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# Picosecond laser welding of optical to structural materials

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- Invited Paper -

**Abstract**

We report on recent progress to develop an industrially relevant, robust technique to bond highly dissimilar materials using an ultrashort pulsed laser micro-welding technique. Tight focusing of light from a picosecond (ps) pulsed laser (in our case a 5.9ps, 400kHz Trumpf laser operating at 1030nm) at, close to, the interface between two materials allows for simultaneous heating of both. This absorption rapidly, and locally, heats the material leading to plasma formation from both materials. With suitable surface preparation this plasma can be confined to the interface region where it mixes, cools and forms a true weld between the two materials. In this presentation I will provide an overview of the ultrashort laser welding process and concentrate on our recent results. Results are presented for fused silica glass to aluminium, copper and stainless steel; borosilicate glass to silicon; and sapphire to stainless steel.



*Keywords:* dissimilar materials; welding; ultrashort pulses

## 1. Introduction

### *1.1. Background*

The manufacture of complex optical systems typically requires the bonding of highly dissimilar materials (e.g. optical glasses or crystals to metals), with high precision. Many different techniques have been used, with the most common being adhesive bonding; however the adhesives used typically have problems with creep, thermal conductivity, aging; also outgassing if used in a vacuum application. Furthermore the application of an adhesive in a manufacturing situation always poses the risk of contamination of nearby high precision optical surfaces.

The development of high average power ultrashort pulsed lasers has provided a viable alternative, that of directly welding such materials, despite their highly dissimilar thermal and other properties. Such welding provides a very small heat affected zone (HAZ), giving an essentially cold process. However, various aspects of the process and materials to be joined must be highly controlled; in our work our focus has been to develop processing strategies that are sufficiently robust for real industrial application.

### *1.2. Ultashort pulsed laser micro-welding - process principles*

The principle of ultrashort pulsed laser micro-welding for bonding an optical component (e.g. glass) to a structural component (e.g. metal) is straightforward. The two materials are brought into very close contact and the ultrashort pulsed laser is focused through the optical material, providing a small focal spot at its interface with the structural material. The radiation is absorbed through a combination of linear and non-linear processes (dependent on the material composition), leading to a micro-plasma (and through thermal accumulation a melt region surrounding the micro-plasma) that, once cooled, forms a solid weld. As the focal spot is translated across the interface a true weld is formed between the two materials as the

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plasma mixes (Fig. 1). It is also possible to weld together two optically transparent materials, since the high peak power of the ultrashort pulsed light can drive a non-linear absorption process at the interface, and indeed a number of groups including Tamaki et al., 2006; Horn et al., 2007 and Wantanabe et al., 2006 have used this process to weld glass to glass, a process that has recently been developed into a commercial product by Primoceler, 2016.

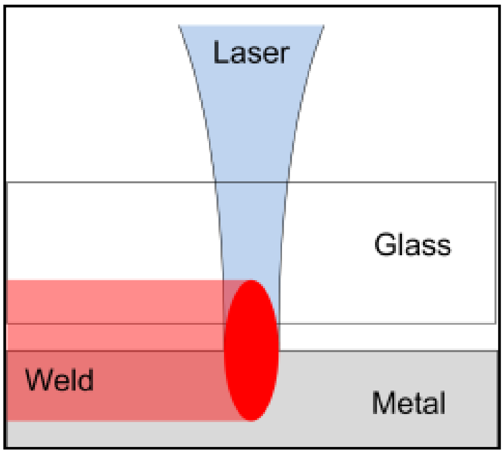


Fig. 1. Illustration of ultrashort pulsed laser micro-welding principle.

A key feature of the ultrashort pulsed laser welding process is that the tight focusing and nonlinear absorption in the optical material enables highly accurate placement of a laser beam absorption micro-volume within an otherwise transparent material. This highly localised absorption generates a micro-plasma below or at the interface. This plasma will, through thermal accumulation over multiple pulses, generate a melt volume (Heat Affected Zone, HAZ) that can expand to fill a gap before solidifying into a join, as described by a number of authors including Huang et al., 2012; Watanabe et al., 2012; Richter et al., 2012; Wang et al., 2015. Importantly the very short pulse duration allows for direct bonding of materials with highly dissimilar thermal properties as the interactions occur on a significantly shorter timescale than thermal expansion or conduction.

While it is possible to obtain highly localised welds with a single shot system, as reported by Watanabe et al., 2012, it is more useful in general to use thermal accumulation for fast and efficient generation of micro-welds. It is therefore essential that individual pulses arrive before the energy of the previous pulse can significantly dissipate. While this is clearly material dependent it is on the order of a few microseconds and as a result laser repetition rates of a few hundred kilohertz or higher are required, see Richter et al., 2012. Beyond this the requirements for laser micro-welding are broad. To date there has been considerable work in this area using both femtosecond lasers (e.g. see Huang et al., 2012 and Hélie et al., 2012) and less expensive (but less precise) picosecond systems, see Carter et al., 2014. It is one of the significant strengths of this process that a large range of materials can be welded together with essentially the same laser system.

Successful welding is dependent on the ability to successfully confine the initial plasma in the focal volume of the incident radiation; i.e. to prevent the plasma from escaping before the melt zone can form. This has been perceived as a requirement for the gap between the two materials to be sufficiently small that the plasma cannot escape. In most cases optical contact (< 1 µm) has been regarded as a requirement, for example see Hélie et al., 2012. If such an extremely close contact is necessary, this puts a significant limitation on both the flatness and the smoothness of the materials to be bonded. A number of relevant materials, e.g. optical glasses, crystals etc. are commercially available with suitable (λ/4) flatness as standard; other materials, particularly metals, require significant, careful processing to achieve this surface finish. Even with completely flat and smooth surfaces care must also be taken to ensure that the surfaces are clean otherwise the presence of particular matter will prevent close contact. Hence it is only by relaxing this requirement that the process can be used as a high yield manufacturing process at reasonable cost, in particular for the glass-to-metal bonding; hence a key focus of our research has been to develop a process that can contain the plasma without requiring such close contact.

## 2. Experimental

A range of different ps and fs lasers have been deployed for ultrashort pulsed laser welding. In our experiments we have used a Trumpf Tru Micro 5X50. This laser produces 5.9 ps pulses centred at 1030 nm with a base repetition rate of 400 kHz. While lower repetition rates are possible via pulse picking, since there is a minimum repetition rate required to enable thermal equilibrium all experiments have been carried out at 400 kHz. This laser is capable of providing pulse energies of up to 125 μJ, however pulses of only 5-25 μJ are typically required (depending on materials) for successful welding. It is therefore possible to achieve effective micro-welding using a lower power, less flexible and less expensive laser system. Our experimental setup is shown in Fig. 2, and includes a half wave plate and polarizing beam splitter as an external variable attenuator.

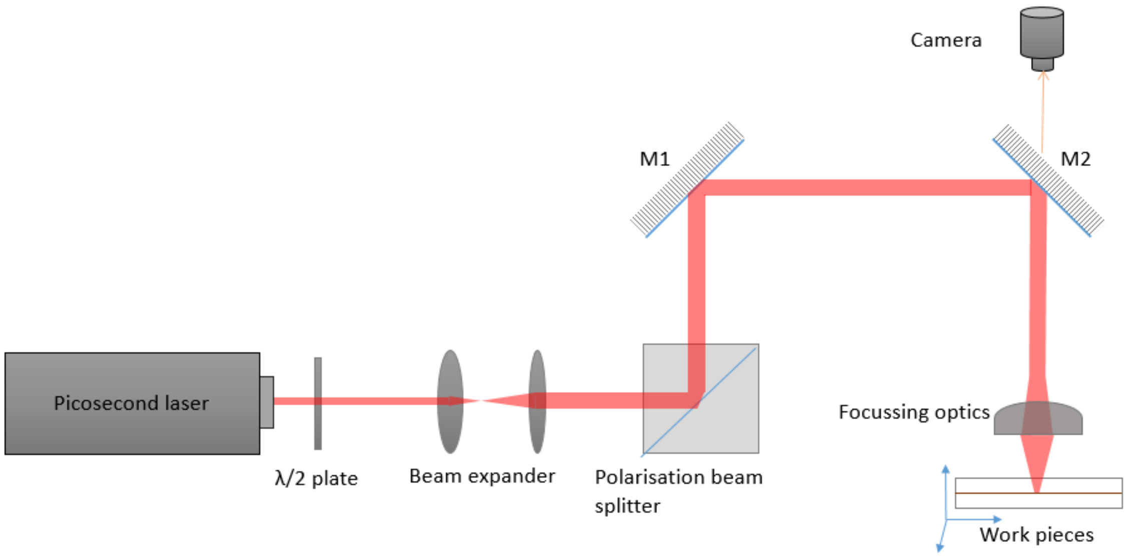


Fig. 2. Schematic of ultrashort pulsed laser micro-welding setup: M1 and M2 are fixed dielectric mirrors.

To prevent excessive thermal stress, particularly when welding highly dissimilar materials it is necessary to limit the focal volume. This is achieved with a high NA lens arrangement; typically a 10 mm diameter beam is focused through a 10 - 20 mm aspheric lens with a 1030 nm anti-reflection coating. In an ideal setup a weld geometry would be drawn with a scan head, however sufficiently short focal length scan optics are not generally available and as such a fixed lens has been used with translation provided by Aerotech screw stages with pizeo nano-positioning sub-stages for x and y movement. This arrangement typically gives a numerical aperture of 0.25-0.5, and a small focal spot of the order of 1.2 μm; although this will be enlarged through aberrations when focusing into a flat optical material, this is investigated in detail by Cvecek et al., 2012.

Accurate positioning of the focal volume of the weld is critical to provide successful welding however positioning the focus in relation to two perfectly mated surfaces is not trivial. We therefore employ a camera to image the back reflections generated by the material-air interface. In our arrangement the CCD has no focusing optics. Thus the back reflection from the upper material-air interface will be focused on the CCD by the focusing optics when there is a slight, known, constant defocus to the interface. By translating by this known quantity it is therefore possible to focus onto the interface with an accuracy better than ±10 μm, provided that the optical thickness of the material is well characterized.

Experience in the micro-welding process has shown that unless the two materials are essentially perfectly flat (e.g. optical glass and Si wafer), it is necessary to use force to push the materials into contact. Typically a pressure of 100-150 kPa has been employed. This pressure is applied with a pneumatically actuated piston; similar approaches have been widely reported, e.g. by Huang et al., 2012 and Watanabe et al., 2012. This piston presses the samples into a recess that forms a symmetric loading system. The piston is aligned such that an area of optical contact is formed aligned with the incident laser beam.

A typical weld strategy involves an Archimedean spiral with a pitch of 0.1-0.15 mm beginning at 25π (radius of 2.5 mm) and winding inward to a final position of 2π (0.1 mm radius) at a constant velocity of 1 mm $s^{-1}$. This arrangement effectively creates a 2.5 mm diameter spot weld.

In order to evaluate the strength of the resulting weld structures shear tests have been carried out. Fig 3 is indicative of the apparatus used for these tests. Here two aluminium blocks have been constructed to fit two dissimilarly sized materials. These are then tested to destruction through the application of shear force, with the break strength being recorded. Since glass is a brittle material it is essential to carry out a statistically significant number of tests for each weld parameter and material combination. Typically 20 tests are carried out.

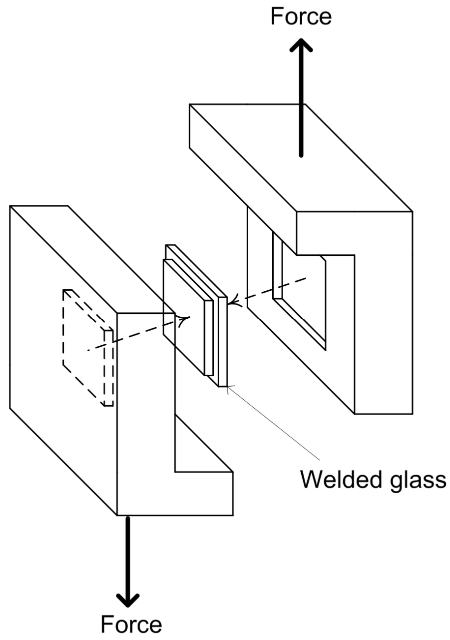


Fig. 3. Illustration of the shear test rig used to determine the strength of the welds. In this example two glass plates are under test. Similar rigs have been constructed for a range of material combinations and sizes, Carter et al., 2014.

## 3. Results and discussion

There is typically a combination of linear (on the metal surface) and non-linear (within the glass) absorption processes that drive the ultrashort pulsed laser welding process. This combination requires careful balancing; primarily though careful control of the focal plane of the laser beam. The requirements for this vary depending on the material combination. Fig. 4 gives examples of proof of principle bonding between a range of highly dissimilar materials. To date aluminium, copper, stainless steel, silicon and silicon carbide have been demonstrated to weld to $SiO_2$, borosilicate and sapphire with pulse energies between 2.5 and 25 µJ, see Carter et al., 2014. Importantly, we have demonstrated that it is not necessary to polish a metal surface prior to welding; simpler surface preparation can instead be used. In contrast to the glass-glass welding process, where a periodic HAZ is typically observed the weld seam appears continuous. However the weld is still optically scattering, and therefore appears dark in bright field microscopy. The spiral welding approach shown in this figure has been found to provide a repeatable welding process with minimal cracking. The discontinuities are due to backlash on the linear stages used; new stages that do not show this problem have since been used and there is no significant difference in weld strength.

The stainless steel examples (in Fig 4) each has a crack running around the exterior of the 2.5 mm diameter weld. These cracks represents a bulk thermal strain relief in the glass and self terminates after ~ 200 µm in the glass. It is particularly interesting to note that cracks of this form generally only occur when bonding to Stainless Steel. This is likely due to the low thermal conductivity (for a metal) of stainless steel.

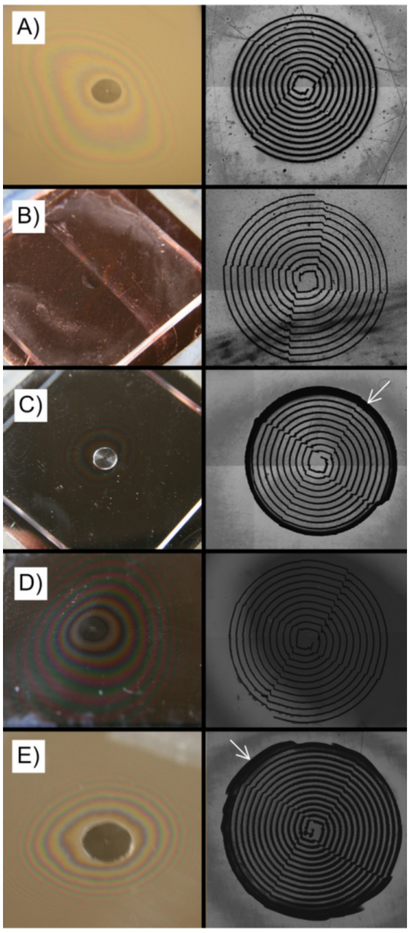


Fig. 4. Examples of a) aluminum to SiO2, b) copper to $SiO_2$, c) stainless steel (304) to $SiO_2$, d) silicon to borosilicate and c) sapphire to stainless steel (304). The stainless steel examples exhibit a crack around the weld perimeter (indicated by arrows) which propagates ~ 200 µm into the glass/sapphire, see Carter et al., 2014.

During the weld process (a few minutes) a thermal gradient is established around the weld perimeter. In stainless steel this thermal gradient is very steep due to the low conductivity. Once the weld cools this thermal gradient translates to a stress gradient through thermal expansion and the perimeter cracks. More recent results suggest that crack free welding in these materials is possible with careful control of the incident power, however shear tests to demonstrate the weld strength have not yet been published.

Fig. 5 shows a typical Weibull plot for the shear test results of Bk7-Al:6082 welding. Here the weld strengths have been calculated based on the 2.5 mm diameter of the weld structure. The failure mechanism is in the glass, around the HAZ. Note that the strength of these welds is typically somewhat lower (due to thermal stresses) than similar glass-glass welds, although the weld parameters here still require optimization.

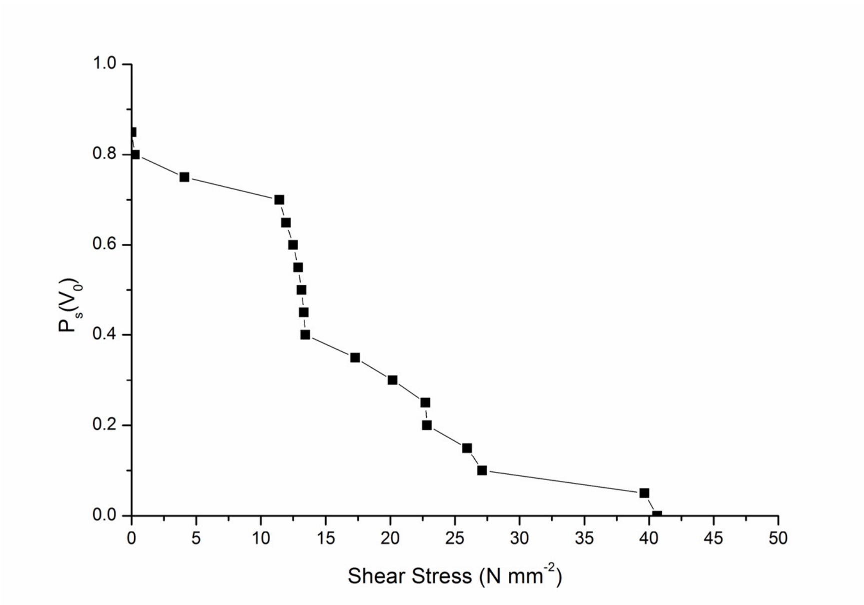


Fig. 5. Example Weibull plot of the survivability of a 2.5 mm diameter BK7-Al:6082 weld with un-optimized weld parameters. Note that no attempt has been made to fit a Weibull modulus due to the apparent spread in the weld strength.

## 4. Conclusion

Ultrafast (ps) laser micro-welding is an effective process in bonding a range of optical and structural materials. Whilst it is necessary to carefully prepare material surfaces we have demonstrated that optical flatness is not a firm requirement. Of particular importance to industry is the range of materials that can be directly bonded with essentially the same laser parameters shows significant versatility.

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