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Laser welding of transparent polymers by using quasi-simultaneous beam off-setting scanning technique

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Abstract

Traditionally laser polymer welding has been done by using lasers with wavelength of c. 1 μm wavelength. With this wavelength one of the pair of polymers to be joined needs to be transparent and one absorbing, usually clear and black, respectively. Joining of two transparent polymers with laser has been possible only by using absorbing additive between the samples or by doping the polymer with absorbing additive. During the last years lasers with new wavelengths between 1.4 to 2 μm have been developed. With this wavelength range welding of the transparent polymer to another transparent one without any absorbing additives is now possible. In this paper joining of transparent to transparent polymers with quasi-simultaneous laser welding (QSLW) technique and fibre lase with wavelength of 1.94 μm is studied. Also a new scanning technique for QSLW is introduced. In this technique laser beam path is off-setting to a different place in every scanning round. This way the Gaussian beam shape of fibre laser can be smoothened to be more suitable for polymer welding and more flexibility on laser welding of polymers is achieved without losing the benefits of quasi-simultaneous laser welding.

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Keywords: laser polymer welding; transparent polymers; new wavelengths

1. Introduction

Laser welding of polymers have been studied and used in industry for a long time, Bachmann and Russek (2002), van Engen et al (2001) and Boglea et al (2010). Traditionally trough transmission laser welding (TTLW) with ~1 μm lasers has been used. In TTLW one joining partner needs to be transmissive and the other absorbing for laser wavelength used. Usually samples to be joined are clear and black. Many polymers are highly transmissive for ~1μm wavelength in their natural state. Polymers doped with black pigment, normally with carbon black are highly

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Nomenclature

QSLW	Quasi-simultaneous laser welding
TPE	Thermo-plastic elastomer
TTLW	Through transmission laser welding
TWIST	Transmission welding by incremental scanning technique

absorptive for ~1 μm wavelength. In TTLW laser beam goes through the top transmissive polymer and absorbs to the surface of the lower absorptive one. Special optical properties of polymers are needed in TTLW so material properties and pigments have been developed to be suitable specially for laser welding. Nowadays different transmissive and absorptive colour polymers at ~1 μm are available, Basf and Treffert (2013). Joining of two transparent polymers with ~1 μm laser is possible only by using laser absorbing additive between the samples or by doping the polymer with absorbing additive.

There are different welding methods to weld polymers with TTLW technique. One of those is quasi-simultaneous laser welding (QSLW) process which means that the laser beam is scanned with a high speed several times along the welding path so that the entire weld seam is melted almost at the same time. Many advantages can be achieved with this process. One of the most important advantages is the lower sensitivity for joint air gaps because of the almost simultaneous melting, Jansson et al (2004).

During the last years lasers with new wavelengths between 1.4 to 2 μm have been developed, Westphäling (2013), Limo (2013). With this wavelength range welding of the transparent polymer to another transparent one without any absorbing additives has become possible. The process is based for the volume absorption of transparent polymers with these wavelengths. Only a few studies of joining transparent polymers with new wavelength lasers are published, Roesner et al (2008), Boglea et al (2010a), Mungareev et al (2012), IPG (2012). In these studies welding techniques have mainly been contour welding or transmission welding by incremental scanning technique (TWIST). In this paper joining of transparent to transparent polymers with QSLW technique and 1.94 μm fibre laser have been studied.

Nowadays fiber lasers are often used for TTLW of polymers due their low price and high flexibility. Fiber laser beam is Gaussian beam shaped and the size of the spot is small and the power density is high. This type of beam is not optimal for laser welding of polymers where a more even power distribution is better. Polymers have relatively low melting temperatures and the temperature difference between overheating and melting is low. If Gaussian beam is directly used the middle of the weld may be over heated before the edges of the weld are melt. Also in many applications the wanted width of the weld is higher than achieved with Gaussian beam of fiber laser. Different strategies have been developed to overcome this issue. For example, optical beam shaping elements can be used to produce the intensity profile and the spot size wanted, Vogler (2012). There are also scanning methods which can be used for widening the weld width and smoothen the heat input like in TWIST, Boglea et al (2010b). By using a scanning method more flexibility can be achieved due the weld width can be varied only by changing the program of the scanner. In some applications it is advantageous to use QSLW process and this why the QSLW process needs to be developed more. In QSLW Gaussian beam can be smoothened with beam shaping optics. Incremental scanning method during QSLW process is not possible to use due to the speed and accuracy limitations of the scanners. In this study a scanning method for QSLW was developed to overcome the effects of Gaussian beam and to achieve the process flexibility with scanning technique. In this new QSLW technique laser beam path is off-setting to a different place in every scanning round. This way the middle point of the beam, where the intensity is highest, is in a slightly different place in every round and whole weld area will be heated evenly. Also, if beam is scanned in different place after ever scanning round, the weld should become wider. This way wider weld and smaller heat input in weld area compared to simply Gaussian beam can be achieved. Beam off-setting technique is used with 1.94 μm laser to weld the transparent samples to each other.

2. Experimental Procedure

Welding tests were done by using IPG Thulium fiber laser TLR-120-WC with a wavelength of 1.94 μm. Laser beam was guided by Scanlab IntelliCube10 scanhead to working field. Scanning optic used was f100 f-theta optic. The samples were pressed against the optical glass with the pneumatic clamping fixture during welding.

Material used in the experiments was natural TPE-A which is a flexible polyamide without plasticiser consisting of a regular linear chain of rigid polyamide segments and flexible polyether segments, Pebax (2013). Test samples were flat 1 mm thick plates. Absorption of 1 mm thick TPE-A plate with 1.94 μm wavelength is 29 %. Spectral range of material with different wavelengths is in figure 1.

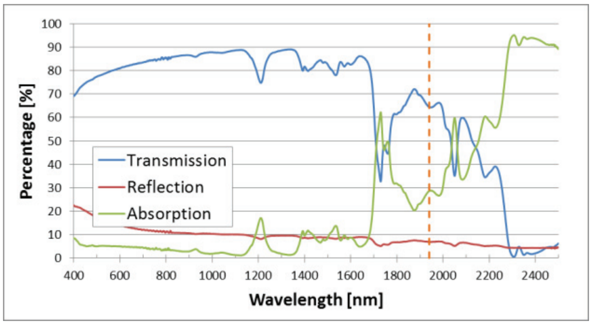

Fig.1. Spectral range of 1 mm thick natural TPE-A polymer, 1.94 μm wavelength is marked as orange dash line.

Joint configuration used was lap joint. In the tests conventional QSLW technique and beam off-setting technique were used. Scanning speed (5 m/s) and number of scans (~200) were kept constant. Laser beam was defocused -5 mm from the surface of the upper polymer and the calculated spot size on this point was 260 μm. Parameters varied were laser power, and in off-setting tests width of the weld, line distance and direction of scanning. The length of the weld was 100 mm and welding time was 4 seconds.

In the beam off-setting technique, laser beam was off-set in a defined distance (=A, Fig 2) from the original line in a defined amount of times (=X) to achieve the wanted weld width (=B, Fig 2). Off-setting loop was repeated defined times (=Y) to achieve the wanted total number of scans (X*Y) which was ~200 scans in these tests. Different line distances (A) and widths of the weld (B) were studied. Different scanning directions (=C, Fig 2) was also studied. Scanning was done to one direction (left to right = 1) and to two directions (left to right to left =2).

First the QSLW of transparent polymers with 1.94 μm laser was studied. Welding speed was 5 m/s, number of scans 198 and laser power used was between 72 W and 96 W.

After the conventional QSLW tests were done, the beam off-setting technique was studied to achieve wider welds. Welds with various widths using off-setting technique were done and these were compared to QSLW. Programmed weld widths were 1 mm and 0.5 mm, line distance was kept constant 0.1 mm and scanning direction was 1-directional. Laser power used was between 66 W to 96 W.

In the second beam off-setting tests the effect of scanning direction was studied. The width of the weld was selected to be 1 mm and line distance 0.1 mm. With 1-directional scanning technique (case 1 in Fig 2) one beam off-setting loop was 11 scanning rounds. In the 2-directional scanning technique (case 2 in Fig 2) one beam off-setting loop was 22 scanning rounds. To achieve 198 scans off-setting loop was repeated 18 times with 1-directional scanning and 9 times with 2-directional scanning. Laser powers used were between 84 W to 96 W with both techniques.

Also the effect of the line distance was studied. The width of the weld was 1 mm and line distances used were 0.05, 0.1 and 0.2 mm. Scanning direction was selected to be 1-directional. One off-setting loop with 0.05 mm line distance includes 21 scans. To achieve ~200 scans off-setting loop was repeated 9 times which means 189 scans. With 0.1 mm line distance one loop was 11 scans and the loop was repeated 18 times so total number of scans was 198. With 0.2 mm line distance one loop was 6 scans and this was repeated 33 times which means total number of scans 198. Laser power used was between 84 to 102 W.

Three samples have been welded with each parameter setups. All samples were visually inspected. Microtome cuts were done for one sample and tensile testing for two samples. Strength values were presented as N/mm which means the maximum tensile force/weld length unit.

3. Results and discussion

First the QSLW of transparent polymers with 1.94 μm laser was studied. Scanning speed (5 m/s) and number of scans (198) were kept constant. Laser power was varied to find out the optimal power level. It was noticed that it is possible to weld transparent polymers to each other with a 1.94 μm laser, QSLW technique and lap joint configuration. Absorption of the used 1 mm thick polymer is 29 % and transmission 64 % which means that most of the beam goes through of the upper polymer and some part of it is absorbed. Rest of the beam (below 10 %) is reflected from the polymer. Transmitted part of the beam goes to the lower polymer. The amount of absorbed energy was enough to melt the upper and lower polymer and to form a weld.

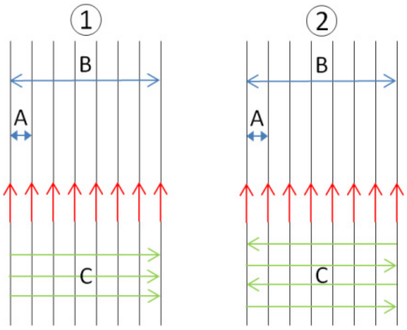

Fig. 2. The schematic drawing of beam off-setting technique.

In Fig. 3 there are weld dimensions (width and height) measured from the photos of microtome cut. It can be seen that the weld width and height is increased when the laser power (heat input) is increased. Even if the polymers have a low thermal conductivity some amount of heat is conducted from the beam interaction point to wider area inside of the polymer. With higher heat input the heat conduction is also higher and the polymer is heated and melted from wider area and this way the width and height of the weld is larger. Gaussian beam has also an effect on weld formation. If a low laser power is used, the beam intensity might be high enough in the middle to melt a polymer but not high enough in the edges. When power level is increased the energy in the edges is also increased and weld became wider.

The weld height/width relation is decreased when the laser power is increased, which means that weld width is increased more than the height when the laser power is increased. This can also be seen from the microscopic photos of the microtome cuts in Fig. 4. As described earlier the heat conduction and the Gaussian beam shape effects on the size of the weld when the power is increased. Heat conduction affects both the width and height but the Gaussian beam effects only on the weld width. This why the width of the weld is increased more than the height when the laser power is increased.

Weld shape is quite high and narrow which can be seen in the microtome cut photos, Fig.4. The height of the weld is caused by the volume absorption of the material. Most of the weld is in the upper part, because the beam comes to the material from that direction. Some part of the beam is absorbed by the upper polymer and some part of it is reflected. This way the power level which reaches the lower polymer is smaller. This is the reason why most of the weld is in the upper part.

In Fig. 5 there are the strength of the weld (N/mm) and the width of the weld with different laser powers used. The highest strength 14.4 N/mm was achieved with 96 W laser power. Because the width of the weld is increased the strength (N/mm) is also increased when the laser power is increased. There was some destroying/overheating in the middle of the weld in one of the three samples welded with 96 W laser power (Fig. 6). Due to the Gaussian beam shape of the laser beam of the fiber laser the middle of the weld heats more and the destroying is that way in the middle. Also in the middle it can be seen darker weld than in the edges of the weld, which is probably due to the higher temperature in the middle of the weld.

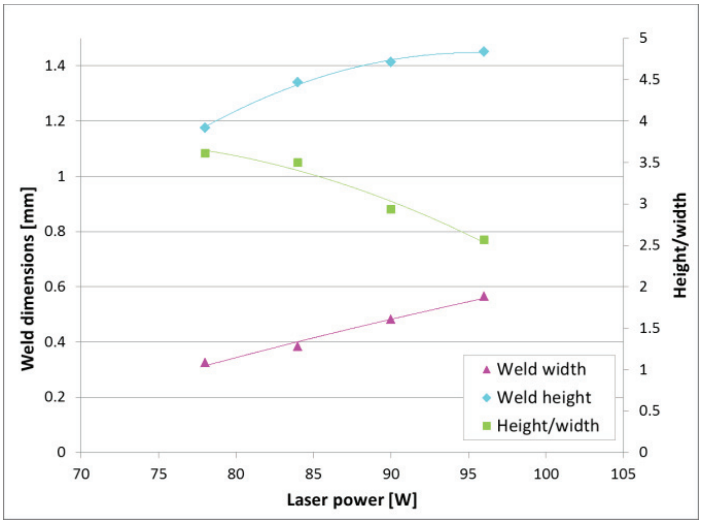

Fig. 3. Weld dimensions and the height/width relation with different laser powers used.

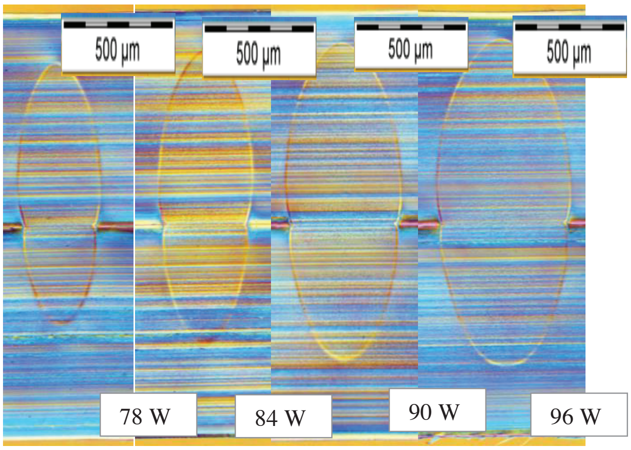

Fig. 4. Microtome cuts of QSLW samples welded with different laser power.

After QSLW tests have been done, the beam off-setting technique was studied to achieve different weld widths. Beam scanning path was set so that 1 and 0.5 mm wide welds could be achieved. These results were compared to the traditional QSLW.

In the welding tests it was noticed that welds done with QSLW and 0.5 mm off-setting was formed with lower laser powers than weld done with 1 mm off-setting. . When wider off-setting is done, more laser power is needed to achieve same heat input/area unit.

In Fig. 7 there are the weld dimensions with different off-setting widths and traditional QSLW technique. With a 90 W laser power the difference in the weld width is not significant. Weld width is 0.48, 0.50 and 0.48 mm when using QSLW, 0.5 and 1 mm off-setting, respectively. In the welding tests same amount of energy was brought to the weld during welding despite of the set off-setting width. When the beam was spread by off-setting technique the heat input/area unit was lower with a larger off-setting width. This is the reason why the measured width of the weld is the same even if the beam off-setting was used or not.

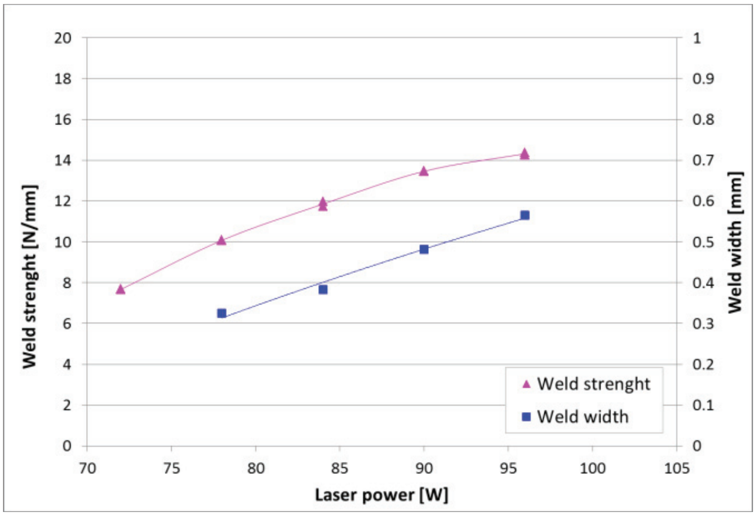

FIG. 5. Weld strength and weld width of transparent TPE-A polymer welded with QSLW technique.

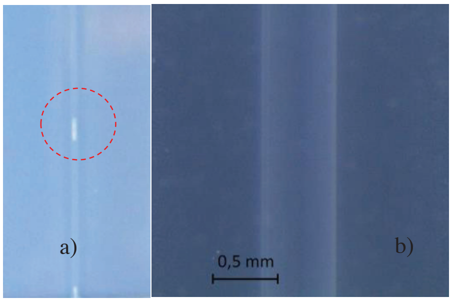

Fig. 6. Photos of QSLW, scanning speed 5 m/s, number of scan 198, laser power 96 W. a) overheating in the middle of the weld. b) microscopic photo (no overheating).

Higher laser power (96 W) can be used with QSLW technique and 1 mm off-setting without over-heating of the material. Measured weld widths were 0.57 mm (QSLW) and 0.63 mm (1 mm off-setting). The difference between weld widths was not high. It is natural that higher laser power with 1 mm off-setting results in, a wider weld.

Difference in weld height was much notable than the difference in the weld width when using off-set technique. The weld was higher by using QSLW than with off-setting technique. Also with wider off-setting the height of the weld was lower. This can be also seen in the microtome cuts (Fig. 8). With laser power of 90 W, the weld height was 1.41, 1.12 and 0.81 mm by using QSLW, 0.5 and 1 mm off-setting techniques. The microtome cuts of the welds with 96 W laser power are shown in Fig. 9. It was seen in the QSLW tests that with the higher heat input the higher is the weld. In these tests the heat input per area unit is highest in QSLW and lowest in 1 mm off-setting welds. This way also the height of the weld is highest with QSLW and lowest in the 1 mm off-setting.

In the microtome cut photos it can be seen that in the 1 mm off-setting the weld is much more in the side of the top part than in the bottom part compared to QSLW or 0.5 mm off-setting.

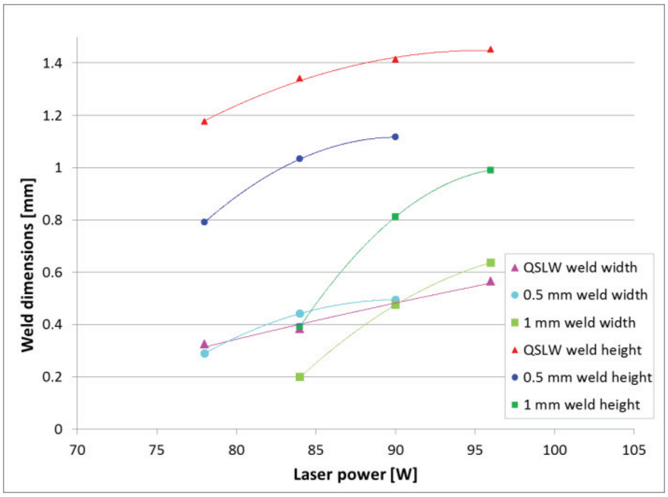

Fig. 7. The measured weld width and weld height with different laser power and nominal off-setting weld width used.

In Fig. 10 there is weld height/width value calculated. In the figure it can be seen that the value is highest with QSLW technique and lowest with the 1 mm off-setting. This means that with QSLW welds are higher and narrower and with beam off-setting technique the weld shape is more round. Rounder beam shape was due to the fact that the heat was spread to the wider area and heat input per area unit was lower with beam off-setting technique.

A slight difference can be seen in the weld strength when 90 W laser power was used (Fig. 11). The weld strength was 13.5, 15.0 and 14.4 N/mm when using QSLW, 0.5 and 1 mm off-setting techniques. The difference was insignificant and the strength values correspond well to the weld widths achieved. The highest weld strength 17.0 N/mm was achieved with 1 mm off-setting and 96 W laser power. QSLW weld strength was 14.4 N/mm with same laser power. With this laser power the 1 mm off-setting weld was also wider than QSLW weld which once again corresponds well to the strength values.

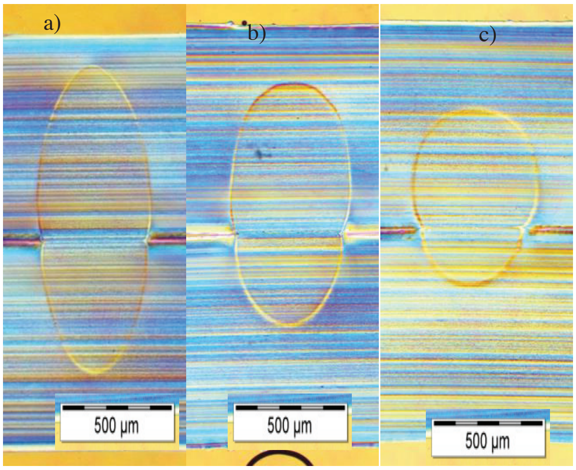

Fig. 8. Microtome cuts a) QSLW, b) 0.5 mm offset and c) 1mm offset technique welded with 90 W laser power.

The next step was to investigate the effect of scanning direction in the beam off-setting technique. 1-directional and 2-directional scanning were used. It was noticed that slightly wider welds (figure 12) were achieved with 2-directional technique (0.69 mm) compared to 1-directional technique (0.63 mm) with same parameters used, although the height of the weld was same, 1.00 mm (2-dir) and 0.99 mm (1-dir).

b)

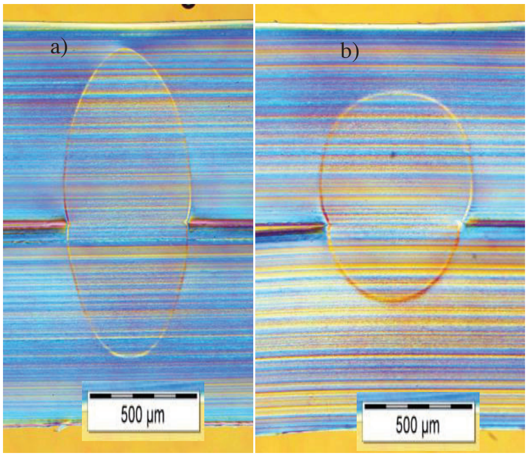

FIG. 9. Microtome cuts a) QSLW and b) 1mm offset technique welded with 96 W laser power.

Microtome cut photos of the welds are shown in Fig. 13. In the photos it can be seen that the weld shape was quite the same with 1- and 2-directonal welding if the same laser power was used. 2-directional welds were slightly rounder than 1-directional. In 2-directional technique the temperature in the weld edges was temporarily higher than in the middle of the weld due the beam starts next scanning round from the same edge. In 2-directional technique the heat distribution on the weld is assumed to be M-shaped across the weld. In the 1-directional technique the heat is divided more evenly because scanning round starts always from opposite edge than it ends. Due to the higher heat on sides of the weld the width of the weld was slightly higher and the shape of the weld was rounder.

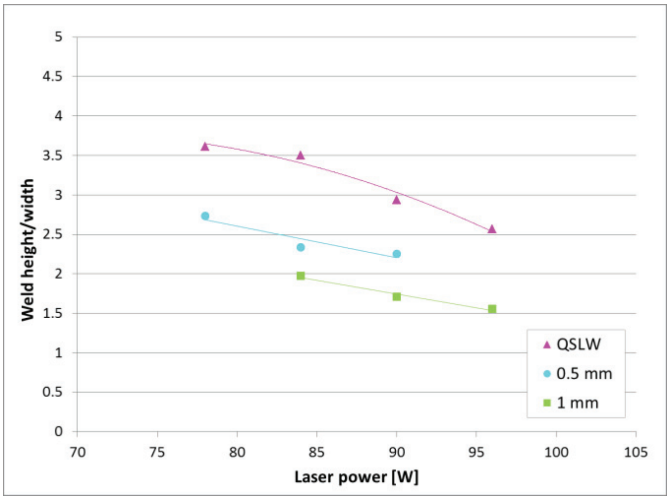

Fig. 10. Weld height/width with QSLW and beam off-setting technique.

Due to the wider welds the strength of the weld was also slightly higher with 2-directional technique (17.8 N/mm) than 1-directional technique (17.0 N/mm) (Fig. 14). The difference between weld widths and strength is insignificant.

The effect of line distance (A in Fig 2) was studied by using distances 0.05, 0.1 and 0.2 mm. There was a slight difference in the weld width with different line distance when the same laser power was used. A lower weld width was achieved with a higher line distance (Fig. 15). With a 96 W laser power the weld width was 0.57, 0.63 and 0.59 mm when using the line distances of 0.05, 0.1 and 0.2 mm, respectively. Weld height was 0.92, 0.99 and 0.85 mm, respectively. With a 0.2 mm line distance higher laser power, 102 W, can be used and this way a higher weld width 0.70 mm and the same weld height 0.99 mm can be achieved as with a smaller line distance and 96 W laser power. With 0.05 mm line distance the number of scans was 9 scans less than in the two other test setup. This might cause some difference to the results. Lower number of scans was used due the different divisibly of beam off-setting loop between the different line distances.

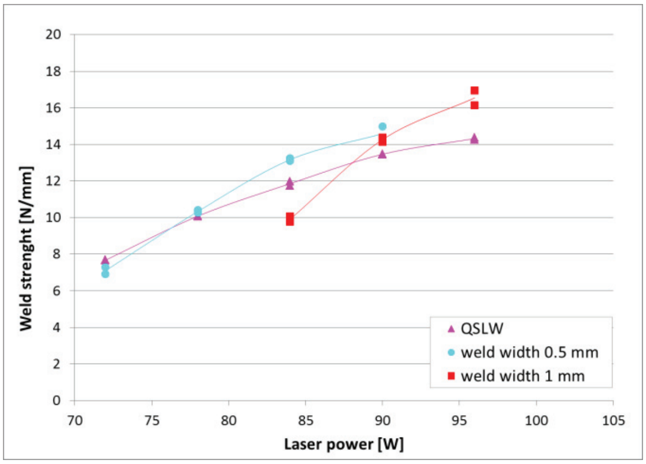

Fig. 11. The weld strength with different laser powers and weld widths used.

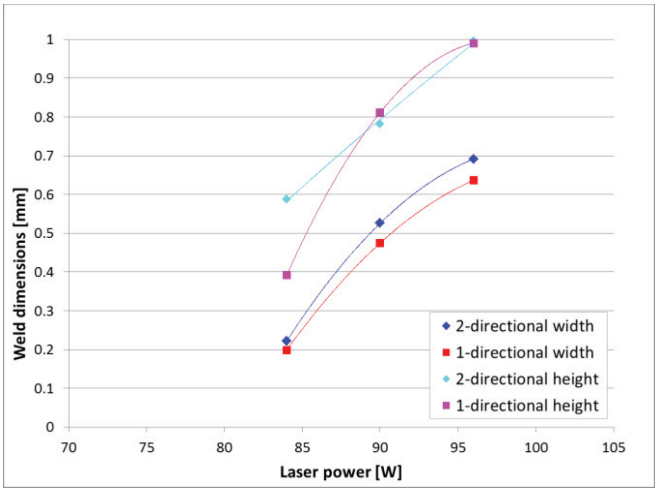

FIG. 12. The width and the height of the weld of 1- and 2-directional welding with different laser powers used.

In the Fig. 16 there are microtome photos of the welds. With a 0.2 mm line distance (c and d) the weld shape is not as smooth as with other line distances. With a higher line distance the heat input is not as even as it is with other line distances. With a smaller line distance the beam (ø 260 μm) has more overlap and the heat distribution is therefore more even. With 0.2 mm line distance the effect of Gaussian beam distribution can be seen and individual scans can be noticed. It can also be seen that with a higher line distance more laser power is needed for forming a weld.

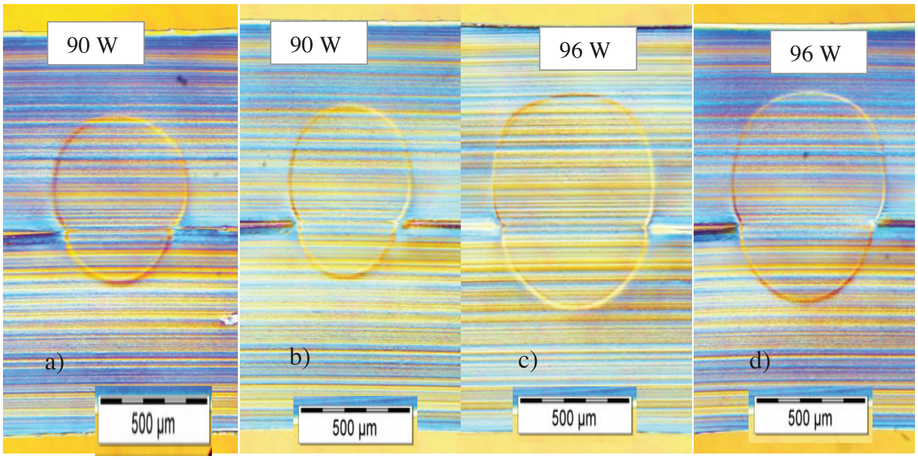

Fig. 13. Microtome cut photos of the 2-directional (a and c) and 1-directional (b and d) welds with laser power of 90 W and 96 W.

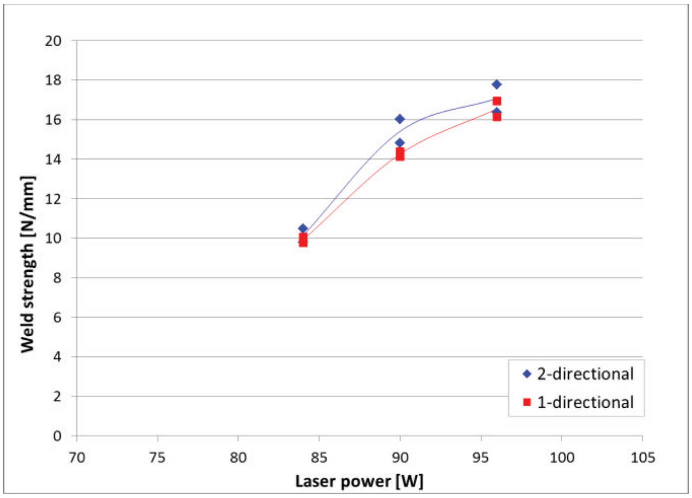

Fig. 14. The strength of the weld of 1- and 2-directional welding with different laser power used.

The difference in the weld strength was only small with the same laser power used (figure 17). With 96W laser power the weld strength was 16.6, 17.0 and 16.7 N/mm with a line distance of 0.05, 0.1 and 0.2 mm, respectively. This was an expected result since the same amount of energy per area unit was brought.

Although with a 0.2 mm line distance a higher laser power was needed to form a weld, a higher power can be used without destroying or burning the polymer. The highest strength 18.4 N/mm was achieved with 0.2 mm line distance and 102 W laser power.

With all the tested parameters and techniques the highest weld strength 18.4 N/mm was achieved with 1-directonal scanning, 0.2 mm line distance and 102 W laser power. Also the weld width was then the highest 0.70 mm. With the off-setting scanning technique a wider weld and higher weld strength can be achieved compared to traditional QSLW. With QSLW the highest achieved weld strength was 14.4 N/mm and highest weld width was 0.56 mm. Strength and width were 22 % and 20 % higher with the off-setting technique, respectively. In beam off-setting technique higher heat input will be needed in the sides of the weld to achieve the wanted width. This could probably be achieved e.g. by an uneven line distance so that in the sides of the weld the line distance is smaller than in the middle of the weld.

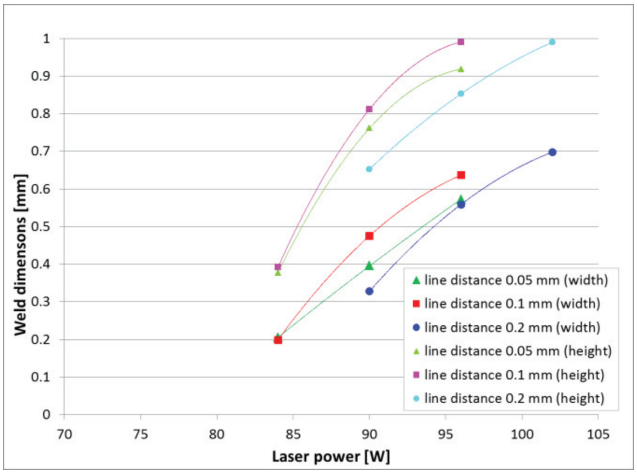

FIG. 15. The width of the weld and the height of the weld with a varying line distance as the function of laser power used.

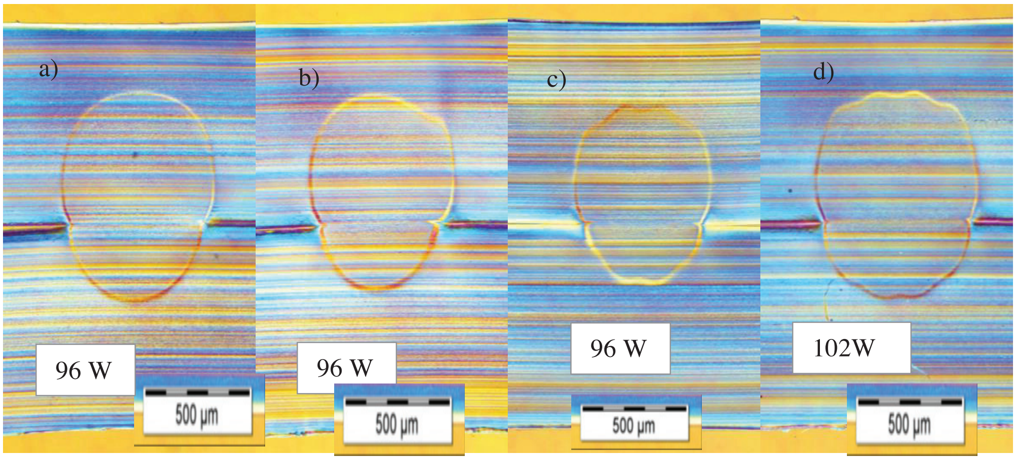

Fig. 16. Microtome cut photos of the 0.05 mm (a), 0.1 mm (b) and 0.2 mm (c and d) line distances.

Laser welding of clear polymers with 1.94 μm lasers is a sensitive process for impurities due to the fact that laser power needed is higher than in traditional TTLW. Laser beam absorbs easily impurities on the surface or the contact area of the polymers and burning on the surface or inside of the material can be happened. This could also be seen in the test. In some cases it was noticed destruction or burning of the polymer, independently of the laser power. This was traced to be caused by dirt on the surfaces.

3. Conclusions

Laser welding of transparent polymers is a very new technique especially with QSLW. In this study it was shown that quasi-simulataneous laser welding of transparent thermoplastic elastomer TPE-A was possible. Also the beam off-setting scanning technique was developed and effect of the scanning parameters was studied. It was noticed that the effect of scanning direction and line distance was insignificant for the tested range. The highest weld width and this way the highest strength (18.4 N/mm) in this study was achieved with 0.2 mm line distance.

If beam off-setting technique is compared to traditional QSLW, a wider weld and a higher strength was achieved with off-setting technique. With QSLW the weld width was 0.57 mm, height 1.45 mm and strength 14.4 N/mm. With off-setting technique the same values were 0.70 mm, 0.99 mm and 18.4 N/mm respectively. The most important difference between traditional QSLW and beam off-setting techniques were in the shape of the welds which were quite different. With QSLW the weld is higher and narrower compared to the off-setting technique weld which shape is much rounder. The height of the weld is an important factor when thin samples are welded. With the beam off-setting technique the same weld width can be achieved with a lower height compared to the traditional QSLW. So, thinner material can be welded with a beam off-setting technique without melting the whole thickness of the upper plate. This way the surfaces of the upper and lower part can be left unmelted.

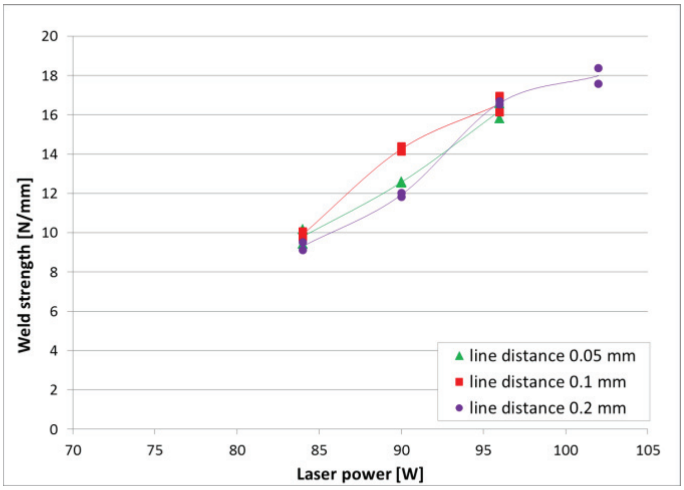

FIG. 17. The weld strength with a varying line distance and laser power used.

Beam off-setting technique needs to be developed to achieve a different kind of heat distribution. In the sides of the weld there needs to be more heat than in the middle of the weld so that the wanted weld width can be achieved. This can be done by an uneven line distances so that in the sides the line distance it is smaller than in the middle of the weld.

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