Avoiding the requirement for pre-existing optical contact during picosecond laser glass-to-glass welding

Citation for published version:
Chen, J, Carter, RM, Thomson, RR & Hand, DP 2015, 'Avoiding the requirement for pre-existing optical contact during picosecond laser glass-to-glass welding', Optics Express, vol. 23, no. 14, pp. 18645. https://doi.org/10.1364/OE.23.018645

Digital Object Identifier (DOI):
10.1364/OE.23.018645

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Optics Express

General rights
Copyright for the publications made accessible via Heriot-Watt Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
Heriot-Watt University has made every reasonable effort to ensure that the content in Heriot-Watt Research Portal complies with UK legislation. If you believe that the public display of this file breaches copyright please contact open.access@hw.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Avoiding the requirement for pre-existing optical contact during picosecond laser glass-to-glass welding

Jianyong Chen,* Richard M. Carter, Robert R. Thomson, and Duncan P. Hand

Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK

*jc317@hw.ac.uk

Abstract: Previous reports of ultrafast laser welding of glass-to-glass have indicated that a pre-existing optical contact (or very close to) between the parts to be joined is essential. In this paper, the capability of picosecond laser welding to bridge micron-scale gaps is investigated, and successful welding, without cracking, of two glasses with a pre-existing gap of 3 µm is demonstrated. It is shown that the maximum gap that can be welded is not significantly affected by welding speeds, but is strongly dependent on the laser power and focal position relative to the interface between the materials. Five distinct types of material modification were observed over a range of different powers and surface separations, and a mechanism is proposed to explain the observations.

©2015 Optical Society of America

OCIS codes: (320.7090) Ultrafast lasers; (190.7110) Ultrafast nonlinear optics; (350.3390) Laser materials processing; (240.5770) Roughness; (160.2750) Glass and other amorphous materials.

References and links

1. T. Tamaki, W. Watanabe, and K. Itoh, “Laser micro-welding of transparent materials by a localized heat accumulation effect using a femtosecond fiber laser at 1558 nm,” Opt. Express 14(22), 10460–10468 (2006).
2. I. Miyamoto and J. Gottmann, “Local melting of glass material and its application to direct fusion welding by Ps-laser pulses,” J. Laser Micro/Nanoen. 2(1), 7–14 (2007).
3. W. Watanabe, S. Onda, T. Tamaki, K. Itoh, and J. Nishii, “Space-selective laser joining of dissimilar transparent materials using femtosecond laser pulses,” Appl. Phys. Lett. 89(2), 021106 (2006).
4. A. Horn, I. Mingareev, A. Werth, M. Kachel, and U. Brenk, “Investigations on ultrafast welding of glass–glass and glass–silicon,” App. Phys. Adv. Mater. 9(1), 171–175 (2008).
5. Y. Ozeki, T. Inoue, T. Tamaki, H. Yamaguchi, S. Onda, W. Watanabe, T. Sano, S. Nishiuchi, A. Hirose, and K. Itoh, “Direct welding between copper and glass substrates with femtosecond laser pulses,” Appl. Phys. Express 1(8), 082601 (2008).
6. S. Richter, S. Nolte, and A. Tümmermann, “Ultrashort pulse laser welding - a new approach for high-stability bonding of different glasses,” Phys. Procedia 39, 556–562 (2012).
7. B. Goss, “Bonding glass and other substrates with UV curing adhesives,” Int. J. Adhes. Adhes. 22(5), 405–408 (2002).
8. J. Bovatsek, A. Ara, and C. B. Schaffer, “Three-dimensional micromachining inside transparent materials using femtosecond laser pulses: new applications,” Lasers and Electro-Optics, 2006 and 2006 Quantum Electronics and Laser Science Conference. CLEO/QELS 2006.
9. T. Tamaki, W. Watanabe, J. Nishii, and K. Itoh, “Welding of transparent materials using femtosecond laser pulses,” Jpn. J. Appl. Phys. 44(22), L687–L689 (2005).
10. I. Miyamoto, K. Cveeek, Y. Okamoto, and M. Schmidt, “Novel fusion welding technology of glass using ultrashort pulse lasers,” Phys. Procedia 5, 483–493 (2010).
11. M. Shimizu, M. Sakakura, M. Ohnishi, Y. Shimotsuna, T. Nakaya, K. Miura, and K. Hirao, “Mechanism of heat-modification inside a glass after irradiation with high-repetition rate femtosecond laser pulses,” J. Appl. Phys. 108(7), 073533 (2010).
12. D. Hélie, M. Bégin, F. Lacroix, and R. Vallée, “Reinforced direct bonding of optical materials by femtosecond laser welding,” Appl. Opt. 51(12), 2098–2106 (2012).
13. I. Miyamoto, K. Cveeek, and M. Schmidt, “Crack-free conditions in welding of glass by ultrashort laser pulse,” Opt. Express 21(12), 14291–14302 (2013).
1. Introduction

Ultrafast laser welding has received significant attention due to its highly localized heating [1–3], coupled with the ability to join optically transparent materials. The manufacture of integrated optical, mechanical and electronic devices often require the joining of glass to glass, or glass to a dissimilar material, whilst maintaining the glass surface conditions and optical properties [4,5]. Current techniques rely on adhesives or interlayers which can suffer from issues such as creep, out-gassing or aging [6,7]. In order to join two transparent materials with conventional laser welding, an optically-absorbing intermediate layer is required [1]. This layer is not necessary with ultrafast laser welding, since it is enabled by the nonlinear absorption of the laser radiation due to high peak power of the laser pulses. By bringing two material surfaces into close contact and focusing the ultrafast laser pulses at the interface, a highly localized melt zone (typically 50–200 µm across a weld seam) can be induced, which then solidifies to form a strong bond, permanently welding the two materials together. The highly localized nature of the nonlinear absorption means that welds can be created whilst avoiding excessive heating of the surrounding material – important for joining materials with significantly different thermal expansion coefficients [1,8].

Ultrafast pulses from picosecond and femtosecond lasers, with high peak power and high repetition rates, have been used for glass welding since the work of Tamaki et al [9] in 2005. For ultrafast laser bonding to work, the peak intensity of the focused laser beam must be sufficiently high to generate free electrons in the focal volume through nonlinear absorption processes (either multi-photon or tunneling). These free electrons then act as seed electrons for single photon absorption (Joule heating), avalanche ionization, and plasma formation. Ideally, the laser must also exhibit a sufficiently high pulse repetition rate (100’s of kHz) for heat to accumulate in the weld region. This heat accumulation results in more efficient energy absorption, through phonon assisted absorption, and increases the physical size of the melt volume, known as the heat affected zone (HAZ). The size of the HAZ, and hence the cross-sectional area of the resultant weld, depends on the parameters used, such as sample translation speed, laser power and pulse repetition frequency. Although ultrafast laser welding is highly localized in nature, stress may accumulate around the weld seams, and excessive residual stress may crack the sample [10,11], particularly when welding a large continuous area or with two materials of different thermal expansions. An appropriate laser illumination strategy is therefore required to reduce the stress accumulation.

A particular issue with ultrafast laser welding is an assumed requirement for close contact between the surfaces to be joined. Previous reports on ultrafast laser welding have identified a requirement for the gap to be ~100-500 nm [1,11–13], in order to avoid cracking or ablation at the interface. Such close contact can be obtained by pressing two flat, smooth and clean surfaces together, and exploiting the van der Waals force to create an optical contact [12,14]. However, it is difficult to obtain optical contact across a large area (several hundred square millimeters or bigger), even with highly polished surfaces and rigorous cleaning processes. Furthermore, the requirement for flat parallel plates is not always compatible with the geometry and shapes of some micro-optical systems, in particular recessed surfaces that are not easy to clean or polish. In this paper, we have therefore concentrated on understanding the impact of the surface separation on the ultrafast laser welding process itself and using this...
knowledge to determine laser parameters and approaches capable of welding surfaces separated by a few microns. This will greatly expand the real-world applications of ultrafast laser welding. Samples with controlled gaps were prepared to enable investigation of the relationship between the pre-existing gap with laser power, process speed, and focal position when achieving a successful weld.

2. Experimental setup

Our experiments were performed using a Trumpf TruMicro 5 × 50 laser, that emits 5.9 ps pulses of 1030 nm light at a with repetition rate of 400 kHz. The laser beam was focused by a 10 mm aspheric lens (Thorlabs, AL1210-B, NA = 0.54), resulting in a ~1.3 µm diameter spot at the focal point. Two types of sample structure were used to provide controlled and measureable gaps: (i) an optic with a gently curving surface (long focal length cylindrical lens) was used together with a flat glass wafer [Fig. 1] and (ii) a series of grooves were accurately etched into the surface of a flat glass wafer, which was then welded to a another planar glass wafer [Fig. 2].

With setup (i), the cylindrical lens used was a Thorlabs, N-BK7 Plano-Convex Cylindrical Lens, 1000 mm focal length, and the glass wafer was Schott, BOROFLOAT 33. Both the wafer and cylindrical lens were cleaned with acetone and methanol and pressed together with a clamp, as shown in the schematic in Fig. 1. This resulted in a thin optical contact line (A, perpendicular to the plane shown), with interference fringes either side of the optical contact area. To generate the welds, the laser beam was scanned across this optical contact line. During this process, the laser spot first encounters a large gap between the materials, which decreases in size to a minimum, before expanding again. Subsequent weld lines were then created in parallel with the first, using a range of pulse energies (2.45–4.43 µJ, steps of 0.245 µJ) and scan speeds (0.6–3 mm s⁻¹, steps of 0.4 mm s⁻¹).

![Fig. 1. Schematic of cylindrical lens setup used for the gap welding experiments. The cylindrical lens is N-BK7 and the flat glass wafer is 1 mm thick BOROFLOAT 33. The lens radius of curvature R, is 516.8 mm. Individual weld lines are created perpendicular to the line of optical contact (A) scanning from left to right.](image)

Provided that the radius of the cylindrical lens is sufficiently large in comparison to the weld length (AD), the gap (AB) at any point (D), can be easily calculated by measuring the distance (AD) away from the line of optical contact with a geometrical relation [Eq. (1)]:

$$AB = \frac{BC^2}{2R - AB} = \frac{AD^2}{2R}$$  \hspace{1cm} (1)

Two potential issues with this method is that (a) the glass wafer will bend slightly in the clamp, and (b) previous welding seams may pull (or push) the two surfaces closer together (or further apart), hence the gap distance calculation is subject to some error. Due to these uncertainties, experiments involving varying the focal position of the laser were not attempted with this setup.
Setup (ii) provided a more reliable and repeatable way of generating discrete controlled
gaps between the two surfaces to be welded. Reactive-ion etching was used to create a series
of grooves on a fused silica wafer with depths of 1, 2, 3, 4 and 5 µm (with depth accuracy ±
5%) and a width of 1 mm. The etched and cleaned surface was then clamped against a second
fused silica wafer, providing optical contact at all points apart from the etched grooves [Fig.
2]. To create a weld, the laser beam was scanned perpendicular to the grooves. In this
arrangement the weld begins and ends in a region of optical contact. Repeated parallel scans
with different pulse energies (10.10 to 21.33 µJ, in steps of 0.28 µJ), as well as different focal
positions (from −21.2 to −172.7 µm in steps of −2.97 µm, Note: zero is defined as the lower
surface of the top glass wafer, and a negative focal position is below this interface). All
experiments were carried out with constant laser spot scanning speed of 2 mm s⁻¹. In this
experiment we used fused silica rather than borosilicate, however from our previous work
[15] we expect the results to be comparable to borosilicate, although with a slightly higher
pulse energy required for successful welding.

![Fig. 2. Schematic of cross-section of planar substrate arrangement. The fused silica wafers are
1 mm thickness, with etched grooves depths of 1.0 µm, 2.0 µm, 3.0 µm, 4.0 µm and 5.0 µm,
widths of 1 mm and separations of 2 mm.]

3. Results

The results obtained using setup (i) are presented in Fig. 3. To investigate the effect of laser
spot translation speed, welds were attempted using a constant pulse energy of 2.95 µJ. As
shown in Fig. 3(a), it can be seen that successfully welded seams are strongly differentiated
from un-welded (ablated) regions. It can also be seen that the weld lines become thinner as
the laser spot scan speed is increased. Over the parameter range investigated, however, we
observed no obvious trend linking scan speed with the gap that could be successfully welded.
This observation is interesting, given that the exposure energy line densities used in this
experiment ranged over 5 times, from 1.97 J mm⁻¹ to 0.39 J mm⁻¹ although the spot to spot
overlap remains extremely high.
Fig. 3. Welds of flat borosilicate glass (1 mm thickness) to N-BK7 cylindrical lens with different parameters. Each parameter consists of a set of 5 welding lines (100 µm separation) of identical welding parameters. A) 7 sets of welding lines (250 µm separation) with a pulse energy of 2.95 µJ, and different scanning speeds (left-to-right: 0.6, 1.0, 1.4, 1.8, 2.2, 2.6 and 3.0 mm s\(^{-1}\)). B) 9 sets of welding lines (250 µm separation) with the same scanning speed of 1 mm s\(^{-1}\), and different pulse energy (left-to-right 2.45, 2.70, 2.95, 3.20, 3.45, 3.70, 3.93, 4.18 and 4.43 µJ). The focal position of the laser is 72.7 µm below the bottom surface of the flat glass wafer. In both images, the red arrows indicate the direction of the laser translation.

Fig. 4. Comparison of start-gaps and end-gaps for different incident average powers used in Fig. 3(b). Linear fits indicate that end gaps are roughly twice as large as start gaps.

To investigate the effect of laser power on the gap size that could be bridged, a constant scan speed of 1 mm s\(^{-1}\) was used, but the pulse energy was varied from 2.45 µJ to 4.43 µJ, in steps of 0.245 µJ. As can be seen in Fig. 3(b), we observed that higher pulse energy enabled successful welds across larger gaps, as might be expected, although we also observed that too...
high an average power also induces cracking in the sample. Interestingly, from Fig. 3(b), there appears to be a difference in the size of the gap that can be bridged either side of optical contact in that a larger gap can be bridged if the welding process has already begun. For clarity, we will refer to the size of gap at the point that the weld is initiated as the “start gap,” and the size of the gap at the point that the weld fails as the “end gap.” Figure 4 presents a comparison of start gaps and end gaps calculated from Eq. (1) using the data obtained from Fig. 3(b). As can be seen in Fig. 4, “end gaps” are roughly twice as large as “start gaps” for the same welding parameters. Interference fringes can be clearly observed across the sample, which provide a measure of the gap at any particular point from which the gap calculations could be verified. These fringes are distorted between weld seams, indicating that the welds themselves have locally altered the gap between the two glass materials, i.e. pulled the glass together or distorted the interface. This effect, combined with the bending in the glass slide, result in an uncertainty in the absolute values presented in Fig. 4. The error bars in Fig. 4 are based on the standard deviation of the observed results.

The etched groove experiment (setup (ii)) provides a more precisely controlled, albeit discretized, measurement of the gap before welding. It was found that the results obtained could be broadly characterized into one of four states: plasma ablation, HAZ ablation, intermittently welded and continuously welded, as illustrated in the inset in Fig. 5, which was achieved using a 2 µm gap. Each set of parameters was characterized through a combination of examining the top down weld structure [Figs. 5(a)-5(d)] and by examining the cross-section. The plasma ablation region appears as a thin clean line, Fig. 5(a); HAZ ablation is indicated by a line with material redeposited either side of the ablation line, Fig. 5(b); For our purposes, we classified intermittently welded as being a mixture of HAZ ablation and weld beads with at least 25% of the weld line consisting of beads, Fig. 5(c); For almost all cases of continuously welded the weld line becomes thinner and less homogeneous in the gap region, Fig. 5(d). This is likely a combination of distortion to the focal spot caused by the gap and the somewhat rougher etched surface. In most cases there is evidence of a protrusion as the laser first enters the gap. This is most striking in the continuously welded example [Fig. 5(d)] where the weld seam maintains almost its full cross-section for the first ~100 µm. This effect does not occur as the laser moves from gap to optical contact at the bottom of the etched region [Fig. 5(d)].

The classifications outlined above are used in the main part of Fig. 5 to define a parameter map for these four states as a function of groove (gap) depth and average power at a fixed focal position of −72.7 µm and laser spot scanning speed of 2 mm s⁻¹. It should be noted that although the gaps tested are 1.0, 2.0, 3.0, 4.0 and 5.0 µm, the pulse energies tested are at 0.28 µJ increments giving a total of 41 individual tests per gap size, only those points on the boundaries between classifications have been plotted. Determining the exact boundary between the states is challenging in some cases, particularly with the intermittently welded case, error bars are therefore provided.
Fig. 5. Parameter map illustrating the classification of weld results with varying gap distance and average laser power. Plotted points indicate changes between the different process classifications with a resolution of 1.0 µm in depth and 0.28 µJ in pulse energy. The blue dashed line indicates the average power used in Fig. 6. The inset shows different welding patterns of (a) Plasma ablation, (b) HAZ ablation, (c) Intermittently welded and (d) Continuously welded. The cross-sections of these example welds are shown in Fig. 9. The red stars indicate the position of these results.

The results here agree with the cylindrical lens welding experiment: that increased power allows a larger gap to be successfully bridged, with an almost linear relationship. For a particular gap size the welds cycle through all four states which is expected. By increasing the average laser power, an intermittently welded or even HAZ ablation can become a continuously welded region, but at some point material cracking due to excessive pulse energy will become an issue. It is worth noting that cracking was not observed in any of the etched groove experiments and hence tests with higher average powers are feasible.
Fig. 6. Parameter map illustrating classification of weld results with varying gap distance and focal position with a constant pulse energy of 18.23 µJ. Plotted points indicate the position of the change between the different result classifications with a resolution of 1.0 µm in depth and 2.97 µm in focal position. The blue line indicates the focal position used in Fig. 5. The fifth state appeared when the focal position was too deep and the laser induced modification is below the interface. a, b, c, d in the graph indicate the positions of cross-sections in Fig. 10.

Figure 6 shows a parameter map as a function of groove (gap) depth and focal position with a fixed pulse energy of 18.23 µJ and speed of 2 mm s⁻¹. As the focal position is moved further from the interface a fifth state appears: HAZ under the interface. This occurs when the HAZ forms far below the interface and the plasma/melt is insufficient to reach the gap area and fill it. There was no observation of the “plasma ablation” state for this experiment.

The graph demonstrates that the ability to weld across a gap changes dramatically with focal depth. From Fig. 6, the graph could be classified as 3 types of welding mechanisms as the focal position changes: welding from above the interface (~21.2 µm to ~55 µm), welding from below the interface (~55 µm to ~120 µm) and the HAZ fully below the interface (~120 µm to ~172.7 µm). Again each set of parameters was characterized through a combination of examining the top down weld structure and examining the cross-section. Generally speaking, the different welding mechanisms depend on whether the main laser absorption position is in the upper sample or in the lower sample (which will be discussed in detail in part 4). It should be remembered that Fig. 5 and Fig. 6 show two dimensional slices from the three dimensional space of power, focal depth and gap width. From Fig. 5 it is clear that the intermittently welded region and HAZ ablation region in Fig. 6 can, potentially, be changed to continuously welded and intermittently welded if the average laser power is increased. A combined analysis of Fig. 5 and Fig. 6 provides suitable parameters to be used for successful welding.
4. Discussion

Two immediate conclusions can be made from the experiments we have conducted. First, a larger gap can be welded once the weld process has started, as illustrated in Fig. 4 and as is visible in Fig. 5(d). Secondly, in a non-intuitive and non-trivial manner, the position of the laser focus relative to the gap has a significant influence on the gap could be bridged. To explain the absorption mechanism, it is necessary to examine at the cross-section of a typical weld formation [Fig. 7] and the evolution of this formation over time. An experiment was thus carried out varying the number of incident pulses, at 21.25 µJ, (repetition remained 400 kHz with the beam translated at 2 mm s$^{-1}$) focused inside a thicker sample of fused silica, the results of which are presented in Fig. 8.

Fig. 7. Diagram of welding formation between two surfaces (the insert welding figure: fused silica and fused silica, 18.29 µJ, 2 mm s$^{-1}$ with a 2 µm gap).
Fig. 8. Evolution of plasma affected region and HAZ with increasing incident pulses of 21.25 µJ in a single fused silica sample. The nominal focal position is indicated by the blue line. There is no visible (permanent) modification to the fused silica for 240 pulses or less. Phase contrast imaging has been used to provide clearer images.

In Figs. 7 and 8 it is possible to see the effects of the various stages of absorption as the process develops. The first pulses are initially absorbed at and around the geometric focus, through a nonlinear absorption process. These initial pulses provide, in this case, no permanent modification to the glass [Fig. 8 (< 280 pulses)] but the temperature of the material in and around the geometric focus increases. This leads to phonon assisted absorption creating a micro-plasma with a very limited melt region surrounding it [Fig. 7(point 1)]. NB due to spherical aberration resulting from focusing through the top surface of the glass, this focus is elongated. Subsequent pulses are more readily absorbed and the absorption region moves incrementally closer to the source rapidly expanding the plasma affected region along the laser beam axis in a filament [Fig. 7(point 2), Fig. 8 (280 pulses) and 8(480 pulses)].

As the absorption region moves upwards there is eventually sufficient thermal diffusion to form a HAZ and this begins to expand laterally [Fig. 7 (point 3), Fig. 8 (520 pulses)]. This process continues until the absorbing region has moved so far out of focus that absorption drops to an un-sustainable level [Fig. 7 (point 4), Fig. 8 (~2000 pulses)]. At this point the formation terminates and the process begins again at the geometric focus as the laser is translated laterally. During this process material in the plasma affected region mixes and a true weld is formed in this area [15]. Thermal diffusion generates a HAZ but the limited mixing of material is insufficient to form a true weld [Fig. 7 (insert)]. It is known that the HAZ represents the melted glass region [10,13]. Recently it has been shown that even regions outside the melt zone exhibit clear expansion of the order of several hundred nm [16] and possibly as much as 1 µm which has been demonstrated as being of benefit to glass-glass welding [17]. The ability of this formation to bridge a gap between two surfaces is therefore highly dependent on the size of the HAZ (melt zone) has reached as the formation approaches the gap. This is in turn dependent on the welding parameters and particularly on the focal position.

Figure 9 shows the cross-sections of the structures shown in the inset of Fig. 5 and illustrates the impact of varying incident average power (pulse energy) on the evolution of the weld structure. If the laser power is too low then the formation terminates before a HAZ can form [Fig. 9(1)]. This forms a plasma modified region which can, depending on the focal position relative to the gap, be entirely subsurface [Fig. 9(a)] or a thin, clean, ablation of the surface.
Fig. 9. Left: cross-sections of different welding patterns of etched grooves experiments labeled marked points in Fig. 5. A to D: pulse energy used was 10.1, 11.23, 12.9 and 18.8 µJ respectively. Right: illustration of the evolution of the weld structure with varying incident average power. 1) low power without HAZ; a neat plasma modification line in the bottom glass. 2) plasma escapes with ejecting melt creating irregular ablation, 3) plasma generated at both the top and bottom material but neither of them are strong enough to generate a stable bond, 4) melt bridging the gap providing a bridging corridor for the plasma and a continuous weld.

With increased incident laser power [Fig. 9(2)] the combination of plasma and melt creates a large amount of ejecta and an ablation line with significant re-deposition and surface damage [Figs. 5(b) and 9(b)]. With a further increase in power there are sufficient ejecta (plasma and melt) to transmit heat across the gap, essentially by sputtering material onto the opposite surface. This transmitted heat allows the absorption plane to jump the gap without filling it giving rise to ablation from both surfaces [Fig. 9(3)]. If, however, the incident energy is sufficiently strong the melt zone will be well enough developed as it approaches the interface to expand and fill the gap ahead of the plasma [Figs. 9(c) and 9(d), also in Fig. 5]; the approaching laser absorption region pushes a bow wave of melt into the gap which initially narrows the gap and eventually fills it forming a bridge which the plasma region can follow. This explains the ability for an already formed weld to bridge a larger gap than an unformed weld in Fig. 4 and welding protrusion in Fig. 5(d) as the melt can be pushed laterally into the gap ahead of the laser translation.

Fig. 10. Left: cross-sections of different welding patterns of etched grooves experiments labeled marked point in Fig. 6. A-D.: focal position is $-24.1$ µm, $-40.0$ µm, $-86.5$ µm and $-107.3$ µm respectively. Right: illustration of mechanism of left photo.
Figure 10 illustrates the proposed explanation applied to the 4 types of welding in Fig. 6 with cross sections of different typical areas from Fig. 6 presented in the left of Fig. 10. If the focal position is close to the interface then the absorption plane will quickly jump the gap and the laser energy is mainly absorbed in the upper glass and an upper HAZ is generated. Here the melt expands downward filling the gap from above and forming a join [Fig. 10(1)]. In this experiment a focal position of between $-21.2\,\mu m$ and $-55\,\mu m$ therefore results in the upper material absorbing the bulk of the laser energy. With a deeper focal position, HAZ is generated first in the lower region and then jumps the gap to the upper region. This jumping behavior can be seen from the discontinuous structure in Figs. 10(a) and 10(b). For smaller gaps there is sufficient combined melt from either side to fill the gap and hence the gap still could be welded. For larger gaps the combined melt is insufficient fill the gap, as seen in Fig. 10(2), so intermittently welded or even HAZ ablation regions are formed in Fig. 6 (typically for a gap $\geq 3\,\mu m$). As the focal position is further lowered such that the focal region is entirely below the gap, the HAZ forms only in the lower glass. For a small range of focal depths the melt is sufficiently well formed to bridge the gap from only one side forming a true weld. Hence intermittently welded and continuously welded regions return for deeper focal positions from $-55\,\mu m$ to around $-120\,\mu m$. With a further deepening in focal position the plasma and melt are too far from the surface to reach the gap, this generates a HAZ either entirely below the interface or with insufficient melt to bridge the gap as the top of the tear drop HAZ formation ($> -120\,\mu m$ in Fig. 6).

5. Conclusions

We have carried out welding of two glass parts with a controlled gap, either by using a sample with a curved surface (cylindrical lens) together with a glass wafer, or two wafers, one which has a series of grooves etched into the surface. Results demonstrate the ability of the ultra-short pulsed laser welding process to bridge small gaps. For the cylindrical lens experiment the effect of direction, speed and power were investigated. Power was demonstrated to be critical in determining the weld-able gap while speed, by comparison, appears less critical, at least over the tested range. Most interestingly the experiment demonstrated that the weld-able gap increased, by a factor of two, once the welding process had begun. The etched groove experiment provided a more precise but discretized method to determine the maximum possible weld-able gap. The results for increasing average power (pulse energy) agreed well with the cylindrical lens experiment and also demonstrated the key influence of the focal position for larger gap welding. Here the unexpected result is that focusing close to or within the interface allows for melt to flow “backward” filling the gap with material from the upper glass. As this weld is formed primarily of melt rather than micro-plasma there is likely little intermixing of material and hence a weaker bond rather than a true weld. This result may, however be of interest when attempting to weld glass to an opaque material. For both experiments roughly 3 $\mu m$ gaps were successfully welded with borosilicate glass and fused silica.

A theory describing the mechanisms by which a flow of melt can bridge the interfaces has been proposed as an explanation for these observations. This indicates the importance of choosing appropriate focal position and incident power for bridging gaps. This proposed process requires thermal accumulation to create a HAZ around, and ahead of, the plasma affected region. This restricts the minimum repetition rate of the laser (in fused silica to typically $\sim 200-400\, kHz$) to allow for thermal accumulation but not the maximum repetition rate. It should also be noted that fs lasers will generate the same HAZ/plasma regions and hence should be able to take advantage of the same processes. The results are highly significant for ultrashort pulsed laser welding as they significantly relax the requirement for surface preparation and fit-up between parts, which are otherwise prejudicial to the industrial implementation of this otherwise attractive joining process.
Acknowledgments

This work was supported by Renishaw plc and the UK Engineering and Physical Sciences Research Council through the EPSRC Centre for Innovative Manufacturing in Laser-based Production Processes (EP/K030884/1). The authors would like to thank Renishaw plc and Heriot-Watt University for a Ph.D scholarship. RRT thanks the UK Science and Technology Facilities Council (STFC) for support in the form of an STFC Advanced Fellowship (ST/H005595/1).