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Strategies for Polymer Welding with High-Power Diode Lasers

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Abstract Diode lasers have become an important tool for polymer welding in automotive industries, in medical and electronics manufacturing. High efficiency and well fitting beam quality make them a perfect tool for industrial applications. With adapted optics it is possible to fit the laser spot shape to the geometry of the work piece. Galvo scanners are the most flexible tool to apply local and precise dose of heat to the work piece. If this flexibility is not needed, the laser spot can be customized by optics to line, circular or arbitrary shaped geometries. For joining transparent parts either an absorbing layer or diode lasers with a wavelength of 1940 nm can be used.

Introduction

Laser beam welding of thermoplastics has advantages compared to other technologies like ultrasonic or vibration welding. Thermal load and mechanical stress for the welded parts are very low. It is contactless, clean and offers high-quality welding seams. High flexibility and easy joint design make laser beam welding an accepted method for industrial production.
In laser transmission welding the beam passes through the transparent upper part (LT) to the absorbing (LA) part. The laser energy heats up the polymer which expands, melts and increases the weld pressure. The laser transparent part is melted by the transferred heat. After solidification the welding is complete. The quality of the welding joint is depending on many factors:

- Optical properties of material (transmission, reflection, scattering and absorption)
- Other material properties (melting temperature, additives, filler material, compatibility, …)
- Part and joint design
- Fixture
- Process parameters (laser energy, wavelength, heating rate, clamping pressure, …)

Depending on how the parts are exposed to the laser radiation, mostly four methods can be distinguished. Contour, quasi-simultaneous, simultaneous and mask welding (compare Fig. 1). Contour welding is characterized by a relative movement of part and laser optics mostly with mechanical axes. If more than one lap is needed to weld the parts, the fusion zone has significantly cooled down before the laser beam heats it up again.
In quasi-simultaneous welding the laser beam is moved on a fixed work piece with mirrors on galvanometer scanners. Typically, the laser beam is doing several laps on the welding contour fast enough to avoid significant cooling of the welding zone between two laser exposures. This results in a uniform heating and collapse of the welded part with high quality and stable performance. It is also possible to implement set path measuring for quality control like used in ultrasonic welding.
Simultaneous welding means that the entire weld surface is heated, melted and welded simultaneously. Simple structures like lines or circles can be generated with external optics. Complex contours need alignments of several diode laser modules along the welding path.
With mask welding the part is scanned with a laser line whereas all areas which should not be exposed to the laser are covered by a metallic mask. It is often used for welding small and fine structures. [1]

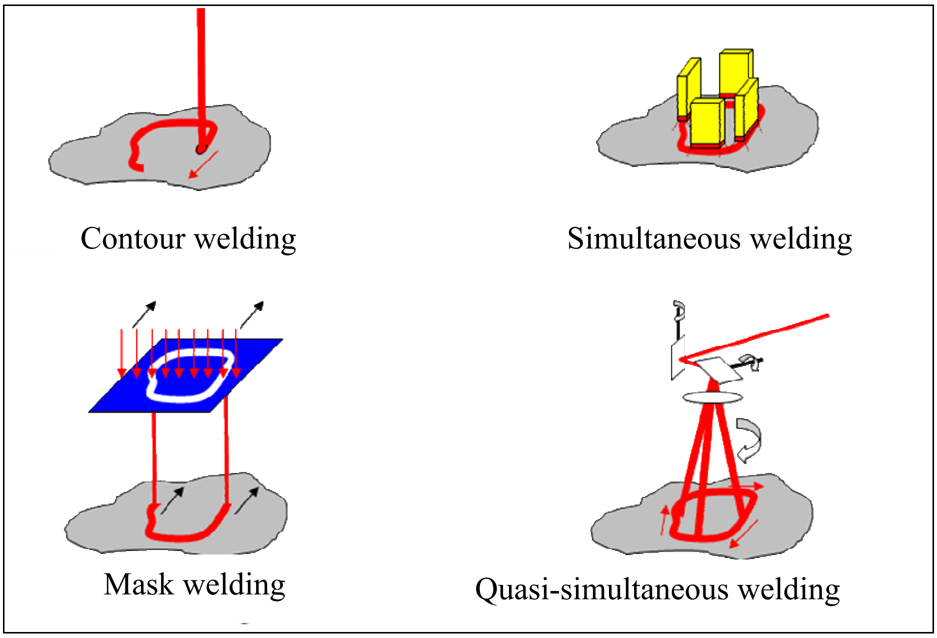

Fig 1. Methods used in laser-based plastics welding [4]

Most common laser sources used are solid-state and diode lasers. Diode lasers are highly efficient and offer a wide variety of wavelengths in the near-infrared range (NIR) from 700–2000nm. Another advantage is the easy modulation of the power level. Compared to other laser types, diode lasers convert the supplied energy (current) directly into laser radiation. This, for example, allows closed-loop temperature control of the welding process by using a pyrometer. The pyrometer is detecting the thermal radiation caused by the welding process and calculates the temperature of the welding spot. The pyrometer can be integrated into the processing head so that laser and pyrometer detector are coaxial and have the same field of view.

Comparison of contour, quasi-simultaneous and simultaneous welding

After defining the right materials for a product and designing the part for laser welding, the right method has to be chosen. The welding strength is comparable for all methods and mainly determined by the maximum temperature during the welding process [2]. The spot size of the laser has to be chosen according to the width of the welding seam. For very wide seams the spot can be expanded by using adapted optics. The part dimensions have also to be considered for choosing the right welding method.

With contour welding the size of the parts is only limited by the handling system. Very small and sophisticated structures of sensors can also be welded as well as big parts like car lamps or air tunnels. The required laser power is typically low (< 100 W) and closed-loop process control with pyrometer can be integrated. The typical welding speed is in the range of several meters/minute.

For quasi-simultaneous and simultaneous welding no mechanical axes are needed to move laser head or part. The size of the parts is limited by the working area of the F-Theta lens. The longer the focal length the bigger the field size gets. The minimum spot size d_{min} can be estimated according to Equation 1 where f_θ is the focal length of F-Theta lens, D_a is the galvo aperture, N.A. the numerical aperture of the fiber and d_F the fiber diameter.

$$d_{min} = 2 \cdot \mathrm{N.A.} \cdot f_\theta \cdot d_F / D_a \qquad (1)$$

With a typical setup like shown in Fig. 2 the minimum spot diameter is 800 µm. In practice, the spot size is about 10-15 % bigger.

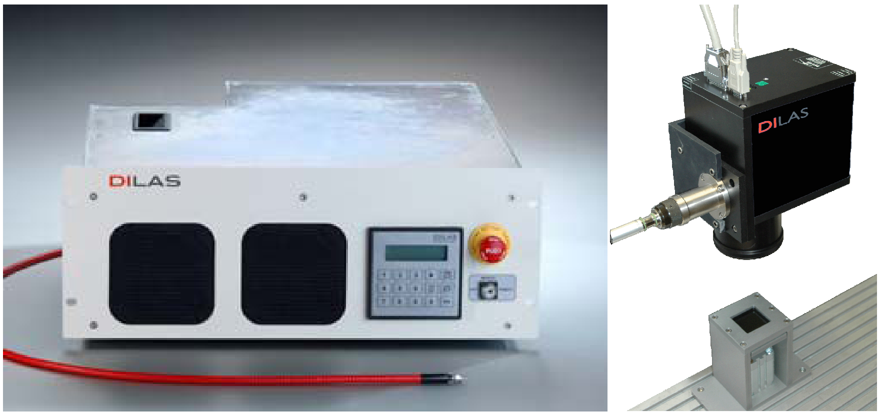

Fig.2: Diode laser source (left) and galvo scanner (right)
Diode source: 200 µm with N.A. 0.2
Galvo: 20 mm aperture
F-Theta: 163 mm

The working field is here about 100 mm x 100 mm. For bigger parts a longer focal length has to be chosen.
The required laser power is higher than for contour welding (100-400 W) and closed-loop process control with pyrometer is only possible within certain limits [3]. The usage of set path measuring like in ultrasonic welding is feasible. The welding geometry can be easily adapted with the CAD interface of the galvo. Therefore, it is a highly flexible method if different designs have to be welded on the same machine.
In simultaneous welding the laser beam is arranged to illuminate the complete welding area. Depending on the part size the laser radiation can be coupled into fiber bundles which are integrated in the clamping tool. This allows simultaneous welding of arbitrary shaped parts but is inflexible if changes in parts or tooling are needed. If parts with rectangular or square shaped geometry have to be welded, the usage of line-shaped laser spots is advantageous. Beam shaping is done after the fiber and allows modification of length and width of the line.
Quite important are circular geometries like axial or radial welds.

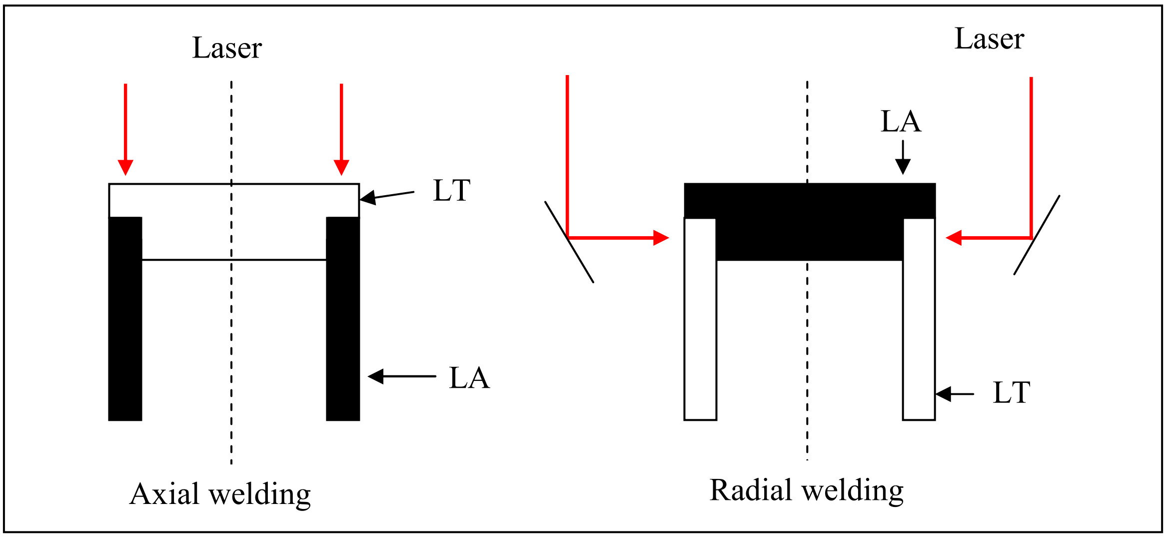

Fig.3: Typical cap-to-tube joining with ring focus

In high-volume production it is not always possible to rotate the part. Therefore the focus geometry out of the fiber can be ring-shaped to allow axial welding easily. Diameter and thickness can be adapted to the part geometry. With an additional mirror it is also possible to weld radial without rotating the part (Fig. 3).

Table 1: Comparison of different welding methods

	contour	quasi-simultaneous	simultaneous
required laser power	20 - 100 W	100 – 400 W	50 W – kW(1)
mechanical axes needed	yes	no	no
closed-loop process control	yes	limited	no
set path measuring	no	yes	yes
flexibility	+	++	--
part dimensions	not limited	limited by field size	not limited
typical welding speed	< 10 m/min	0,5 - 10 m/s	< 1 s
costs (laser source + optics)	++	0	+

(1) dependent on part size

Welding transparent polymers

It is quite common to use colored materials which have the same appearance but different behavior to the laser radiation. The material properties can be adapted by using pigments. Car keys are a well-known example for a black on black welding where the upper part is transparent to the laser radiation but appears to be black. For transparent polymers the usage of pigments does not work that well. All pigments cause a certain shading of the part which is not always acceptable in medical device manufacturing or packaging industry.
One solution is the usage of an absorbing layer or liquid like Clearweld© between the parts. The layer absorbs the laser radiation and transforms it into heat. This allows plasticization and bonding between the joining parts. After welding the tint of the absorber is changed to almost clear. [5]
Another possibility is to use the natural absorption of polymers at wavelengths > 1.800 nm (Fig. 4).

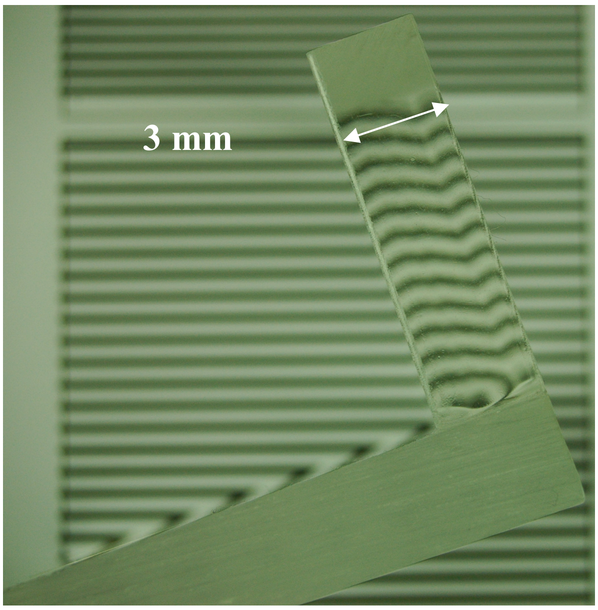

Fig. 4: Filet weld in PMMA without additives using 1940 nm diode laser.
The cross section is completely welded.

This type of joining is caused by volume melting and is more comparable to metal welding. It has a tactual weld surface and defined penetration depth. Nevertheless, this method offers a big potential for welding of foils (PP, PE, …) used in medical device manufacturing because no additives or absorbers are needed.

Summary

To choose the most economic laser welding method many factors have to be considered. Besides material and joint preparation, welding width, part size and welding geometry have a significant influence. Changing part design and joint geometry during production demand flexible welding methods. Simultaneous welding with adapted optics is an interesting method especially for high-volume production when flexibility is not needed. Joining transparent parts without additional absorbers is possible by using diode lasers with wavelengths > 1800 nm

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