Quasi-simultaneous laser beam welding of polymers in closed loop

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Abstract

Polymer welding with lasers is getting a state-of-the-art tool in medical device manufacturing and automotive production. Most commonly used are contour welding and quasi-simultaneous welding. An advantage of contour welding is the availability of closed-loop pyrometer-controlled processing optics. On-axis sensors are used for measuring the part's temperature. The pyrometer controller allows the storage of process data for documentation and quality analysis. The new optics developed combine the benefit of contour welding with the speed and addressability of quasi-simultaneous welding. Possibilities and limits of quasi-simultaneous closed-loop welding will be discussed with examples of industrial applications.

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 non-contacting, clean and offers high-quality welding seams. High flexibility and easy joint design makes laser beam welding an accepted method for industrial production.

The method is well known. The welding partners are overlapping. One is transparent for the laser (LT), the other is absorbing (LA) and melts when exposed to laser radiation through the transparent part. Due to mechanical contact which allows heat transfer between the partners the laser transparent part melts as well. The impact on the parts from a fixture or caused by the part design results in the mixture of the melt pools.

Depending on how the parts are exposed to the laser radiation mostly four methods can be distinguished. Contour, quasi-simultaneous, simultaneous and mask welding. 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 and mask welding are used for special arrangements and will not be discussed in this paper.

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 [1]. 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. All following considerations are based on the usage of diode lasers.

Preconditions for closed-loop welding with pyrometer

Pyrometers can be characterized by sensitivity (minimum detectable temperature), speed (measuring frequency) and accuracy (signal / noise ratio). High speed measuring and accurate temperature detection are resulting in less sensitivity. Compared to other processes like hardening of metals, polymer welding is working in a lower temperature range. Therefore, the signal level for the measuring temperature is quite weak and limits possible speed and accuracy.

To avoid interference between pyrometer and laser source, the detector of the pyrometer must be sensitive for wavelengths different from the laser. Pyrometers used in materials processing mostly use detectors which are sensitive from 1800nm to 2100nm whereas lasers are used at 808 nm or 980 nm wavelength. Therefore, the laser transparent part has to be also transparent for radiation detectable by the pyrometer. Filler materials like glass fibers, pigments etc. have an influence on the pyrometer reading due to absorption or scattering of the nominal radiation in the NIR. This reduces the signal level of the pyrometer and the minimum detectable temperature increases. Figure 1 shows the influence on the measured temperature depending on colouring and material thickness for polypropylene.

Assuming that for closed-loop process control the laser power should be modulated at least within the spot size of the laser beam, the minimum control frequency results in

$$f_{con} \geq \frac{V}{d_{spot}} \tag{1}$$

where f_{con} is the control frequency of the pyrometer (Hz), V is the welding speed (mm/s) and d_{spot} the diameter of the laser spot on the work piece (mm).

For contour welding with a typical welding speed of 5m/min and a spot size of 600µm the pyrometer has to adjust the laser power at least with 140Hz. The measuring frequency f_{pyro} needs to be higher by a factor of 2 to 3.

$$2 \cdot f_{con} \leq f_{pyro} \leq 3 \cdot f_{con} \tag{2}$$

In this example the measuring frequency of the pyrometer should be between 280Hz and 420Hz. Today digital pyrometers are used with f_{pyro} up to 10kHz. Besides the capability of the pyrometer to support the closed loop process with sufficient speed it has to be assured that the laser itself can be modulated fast enough. For diode lasers the modulation is limited by the power supply which is applying up to 80A to the diode laser module. Fast power supplies allow modulation frequencies up to 2kHz.

Contour welding in closed loop

The pyrometer is used to keep the temperature in the welding zone within a defined range by modulating the laser power according to a software algorithm. Possible reasons for changes in the temperature are variations in welding speed, different material properties along the welding path, contaminations or bad contact between the parts. Figure 2 shows an example of contour welding with constant laser power in open loop. The temperature during the welding process is stable within a range of 20K, except for two peaks in the middle and the end of the process with up to 60K higher temperature. This results from inflection points of the robot axis with lower welding speed. Hot spots in the welding seam can have a negative influence on the mechanical properties. Figure 3 shows the same part welded in closed-loop temperature control. The temperature is stable within a range of 5K and even at the inflection points no significant influence on the temperature can be observed.

If the gap between the joining parts is too big even in closed loop, it is not possible to achieve proper welding results. Figure 4 shows the influence of bad part geometry on the temperature signal and the controller output. The welding quality is not sufficient but the imperfection can be detected and appropriate action can be taken for quality sensitive production e.g. in Medical Device Manufacturing or automotive industries.

Quasi-simultaneous welding in closed loop

In quasi-simultaneous welding the laser beam is moved by fast beam deflection units like galvanometer scanners and focused on the work piece by flat-field lenses. Compared to contour welding with fixed optics, the laser beam is moved off the lenses' optical axis and is no longer parallel to it. This has some serious consequences for the usage of pyrometers. Optical properties like focal length and anti-reflective coatings of standard flat-field lenses are only working in a small dedicated wavelength range. The foci for the different wavelengths of pyrometer and laser are not congruent due to color aberration. This means that during the welding process the pyrometer would detect radiation not from the laser focus but from somewhere else. Closed-loop processing or even temperature monitoring would not be possible. With a special designed optic it is now possible to have a color corrected flat-field lens where pyrometer and laser focus are congruent again.

Typical welding speeds for quasi-simultaneous welding can be up to several meters per second. It is assumed that the color corrected flat field optics delivers a spot size of 1.4mm and maximum modulation frequency of the power supply f_{con} is 2kHz. Therefore, f_{pyro} needs to be between 4kHz and 6kHz which is close to the pyrometer limits. Using equation (1) the maximum welding speed is theoretically 2.8m/s.

Practically, the maximum welding speed is for several reasons much lower. To achieve a stable closed-loop process, the minimum detectable temperature must be significant lower than the process temperature. Material properties and thickness have a negative influence on the sensitivity (comp. Figure 1). To increase the signal/noise ratio and therefore accuracy, f_{pyro} needs to be reduced. Typical welding speeds used for closed-loop quasi-simultaneous welding in industrial applications are 300mm/s– 600mm/s and are very much depending on the parts geometry and materials composition.

To examine the welding properties, a box-shaped test part has been designed which typically could be used in automotive industries. The cover has been made of glass fiber filled natural PBT (Ultradur® B4300G6 with 30 % glass content by weight). For the housing the same material has been used, yet with black pigments. Variations of welding speed, laser power and number of laps have been tested. The welding quality has been examined by bursting the boxes with compressed air.

In open loop the process window is quite narrow. With constant welding speed the laser power had to be stable within ±2 %. The temperature feedback for a single welding lap is shown in Figure 6. Each side of the box gives a different temperature signal which seems to be related with the orientation of the glass fibers. The total temperature difference is about 100°C. This explains the narrow process window: Each variation in the line energy (power/speed) causes overheating of side 3 or weak welding of side 1. The achieved burst pressure is between 11bar (160psi) and 11,4bar (165psi).

In closed-loop, welding speed and number of laps have been held constant whereas the set temperature of the pyrometer has been varied. The temperature characteristic besides the peaks at the end of each lap is much more constant (Figure 7). The modulation of laser power is following the temperature characteristic of Figure 6. The set temperature can be varied from 210°C to 280°C without significant influence on the welding result. Figure 8 shows burst pressure versus set temperature. The process window is wider than in open loop and the burst pressure exceeds 11,7bar (170psi).

Limits

The welding process is limited by the optical properties of the laser transparent part in the measuring range of the pyrometer. The transparency in the NIR determines the maximum achievable welding speed. The feasibility of closed-loop process has to be tested for each product up front. The part dimensions are limited by the color-corrected flat field lens and the available scanning units.

Conclusion

With newly developed optical components and fast reacting laser sources, quasi-simultaneous welding of polymers in closed loop is possible. Tests show a more stable welding process with a wider process window. The method offers new possibilities for industrial production to reduce scrap. The consisting documentation of relevant process parameters like temperature and laser power is now possible.

Acknowledgement

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References

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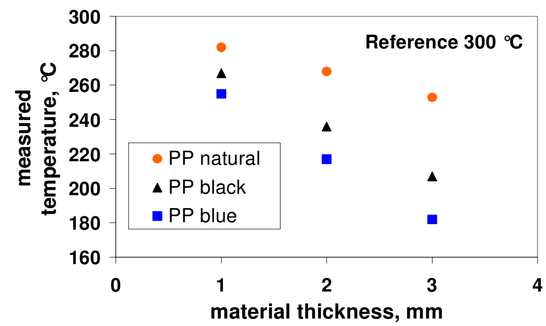

Figure 1.Influence on measured temperature of different colored, laser transparent PP.

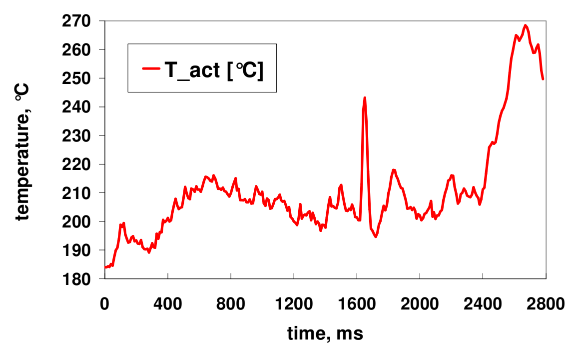

Figure 2.Temperature profile during contour welding with constant laser power.

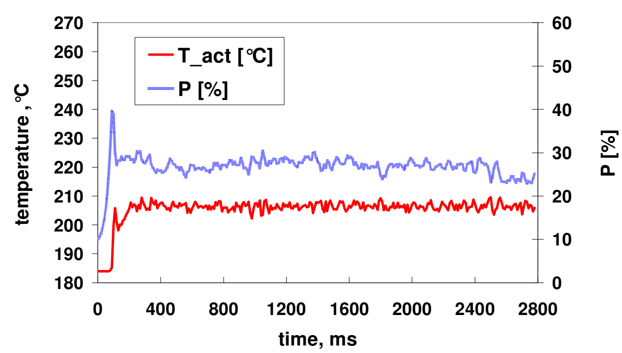

Figure 3.Temperature profile during contour welding with closed-loop pyrometer control.

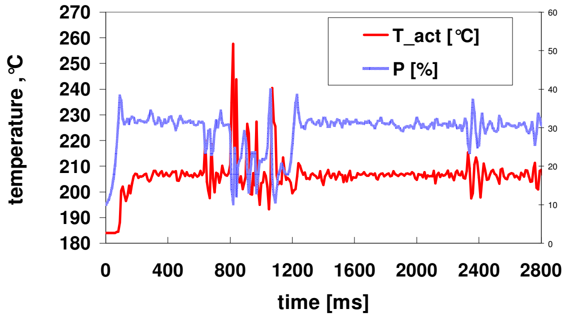

Figure 4.Temperature profile during contour welding with bad part fitting and closed-loop pyrometer control.

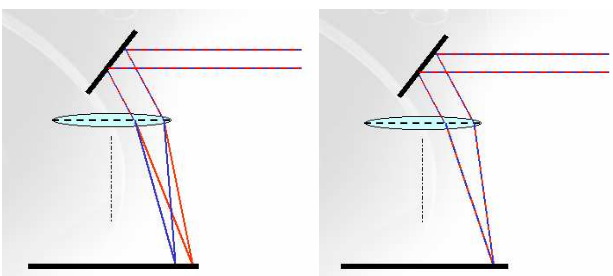

Figure 5.Standard flat-field optic (left) shows different foci for pyrometer and laser whereas color-corrected flat-field lens (right) shows same focus [2].

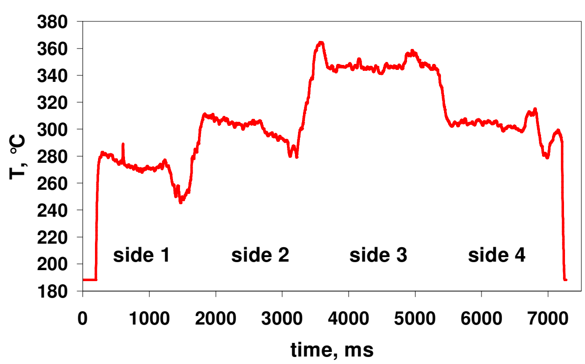

Figure 6.Temperature profile of glass fiber filled PBT box - welding with constant laser power, single lap.

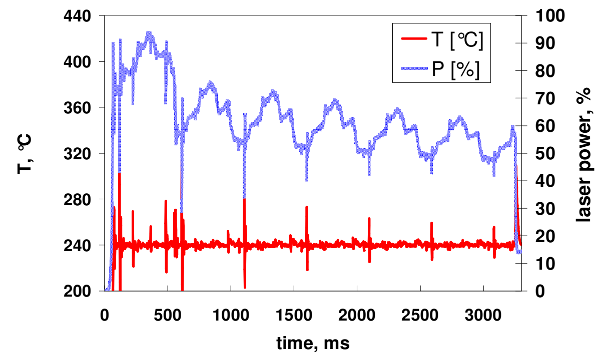

Figure 7. Temperature profile and laser power of glass fiber filled PBT box - welding with closed loop, 7 laps.

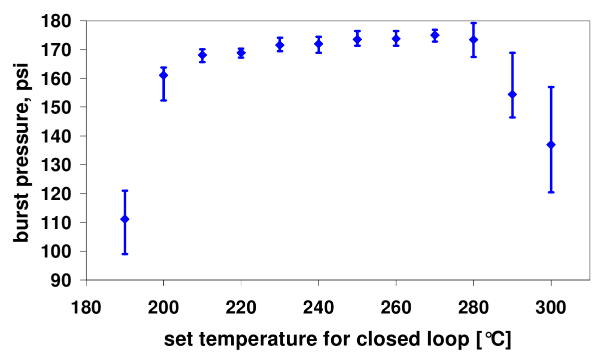

Figure 8.Burst pressure of glass fiber filled PBT quasi-simultaneous welded in closed loop.

Key Words: Polymer welding, Diode lasers, Pyrometer, Closed loop, Quasi-simultaneous, Process Control