Welding of Glass and Copper with a Rough Surface using Femtosecond Fiber Laser Pulses

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Welding between glass and copper with a rough surface is demonstrated using a femtosecond laser without a holder. Laser pulses from a femtosecond fiber laser with a repetition rate of 1 MHz are focused at the interface of glass and copper. We investigated the welding conditions between glass and copper with a rough surface by changing the scanning speed, line interval, and focal position. Direct welding between glass and copper with surface roughness (Rz of 7.8 μm and Ra of 0.21 μm) was accomplished with no pressure assistance.

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1. Introduction

Micro-joining/welding is of great importance for numerous applications, including the production of electronic, electromechanical and medical devices, sensors, and microfluidic devices. Compared to widely used joining techniques such as anodic bonding, fusion bonding, and hydrofluoric acid bonding, laser joining is more suitable for high-flexibility and high-precision manufacturing/integration of small parts [1, 2].

Direct laser joining of two substrates of transparent materials using femtosecond laser pulses has been demonstrated [3–8]. When a femtosecond laser pulse is focused at the interface of two transparent substrates, localized melting and quenching of the two substrates occur around the focal volume because of nonlinear absorption. The substrates can then be joined by resolidification of the materials [9]. Ultrafast laser welding has been used for glass–glass joining [9–19]. An important benefit of ultrafast laser welding is that it achieves welding between dissimilar materials with different thermal expansion coefficients.

Glass–metal welding is important for the hermetically sealed packaging of electronic components within a single container. Some examples are the passivation or hermetic sealing of solar collectors and electric devices. Particularly, hermetic sealing (i.e., air-tight seal) can secure electronic components from any external factors that might affect their functions and workable lifetimes. In glass–metal welding, glass is transparent to the incident laser beam. Nonlinear absorption in glass and linear absorption in metal melt the glass and the metal simultaneously. Glass–metal welding with ultrashort lasers has been reported [20–24]. Ozeki *et al.* reported femtosecond laser welding between copper and glass substrates to demonstrate the effectiveness of using femtosecond laser pulses compared to nanosecond ones [20]. Samples were stacked with a holder to reduce the gap separating glass and metal. To obtain sample gaps of a few micrometers, samples are pressed, thereby adding residual stress on the welding interface and causing cracks and inconveniences that hinder welding processes. Practical applications demand simplification of welding processes. For large-area welding, it is difficult to obtain close contact in large areas. Zhang e*t al.* described welding between glass and metal. After polishing and washing of the sample surfaces, the samples are contacted without pressure [21]. The gap was less than the detection wavelength, as demonstrated by observation of Newton's ring. No holder was used. However, polishing of the sample surface is required. Both reports describe femtosecond lasers with a repetition rate of 1 kHz used for glass and copper welding [20, 21]. Earlier reports of welding of glass and polished copper describe processes with and without a fixture [20,21].

This report describes welding between glass and copper with a rough surface using a femtosecond fiber laser. Laser pulses from a femtosecond fiber laser with a repetition rate of 1 MHz are focused at the glass–copper interface. We investigated the influence on the welding state by changing the scanning speed, line interval, and focal position.

2. Femtosecond laser welding of copper and glass

Figure 1 portrays a cross section diagram of the laser welding. Femtosecond laser pulses were focused at the interface between copper and glass by a lens. Welding can be conducted while moving the samples. When femtosecond laser pulses are focused at the glass and copper substrate interface, the intensity in the focal volume can become sufficiently high to initiate absorption through nonlinear field ionization (multiphoton absorption and tunneling ionization) and avalanche ionization. This nonlinear absorption results in the creation of plasma that is localized in the focal volume. Subsequently, localized melting and quenching occur at the interface of the two substrates around the focal volume. Then resolidification of the materials can join the samples. Translation of the focal volume along the interface creates welding volume. Femtosecond laser welding has several important features: Materials with different thermal expansion coefficients can be joined. Moreover, the influence of heat is slight. Fine joining is possible.

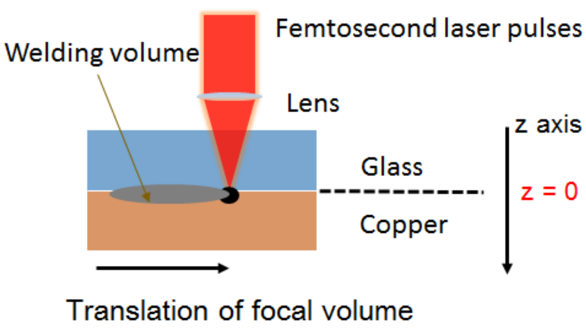


Fig. 1. Scheme showing the cross section of femtosecond laser welding between glass and copper.

3. Experimental setup

Figure 2 portrays a scheme for the experimental system of laser welding between glass and copper. The experiments were conducted using a femtosecond fiber laser (FCPA μJewel D-1000-UG1; IMRA America Inc.) with a repetition rate of 1 MHz, central wavelength of 1064 nm, and pulse duration of 550 fs and power of 1 W. As a glass sample, we used a white glass substrate (B270; Schott AG). The glass substrates were optically polished. Copper substrates were used as supplied, with a rough surface. We mounted samples onto computer-controlled stages (V-102.2L; Physik Instrumente GmbH and Co. KG). The laser pulses were focused using a 20× objective lens (LMPlan 20×IR; Olympus Corp.) at an interface between the glass substrate and copper substrate with a numerical aperture (NA) of 0.40. The waist (radius) of the beam focused with NA = 0.4 lens is $w_o = 0.61\lambda/\mathrm{NA} = 1.6$ μm. The laser energy of 1.0 μJ/pulse corresponds to laser fluence of 11.1 J/cm^2. The pulse energy was controlled using a neutral density (ND) filter. The copper surface morphology was observed using a confocal laser scanning microscope (VK-X200; Keyence Co.). After welding, the cleaved surfaces of glass were characterized using X-ray photoelectron spectroscopy (XPS, ESCA 3057; (Ulvac-PHI, Inc.).

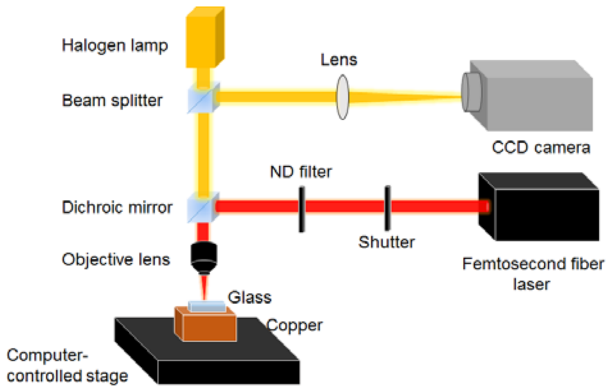


Fig. 2. Scheme for femtosecond laser welding system.

Figure 3 presents a translation method for welding. Welding lines were inscribed by parallel lines of modified materials with different line intervals. Individual lines were inscribed by translating the sample once through the laser focus and a shutter. Adjacent lines were inscribed using the same sample translation directions. Complete welding lines were constructed by repeating this process several times. The sample was translated at various speeds with different line intervals. The translation size was 2 mm × 2 mm or 1 mm × 1 mm. Scan speeds were changed at 0.5, 1, and 1.5 mm/s.

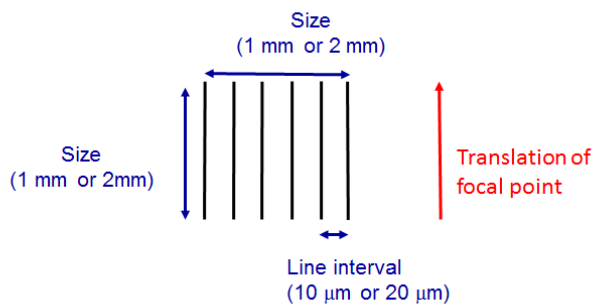


Fig. 3. Illustration of translation method used for welding.

4. Experimental results and discussion

Figure 4 shows samples to be welded. After washing copper and glass substrates with methanol, we placed a copper substrate on the mount and put a glass substrate on the copper plate. It is noteworthy that no fixture was used.

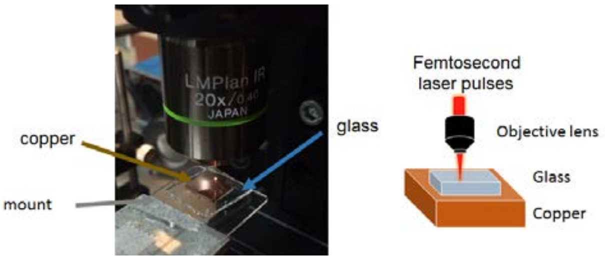


Fig. 4. Samples to be welded. A glass substrate was put on the copper plate without a fixture.

Figure 5 presents an optical image of a copper plate with a rough surface. Commercially available copper plate was used as-is from the supplier. No surface treatment was applied. The copper surface morphology was observed using confocal laser scanning microscopy. The maximum Rz was measured as 7.8 μm. Ra was 0.21 μm, which is rougher than that of polished surfaces used for glass/metal welding in an earlier study [20, 21], or for glass/aluminum welding (Ra of 100 nm [22] and 288 nm [24]).

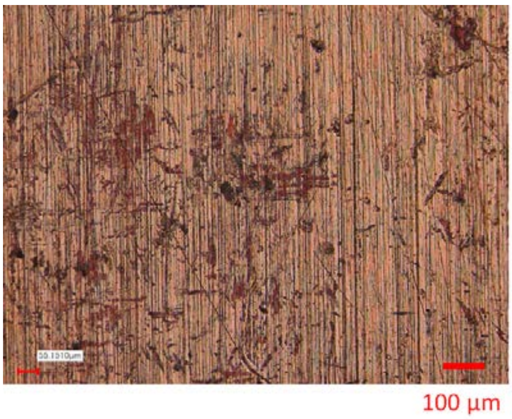


Fig. 5. Optical image of copper surface before welding. The height distribution was measured using confocal microscopy.

Figure 6 depicts a typical image of welded copper and glass. The copper was 10 mm × 10 mm. The glass size was 5 mm × 5 mm. The glass thickness was 1 mm. Welding was done using pulse energy of 1 μJ/pulse, scan speed of 1 mm/s, and line spacing of 10 μm. The welding area was 1 × 1 mm^2. Material modifications were observed in the welded area.

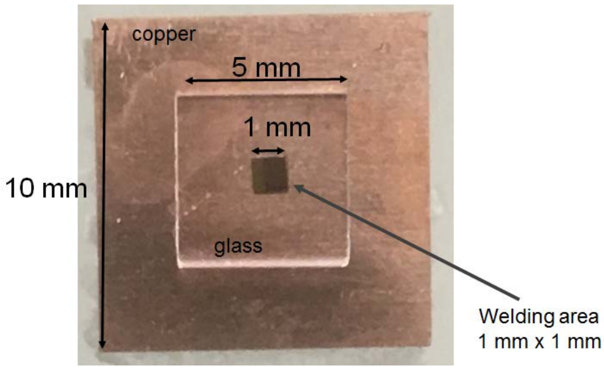


Fig. 6. Welded copper and glass.

We investigated the influence of line intervals, scanning speeds, and the welding area on the welding. Table 1 presents welding conditions for various line intervals and scanning speeds. In a welding area of 1 × 1 mm^2 and 2 × 2 mm^2, and line intervals of 10 μm, welding was successful at all speeds (0.5, 1, and 1.5 mm/s). In a welding area of 1 × 1 mm^2 and 2 × 2 mm^2, with line intervals of 20 μm, welding was not successful. We categorized successful welding using a simple shear test.

Table 1. Welding conditions for various line interval and scanning speeds. The focal position was set as z = 0.

Welding area 2×2 mm²				
		Scanning speed [mm/s]		
		0.5	1	1.5
line interval (μm)	10	○	○	○
	20	×	×	×

Welding area 1×1 mm²				
		Scanning speed [mm/s]		
		0.5	1	1.5
line interval (μm)	10	○	○	○
	20	×	×	×

To investigate focal plane effects on welding, we changed the focal position along the z axis. It is noteworthy that z = 0 was the glass–copper interface. Table 2 shows the welding result under the condition of a changed focal point. The focal point is lowered from the copper surface in the z-axis direction. The scanning speed was fixed at 1 mm/s.

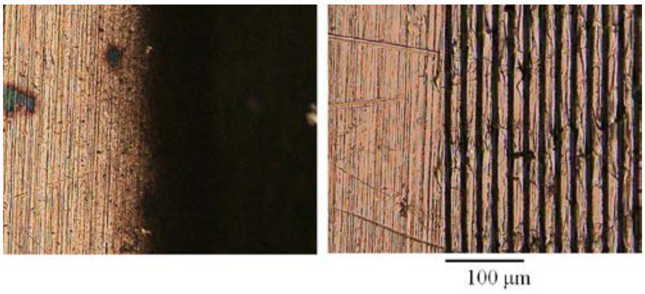
At the 10 μm line interval, both in the welding area of 2 × 2 mm^2 1 and 1 × 1 mm^2, welding can be successful at (z = 0, 10, 20, 30 μm).

At the 20 μm line interval, in the welding area of 2 × 2 mm^2, welding was possible under the condition that the focal point is lowered from the copper surface (z = 10, 20, 30 μm). In the welding range of 1 × 1 mm^2, welding can be successful with z = 20 μm. At the 20 μm line interval, the welding area was small. Therefore, welding was unsuccessful with z = 0, 10 and 30. Successful welding at around z = 20 μm, probably achieved by self-focusing in glass [25].

Table 2. Welding conditions for different focal positions

Welding area 2×2 mm²					
		focal position [µm]			
		z = 0 (surface)	z = 10	z = 20	z = 30
line interval (µm)	10	○	○	○	○
	20	×	○	○	○
Welding area 1×1 mm²					
		focal position [µm]			
		z = 0 (surface)	z = 10	z = 20	z = 30
line interval (µm)	10	○	○	○	○
	20	×	×	○	×

We investigated welding in conditions with a fixture and without a fixture. The focal point was set as z = 20 µm. Welding was done with a period of 20 µm. Figure 7(a) shows an optical microscopic image of cleaved copper surface after welding without a fixture. As shown in Fig. 4, we put a glass substrate on the copper substrate as in previous experiments. No clamp was used. In Fig. 7(a), welding lines were not observed. The translation area was filled. Debris by ablation was found outside the laser-irradiation area. In Fig. 7(b), the glass and copper samples were clamped to achieve an air gap of a few micrometers range by observation of interference fringes (such as Newton rings) under white light illumination [20]. In this welding condition in Fig. 7(b), the welding seam showed narrow welding lines. Results of an earlier study suggest the influence of laser ablation on welding quality between the glass and SiC [26]. When the inner gap separating the samples was enlarged, laser ablation was not suppressed. Therefore, debris was observed in Fig. 7(a). In welding without a fixture, debris from ablation was attached to the glass substrate. Welding between glass and copper with a rough surface was accomplished.



(a) (b)

Fig. 7. Comparison of results obtained with and without a gap. Optical microscopic image of cleaved copper surface after welding: (a) without a fixture and (b) with a fixture.

Jointed samples were cleaved and characterized using XPS. Base pressure in the analysis chamber was approx. 10^{-9} Torr. Cu Kα was used as the X-ray source. The take-off angle of the photoelectrons was 45°. The surface of the cleaved glass substrate was analyzed as presented in Fig. 8. The doublet peaks of $Cu2p_{1/2}$ and $Cu2p_{3/2}$ were observed respectively at 953 eV and 934 eV, meaning that copper melted by ablation was attached to the glass substrate. Metal particles produced by femtosecond laser ablation were regarded as acting as the adhesive for welding.

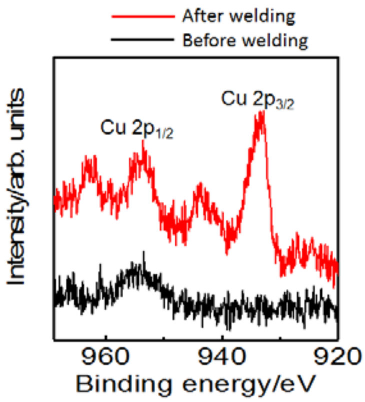


Fig. 8. Cu2p XPS spectra on the cleaved glass surface after welding glass and copper.

We applied a simple shear test to estimate the joint strength after welding the substrate. When the sample was cleaved, we ascertained the joint strength by dividing the load by the welding area. The maximum applied force was 4 N. If we assume that the welded zone is 2×2 mm², then the joint strength was 1 MPa. The shear strength described in an earlier study [21] was found to be 2.3 MPa for welding between the glass and polished copper without pressure. The strength of femtosecond laser welding with a rough surface was of the same order.

5. Conclusion

We demonstrated welding between glass and copper with rough surface by focusing femtosecond laser pulses at 1 MHz. This report described the joining of glass and copper with rough surfaces (Rz of 7.8 µm and Ra of 0.21 µm), which was accomplished with no pressure assistance. We investigated the welding conditions: scanning speed, period, area, and focal position. Future work shall include measurement of the gap separating glass and copper, influence of the gap on welding, influence of a rough surface on welding, and measurement of mechanical strength (tensile stress, shear stress). The welding technique requires no polished metal surface or fixture to achieve close contact between the glass and the metal. This gap-bridging welding technique between glass and metal with surface roughness offers the versatility of large area joining and decreased residual stress with flexibility.

Acknowledgments

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