DEVELOPING COST EFFECTIVE LASER WELDING PARAMETERS FOR WELDABLE RESINS AND APPLICATION TO THE MEDICAL SEGMENT
Gareth C McGrath and William H. Cawley, GENTEX Corporation, Carbondale, PA 18407-0315, USA

Abstract

The medical segment remains an innovative market, where new products are introduced to meet the trend towards customer empowerment in healthcare. Laser welding of plastics is one area that is evolving rapidly as new lasers and associated benefits emerge. The benefits to the medical segment are:

- minimum material displacement,
- low thermal and mechanical stresses induced,
- no vibration and so no mechanical damage to a part,
- no particulates.

This paper will look at the development of a predictive model for laser welding using NIR absorbers. A Design of Experiment (DOE) approach will determine the relationship between factors affecting the process (absorber concentration; energy density of the laser beam; material thickness and applied pressure) and the output of the laser welding process. This approach allows the medical segment to reduce the time in the development phase and move forwards to process specification and implementation with confidence.

Introduction

Laser welding of plastics is an established process for joining thermoplastic components. Diode and Nd:YAG (neodymium-doped yttrium aluminium garnet is a crystal that is used as a lasing medium for solid-state lasers), lasers, have been used to weld plastics for a number of years. Recently the use of fibre lasers has become significant in this process. All of these lasers rely on through transmission laser welding (Figure 1). In this process, laser radiation passes through a “laser transparent” upper layer and is absorbed by a “laser absorptive” lower layer. The absorbed radiation is converted into heat near the interface of the two layers. The heat is conducted from the interface to the upper and lower levels causing the materials to melt and flow together to form a weld.

Thermoplastics generally transmit light in the infrared energy range, so the transmission welding process requires the use of an additive to increase the ability of the plastic to absorb infrared light. Carbon black is used as an infrared energy absorber in a variety of laser welding applications.

A second method of increasing the infrared absorption of plastics is to add an organic absorber to the plastic. A system that enables the welding of transparent or opaque plastic materials was developed by TWI Ltd in conjunction with Gentex Corporation. The process utilizes organic, near infrared absorbers as coatings on polymers or as additives to resins.

Organic absorbers can be directly incorporated into the plastic material during extrusion and moulding operations. An absorber is selected so that its maximum absorption wavelength matches the wavelength of the laser used in a specific application. Once the plastic contains the absorber, the welding process is similar to that used with carbon black welding. However, the use of infrared absorbers facilitates more colour flexibility. Ideally, the additives have high absorptions in the near infrared range and low absorptions in visible range of the electromagnetic spectrum. As with carbon black welding, one of the parts serves as an absorber, while the other part transmits the laser energy.

The absorbers can also be incorporated into thin films. These films can be placed between two substrates and used to create a weld joint when exposed to an infrared laser. The material can also be insert moulded into other parts. The same principle can be used to co-extrude tubing so that the outer layer of tubing will weld to a secondary device, as in welding medical tubing to luer lock connectors.

An absorber can also be applied as a coating to the surface of one of the parts at the weld interface. The coating absorbs the laser energy and converts it to heat energy. This allows the plastic on either side of the surface interface to flow together to form a weld joint. The coloration of the coating is dissipated in the reaction, thereby permitting the formation of a transparent weld joint. As this occurs, the ability of the absorber to convert infrared light to heat is lost and any additional infrared energy is transmitted through the lower layer. This results in a relatively small heat affected zone adjacent to the weld. The use of a coating also permits the simultaneous welding of multiple layers of material.

Laser welding has become more widely used in the past couple of years as understanding of the technology increases. Smock recently indicated four factors for accelerated interest in laser welding as a method of joining plastics [1]. The first is that major resin companies are expanding materials choices for laser welding of black and other colour plastics. Secondly, familiarity with the technology is increasing among design engineers. Thirdly, a difficult litigation struggle over patent issues in Europe is being resolved. Finally, new equipment technology is expanding joining options.
**Laser welding** is a non-contact welding method, so the surfaces should not be marred and delicate parts are not damaged. The welding is precise and accurate because the energy is utilized only at the interface of the parts. The parts are generally fixed and a laser moved so that the laser beam is directed only at the area that is welded. This permits flexibility in the shape and design of the part. A laser is capable of creating virtually any pattern and can reach recesses that are inaccessible to other welding methods. Parts that are too flimsy for ultrasonic welding can be laser welded. In addition, part size is not as critical. Parts ranging in size from 2mm up to 4 feet have been welded. There is no vibration of the parts. The weld can be located very close to other parts without affecting them. This permits the welding of parts that contain fragile sub-assemblies. Laser welding does not rely on collapse of the plastic to form a weld.

There are some disadvantages to using laser welding. The biggest deterrent to the use of laser welding has been the cost of equipment. Speed of operation is tied to the laser power that is used. As power is increased, the cost of the laser can escalate rapidly. In addition, the materials for laser welding have been limited to compatible thermoplastics where one of the two materials is transparent to laser light and the other absorbs laser energy. This traditionally meant that one part had to be black or gray because of the use of carbon black as an absorber. The use of organic infrared absorbers has expanded the use of laser welding to coloured and clear parts.

**Material Selection**

When considering laser welding for a process the first concern is the ability of the material to be welded. The material used in laser welding, as in any type of plastic welding, must be a thermoplastic.

A second consideration in the welding of plastics is the miscibility of plastics. As a rule, resins will weld to themselves.

Another point of interest is the melting points of the plastics that are being welded. As with miscibility, this should not be a problem when welding two similar materials. However, it can prevent the welding of two dissimilar materials. Since thermoplastics have a melting range rather than a sharp melting point, it is possible that two dissimilar materials will soften in overlapping ranges. If this is the case, the material should both melt with a given amount of laser energy. It is more probable that one part will melt to a greater extent than the other will, but for rigid parts, this may be sufficient to create a weld. Since the temperature of the heat affected zone is very high for a very short period, both parts can reach their melting points without a thermal degradation of either part.

The energy available for welding at the interface of the parts is that energy which is transmitted through the top part. Any energy that is absorbed or scattered is not available for welding of the parts. If, for example, a part is loaded with glass fibre, the input energy will have to be increased in order to obtain an optimum weld joint.

Refraction is more of a concern with amorphous plastics since semi-crystalline materials will tend to cause scattering of light. Refraction usually does not affect laser welding where the laser beam is delivered perpendicular to the work surface. An exception would be in the case where the laser beam must pass through several layers of plastic to reach the weld interface. Refraction is of greater concern in welding operations in which the angle of incidence is not perpendicular to the work surface. This would be the case for scanning (quasi-simultaneous) welding. This optics system uses mirrors to deflect the laser beam from a fixed position around the weld area. As a result, the beam strikes the surface of the part at an angle. The refraction angle will increase, as the part size is increased [2].

The thickness of parts is also something that should be considered. Semi-crystalline plastic parts will diffuse laser energy. For very thin plastics, the scattering of light is not a concern. However, as the thickness of semi-crystalline parts increases the amount of energy available for welding can be reduced significantly. For materials such as polyethylene and polypropylene, the thickness of the part may become a limiting factor. As a guideline, the thickness of semi-crystalline parts should be between 1 and 5mm.

Thin films also require special attention. The obvious problem that may be encountered is that the film will overheat and be destroyed. This problem can be overcome by controlling the welding parameters when welding films-to-films. However, when welding films-to-rigid plastics, control of the temperature becomes more important. The majority of the melting will occur at the film while the rigid plastic may not reach a temperature that is sufficient to create a true weld.

**Part Design**

Part design is important and attention to welding requirements should be assessed during the part design phase of the project. As compared to other welding techniques, a laser weld has a narrow heat affected zone. A typical laser weld is shown in Figure 2.

When two substrates are welded, the polymer chains diffuse across the interface and a bond is formed by entanglement of the chains. There is evidence that materials with a very high melt flow index (Hostaform H4320) can form strong welds [3].
The preferred mating surface for laser welding is a flat surface to another flat surface. Unlike vibration or ultrasonic welding, energy directors are not required. The welding of the parts occurs through diffusion of the molten plastic from one part to the other. Collapse of the weld joint causes new material to be introduced into the weld zone. This new material may not be heated to the required temperature needed for welding, resulting in a cold joint [4]. The collapse of material also requires displacement of the material. In many welding operations, flash traps are included to serve as a reservoir for the excess molten material.

The mating of parts must be considered. For contour welding, gaps should be less than 100 microns. In contour welding, a weld is formed as the weld area is traced by the laser. Once a portion of the part is welded, the remainder of the part is essentially locked in place. If a gap exists between the top and bottom parts, the materials cannot intermix and a weld will not be possible. Moreover, in contour welding there is little chance of forcing the parts together to overcome the gap. However, if a simultaneous or a scanning (quasi-simultaneous) laser is used, the parts will be heated more slowly. This allows the two parts to soften and to settle out because of the applied clamping pressure. As the parts heat up, gaps can be closed and welds formed in what would otherwise be poor weld areas.

Rough surfaces can be either a bad or a good feature in the part design. Rough surfaces can result in poor surface-to-surface contact and weaker welds. The roughness may be caused by problems in the moulding of the parts. Alternatively, they may be designed into the part, as in the case of a part with a matte surface. With a matte finish, the total surface area in contact with the opposing part is greatly reduced. Welding will only occur at the high points in the matte finish. Since the parts are not collapsed to any significant degree, the total surface-to-surface contact may never be achieved. Conversely, some surface roughness may be beneficial to laser welding. For difficult to weld parts, such as some fluoropolymers, welding can be improved by abrading the surface of the part. There are also cases where a protective coating is applied to the surface of a part, such as a scratch resistant coating on polycarbonate. Without abrasion, this coating will not permit the welding of the base material. Finally, a controlled roughness may be of value when using simultaneous welding. The simultaneous heating of the entire weld area allows the rough surface to provide a starting weld. Additional heating levels the surface and finishes the welding process.

Warped parts can cause gaps in the weld joint. Warping will be more evident with thin, flexible parts. It is possible to overcome warping by increasing the clamping pressure on the parts. Generally, the source of warping is the moulding operation. It may be possible to overcome the problem by working with the mould designer to minimize the warping in the weld joint areas. It may also be possible to “flatten” the parts by annealing them prior to welding. A second source of warping can be the welding operation itself. As a rule, laser welding does not introduce high temperatures outside of the area immediately adjacent to the weld zone. However, if excess heat is imparted to a thin, flexible part, the part may warp within a few seconds of releasing the clamping pressure. This problem can be reduced by maintaining the clamping pressure until the part cools. Alternatively, heat sinks and use of coolants in fixturing devices can rapidly cool a part and eliminate potential warping problems.

Another consideration in part design is the ability of the laser beam to reach the weld area. The first issue is where the infrared absorber should be added to the parts. In laser welding one part must transmit infrared energy and the second part must absorb it. With a carbon black system or an absorber-in-resin system, one of the parts becomes laser absorptive. The designer must consider which side will see the laser beam first. That side cannot contain the infrared absorber. If a coating is used, the absorbing material is placed on the surface of one of the parts. It will be at the weld interface no matter which side the laser beam is transmitted through. The laser beam can be directed from the top, the bottom or even from the side depending upon the geometry of the part.

A second consideration is that the part must be held in some type of fixture that will apply pressure to the parts. In order for the laser beam to reach the weld area the fixture must be laser transmissive. Glass or PMMA is generally used to provide a pathway for the laser beam. It is possible that minimal fixturing will be required. For example, bottle caps can be welded without applying additional pressure to the parts. In addition “pressure fits” such as in tubing-to-tubing may provide enough contact to permit welding. Generally, the applied pressure is meant to provide intimate contact between parts and is not meant to force the parts to intermingle.

Another consideration is the possibility of interference of the laser beam by the part itself. For example, an entry port on a medical device may be located directly above the weld area. If the laser beam has to pass through the port before reaching the weld area, the light may be diffused in that area and result in a poor weld. It might be more practical to apply the laser beam from the opposite side.

When working with tubes and multiple layers it may be advantageous to use an absorbent coating rather than adding an infrared absorber to the resin. With a coating, the absorbing properties of the coating are ablated upon contact with laser beam. Therefore, when welding tubing that has been coated, it is preferable to traverse the tube in one pass rather than welding the circumference of the
tubing. This will reduce the processing time and reduce fixturing costs. When welding multiple layers with a coating system, it is possible to stack the parts and to weld multiple layers in one pass of the laser beam.

**Laser Source and Optics System**

Three laser sources are commonly used to weld plastics. These are diode lasers, Nd:YAG and fibre lasers. Diode lasers operate in the 800 to 1000nm range; Nd:YAG lasers operate at 1064nm and fibre lasers operate in the 1070 to 1100nm range. Diode lasers have the advantage of low cost, small size and high energy efficiency. Nd:YAG lasers are larger but have a better beam quality than diode lasers. Fibre lasers produce smaller beams and can produce higher energy densities at lower laser powers.

Four optics systems are used in plastic laser welding. In contour welding, a single beam is used to trace the weld area. It is roughly analogous to metal welding where a high energy arc is run along the length of a weld joint. In simultaneous welding the energy from a laser is divided into sections and directed to a segment of the weld area. The laser shutter is opened, flooding the entire part with laser energy for a specific period. In scanning (quasi-simultaneous) welding the laser beam is bounced off moving mirrors and directed to a spot on the weld line. The beam is repeatedly moved over the length of the weld at a high speeds. This causes an incremental increase in weld temperature over the entire weld area. In curtain welding a series of diodes are used to produce a continuous band of laser energy. The part is passed under the band of light, which welds the entire surface area of the part.

The achievable weld strengths of plastics will vary from polymer to polymer. In order to evaluate the weld strength the energy density used to create the welds should be considered. The amount of laser energy that a weld joint experiences will depend upon the power of the laser used in the welding, the beam diameter of the laser and the speed at which the welding is done. If the laser power is increased, the energy that is available at the weld will also increase. It is also possible to increase the available energy by reducing the beam size. If 50 watts of laser power is spread over 4mm diameter, the energy per unit area will be less than if the same 50 watts of power is spread over 2mm diameter. Similarly, the energy can be increased by slowing the speed. In order to ensure consistency, the amount of energy available for a welding operation is generally expressed as the laser’s energy density. Energy density is a function of laser power, beam diameter and welding speed as shown in Equation 1.

\[
\text{Energy Density} = \frac{\text{Power}}{\text{Beam}} \times \text{Speed}
\]

\[
\text{Energy Density} = \text{Joules/mm}^2 \quad \text{(Eq. 1)}
\]

An understanding of laser systems is a necessity when considering infrared laser welding. The choice of the laser optical system is often affected by the weld width of the part.

Process parameters are critical for optimizing the process. A plot of energy density and tensile strength shows how the welding can be optimized. At lower energy only adhering occurs. At higher energy decomposition occurs. Overheating of parts and cooling of parts should be understood. Overheating of parts can cause warping or entrapped bubbles during welding.

Understanding of the laser welding process is an important factor in development of this joining technique. The lack of attention to part design can lead to poor joints and high tooling costs.

**Weld Strengths**

As discussed above, the weldability of resins is determined by several factors. These include:

- Presence of inorganic additives - carbon black, large amounts of titanium dioxide
- Large percentage of fillers in thick parts
- Semi-crystalline polymers in thick parts
- Metal at the interface - may cause burning
- Dissimilar plastics – non-miscible parts
- Large difference in melting temperatures
- Plastics with low critical threshold for burning, such as polycarbonate
- Air gaps at joints must be eliminated.

The weld strength that is achievable for various polymers is therefore dependent upon the basic composition and design of the welded part. The weld results do not follow the standard rule of thumb for metal welding. That is the weld will usually not have greater strength than the parent material. A study various plastics that were joined in a butt-weld indicates the relative strengths that may be achieved for these plastics [5].

**Parameter Selection**

Data generated from a DOE helps choose production parameters for an application to maximize a desired result, as shown in Figure 3. A directory of these plots is available for expediting the optimisation of welding parameters. Thus, the costs for optimizing the welding parameters are minimised and the risks in the development cycle can be contained.
Summary

The following guidelines summarise the essential issues that must be addressed when laser welding plastics:

- The materials must be thermoplastic and not thermoset.

- Since polymers do not inherently absorb infrared laser energy, an absorber must be added to enable laser welding. Organic absorbers require higher energy than carbon black. This is dependent upon concentration of the carbon black versus the organic absorber in a part.

- Some plastics are susceptible to burning due to laser induced breakdown. This is a result of reaching a threshold energy density at which the plastic changes from being highly transmissive to highly absorptive. e.g. polycarbonate, polyetherimide and polysulfone.

- The joint and part designs can have an effect on the welding results. The surface at the interface and any areas exposed to the laser, such as the surface of a transmitting substrate, should be free of laser contamination, such as dirt particles and stray ink marks. Smooth surfaces are preferred. Matte surfaces can be welded but the surface irregularities may result in reduced weld strength. Welded surfaces should be parallel to ensure complete contact.

- Surface flatness may affect welding. The fit-up between the two substrates may be important depending on the substrate polymer and grade (melt flow). It may affect the amount of clamping pressure that must be applied to the parts and require higher energy density in order to cause more material to melt.

- DoE studies expedite the selection of optimum parameters.

References