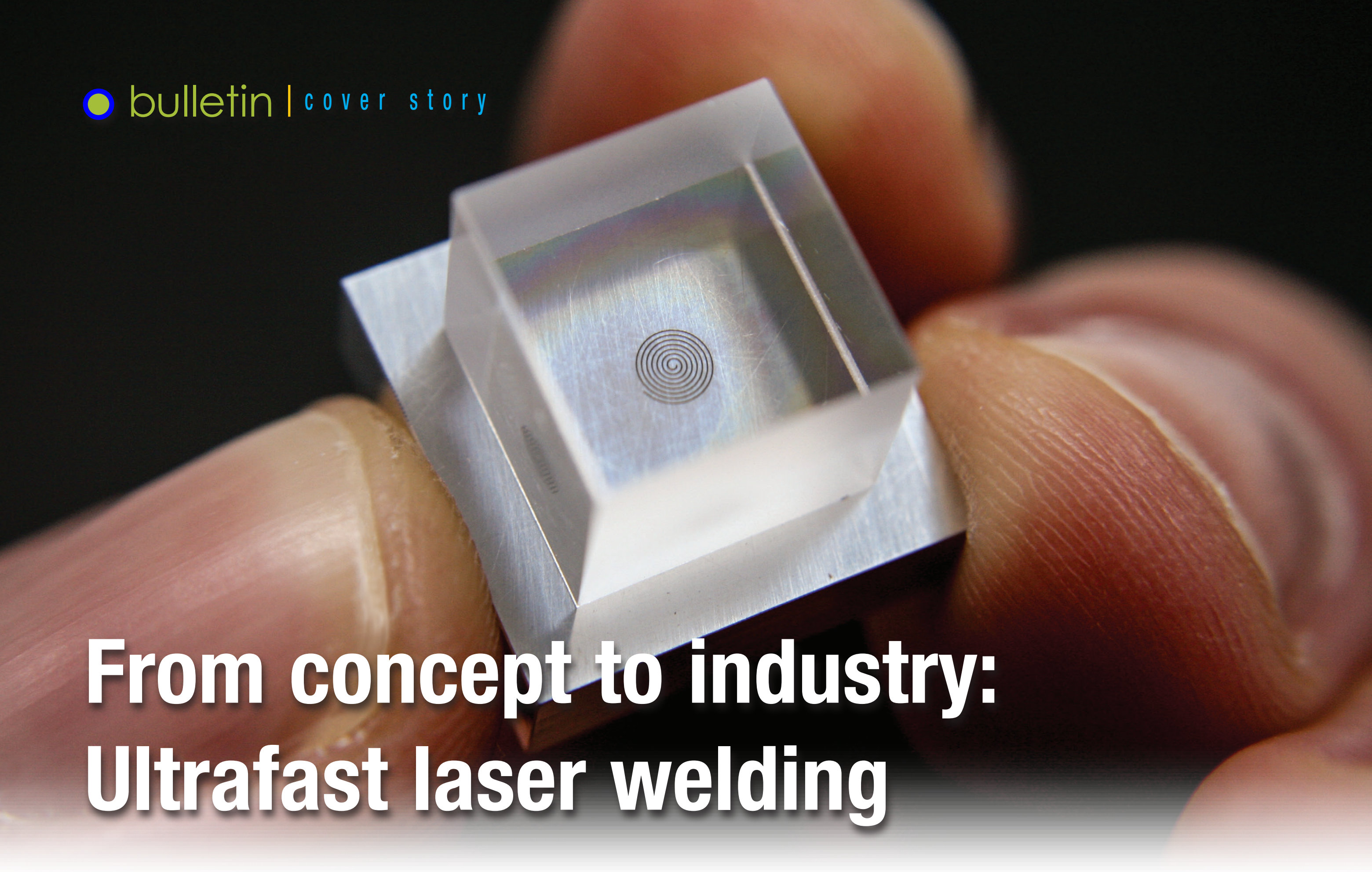


From concept to industry: Ultrafast laser welding

By Richard M. Carter

Ultrashort pulse laser welding has the potential to transform optomechanical component manufacturing—and research around the world is helping to move this technique from concept to industry.

When manufacturing optomechanical components, one of the more problematic steps is bonding the optical components to a structural body. Such optical components can include a whole variety of glass and crystal materials, but these materials are normally chosen for their optical properties rather than their structural or mechanical performance. Because it usually is inadvisable to manufacture the structural chassis from similar (i.e., glass) materials, this decision inevitably leads to a significant mismatch between the properties of the optic and its mount, most significantly in their thermal properties.

There are essentially two options when joining dissimilar materials. The first option involves using some form of clamp or mechanical fixing. In this case, the mismatch in thermal properties is less of an issue; however, such an approach requires additional design engineering and several manufacturing steps. Thus cost, mass, volume, and scope for misalignment can all increase, which can significantly impact applications.

The other option is to use some form of bonding interlayer. This interlayer can take the form of an adhesive, frit, or solder, for example, depending on the precise materials involved. However, creating a reproducible manufacturing process with these materials is rarely as simple as one might wish. For example, issues in the use of adhesives for high-precision optics are well known and can be attested to by

Capsule summary

A SHORT HISTORY

Since researchers at Osaka University (Japan) published a paper in 2005 showing that ultrashort laser pulses could weld transparent materials together, a substantial amount of research worldwide has demonstrated new material combinations as well as generated knowledge on fundamental laser–material interactions.

BROAD POTENTIAL

The applicability of the technique is very broad, from the types of materials welded together to the wavelength of laser used, thus giving laser manufacturers the ability to offer a suitable system provided they have sufficient knowhow of the focusing and material handling requirements.

BUDDING INDUSTRY

A few companies have adopted ultrashort pulse laser welding as an industrial process because, despite the high cost, this technique offers the key advantages of a limited thermally affected zone, the ability to join a range of materials, and the ability to do so without introducing an interlayer.

anyone who has attempted to develop a reproducible high-precision adhesive process. Therefore, in general, considerable time and money usually are needed to develop sufficient art for a reliable, high-precision process.

Furthermore, these bonding processes fundamentally rely on the introduction of an interlayer in some form, which often generates its own problems. A common manifestation is creep, or part movement during curing. But often more problematic is material aging performance, with outgassing a particularly significant issue for systems where strict atmospheric control needs to be maintained to avoid reducing system lifetimes and/or performances (e.g., vacuum systems and some lasers).

Because of these limitations, an alternative, direct joining technique would be preferred. The obvious solution therefore would be to directly weld the two components together.

Be it a torch, arc, friction, or laser, welding relies on a source of thermal energy to locally melt material over a scale of millimeters to centimeters. Depending on the technique, the welding process may also involve adding a "filler" material to bridge a gap between the parts. The materials then will mix in a liquid state, potentially combine chemically, and cool to form a welded bond.

When dealing with broadly similar materials, this process generally works extremely well, with the welded material often stronger than the bulk. However, this process breaks down when considering dissimilar material welding, largely due to differences in thermal expansion—when a material begins to solidify, thermal stresses accumulate and result in an almost immediate failure of the weld. Thermal stresses can be problematic when considering two different metals, but the issue is even more extreme for optical and mechanical components as these materials can differ in expansion rates by an order of magnitude or more.

Because joining of dissimilar materials is still fundamentally desired, the trick would seem to be to minimize the volume of material that needs to be heated, thus reducing the total amount of thermal stress introduced. Minimizing the volume of heated material can be best achieved by limiting the total thermal energy introduced around the weld zone, i.e., to use a very focused source of heat. The laser is an ideal tool for localized heating because the energy can be deposited exactly where it is required by focusing and scanning the beam across the material interface.

Of course, the use of lasers for welding is not at all new. But there is a significant difference in capabilities depending on what type of laser is used. In general, lasers can be divided into two broad categories. The first is "continuous wave lasers." As the name suggests, these lasers provide a continuous beam of light. If directed onto a material, it provides a continuous thermal input very much like a welding torch and so is not terribly well suited to preventing thermal expansion issues during welding.

The alternative is to pulse the output of the laser because it is then possible to separate the peak intensity in the pulse from the average power delivered by temporally concentrating the energy. The pulse duration and the repetition rate are thus both key factors in how the laser–material interaction will work—and thus key to controlling the thermal profile during welding. For most industrial laser processes, pulse durations are in the order of milli- to nanoseconds (10^{-3} to 10^{-9} s). While short, this duration does not provide a sufficiently high localization of thermal energy to allow for dissimilar material welding. Instead, an "ultrashort" pulsed laser is required, one which produces laser pulses in the order of pico- to femtoseconds (10^{-12} to 10^{-15} s).

Over these extremely short timescales, the laser–material interactions take on some features that can be beneficially exploited, which can be further enhanced by focusing the laser into a very small area. First, the duration of any individual pulse is sufficiently short so there is no time for heat to dissipate through thermal conduction. Hence, the thermal energy will, for a short time, be just as concentrated as the laser energy. Second, while the pulses contain a low amount of energy (10–15 µJ is typical), the combination of temporal and spatial concentration—typically the pulses are focused into spots of 1–4 µm diameter for this type of welding—results in truly enormous energy densities, typically in the order of MW of peak power and GWcm^{-2} in intensity. This amount of energy is more than enough to not only melt but also vaporize material.

The combined effect is that there is a highly concentrated thermal gradient. The area of the weld zone is molten—as is required for welding—but the bulk of the material experiences almost no temperature rise. Furthermore, the thermally affected zone, defined here as the zone which has seen sufficient temperature to melt, is strictly limited in size to only a few 100 µm around the focus. It is this concentration of the temperature gradient that allows for welding of dissimilar materials without excess thermal stress because the total volume of heated material is strictly limited.

However, the extreme thermal gradient presents a new issue to the welding process—material at the focus of the laser beam will be not only melted but also vaporized (in fact, a plasma will be formed). This area essentially becomes a small pocket of high-pressure gas and,

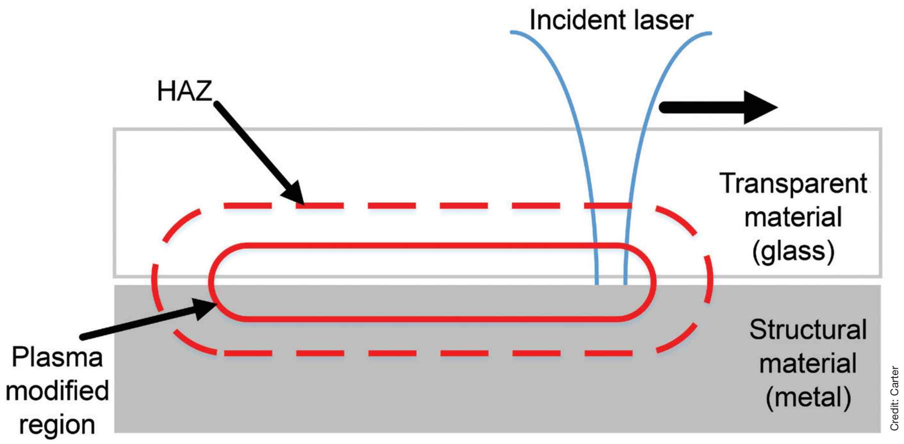


Figure 1. Schematic illustration of ultrashort pulse laser welding. The incident laser is focused through the glass onto the metal surface. By translating the laser along the interface, a weld is formed from an inner plasma affected region and an outer heat-affected zone (HAZ).

depending on the precise dynamics of the laser used, may be surrounded by a region of melted material. Thus, if a weld is attempted on the edge of the parts, this gas will escape as a jet, carrying off much of the melt volume with it and resulting in ablation rather than welding. This phenomenon limits the technique to a lap weld, where the laser is focused through one of the two materials (Figure 1). In this way, the gas is confined until it can cool and form a bond.

There clearly is a limit to the materials that can be welded with this technique as at least one must be transparent to the laser. Typically, these types of lasers operate at a wavelength of around 1,000 nm (in the near infrared part of the spectrum), although there are a range of other wavelengths commonly available. At this wavelength, most optical glasses and crystals will be transparent but all metals and most semiconductor materials will not. Ceramics pose an interesting issue as while several ceramics are nominally transparent at this wavelength, they often are highly scattering due to the fine structure and thus may not be suitable for focusing a laser beam through.

The final aspect of laser–material interactions using ultrashort pulses is the most intriguing: the ability to trigger what is referred to as nonlinear absorption. To understand this process requires some understanding of how light behaves and how it is absorbed by atoms. Light is composed of individual photons, where each photon has a specific amount of energy that is related to the wavelength. At 1,000 nm, glass is transparent because the photons do not have the correct energy to interact with the atoms within the glass. However, if several photons arrive at a single atom at essentially the same time, their combined energy will be enough to trigger absorption.

Under normal circumstances, the probability of photon absorption happening is essentially zero, but a focused ultrashort laser pulse has such extreme photon density that the probability becomes not only nonzero but quite likely. The net result is that it is possible to trigger absorption in otherwise transparent materials but only at the focus of an ultrashort laser pulse—nowhere else is the photon density sufficient to permit this phenomenon. In other words, it is possible to trigger absorption inside the volume of a transparent material.

This ability is extremely powerful because it allows us to control the energy deposition within an otherwise transparent material in three dimensions by carefully positioning the focus using microstages or some form of optical scanner. This effect has been known for some time and has been exploited in a range of applications to alter the glass properties (e.g., to change its refractive index and make waveguides; or to change the reaction of the glass to etchant chemicals, enabling selective etching). However, its potential to applications of laser welding was not appreciated until relatively recently.

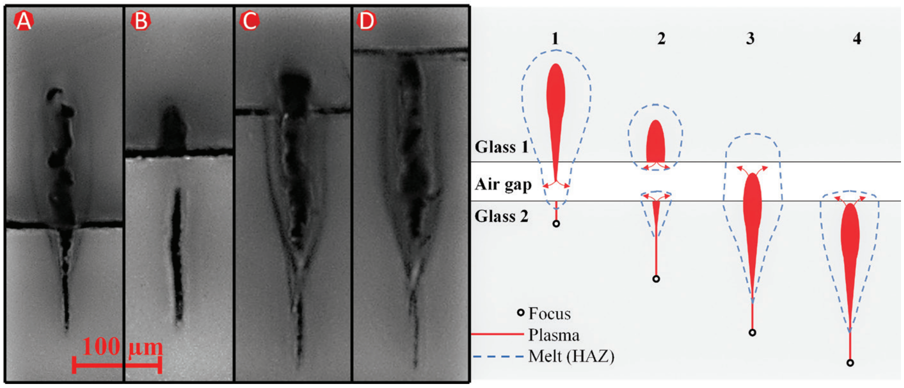
A brief history of ultrashort pulse laser welding

The story of ultrashort pulse laser welding starts in 2005 at Osaka University (Japan) with a paper demonstrating that it was possible to not only modify transparent material using an ultrashort laser pulse but also possible to weld them together.[1] In this paper, they focused a femtosecond laser on the interface region between two glass plates in intimate contact, fusing them into a weld. The importance of this result was clearly well appreciated by the team at Osaka because they were careful to obtain a patent within Japan before publishing.

Further publications from Osaka—including joint publications with RWTH-Aachen University (Germany) and IMRA American Inc. (a Michigan-based U.S. laser company)—expanded the understanding of the process and the range of glasses demonstrated, and also further reinforced the copywrite protection with additional patents in Germany, Japan, the U.S., and worldwide. However, the process they demonstrated relies on the formation of a fusion filament, a feature particular to femtosecond lasers, and it was only applied to transparent (i.e., broadly similar) materials.

This publication set off a bewildering array of research worldwide, with many publications demonstrating new material combinations as well as in-depth studies on the fundamental laser–material interactions, including development of sophisticated theoretical modeling systems. Readers of the *Bulletin* may be interested to note that this work has included welding of transparent ceramics,[2] but for the purpose of this article we will concentrate on developments toward dissimilar material welding.

It would not be till 2007 that Osaka published the first paper in the area of dissimilar material welding, when they demonstrated glass–silicon welding.[3] This achievement was significant as



Credit: Chen et al., *Optics Express*

Figure 2. Illustration of the use of a correctly positioned focal point to create a melt volume to bridge a gap, or local roughness, between two materials. Taken from Chen et al.[8]

it showed that welding was possible between a transparent and opaque material. However, the chemical compatibility of silicon and glass (essentially silicon dioxide) still left open the question of whether the process could be applied more universally to dissimilar materials. Shortly thereafter, the University of Kassel (Germany) published their own demonstration of silicon–glass welding in early 2008,[4] indicating international interest in this development.

Osaka continued to lead in this area, providing the next milestone in 2008 with a publication demonstrating the welding of copper and glass using a femtosecond laser.[5] This study was a major breakthrough as copper, silicon, and oxygen have limited chemical interactivity and thus limited scope to form a purely chemical bond. Nevertheless, a bond was indeed demonstrated, and it could now be said that truly dissimilar material welding was possible.

The following years would see surprisingly few publications in this area, as the majority of research seemingly aimed at similar material welding. It was not until 2011 that the next novel material demonstration was made: The University Laval (Canada) with a paper exhibiting welding of fused silica to both copper and tungsten.[6,7]

It is worth noting that up to this point all dissimilar material welding was carried out using a femtosecond laser. Although pico- and femtosecond lasers are both referred to as ultrashort lasers, there are significant differences in the way the laser–material interactions occur and thus their capabilities. As previously mentioned, femtosecond lasers are able to generate high aspect ratio filaments of plasma due to a complex self-focusing effect in material, while almost entirely avoiding the generation of molten material when using a low repetition rate (typically 1–10 kHz). This situation results in an extremely high aspect ratio weld structure but one which is generally quite intolerant to any gap between the two materials because even a micrometer level gap will allow the gas to escape. As such, submicrometer contact (often referred to as optical contact) is required between the two materials to prevent plasma from escaping—in effect holding the material together using van der Waal's force until it can be reinforced into a weld.

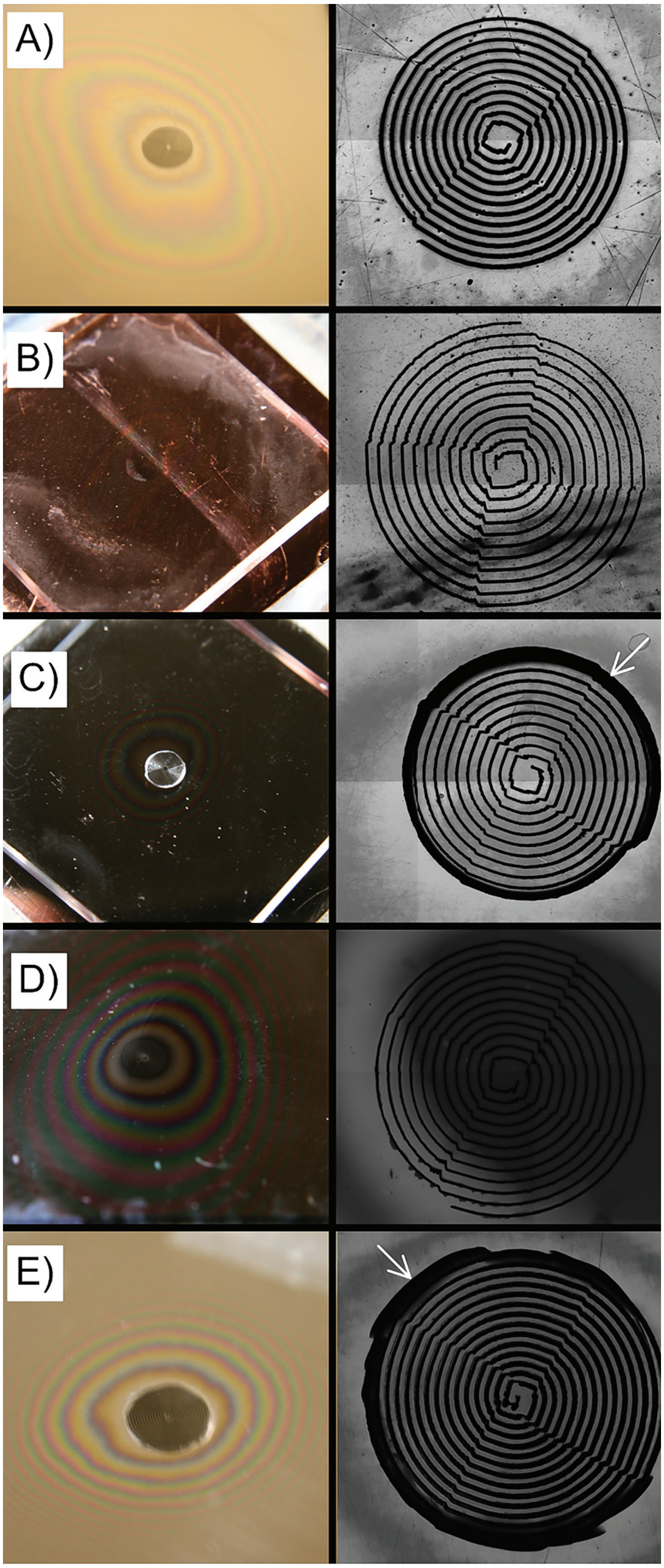
Higher repetition rate and picosecond laser systems, in comparison, produce a teardrop-shaped weld feature that typically exhibits a small but significant melt volume. This melt has been demonstrated to be useful in assisting confinement of the plasma (Figure 2) and thus in reducing the requirement for surface contact during the bonding process. However, it has the disadvantage that more care needs to be taken to ensure that the laser focus is accurately positioned and that increased gaps between materials will result in decreased weld strengths.[8]

In my own research group at Heriot-Watt University (Edinburgh, Scotland), we demonstrated welding using a picosecond laser with a paper in 2014.[9] In this case, additional proof-of-principle demonstrations expanded the range of materials to include new metals and a crystal: aluminum, stainless steel, silicon, and copper welded to glass and sapphire (Figure 3). Since 2014, several other universities have published works demonstrating welding of various combinations of these materials, indicating a widespread interest in this novel capability, including the universities of Tampere (Finland),[10] Okayama (Japan),[11] Nara (Japan),[12] Kyiv (Ukraine),[13] Guangdong (China),[14] and the Key State Labs in Xian (China).[15] However, it is only very recently that there were published demonstrations of further material combinations. In 2020, NASA (U.S.) demonstrated the bonding of several glasses and crystals to metals, including invar, titanium, calcium fluoride, and Zerodur (a specialist low thermal expansion glass from Schott).[16] More recently, Jena (Germany) made a significant contribution by demonstrating silicon–copper welding, where the silicon is the transparent optical material.[17]

Current capabilities and potential

The range of materials with published demonstrations include optical glasses, crystals, metals, ceramics, and semiconductors. Thus, the applicability of the technique is very broad. While some material combinations appear to be simpler to weld than others (usually demonstrated by a wider, more forgiving process parameter space), there is no clear link between material properties and the capability or ease of welding.

From my own experience, it is possible to weld almost any two materials provided they can be prepared properly. All that is required is time, effort, and sufficient samples to carry out a study of the welding parameter space. Indeed, the only material we have failed to weld entirely was not a single material but rather a mix of silicon carbide and aluminum with individual grains of each at multimicrometer sizes. Because these grains are larger than the laser spot size used for welding, the process is not really applied to a single material and hence unsurprising that no single set of welding parameters could be obtained for the combination.



Credit: Carter et al., *Applied Optics*

Figure 3. Our first of proof-of-principle welds in (A) Al-SiO_2 (B) Cu-SiO_2 (C) Stainless steel–BK7 optical glass (D) Si-SiO_2 (E) Stainless steel–Sapphire. These 2.5-mm diameter spirals are typical of a "spot weld arrangement." Note the backlash in our stage control—we have come quite a way since these samples! Taken from Carter et al.[9]

In terms of suitable optical sources, most work was carried out with lasers operating around 1,000 nm. However, there are examples in the literature from 515–1,558 nm, demonstrating that the precise wavelength (within reason) of the laser is not critical. Pulse durations also seem to widely vary, albeit always within the ultrashort pulse range, with demonstrations from 50–2,000 femtoseconds, which is likely more indicative of available lasers within disparate research labs than any fundamental requirement on pulse duration. Similarly, the repetition rates used vary from 1 kHz to several MHz, although here there seems to be a clear difference between femtosecond filament-based welding at low repetition rates and pico-/femto- processes at repetition rates exceeding 100 kHz, which rely on the formation of a melt volume and are more tolerant to surface roughness.

The overall picture, therefore, is that although the welding process requires optimization for each material combination and laser system, the required technical specifications for that laser are quite broad, allowing a wide range of laser manufacturers to be able to offer a suitable system provided they have sufficient knowhow of the focusing and material handling requirements.

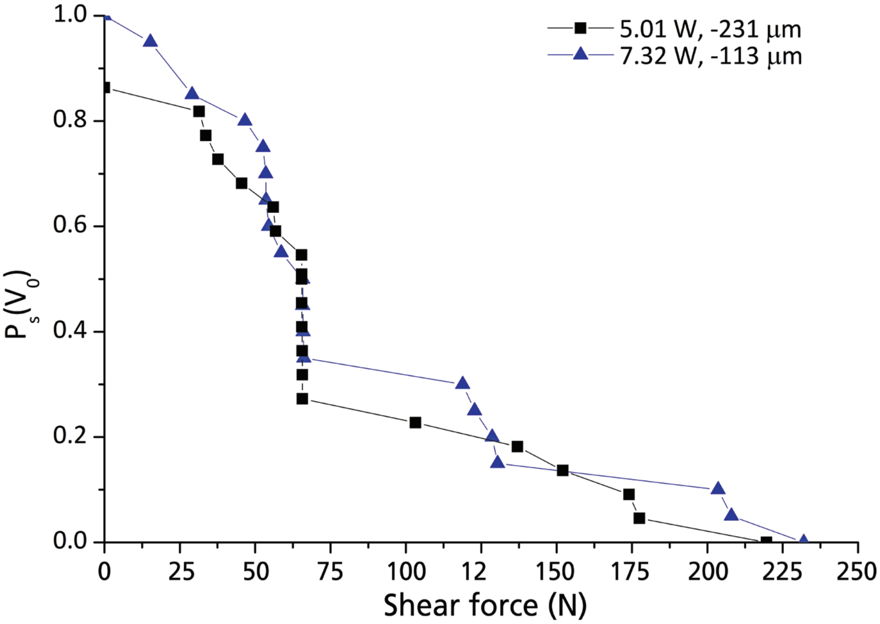
The quality of bonds is more difficult to assess because the majority of these tests are in a proof-of-principle stage with limited statistical information regarding the strength and yield, among other properties. To the best of my knowledge, the only in-depth analysis looking to optimize a dissimilar welding process was carried out at Heriot-Watt,[18] although readers will readily appreciate that this kind of detailed research does not always make it into published papers—particularly where there is a potential for industrial application and new product development.

Where the quality of these welds was investigated, they tend to rely on some form of mechanical strength for quantitative evaluation. Typical arrangements involve a pull, shear, or some form of wedge/knife inserted in the gap between the components after welding, with the force required to break the bond being logged. It is prudent to be cautious in directly comparing the absolute values of weld strength between published techniques because the techniques usually are not directly comparable to one another and there is as yet no clear ISO standard for evaluating these types of bonds. Nevertheless, such results are suitable for identifying an optimum for a specific welding process and will, at the least, provide a reasonable estimate of expected strength, as can be seen in Figure 4.

One of the issues that becomes quickly apparent is in how the welds fail. This failure is almost always in the glass—often with a volume of glass left attached to the structural component after failure—because the welding process creates a defect in the glass. At the boundary of the glass melt zone, there is an abrupt change to the fictive temperature, which manifests as a visual change in refractive index as well as local stress. Studies indicate it is this line that most often fails (Figure 5).[9] The glass–metal weld, despite exhibiting complex chemistry, microcracks,[19] which in standard welding would all be causes for concern but is not normally the source of failure.

Thus, in almost every case it is the optical component that fails first. Because the optical component usually is a brittle material, the difficulty then is that the "weld" failure is brittle as well—with all the accompanying statistical variation this failure implies. To obtain reliable data on the strength of the bonds, it is thus not only necessary to carefully design a measurement technique but also to measure a large number of components to build up a statistically meaningful set of data. Nevertheless, results from across the published record suggest bonds that are at least as strong as equivalent adhesives and, in some cases, more than ten times stronger—certainly sufficient for current applications.

It is crucial to note that these studies reveal that both the strength and the reliability (yield) is tightly intertwined with material preparation. As mentioned, to obtain a strong, reliable bond, the materials should ideally be placed in intimate, optical contact before welding. This placement is clearly more readily achieved with materials that are extremely flat, smooth, and clean. While easily achieved in optical components (as these are already prepared to high specifications with sub micrometer or even 10s of nanometer roughness and flatness), preparing structural materials to the same specification is a nontrivial problem that scales with the required contact area.



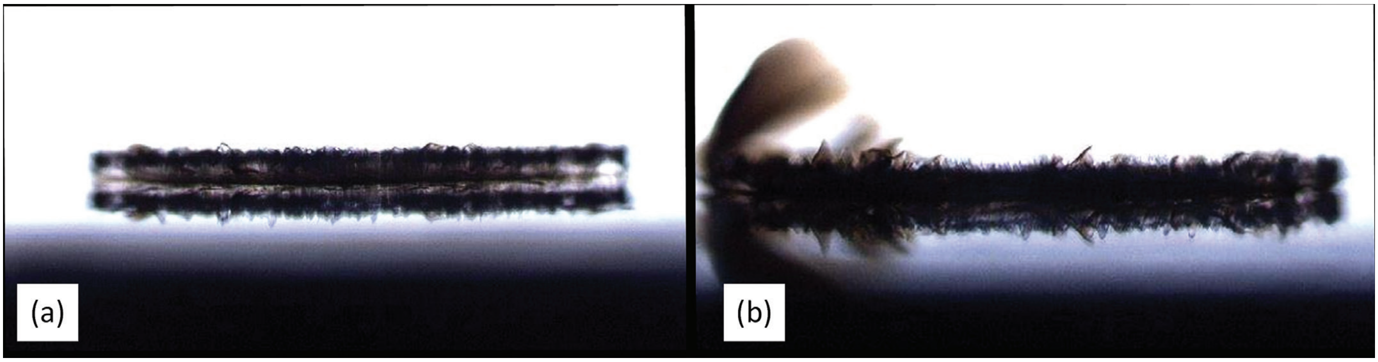
Credit: Carter et al., *Applied Optics*

Figure 4. Example of weld strength statistics for Al–BK7 bonding. In this case, 20 samples for each of two processing parameters (average power and focal position) were tested. The bonds here are single 2.5-mm diameter spot welds and are required to sustain only 7 N of shear force for this application. Taken from Carter et al.[9]

The common option at present is to polish the material to an essentially mirror finish via lapping, thus providing both the required roughness and flatness. This process is both slow and expensive, but with the right equipment and expertise, it is reliable for most materials (aluminum being a key exception). Unfortunately, lapping requires the target surface to be both flat and exposed as curved or recessed surfaces (both often desired for optical mounts) are out of the question. While other polishing techniques may be applicable (e.g., chemical, laser) it has yet to be demonstrated that both the required level of flatness and roughness can be achieved in a reliable fashion.

The alternative technique, which Heriot-Watt has developed extensively, is to use the melt generated in a 100s kHz process to fill the gap between the two materials, thus relaxing the requirement to polish the metal surface. To date we have successfully welded surfaces with SA roughness in the order of approximately 1 µm, which is consistent with a high-quality machined or ground surface. However, care still is required so that the surface preparation method does not detrimentally affect the welding because yields varying between 80–97% have been obtained for different preparations methods of what is nominally the same surface finish.

Thus strengths, yields, and material combinations are appropriate for a wide range of applications where a mechanical bond is required. But what of applications where more than a purely mechanical attachment is required? Hermeticity has been demonstrated in glass–glass and glass–silicon welding, but it remains to be



Credit: Carter et al., *Applied Optics*

Figure 5. Illustration of the weld failure mechanism for a glass–metal bond. Both images are taken side on with a reflection of the weld and the metal surface visible toward the bottom of the images. Image (a) is an untested example. Image (b) was taken partway through the welding process, and a crack in the glass has developed. Adapted from Carter et al.[9]

Figure 6. (a) Photograph of an Oxford Lasers C-Series laser micromachining station. Images of example laser welded parts: (b) One-inch, 4-mm thick quartz waveplate welded to stainless steel, (c) Fused silica plate welded to the end of a 40-mm diameter aluminum tube, (d) BK7 prism (18-mm height) welded to a mounting plate. Images courtesy of Oxford Lasers. www.oxfordlasers.com.

Credit: Oxford Lasers

demonstrated if this is the case more generally—although it would certainly be extremely surprising given the weld cross-sections studied thus far to find that it is not. However, a point to consider is that thermal expansion is still an issue for the assembled component. Using an ultrashort laser pulse allows the materials to be bonded but does not change the fundamental fact that two dissimilar materials will expand at differing rates. A purely mechanical bond can be achieved using a series of small spot welds, thus limiting the issue, but for a hermetic seal a continuous perimeter weld will be required which, by necessity, will cover a longer line and larger area, thus giving larger expansion stresses.

Industrial availability and applications

An early adopter of an industrial process was IMRA American Inc. (from at least 2006). Although they currently hold some of the key patents publicly available, information suggests they offer only similar material (glass–glass) welding as a process. A second early entry came in the form of a Finnish company, Primoceler Oy. This company appears to have been a spin out from the collaborative work between Osaka and Tampere around 2013.[10,11] Initially aimed at glass–glass welding, the company also offered glass–silicon welding as part of an all-glass or silicon–glass packaging capability. In 2018, Primoceler was acquired by Schott AG (who also holds an Osaka patent), who now offers glass–glass and glass–silicon welding.

Trumpf (a German laser systems company) also is known to be active in this area, with joint publications with the Universities of Jena and Aachen.[20,21] For the most part, this research seems to be in the area of glass–glass welding (including as part of its own production process for optical fiber end caps), although in the last few years Trumpf showed glass–metal optical mounds with welds at exhibitions, which seems to be as far as the company has taken such applications.

The most recent entry into the field is Oxford Lasers (U.K.). They, in collaboration with Heriot-Watt University, developed a prototype laser welding system for glass–metal welding, including demonstrations of aluminum–BK7 and quartz–stainless steel. Importantly, this prototype is a fully integrated platform based on a standard turnkey laser micromachining platform (Figure 6), the general form of which will be familiar to industrial laser uses. Therefore, it includes the expected capacity to, among other things, generate user-defined laser beam toolpaths and correct for working distances and aberrations in optics, but also an adjustable laser amplifier allowing for both a pico- and femtosecond welding on demand.

The key advantages in ultrashort laser welding are the limited thermally affected zone, the ability to join a range of materials, and the ability to do so without introducing an interlayer. However, the cost of an ultrashort laser system is currently in the order of more than $100k, suggesting applications either require economy of scale or high-value products. From the current industrial players, this suggestion would seem to bear out because, although there are few public examples to draw on. Schott seems to have taken aim at semiconductor device packaging while Trumpf and Oxford Lasers appear to be well set up to cater to high-value optical, optomechanical, and aerospace device fabrication.

In truth, while high-value manufacturing has led the way, the range of potential applications is truly staggering because dissimilar material bonding is an issue in almost all areas of manufacturing, from microdevices up to building-scale applications. We have every expectation that this technique will rise to its potential and prove to be a significant new capability.

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References

[1] T. Tamaki, W. Watanabe, J. Nishii, and K. Itoh, “Welding of transparent materials using femtosecond laser pulses,” *Japanese journal of applied physics*, vol. 44, no. 5L, p. L687, 2005.

[2] E. Penilla et al., “Ultrafast laser welding of ceramics,” *Science*, vol. 365, no. 6455, pp. 803–808, 2019.

[3] T. Tamaki, W. Watanabe, and K. Itoh, “Laser micro-welding of silicon and borosilicate glass using nonlinear absorption effect induced by 1558-nm femtosecond fiber laser pulses,” in *Commercial and Biomedical Applications of Ultrafast Lasers VII*, 2007, vol. 6460: International Society for Optics and Photonics, p. 646018.

[4] A. Horn, I. Mingareev, A. Werth, M. Kachel, and U. Brenk, “Investigations on ultrafast welding of glass–glass and glass–silicon,” *Applied Physics A*, vol. 93, no. 1, p. 171, 2008.

[5] Y. Ozeki et al., “Direct welding between copper and glass substrates with femtosecond laser pulses,” *Applied physics express*, vol. 1, no. 8, p. 082601, 2008.

[6] F. Lacroix, D. Hélie, and R. Vallée, “Optical bonding reinforced by femtosecond laser welding,” in *Optical Manufacturing and Testing IX*, 2011, vol. 8126: International Society for Optics and Photonics, p. 812612.

[7] D. Hélie, F. Lacroix, and R. Vallée, *Bonding of optical materials by femtosecond laser welding for aerospace and high power laser applications* (Photonics North 2012). SPIE, 2012, vol. 8412.

[8] J. Chen, R. M. Carter, R. R. Thomson, and D. P. Hand, “Avoiding the requirement for pre-existing optical contact during picosecond laser glass-to-glass welding,” *Optics express*, vol. 23, no. 14, pp. 18645–18657, 2015.

[9] R. M. Carter, J. Chen, J. D. Shephard, R. R. Thomson, and D. P. Hand, “Picosecond laser welding of similar and dissimilar materials,” *Applied optics*, vol. 53, no. 19, pp. 4233–4238, 2014.

[10] I. Miyamoto, Y. Okamoto, A. Hansen, J. Vihinen, T. Amberla, and J. Kangastupa, “High speed, high strength microwelding of Si/glass using ps-laser pulses,” *Optics express*, vol. 23, no. 3, pp. 3427–3439, 2015.

[11] Y. Okamoto, I. Miyamoto, J. Vihinen, and A. Okada, “Novel micro-welding of silicon and glass by ultrashort pulsed laser,” in *Materials Science Forum*, 2014, vol. 783: Trans Tech Publ, pp. 2792–2797.

[12] M. M. Negrub, D. Hélie, I. V. Yurgelevych, and L. V. Poperenko, “Ellipsometric control of laser welded materials,” in *International Conference on Global Research and Education*, 2017: Springer, pp. 26–31.

[13] J. Zhang et al., “Microwelding of glass to silicon by green ultrafast laser pulses,” *Optics & Laser Technology*, vol. 120, p. 105720, 2019.

[14] S. Matsuyoshi, Y. Mizuguchi, A. Muratsugu, H. Yamada, T. Tamaki, and W. Watanabe, “Welding of glass and copper with a rough surface using femtosecond fiber laser pulses,” *Journal of Laser Micro Nanoengineering*, vol. 13, no. 1, pp. 21–25, 2018.

[15] G. Zhang and G. Cheng, “Direct welding of glass and metal by 1 kHz femtosecond laser pulses,” *Applied optics*, vol. 54, no. 30, pp. 8957–8961, 2015.

[16] R. Lafon, S. Li, F. Micalizzi, and S. Lebair, *Ultrafast laser bonding of glasses and crystals to metals for epoxy-free optical instruments* (SPIE LASE). SPIE, 2020, vol. 11261.

[17] M. Chambonneau et al., “Taming ultrafast laser filaments for optimized semiconductor-metal welding,” *Laser & Photonics Reviews*, 15, 2000433, 2021.

[18] R. M. Carter et al., “Towards industrial ultrafast laser microwelding: SiO$_2$ and BK7 to aluminum alloy,” *Applied optics*, vol. 56, no. 16, pp. 4873–4881, 2017.

[19] O. P. Ciuca, R. M. Carter, P. B. Prangnell, and D. P. Hand, “Characterisation of weld zone reactions in dissimilar glass-to-aluminium pulsed picosecond laser welds,” *Materials Characterization*, vol. 120, pp. 53–62, 2016.

[20] S. Richter et al., “Laser welding of glasses at high repetition rates – fundamentals and prospects,” *Optics & Laser Technology*, vol. 83, pp. 59–66, 2016.

[21] F. Zimmermann et al., *Advanced welding of transparent materials by ultrashort laser pulses* (SPIE LAMOM). SPIE, 2019, vol. 10519.