allowing for a stronger joint. The decomposition product eventually built up to the point where the melt layer thickness no longer removes the products. Because the surfaces were machined, residual stresses may contribute to some of the variation. Additionally, the machined surfaces were not smooth as that which may produced by injection molding. However, the trends were similar at varying powers which suggests that the variation is process related rather than sample related.

The effect of power on weld strength for acrylic is shown in Figure 4.

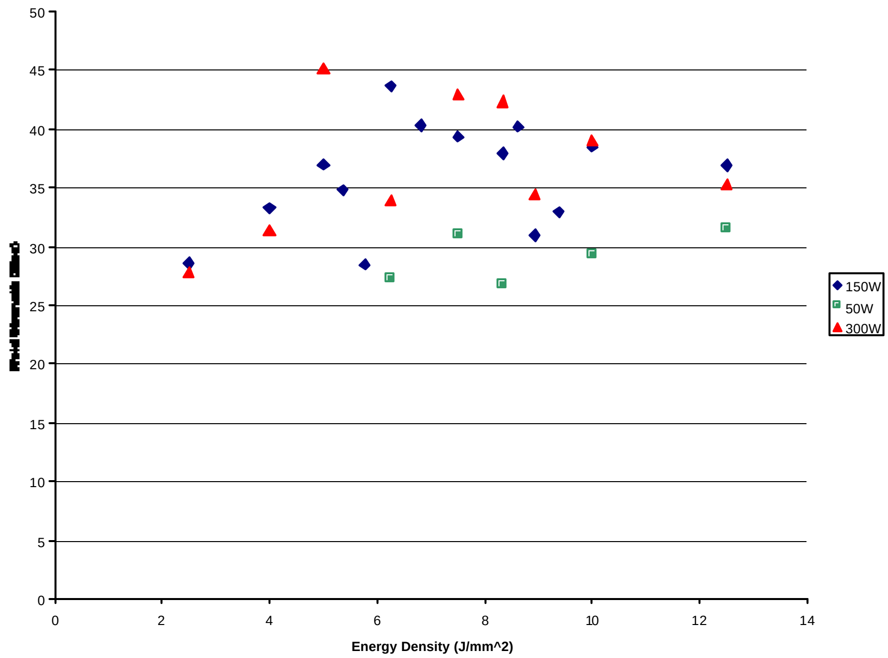

Figure 4. Effect of power on acrylic weld strengths.

The energy densities at various laser powers are not equivalent, for example, an energy density of 10.0J/mm^2 did not produce similar weld strengths at 50W, 150W, or 300W. Low weld strengths were achieved with 50W. The weld strength did not vary significantly with energy density when welded at 50W. Maximum weld strengths at 300W were produced at a lower energy density than 150W or 50W.

There may be a couple contributing factors that accounts for the difference in energy density requirements at various powers. First of all, at low power, slower speeds are required. The material may be molten for a longer time, resulting in more material flow. The large amount of material flow can cause molecular alignment. Secondly, at high powers, the weld is produced at a faster speed. The heating at the interface is more uniform than at slow speeds, in other words, the weld at the starting point has cooled less by time the ending point is reached for faster speeds than with slow speeds. These factors would imply that the pressure required at various powers would different.

The effect of clamping pressure on acrylic welds is shown in Figure 5.

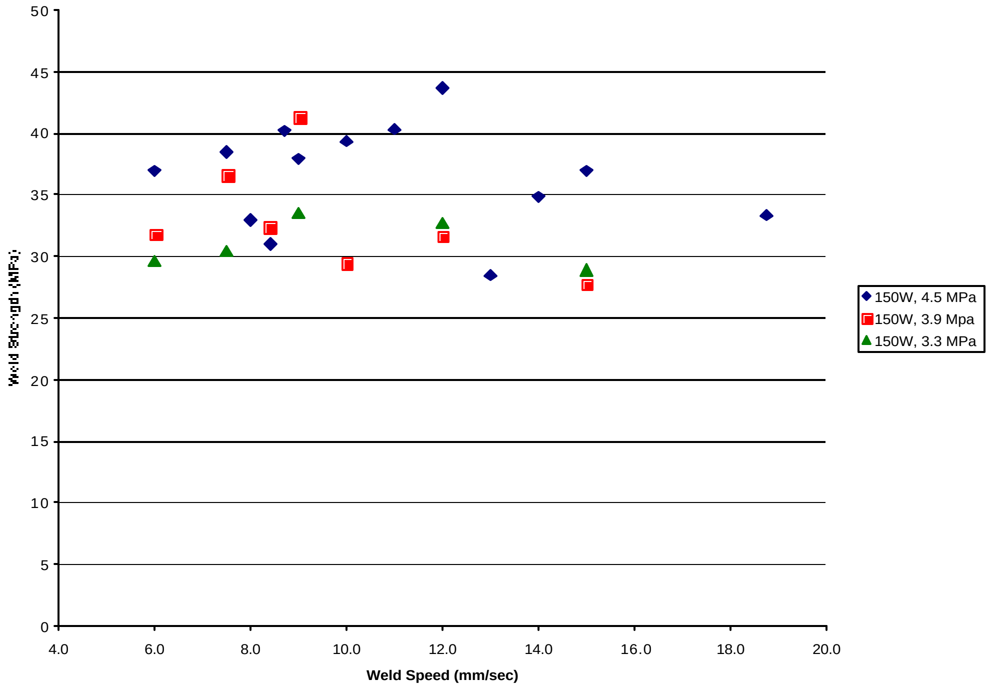

Figure 5. Effect of clamping pressure on acrylic weld strengths.

Maximum strengths were achieved with 4.5 MPa. At slower speeds, the weld strengths at 4.5 MPa and 4.1 MPa showed a difference in strength of only 7%. At faster speeds, the variation was as high as 32%. Clamping pressure is more critical at fast speeds than at low speeds. The highest pressure produced the strongest weld.

The results from quasi-simultaneous welding of acrylic versus single beam welding are shown in Figure 6.

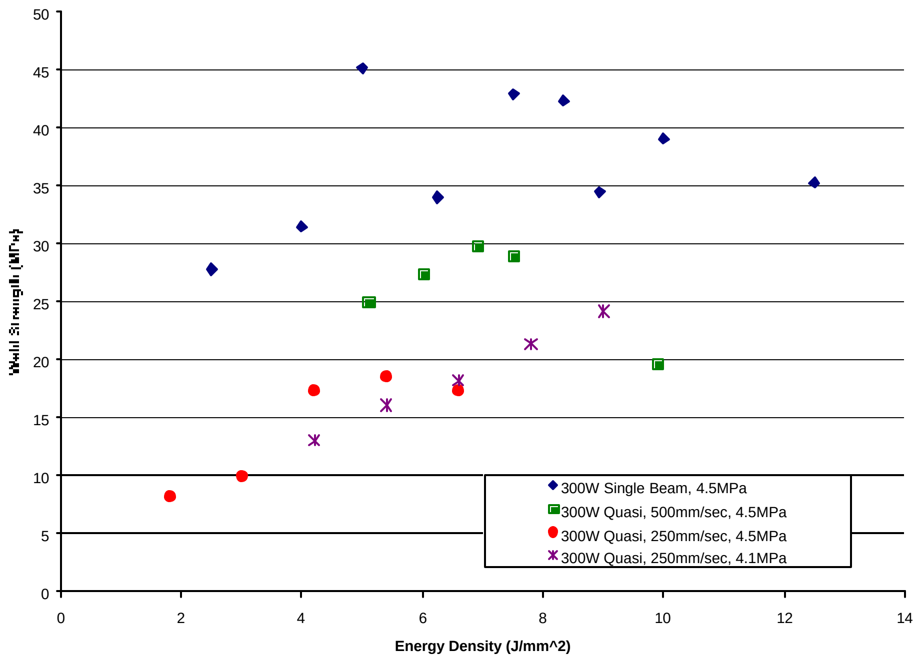

Figure 6. Quasi-simultaneous versus single beam laser welding of acrylic.

The weld strengths of quasi-simultaneous welding were lower than single beam welding. Higher energy densities resulted in excessive melting.

The Clearweld process generates a small melt region; see Figure 7.

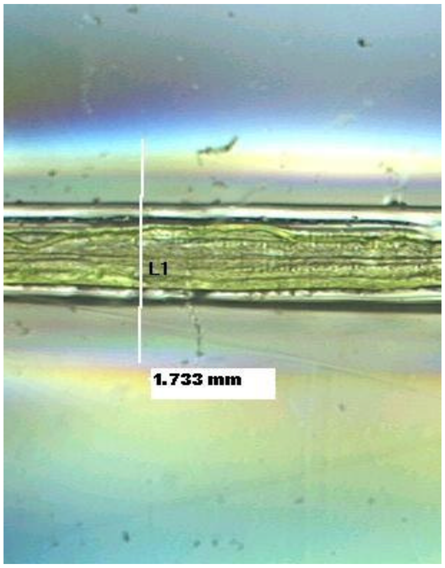

Figure 7. Polarized light microscopy photograph of Clearweld heat affect zone in polycarbonate [4].

In quasi-simultaneous welding, as the name implies, the entire weld region is essentially melted at the same time. The clamping pressure may cause the polymer chains to orient perpendicular to the tensile force, resulting in lower strengths. In single beam welding, only a localized melt region occurs at the laser beam; surrounding areas remain cool. The cool areas may prevent the polymer chains from aligning perpendicular to the tensile force.

Conclusions

Although the highest powers produced the strongest welds, the user may choose to work with a mid-range power because the weld strengths were less sensitive to the variation in speed. The highest pressure of 4.5 MPa produced the strongest welds. Further investigation is needed to examine pressures greater than 4.5 MPa. The use of quasi-simultaneous welding for the Clearweld process also requires more studies in order to improve weld strengths.

References

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