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Advances in Laser Micro-welding of Transparent Hard Brittle (THB) Materials

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Abstract

Transparent hard brittle (THB) materials have attracted much attention due to their properties such as broad spectral transmittance, excellent chemical inertness, and high hardness, but they often face micro-joining challenges in practical applications. Laser processing is a contactless and high-precision processing method, which has become an important technology in the field of micro-welding due to its wide range of applications, easy operation and high efficiency. In this paper, the effects of different lasers in THB due to different energy deposition are analyzed by taking the characteristic time of electron-phonon coupling of 10 ps as the boundary. The article focuses on summarizing the current research status and welding methods of conventional laser welding and ultra fast (UF) laser welding at home and abroad, and puts forward feasible suggestions for future research, which will provide a reference for the in-depth study of laser micro-welding of THB materials.

Keywords

Micro-welding; THB; UF laser; Linear absorption; Conventional laser; Nonlinear absorption.

1. INTRODUCTION

With the continuous technological advances in aerospace, medical devices and microelectronic packaging, products are gradually developing towards multifunctionality and miniaturization, and the demand for micro-nano connectivity devices grows consequently, and the requirements for their performance become increasingly stringent, highlighting the importance of micro-nano connectivity in fabrication [1][2]. However, the THBs used in the practical application of these devices are usually fragile in texture, lack of toughness, poor in high-temperature tolerance, and have a concentrated stress distribution. During the soldering process, it will lead to a large number of defects easy to rupture due to thermal expansion of the material, and it is difficult to meet the increasing connection precision requirements of micro and nanodevices. Therefore, how to realize more efficient and reliable THB micro-connections has become an urgent problem.

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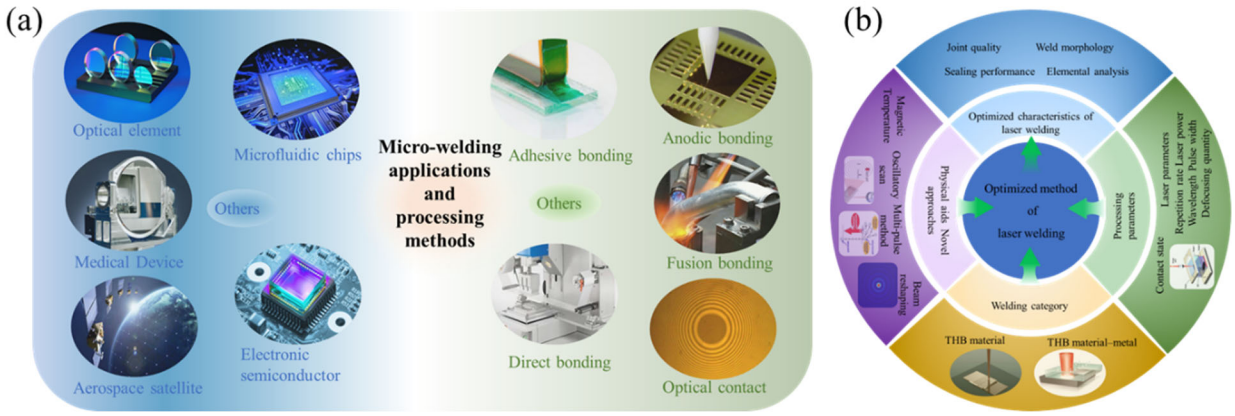


Figure 1. (a) Micro-welding applications and conventional micro-connections, (b) Micro-welding optimization strategy.

As shown in Fig. 1(a), for different micro-welding applications, many scholars have tried various methods to connect THBs, including adhesive bonding [3], anodic bonding [4], optical contacting [5], fusion bonding [6], direct bonding [7], and solid-state bonding [8]. However, these methods still have inherent limitations and shortcomings in achieving reliable and robust bonding, which limits their large-scale applications. Laser micro-welding technology, which possesses the advantages of precise and controllable welding area, low damage and high reliability [9], is considered to be a more efficient method. As shown in Fig. 1(b), in order to further improve the processing efficiency and quality of laser micro-welding, this paper introduces the processing principles and characteristics of two different laser micro-welding, summarizes the current status of domestic and international research and the different welding methods, and evaluates their advantages and disadvantages as well as the potential development direction. This paper aims to provide references for applications in medical devices, aerospace and electronic semiconductors.

2. PROPERTIES

2.1. Conventional laser micro-welding principle of operation

As shown in Fig. 2(a), the conventional laser welding of THB is derived from metal laser welding technology. When the laser radiates to the metal surface, the thin layer of metal directly absorbs the laser energy, as shown in Fig. 2(e), producing a linear absorption effect. When the energy absorbed by the material reaches a thermodynamic critical temperature, the phase explosion triggers the mixing of high-temperature and high-pressure metal vapors with the melt, and these substances fill the base material gap, resulting in a reliable welded joint [10]. As shown in Fig. 2(b), most THB materials are insulators with a large bandgap, which makes it difficult to absorb photons linearly and only achieve absorption of light at specific wavelengths [11], and therefore cannot be welded directly. To solve this problem, conventional laser welding mainly uses two methods: one, as shown in Fig. 2(c), an intermediate layer of material is introduced into the glass contact gap, so that the laser forms an absorption band in the intermediate layer, which linearly absorbs the energy and realizes the welding through heat conduction; and the other, as shown in Fig. 2(d), the transmittance of the lower material is adjusted, so that it acts as an absorbing layer to absorb the energy.

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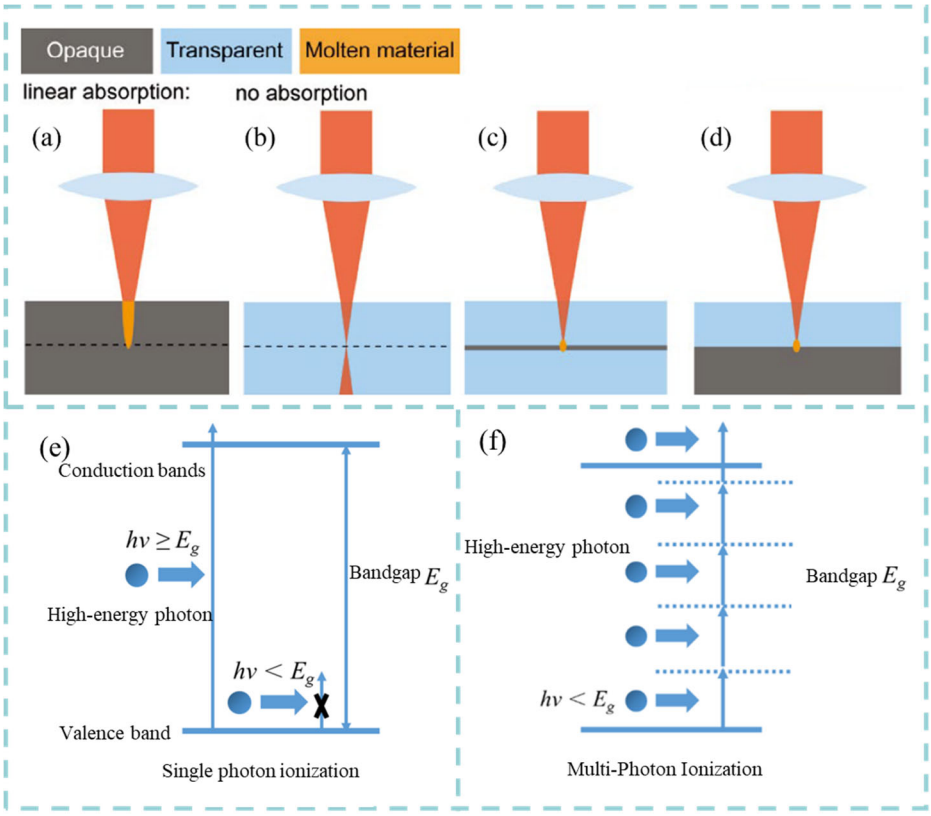


Figure 2. (a) linear absorption effect, (b) no absorption, (c) linear absorption in the middle absorbing layer, (d) linear absorption in the lower opaque material, (e) Single-photon ionization schematic, (f) Multi-photon ionization schematic.

2.2. Conventional laser introduction of intermediate layer substance micro-welding

In fields such as microelectromechanical systems (MEMS), organic light-emitting diodes (OLEDs), and photovoltaic (PV) cells, conventional laser bonding is usually performed by introducing an intermediate layer of material as an absorbing layer to the THB material. This method does not require high temperatures or highly clean surface polishing, is suitable for bonding surfaces with medium roughness, has low bonding temperatures, good airtightness, low interfacial stresses, and effectively overcomes the effects of differences in coefficients of thermal expansion [11]. Common interlayer materials include glass pastes, polymers and metal solder alloys. As shown in Fig. 3(a), Wu et al [12] used a continuous laser as the heat source and glass paste as the interlayer to hermetically weld a variety of micro devices. As shown in Fig. 3(b), Lin et al [13] achieved solder encapsulation of organic light emitting semiconductors (OLEDs) by doping PbTiO3 in a low-temperature glass slurry and successfully bonded samples with glass frit endcaps. S. Emami et al [14] achieved hermetic sealing of soda-lime substrate by employing a continuous laser for sintering the glass slurry where the sintered glass frit thickness was about 12 μm. Wu et al [15] achieved localized laser bonding of glass to silicon by using the polymer benzocyclobutene (BCB) as an intermediate layer as shown in Fig. 3(c). In addition, there are many studies [16][17] using the same principle to realize wafer-level packaging using BCB. Tan et al. [18] successfully achieved bonding using an Au and Sn interlayer consisting of an 80:20 weight ratio (Au:Sn) ratio at a low temperature of 280 °C. Luo et al. [19] successfully bonded glass to silicon using an indium layer of 4 μm thickness as the bonding material and a nanosecond pulsed laser with a shaded mask for energy output. The encapsulation of MEMS was realized by using a 4 μm thick indium layer as the bonding material and a nanosecond pulsed laser with a shadow mask for energy output. The indium layer acts as

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an intermediate layer to absorb energy and promote glass bonding. As shown in Fig. 3(d), Pablos-Martín et al [20] utilized a nanosecond pulsed laser for glass bonding with a titanium film as the absorber, and the joining effect was remarkable. Wang et al [21] added a 30 nm thick titanium coating as the absorber layer between two layers of glass, and the titanium film was fully mixed with the surrounding glass without component segregation or obvious crack extension. Huo et al [22] used a nanosecond fiber laser with a Cr interlayer to weld reinforcement between quartz glass and stainless steel, with a maximum shear strength of 41.4 MPa, which is 40 % higher than the yield without added Cr.

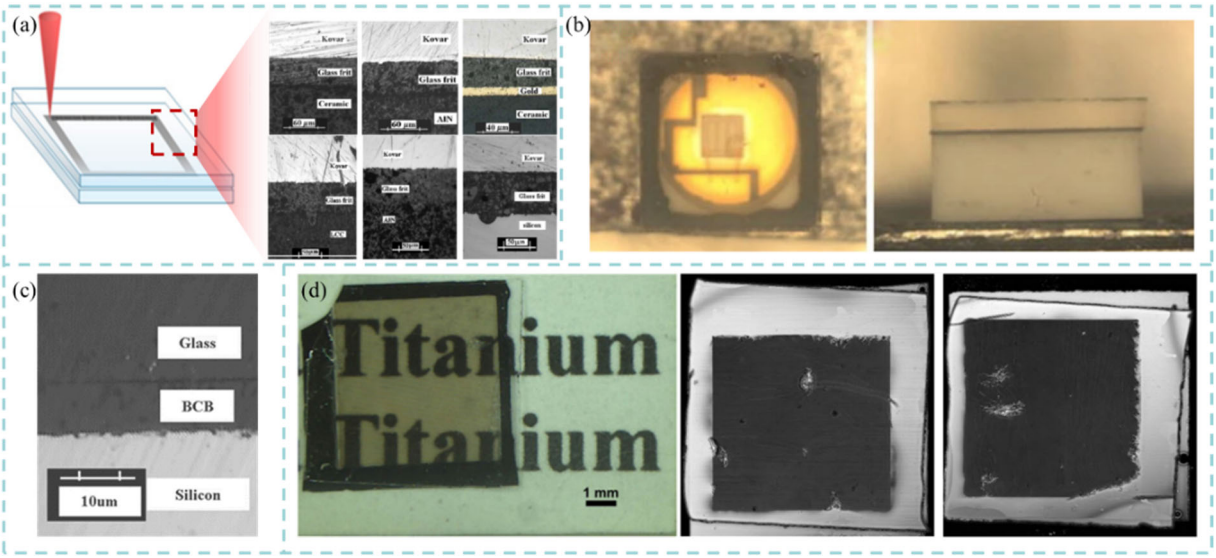


Figure 3. (a) Glass slurry as interlayer, (b) Glass frit end-cap joints welded using low-temperature glass slurry, (c) Polymer BCB as interlayer, (d) Photographs and SAM micrographs of thin glass/Ti film/thin glass bonded samples.

2.3. Conventional laser alteration of lower material micro-welding

As shown in Fig. 4(a), Utsumi et al [23] used a nanosecond laser for direct welding of glass to copper. The laser penetrates through the glass and irradiates the metallic copper surface, which absorbs the laser energy resulting in thermal melting of the contact surfaces and the formation of a stable connection after cooling and condensation. As shown in Fig. 4(b), Zhang et al [24] achieved the bonding of glass to aluminum using a microsecond laser with a shear strength measurement of 8.94 MPa. As shown in Fig. 4(c), Li et al [25] performed laser transmission welding of high borosilicate glass to titanium alloys using an Nd:YAG laser with a pulse width of 2.5 ms with success. As shown in Fig. 4(d), Nguyen et al [26] used a nanosecond pulsed laser to perform laser transmittance welding of glass and copper and conducted an in-depth study on the heterogeneous bonding process. Li et al [27] performed millisecond laser transmittance welding of high borosilicate glass with TC4 titanium alloy, and proposed an anodic oxidation of the TC4 titanium alloy in order to prepare an oxide film on the surface as a glass- metal welding buffer layer, when the thickness of the oxide film on the surface of TC4 titanium alloy is relatively thin, its bonding strength with the glass welded components is higher than that of the untreated TC4 titanium alloy and glass welded components.

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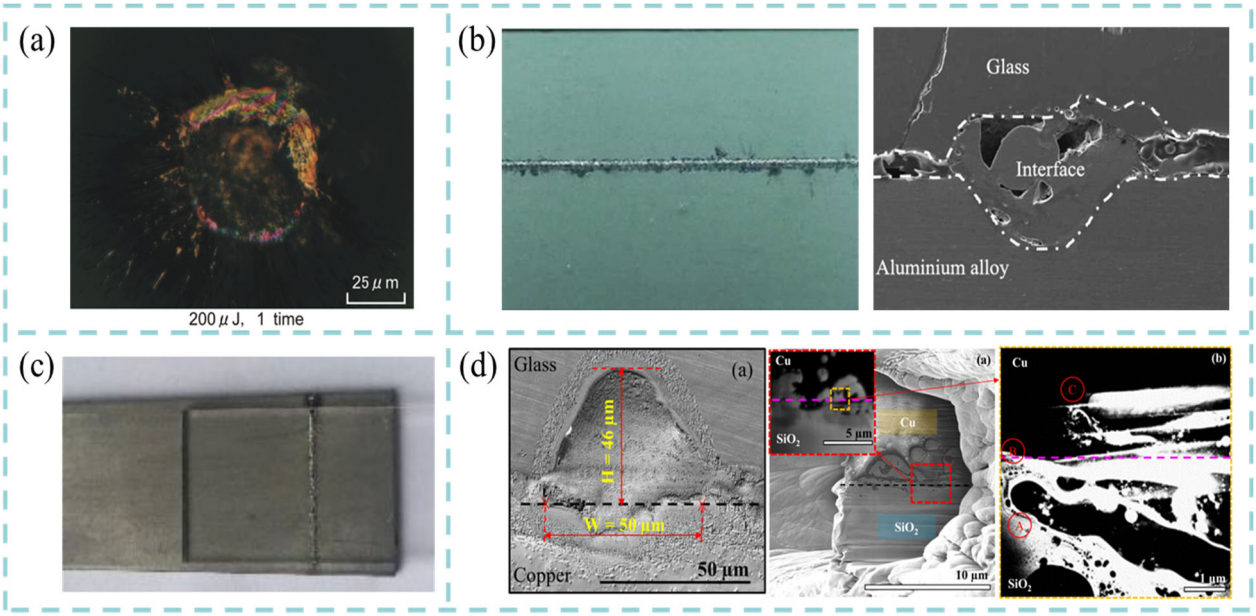


Figure 4. (a) Bonding of glass to copper, (b) Bonding of glass to aluminum, (c) Bonding of glass to titanium alloy, (d) Heterogeneous bonding of glass to copper.

3. UF LASER MICRO-WELDING

3.1. Working principle of UF laser micro-welding

With the rapid development of laser technology, UF lasers have received widespread attention. Its pulse width ranges from picoseconds to femtoseconds, and it is capable of triggering not only linear absorption effects in metallic materials, but also nonlinear absorption effects in THB materials (as shown in Fig. 5(a)) [28]. The generation of this phenomenon depends mainly on the way the pulse width and power density of the laser act on the material (as shown in Fig. 5(b)). Multi-photon ionization is triggered when the laser intensity exceeds a specific threshold (as shown in Fig. 2(f)). When the pulse width is less than 100 fs, electrons can also form free electrons by overcoming the potential barrier and thus tunneling ionization occurs [29]. These two nonlinear ionization modes are capable of exciting nonlinear absorption of photons and converting bound electrons into free electrons, resulting in bandgap jumping of valence band electrons. The free electrons subsequently play a key role in the avalanche ionization process (as shown in Fig. 5(c)). The number of free electrons in the conduction band grows exponentially and the lattice heat is gradually accumulated by inverse bremsstrahlung until a quasi-static state is reached. At this point, the melt at the focal point is thermally melted and solidifies during cooling, resulting in inter-substrate welding [30]. In this process, the dual-temperature model describes the variation rule of electron temperature and lattice temperature with time (as shown in Fig. 5(d)).

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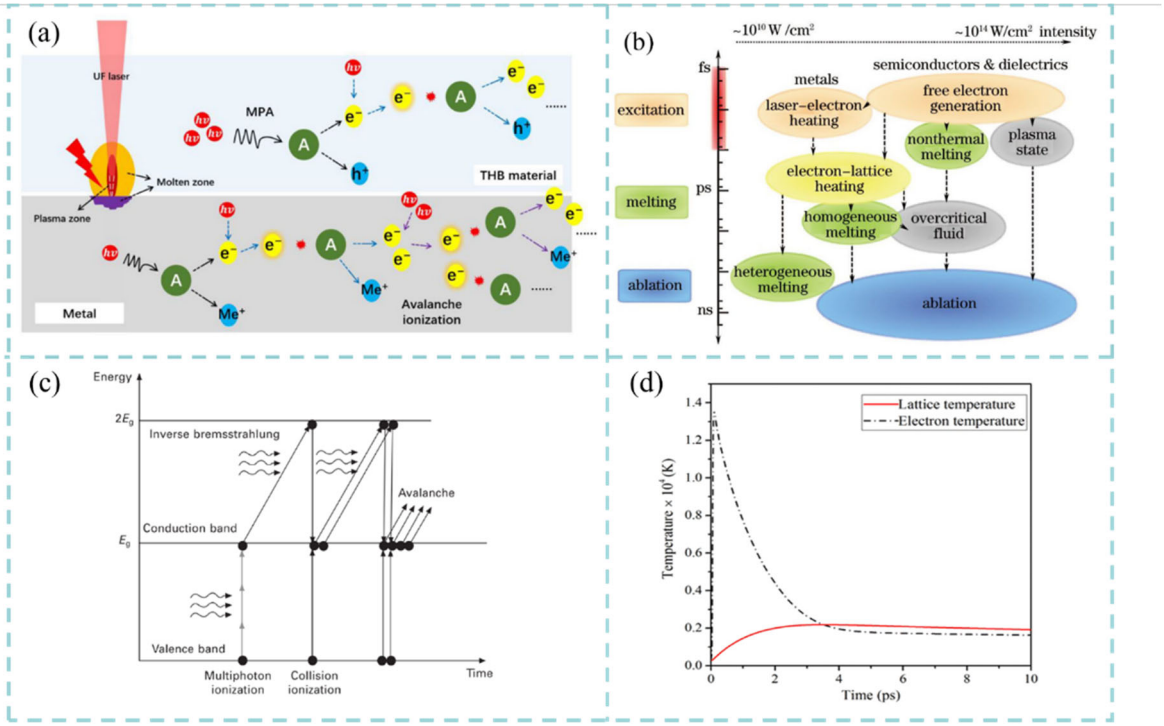


Figure 5. (a) Schematic diagram of laser welding of metal and THB materials, (b) material action modes with different pulse widths and power densities, (c) schematic diagram of avalanche ionization, (d) graph of electron temperature and lattice temperature change patterns with time in the dual-temperature model.

3.2. UF laser micro-welding of homogeneous materials

In 2005, Tamaki et al [31] first utilized a near-infrared UF laser with a pulse width of 130 fs, a wavelength of 800 nm, and a repetition frequency of 1 kHz, which was focused at the contact gap of quartz glass through an objective lens to stimulate a nonlinear absorption effect, and then melted the material at the focal point to fill the gap and cooled down to successfully achieve glass micro-welding. In the process of UF laser welding of glass, the welding area usually presents a droplet-like dual structure (as shown in Figure 6(a)). Due to the ultra-short pulse width, the laser light intensity can reach extremely high values instantaneously, causing the local temperature to rise to thousands of degrees Celsius. However, the extent of the heat affected zone is very small (as shown in Fig. 6(b)) [32]. However, the nonlinear absorption effect of UF lasers produces a more limited amount of molten material [33], making it difficult to achieve welding with large gaps. Therefore, it is usually necessary to ensure that the contact gap meets the optical contact conditions when welding. Optical contact conditions require that the glass sample gap is less than 1/4 wavelength or even within 100 nm [1]. In order to fulfill the condition, the surface roughness of the material can be reduced by cleaning and grinding, which reduces the amount of melt required to fill the gap during the soldering process. In addition, the requirement for optical contact can be met by clamping the sample with a fixture during the soldering process. Tamaki et al [34] used a femtosecond fiber laser with a wavelength of 1558 nm and a repetition frequency of 500 kHz to successfully weld a non-alkaline glass substrate with a joint strength of 9.87 MPa. Tamaki et al [34] used a femtosecond fiber laser with a wavelength of 1558 nm and a repetition frequency of 500 kHz to successfully demonstrate the welding of a non-alkaline glass substrate, and the joint strength reached 9.87 MPa. The process is shown in Fig. 6(c), where the cleaned substrates are first stacked together, then pressurized using a fixture with a lens and three bolts, and finally welded using an UF laser beam focused

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on the interface. Richter et al [35] also successfully welded silica using a fixture in combination with a femtosecond laser (1030 nm, 550 fs) in a process that employed a high 9 MHz repetition frequency. This resulted in a significant increase in the absorption rate and thermal accumulation promoting the expansion of the modified region, thus enhancing the welding effect [34]. It has been shown [36] that high repetition rate lasers operating in the MHz range induce higher absorption rates and thermal accumulation leads to larger modification zones, which are more conducive to welding. Zimmermann et al [37] used similar process parameters to weld borosilicate with joint strengths up to 95% of the substrate, with maximum strengths up to 113 MP. Butkus et al [38] used femtosecond lasers to weld calcium sodium glass, and the state and strength of the joint is shown in Fig. 6(d). The experiments showed that there exists an optimal range of process parameters for glass welding, and micro-welding can be achieved only at the appropriate pulse energy, scanning speed and gap, with a weld width of about 150 μm. Horn et al. [39] used a high repetition rate UF laser with a wavelength of 1045 nm and a pulse width of 350 fs to successfully weld borosilicate glass (D263 glass). Alexeev et al. [40] used a 4 W laser power, 1 MHz and 1 MHz laser power to weld borosilicate glass (D263 glass). successfully welded D263 glass using 4 W laser power, 1 MHz repetition frequency and 20 mm/s scanning speed.

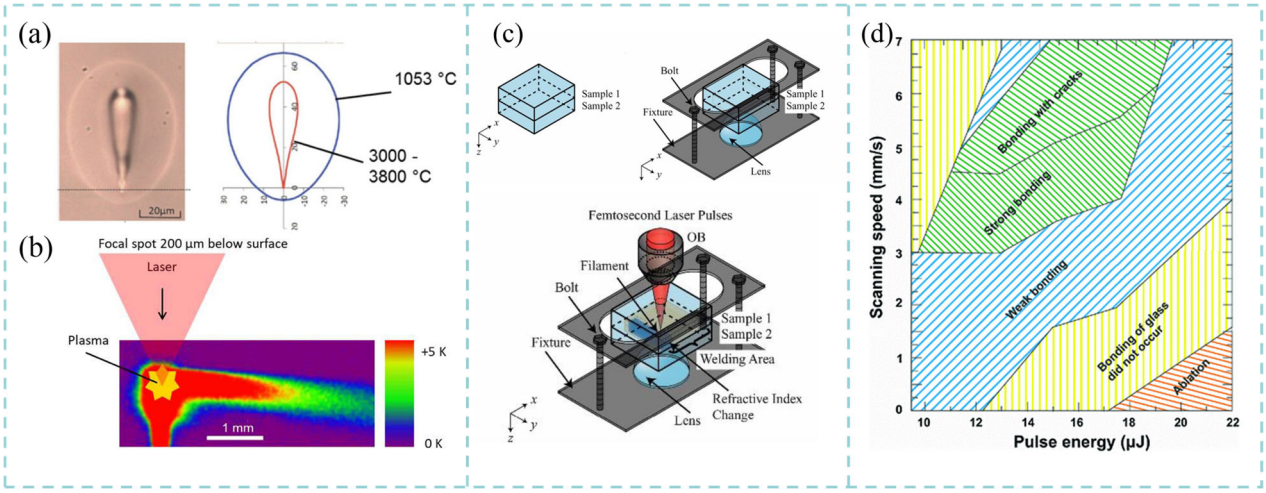


Figure 6. (a) Water droplet-like dual structure, (b) Welding heat affected zone, (c) Optical contact clamping method, (d) Laser welded calcium-sodium glass connection state and strength map.

In addition to femtosecond lasers, picosecond laser micro-welding is even more effective, even making optical contact conditions no longer necessary. Miyamoto et al [41] successfully realized picosecond laser welding of glass materials as early as 2007, laying the foundation for subsequent research. Penilla et al [42] used picosecond lasers to successfully realize welded encapsulation of ceramic components. Jia et al [43] used a picosecond laser to realize non-optical contact natrium glass by multiple scans. picosecond laser to realize the welding of non-optical contact soda-lime glass by multiple scans. Under the appropriate power parameters, the focused picosecond laser can form a melting region, and the multiple scans gradually expand the melting region, and finally realize the welding between two samples. Cvecek et al. [44], for the first time, based on the principle that UF laser irradiation leads to the expansion of the glass volume, used a picosecond laser with a pulse width of 10 ps and a repetition rate of 1 MHz to realize the bridge between the upper and lower glasses, and successfully welded the gap of 1 μm with a laser. Welding glass samples with a gap of 1 μm. Chen et al [45] successfully welded quartz glass with a gap of up to 3 μm using a picosecond laser in a four-stage welding process

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as shown in Fig. 7(a): plasma ablation stage, heat-affected zone ablation stage, intermittent welding stage, and continuous welding stage. In addition to the above mechanism of overcoming the realization of micro-welding by optical contact, Chen et al [46] proposed a novel gap bridging mechanism to successfully realize glass micro-welding with a gap of 10 μm by using a picosecond laser to perform a small-scale fast oscillatory scan at very low numerical aperture. In the experiment, a low laser power density is used, the laser energy deposition is relatively mild, and the non-optical contact spot welding of soda-lime glass is successfully realized by the high repetition frequency NdYVO4 picosecond laser with 1 MHz and the high-speed scanning galvanometer with 103 mm focal length, which carries out high-speed scanning and oscillating in concentric ring mode along the path shown in Fig. 7(b), and the limitations of the optical contact conditions are broken through, and the weld shaping effect is as shown in Fig. 7 (c), the maximum shear strength reaches 64 MPa, and reduces the generation of microcracks and improves the quality of welds. They also successfully performed sealing welding of larger glass gaps based on the same principle [47] with good sealing effect. Subsequently, Chen et al [48] placed a slit aperture in front of the objective lens, changed the circular Gaussian beam to an elliptical Gaussian distribution, and combined it with a 50 MHz ultra-high repetition rate UF laser to fill the larger glass gap, resulting in an average shear strength of 39 MPa, which was successfully welded. Gao et al [49] used a double-pulse femtosecond (fs) laser for high-strength welding of silica gel glass. By controlling the pulse delay of the double pulse, the welding characteristics of quartz glass under different time delays were analyzed, resulting in a welding strength of 57.15 MPa.

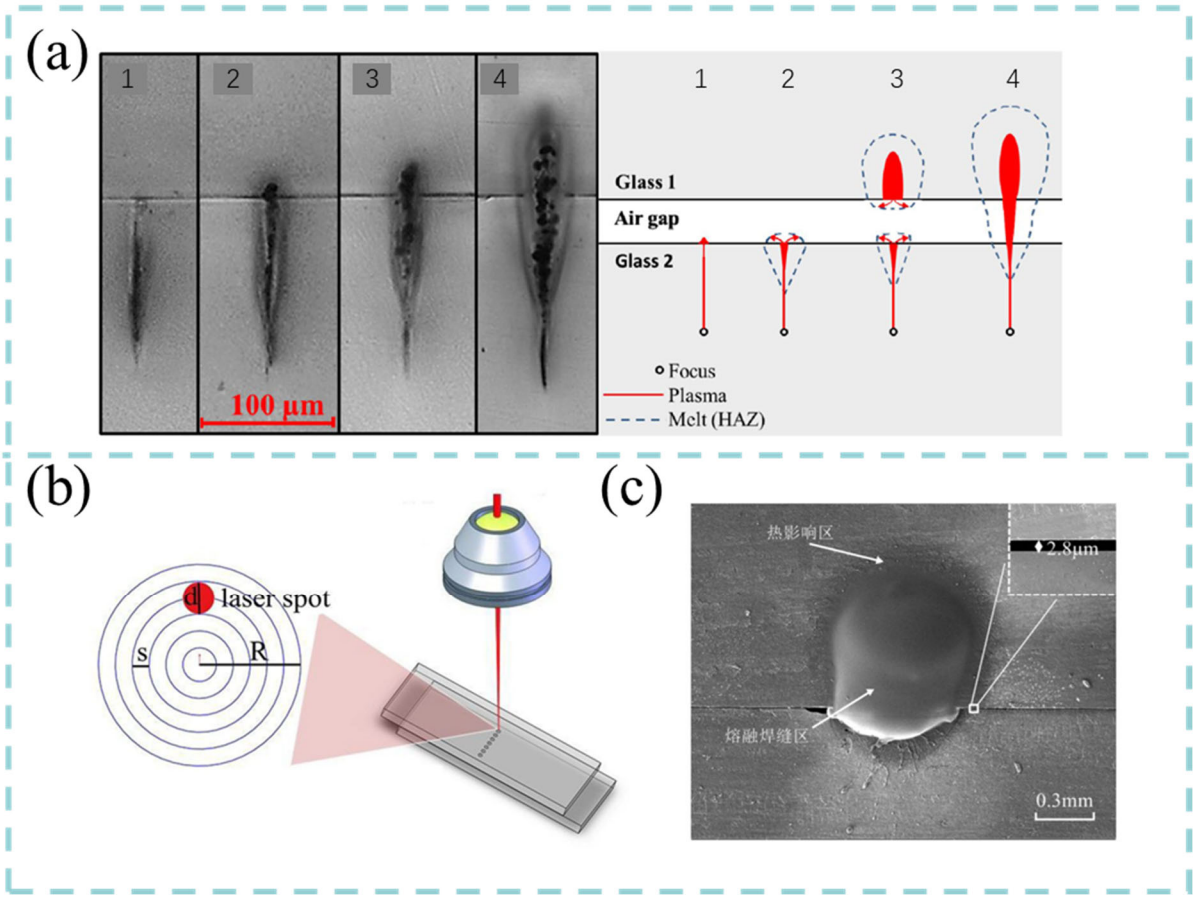


Figure 7. (a) Four stages of the welding process, (b) High-speed scanning oscillation strategy map, (c) Welding topography under non-optical contact.

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3.3. UF laser micro-welding of heterogeneous materials

Joining techniques for heterogeneous materials are important in many applications such as photovoltaic devices, optical windows for weaponry, vacuum-sealed connectors, and medical care [46], mainly including joining of multiple THB materials to each other and THB materials to metals. The thermo-mechanical stresses due to the differences in the coefficients of thermal expansion between the materials are significant, and there are many challenges to achieve a good weld.

In 2006, Watanabe et al [50] first reported the joining of borosilicate glass and fused silica glass with different coefficients of thermal expansion based on nonlinear absorption of a femtosecond pulsed laser, where the material produces localized melting and reconsolidation in the focused region of the laser, and the joint strength of the weld could reach 15.3 MPa. Subsequently, Watanabe et al [51] studied the optimal irradiation conditions required for joining borosilicate glass substrates and fused silica substrates using a 1 kHz femtosecond pulsed laser. borosilicate glass substrates and fused silica substrates under the optimum irradiation conditions required, and the joint strengths were both up to 14.9 MPa, and the joint strengths would continue to increase if the joint samples were annealed. Nordin et al [52] investigated the effect of laser wavelength and pulse width on the welding of monocrystalline silicon to glass, and the results showed that the fracture strengths of the nanosecond laser-welded specimens at a wavelength of 1064 nm were higher than those of the specimens welded at a wavelength of 532 nm. wavelength nanosecond laser-welded specimens; and the fracture strength of picosecond laser-welded specimens was higher than that of nanosecond lasers. Horn et al [53] investigated the changes in the morphology as well as the refractive index of borosilicate glass and silica welds. Richter et al [54] observed the differences in the weld cross-section for four heterogeneous glass combinations as shown in Fig. 8(a) depicting the applied base material and the corresponding homogeneous/non-homogeneous welded samples' fracture strength. Hélie et al [55] used a femtosecond laser to weld BK7 glass to fused silica, as shown in Fig. 8(b).Varying the femtosecond laser energy and comparing the cross sections of the welded samples revealed that, due to the different coefficients of thermal expansion of the glasses, the difference in the volume of fusion at the interface of the weld is also large, which also generates stresses that may even disrupt the optical contact between the samples and ultimately lead to a failure of the weld. In addition, only 0.6 μJ pulse energy is required to achieve this directly, and the SEM image of the cross-section of the optical filament trajectory is shown in Fig. 8(c). Tamaki et al [56] welded alkali-free glass substrates and silicon substrates based on the localized heat accumulation effect using a femtosecond laser with a wavelength of 1558 nm and a repetition frequency of 500 kHz with a connection strength of 3.74 MPa, and between alkali-free alumino-silicate glass substrates, with a connection strength of an even higher 9.87 MPa. Isamu Miyamoto et al [57] proposed a novel micro-welding method for joining glass and silicon using high repetition rate Ps laser pulses, employing a pulse width of 20 Ps pulsed laser and focusing the laser beam through a lens to provide a laser intensity below the photoionization threshold in the glass. The process enables mechanical strengths of up to 85 MPa for welded joints of silicon and aluminum silicate glass, and up to 45 MPa for welded joints of silicon and borosilicate glass, which is a significant increase in weld strength and is more reliable than anodic bonding, and also offers the advantages of high spatial resolution (< 20 μm), high throughput, and no need for preheating and post-heating. It is also worth mentioning that the highest weld strengths of 200 MPa have been achieved for different transparent materials [58].

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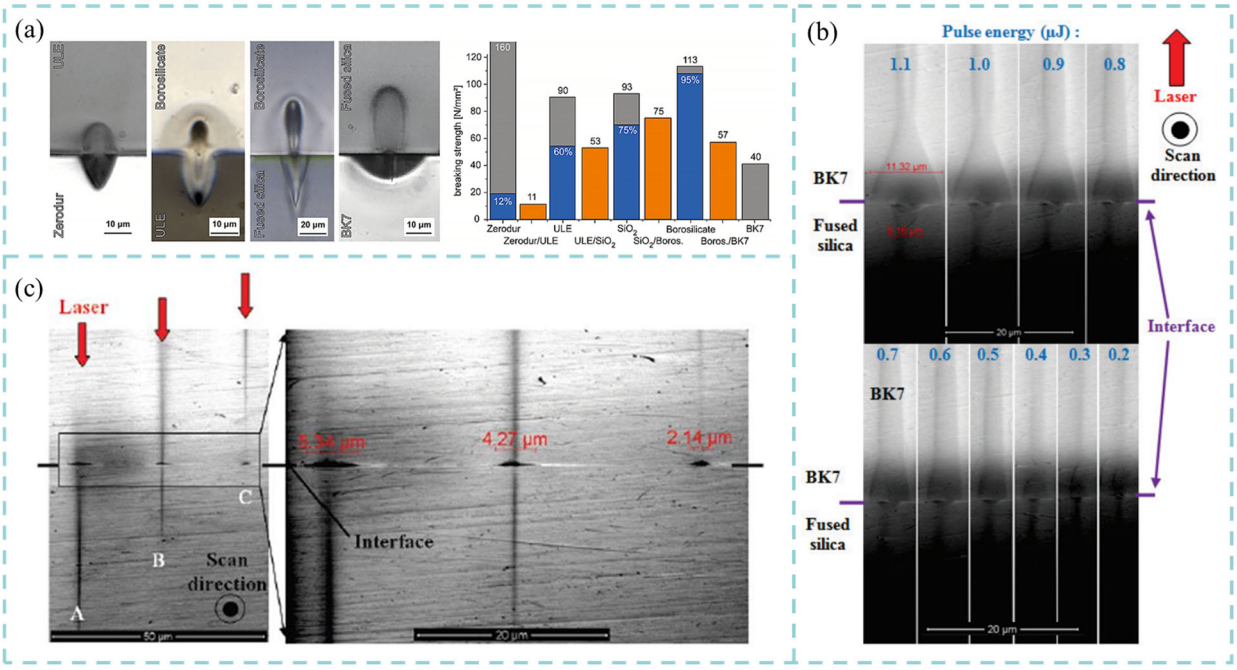


Figure 8. (a) Welding cross-section of four heterogeneous glass combinations, (b) SEM image of the cross-section of a direct bonded light filament in fused silica (bottom) and BK7 (top), (c) Scanning electron microscope image of the cross-section of the light filament trajectory with 0.6 µJ pulses.

The success of welding between THB nonmetallic materials has inspired confidence in the research of laser welding of metals with THB. Ozeki et al [59] successfully welded glass and copper using a femtosecond pulsed laser with a welding strength of more than 16 MPa, which not only resulted in a strong weld with no voids or cracks, but also demonstrated that femtosecond pulsed lasers require less energy and have a smaller heat-affected zone compared to nanosecond pulsed lasers. Carter et al [60] used an infrared picosecond laser to successfully weld a variety of optical materials such as quartz, borosilicate glass, and sapphire to metals such as aluminum, copper, and stainless steel, and the welded products were tested at temperatures ranging from -50 to 90 °C, and were found to be tightly bonded and sufficiently strong to cope with the extreme conditions. Zhang et al [61] used a sample without any auxiliary fixtures without pressure to surfaces were polished and cleaned, and the weld was achieved directly by using a 1 kHz femtosecond pulsed laser to irradiate the alumina silicate glass to metals (aluminum, copper, and steel) with a maximum shear strength of 2.34 MPa. Matsuyoshi et al [62] utilized the same principle to weld glass and copper with rough surfaces without pressure assistance. Experiments using a femtosecond laser at 1 MHz in the form of multiple scans of parallel lines to make ablation debris attached to the glass substrate proved to us that it is possible to achieve a close contact between glass and metal without polishing the metal surface or using fixtures. There is also the flexibility to minimize residual stresses. Wei et al [63] utilized a femtosecond laser to weld glass to copper and constructed acoustic signature signals to assess the quality of the weld for monitoring the weld. In addition to this, Ciuca et al [64] used a picosecond laser to weld quartz glass to metallic aluminum, and experimentally observed that the aluminum substrate was concave at the interface, and the molten aluminum flowed into the glass region under evaporative recoil pressure to produce SiO2/Al mixtures, which involved the formation of nanocrystalline silica and at least two transitional alumina phases in a very short interaction process: γ-Al2O3 and δ-Al2O3, as shown by Fig. 9.

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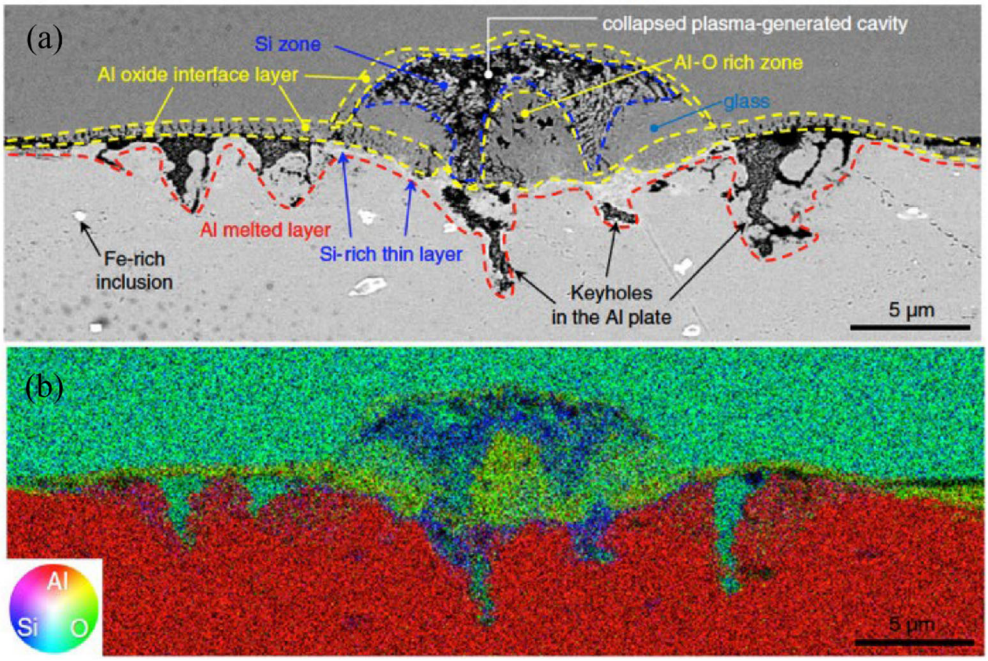


Figure 9. (a) Cross-section of the resulting weld between glass and aluminum, (b) Corresponding energy spectrometer plot.

4. CONCLUSION

(1) Conventional laser micro-welding melts the material by adding an intermediate layer or changing the material of the lower layer using a linear absorption process to deposit energy within the transparent material. This method allows for sealing connections on moderately rough bonding surfaces without the need for high temperatures and highly cleaned finishes, minimizes heat diffusion, locally heats the material, and protects any temperature-sensitive materials located inside the device from damage.

(2) UF Laser micro-welding is a method of localized energy deposition based on nonlinear absorption, and the process allows for direct high-quality connections without the introduction of new material. The laser directly makes the focal point of the material to absorb laser energy with transmissive wavelengths, through the nonlinear effect directly realize the three-dimensional space of transparent materials selective welding, avoiding the addition of new materials with different coefficients of thermal expansion resulting in thermal stress cracks and spattering, overcoming the inherent shortcomings of conventional laser glass welding technology.

In summary, the laser micro-welded glass technology has a wide range of applications, can be processed almost all THB materials and other combinations, the future will be vigorously developed in various fields. In the future, the laser micro-welded glass research direction in the processing method, processing technology will continue to improve the quality of welded joints while focusing on processing efficiency, reduce the process of porosity, micro-cracks and other defects, to achieve large-scale industrialized production and manufacturing.

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REFERENCES

[1] K. Cvecek, I. Alexeev, I. Miyamoto and M. Schmidt: Defect formation in glass welding by means of ultra short laser pulses, Physics Procedia, Vol. 5 (2010), p.495-502.

[2] D.Hélie, M. Bégin, F. Lacroix and R. Vallée: Reinforced direct bonding of optical materials by femtosecond laser welding, Applied optics, Vol. 51 (2010) No.12, p.2098-106.

[3] Y. Zhang, X. Li, Q. Zhu, W. Wei and X. Liu: Photocurable hyperbranched polymer medical glue for water-resistant bonding, Biomacromolecules,Vol. 21 (2020) No.12, p. 5222-32.

[4] K.M. Knowles and A.T. Van Helvoort: Anodic bonding, International materials reviews, Vol. 51 (2006) No.5, p.273-311.

[5] H.I. Smith: Optical-Contact Bonding, The Journal of the Acoustical Society of America, Vol. 5 (1965) No.37, p.928-9.

[6] C. Ageorges, L.Ye and M. Hou: Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review, Composites Part A: applied science and manufacturing, Vol. 32 (2001) No.6, p. 839-57.

[7] Q.Y. Tong, G. Cha, R. Gafiteanu and U. Gosele: Low temperature wafer direct bonding, Journal of microelectromechanical systems, Vol. 3 (1994) No.1, p. 29-35.

[8] J.P. Bergmann, F. Petzoldt, R. Schürer and S. Schneider: Solid-state welding of aluminum to copper—case studies, Welding in the World, Vol. 57 (2013), p. 541-50.

[9] A. Hu and Y. Zhou: Laser welding, microwelding, nanowelding and nanoprocessing, Chinese Journal of Lasers, Vol. 36 (2009) No.12, p. 3149-59.

[10] A. Mathieu, R. Shabadi, A. Deschamps, M. Suery, S. Matteï, D. Grevey and E. Cicala: Dissimilar material joining using laser (aluminum to steel using zinc-based filler wire), Optics & Laser Technology, Vol. 39 (2007) No.3, p. 652-61.

[11] N. Lorenz, S. Millar, M. Desmulliez and D.P. Hand: Hermetic glass frit packaging in air and vacuum with localized laser joining, Journal of Micromechanics and Microengineering, Vol. 21 (2011) No.4, p. 045039.

[12] Q. Wu, N. Lorenz, K.M. Cannon and D.P. Hand: Glass frit as a hermetic joining layer in laser based joining of miniature devices, IEEE Transactions on components and packaging technologies, Vol. 33 (2010) No.2, p. 470-7.

[13] C.Y. Lin, Y.H. Shen, C.C. Huang and S.L. Tu: Laser sealing of organic light-emitting diode using low melting temperature glass frit, Optical and Quantum Electronics, Vol. 49 (2017) No.3, p. 1-0.

[14] S. Emami, J. Martins, L. Andrade, J. Mendes and A. Mendes: Low temperature hermetic laser-assisted glass frit encapsulation of soda-lime glass substrates, Optics and Lasers in Engineering, Vol. 96 (2017), p. 107-16.

[15] Q. Wu, N. Lorenz and D.P. Hand: Localised laser joining of glass to silicon with BCB intermediate layer, Microsystem technologies, Vol. 15 (2009) No.3, p. 1051-7.

[16] N. Lorenz, M.D. Smith and D.P. Hand: Wafer-level packaging of silicon to glass with a BCB intermediate layer using localised laser heating, Microelectronics Reliability, Vol. 51 (2011) No.12, p. 2257-62.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202503_11(3).0008

[17] F. Bardin, S. Kloss, C. Wang, A.J. Moore, A. Jourdain, I. De Wolf and D.P. Hand: Laser bonding of glass to silicon using polymer for microsystems packaging, Journal of Microelectromechanical systems, Vol. 16 (2007) No.3, p. 571-80.

[18] A.W. Tan and F.E. Tay: Localized laser assisted eutectic bonding of quartz and silicon by Nd: YAG pulsed-laser, Sensors and Actuators A: Physical, Vol. 120 (2005) No.2, p. 550-61.

[19] C. Luo and L. Lin: The application of nanosecond-pulsed laser welding technology in MEMS packaging with a shadow mask, Sensors and Actuators A: Physical, Vol. 97 (2002), p. 398-404.

[20] A. de Pablos-Martín and Th. Höche: Laser welding of glasses using a nanosecond pulsed Nd: YAG laser, Optics and Lasers in Engineering, Vol. 90 (2017), p. 1-9.

[21] H. Wang, L. Guo, X. Zhang, J. Dong, Q. Lue, Q. Zhang, Q. Jiang, T. Chen and J. Li: Influence of processing parameters on the quality of titanium-coated glass welded by nanosecond pulse laser, Optics & Laser Technology, Vol. 144 (2021) No.3, p. 107411.

[22] J. Huo, J. Yuan, Q. Chen, M. Luo, J. Lu, J. Xu, C. Li, A. Luo, J. Li and Q. Zhang: Welding reinforcement between silica glass and stainless steel using nanosecond fiber laser with chromium interlayer, Optics and Lasers in Engineering, Vol. 172 (2024), p. 107877.

[23] A. Utsumi, T. Ooie, T. Yano and M. Katsumura: Direct bonding of glass and metal using short pulsed laser, Journal of Laser Micro/Nanoengineering, Vol. 2(2007) No.2, p. 133-6.

[24] M. Zhang, Y.F. Chan, C.J. Chen. and Z.L. Qiu: A new sealing technology for ultra-thin glass to aluminum alloy by laser transmission welding method, The International Journal of Advanced Manufacturing Technology, Vol. 115 (2021) No.7, p. 2017-35.

[25] P. Li, X. Xu, W. Tan, H. Liu and X. Wang: Improvement of laser transmission welding of glass with titanium alloy by laser surface treatment, Materials, Vol. 11 (2018) No.10, p. 2060.

[26] H. Nguyen, C.K. Lin, P.C. Tung. and J.R. Ho: Characterizations of laser transmission welding of glass and copper using nanosecond pulsed laser, The International Journal of Advanced Manufacturing Technology, Vol. 130 (2024) No.5, p. 2755-70.

[27] L. Li, C. Chen, C. Li, M. Xu, M. Zhang, C. Tian and W. Zhang: The influence of anodization on laser transmission welding between high borosilicate glass and TC4 titanium alloy, Optics & Laser Technology, Vol. 181 (2025), p. 111590.

[28] S. Nolte, M. Will, J. Burghoff and A. Tuennermann: Femtosecond waveguide writing: a new avenue to three-dimensional integrated optics, Applied Physics A, Vol. 77 (2003), p. 109-11.

[29] K. Cvecek, R. Odato, S. Dehmel, I. Miyamoto and M. Schmidt: Gap bridging in joining of glass using ultra short laser pulses, Optics express, Vol. 23 (2015) No.5, p. 5681-93.

[30] R. Knechtel: Glass frit bonding: an universal technology for wafer level encapsulation and packaging, Microsystem technologies, Vol. 12 (2005) No.1, p. 63-8.

[31] T. Tamaki, W. Watanabe, J. Nishii and K. Itoh: Welding of transparent materials using femtosecond laser pulses, Japanese journal of applied physics, Vol. 44 (2005) No.5, p. L687.

[32] K. Cvecek, S. Dehmel, I. Miyamoto and M. Schmidt: A review on glass welding by ultra-short laser pulses, International Journal of Extreme Manufacturing, Vol. 4 (2019) No.1, p. 042001.

[33] 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: erratum, Optics Express, Vol. 23 (2015) No.21, p. 28104-5.

[34] 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, Optics express, Vol. 22 (2006) No.14, p. 10460-8.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202503_11(3).0008

[35] S. Richter, S. Döring, A. Tünnermann and S. Nolte: Bonding of glass with femtosecond laser pulses at high repetition rates, Applied physics A, Vol. 103 (2011), p. 257-61.

[36] I. Miyamoto, K. Cvecek and M. Schmidt: Evaluation of nonlinear absorptivity in internal modification of bulk glass by ultrashort laser pulses, Optics Express, Vol. 21 (2011) No.19, p. 10714-27.

[37] F. Zimmermann, S. Richter, S. Döring, A. Tünnermann and S. Nolte: Ultrastable bonding of glass with femtosecond laser bursts, Applied Optics, Vol. 26 (2013) No.5, p. 1149-54.

[38] S. Butkus, E. Gaižauskas, D. Paipulas, Ž. Viburys, D. Kaškelyė, M. Barkauskas, A. Alesenkov and V. Sirutkaitis: Rapid microfabrication of transparent materials using filamented femtosecond laser pulses, Applied Physics A, Vol. 114 (2014) No.3, p. 81-90.

[39] A. Horn, I. Mingareev and A. Werth: Investigations on melting and welding of glass by ultra-short laser radiation, J. Laser Micro/Nanoeng, Vol. 2(2008) No.3, p. 114-8.

[40] I. Alexeev, K. Cvecek, C. Schmidt, I. Miyamoto, T. Frick and M. Schmidt: Characterization of Shear Strength and Bonding Energy of Laser Produced Welding Seams in Glass, Journal of Laser Micro/Nanoengineering, Vol. 3 (2012) No.7.

[41] I. Miyamoto, A. Horn and J. Gottmann: Local melting of glass material and its application to direct fusion welding by ps-laser pulses, J. Laser Micro/Nanoeng, Vol. 2 (2007) No.1, p. 7-14.

[42] E.H. Penilla, L.F. Devia-Cruz, A.T. Wieg, P. Martinez-Torres, N. Cuando-Espitia, P. Sellappan, Y. Kodera, G. Aguilar and J.E. Garay: Ultrafast laser welding of ceramics, Science, Vol. 365 (2019) No.6455, p. 803-8.

[43] X. Jia, K. Li, Z. Li, C. Wang, J. Chen and S. Cui: Multi-scan picosecond laser welding of non-optical contact soda lime glass, Optics & Laser Technology, Vol. 161 (2023) No.3, p. 109164.

[44] K. Cvecek, R. Odato, S. Dehmel, I. Miyamoto and M. Schmidt : Gap bridging in joining of glass using ultra short laser pulses, Optics express, Vol. 23 (2015) No.5, p. 5681-93.

[45] 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: erratum, Optics Express, Vol. 23 (2015) No.21, p. 28104-5.

[46] H. Chen, L. Deng, J. Duan and X. Zeng: Picosecond laser welding of glasses with a large gap by a rapid oscillating scan, Optics letters, Vol. 44 (2019) No.10, p. 2570-3.

[47] H. Chen, J. Duan, Z. Yang, W. Xiong and L. Deng: Picosecond laser seal welding of glasses with a large gap, Optics express, Vol. 27 (2019) No.21, p. 30297-30307.

[48] H. Chen, Y. Rong, Y. Huang and C. Wu: Crack suppression of glass welding by ultrafast laser without optical contact based on light modulation, Optics & Laser Technology, Vol. 164 (2023) , p. 109466.

[49] Z. Gao, J. He, X. Jia, Z. Yi, C. Li, S. Zhang, C. Wang and J.A. Duan: High-Strength Welding of Silica Glass Using Double-Pulse Femtosecond Laser under Non-Optical Contact Conditions, InPhotonics, Vol. 11 (2024) No.10, p.945.

[50] W. Watanabe, S. Onda, T. Tamaki, K. Itoh and J. Nishii: Space-selective laser joining of dissimilar transparent materials using femtosecond laser pulses. Applied physics letters, Vol. 89 (2006) No.2. p.021106.

[51] W. Watanabe, S. Onda, T. Tamaki and K. Itoh: Direct joining of glass substrates by 1 kHz femtosecond laser pulses, Applied Physics B, Vol. 87 (2007), p. 85-9.

[52] I.H. Nordin, Y. Okamoto, A. Okada, H. Jiang and T. Sakagawa: Effect of wavelength and pulse duration on laser micro-welding of monocrystalline silicon and glass, Applied Physics A, Vol. 122 (2016), p. 1-7.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202503_11(3).0008

[53] A. Horn, I.Mingareev and Werth A: Investigations on melting and welding of glass by ultra-short laser radiation, J. Laser Micro/Nanoeng, Vol. 3 (2007) No.2, p. 114-8.

[54] S. Richter, F. Zimmermann, R. Eberhardt, A. Tünnermann and S. Nolte: Toward laser welding of glasses without optical contacting, Applied Physics A, Vol. 121 (2015), p. 1-9.

[55] D. Hélie, F. Lacroix and R. Vallee: Reinforcing a direct bond between optical materials by filamentation based femtosecond laser welding, Journal of Laser Micro Nanoengineering, Vol. 7 (2012) No.3, p.284.

[56] 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, InCommercial and Biomedical Applications of Ultrafast Lasers VII, Vol. 6460 (2007), p. 197-203.

[57] 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 (2015) No.3, p. 3427-39.

[58] I.H. Nordin, Y. Okamoto, A. Okada, H. Jiang and T. Sakagawa: Effect of wavelength and pulse duration on laser micro-welding of monocrystalline silicon and glass, Applied Physics A, Vol. 122 (2016), p. 1-7.

[59] 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, Applied physics express, Vol. 1 (2008) No.8, p. 082601.

[60] R.M.Carter, J.Y.Chen, J.D. Shephard, R.R. Thomson and D.P. Hand: Picosecond laser welding of similar and dissimilar materials, Applied optics, Vol. 53 (2014) No.19, p. 4233-8.

[61] J. Zhang, S. Xu, Y. Dong, C. Zhang, J. Li, L. Guo and Q. Zhang: Microwelding of glass to silicon by green ultrafast laser pulses, Optics & Laser Technology, Vol. 120 (2019), p. 105720.

[62] 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 (2018) No.1, p. 21-5.

[63] W. Wei, Y. Liu, J. Wu, Z. Wei, Z. Zhou and Y. Long: In-situ monitoring method of femtosecond laser welding between glass and copper with acoustic emission, Measurement, Vol. 240 (2025), p. 115568.

[64] 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 (2016), p. 53-62.