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EVELUATION OF MOLTEN ZONE IN GLASS WELDING USING ULTRA SHORT PULSED LASER

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Evaluation of Molten Zone in Glass Welding Using Ultra-short Pulsed Laser

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Abstract:
Fusion welding is well known as the most promising technique in glass joining, since joining can be accomplished without any intermediate layer and mechanical contact. High precision, small heat-affected zone (HAZ) and small shock-affected zone (SAZ) by ultra-short pulsed laser make it possible to perform the process with minimal damages to the surrounding area. However, there still remained a lot of things to be clarified in this process, since glass materials are very sensitive to temperature gradients and available in different thermal properties. In this study, molten zones created by ultra-short pulsed laser in borosilicate glass and fused silica glass were evaluated. Laser irradiation was carried out inside the glass under various processing conditions. Molten zone was observed visually, and its mechanical strength was measured using three points bending test.

Keywords: Glass welding, Ultra-short pulse laser, Borosilicate glass, Fused silica glass, Molten zone, Bubbles

1. Introduction

In the field of information technology industries, glass materials are widely used as optical systems and semiconductor parts manufacturing [1-2]. Parts miniaturization, performance improvement and other demands had required precise joining technique of these materials. In general, the application of adhesive material is used as a main joining technique for ceramics and glass materials [1]. The performance of this technique is greatly influenced by the properties of adhesive material and processing environment. Besides, the joint accuracy would be greatly affected by the inconstant shrinkage of adhesive material. In order to overcome these problems, many attempts had been tried for developing a newly joining technique without adhesive material or interlayer.

It is considered that fusion welding would be the most promising techniques for glass joining, since this joining can be accomplished without any intermediated layer and mechanical contact. The development of ultra-short pulsed laser makes it possible to apply a fusion welding method for glass materials. By using ultra short pulsed laser, the heat affected zone (HAZ) can be minimized. Thermal energy generated by laser beam within picoseconds leads to the selective material removal and instant re-solidification without any fatal damages [3].

Glass materials have highly potential in optics, MEMS, electronics and biomedical applications because of its excellent optical, mechanical and chemical properties [3]. In this study, two types of glass materials were chosen. One is borosilicate glass (Schott D 263), which is most well known for very low coefficient of thermal expansion (~5 ×10^{-6} / °C at 20°C), against thermal shock [4]. This glass is widely used in semiconductor parts manufacturing because of its high thermal stability. Moreover, some of them are used in optical systems due to its high transparency. The other is a fused silica glass which is produced from quartz of exceptional purity with SiO_2 content of 99.9%, and it is widely used in semiconductor industries [1]. **Table 1** shows the thermal properties of both borosilicate glass and fused silica glass.

Table 1: Thermal properties of borosilicate and fused silica glass

Properties	Borosilicate Glass *1)	Fused Silica
Density (g/cm^3)	2.51	2.2
Specific heat c (J/g·K)	0.82	1.1
Thermal diffusivity α (cm^2/s)	0.003	0.008
Melting temperature θ_m (°C)	1051	2000
Thermal expansion coefficient (1/°C)	7.2 x 10^{-6}	5.5 x 10^{-7}

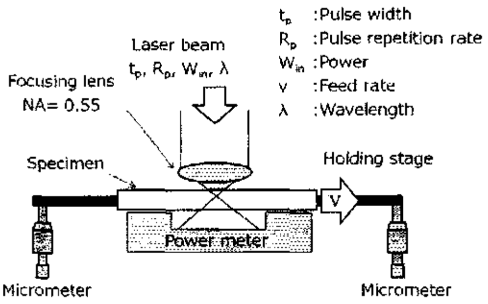
*1) Schott D263

2. Experimental procedures

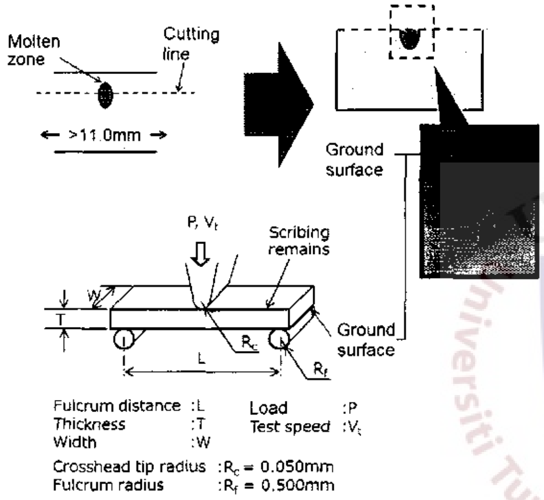
2.1 Experimental apparatus

In order to investigate the molten zone characteristics, laser irradiation was carried out into a single glass plate under various processing parameter conditions. The focus position of laser beam was adjusted by some micrometers below the top surface of specimen as shown in **Figure 1 (a)**.

In order to measure the molten zone strength, specimens irradiated in a single line were cut into 1.5mm width and 11mm length. The upper surfaces were ground and polished to the center plane of molten zone. Then, three point bending test were carried out with the grinded surface (molten zone) facing downward as shown in Figure 1 (b).



(a) Single plate irradiation



(b) Bending test

Figure 1: Schematic diagrams of experimental method

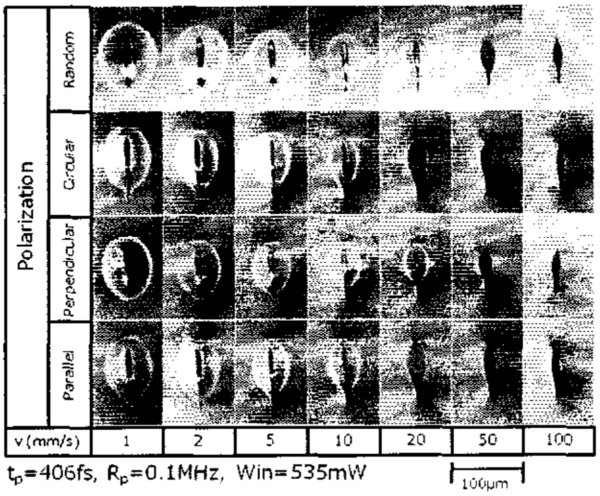
It is considered that the remains of scribing area on specimen surface facing upper side would not affect the measurement results of strength, since the scribed line remained only at upper side of these pieces for bending test.

2.2 Experimental conditions

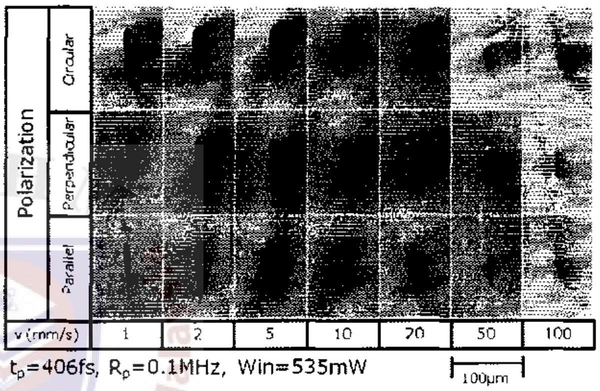
In this study, the influence of polarization, pulse repetition rate R_p and feed rate v were investigated. Ultra-short pulsed laser with 10ps at 1064nm with a beam quality of $M^2<1.3$ and 406fs at 1045nm with a beam quality of $M^2<1.5$ were used in this study. The laser beam was focused into glass material using N.A. 0.55 focusing lens. The processing parameters used in these experiments are as follows.

2.2.1. Influence of polarization

Two kinds of glass – borosilicate glass and fused silica glass were irradiated under various feed rate (10 ~ 200mm/s), pulse repetition rate and different polarization modes.



(a) Borosilicate glass



(b) Fused silica glass

Figure 2: Sectional view different polarization at 0.1MHz pulse repetition rate.

2.2.2. Influence of pulse repetition rate

Laser irradiation was carried out on fused silica glass under various pulse repetition rate condition from 0.1MHz to 0.5MHz with two different feed rate (v=50 and 200mm/s).

Irradiated specimen were cut and polished perpendicularly to the irradiation lines for the molten zone observations. To clarify the characteristics of bubbles and cracks generated in and at the surrounding of the molten zone, they were etched using 1% density of Hydrofluoric acid for 1 hour.

3. Results and Discussion

3.1 Observation of molten zone

Figure 2 shows the molten zones of borosilicate glass and fused silica glass irradiated by various beam polarization. It is proven that the difference of polarization would not bring noticeable effects. However, a thin dark line was created in molten zone of fused silica, since the melting temperature and thermal diffusivity of fused silica are higher than these of borosilicate glass. Lower density also accompanies a higher risk of bubbles generation.

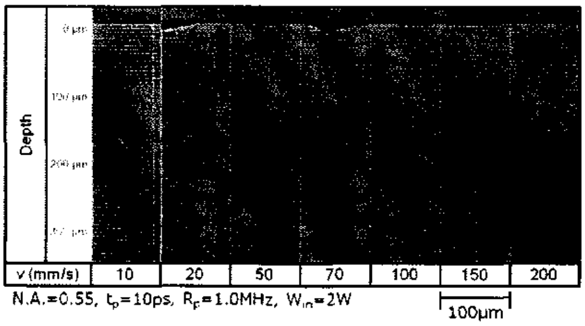


Figure 3: Comparison of fused silica molten zone for various feed rates at W_{in}=2W.

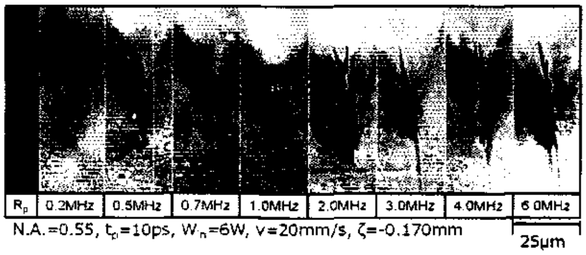


Figure 4: Comparison of fused silica molten zone at bottom tip for various pulse repetition rates at W_{in}=6W

Figure 3 is the comparison of the molten zone of fused silica irradiated using different feed rates. The molten zone size slightly decreased with the increment of feed rate. Bubbles remained inside the molten zone, and the situation of those bubbles appearance was different in feed rate. Bubbles were generated at two separated locations under slower feed rate condition. Their size and position changed with an increase of feed rate. These bubbles merged together in one oblong structure, when the feed rate increased to more than 100mm/s.

Figure 4 shows the comparison of molten zones at bottom tip using different pulse repetition rate at 6W laser power. The figure shows that molten zones evolved in three stages. Lower pulse repetition rate leads to the formation of micro-bubbles at the bottom of the molten zone. The density and size of bubbles decreased with an increase of pulse repetition rate. When the pulse repetition rate was set to 1.0MHz, micro-bubbles were almost disappeared. However, cracks suddenly became very large, when the pulse repetition rate increased more than 2.0MHz. The cracks generated inside the molten zone became longer with the increment of pulse repetition rate.

In the case of constant average laser power, the increment of pulse repetition rate leads to the decrement of absorption as shown in **Figure 5**. This tendency has indicated the transferred heat energy into the specimen became lower. Consequently, less micro-bubbles were generated at the narrow bottom section. When the molten zone was cooled down and re-solidified, the contraction stress acted inside the molten zone and tensile stress were concentrated at the bottom section of narrower part. The stress concentration would lead to crack generation in the bottom side of the molten zone.

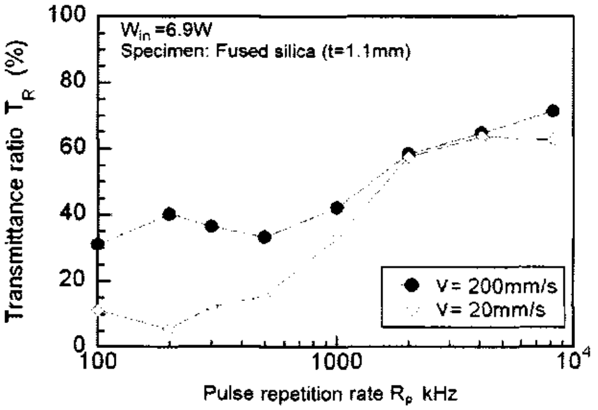


Figure 5: Relationships between transmittance ratio of fused silica and pulse repetition rate at W_{in}=6.9W

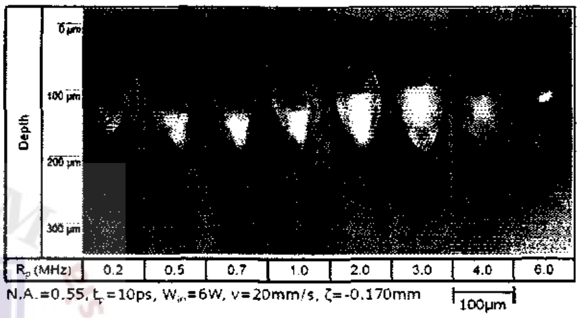


Figure 6: Whole view of fused silica molten zone for various pulse repetition rates at focal depth ζ=-0.170 mm

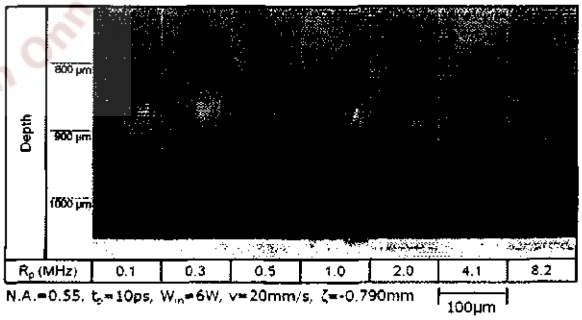
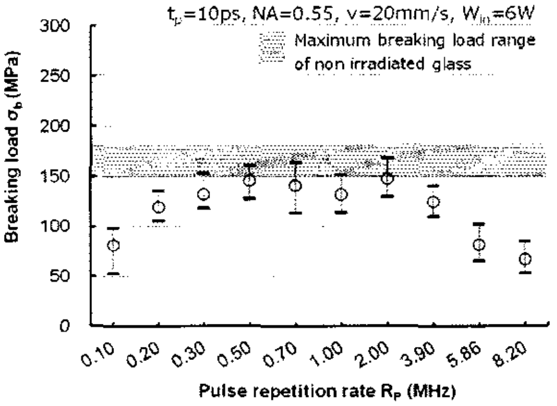
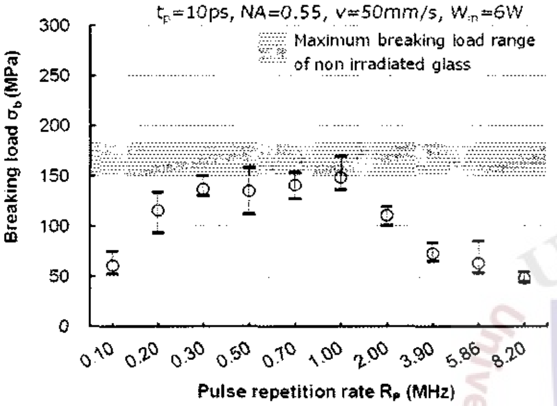


Figure 7: Fused silica molten zone for various pulse repetition rates at focal depth ζ=-0.790 mm

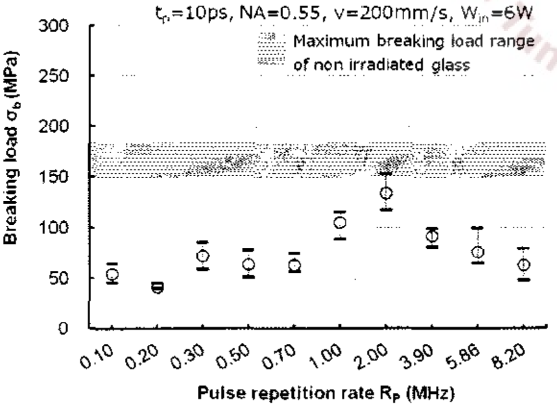
On the other hand, lower pulse repetition rate leads to higher absorption rate and larger heat shock. As a result, micro-bubbles were generated at the bottom tip of molten zone. Extremely high heat energy has caused the expansion of molten zone and generation of cracks at the bottom tip of molten zone. This crack generated outside of the molten zone started from bottom tip and extends downward with decrement of pulse repetition rate as shown in **Figure 6**. It became very obvious, when the laser irradiation was carried out with focal depth ζ= -0.790mm, because the nonlinear absorption rate of glass is significantly affected by the depth of focus position as shown in **Figure 7**.



(a) v=20mm/s



(b) v=50mm/s



(c) v=200mm/s

Figure 8: Breaking load of fused silica molten zone

3.2 Strength measurement

Figure 8 shows the results of three points bending test for fused silica glass for various pulse repetition rates from 0.10MHz to 8.20MHz and feed rate at 20, 50 and 200mm/s. Hatched areas indicate the range of breaking load measured from specimens which are not irradiated. The breaking loads of non-irradiated specimens were between 150MPa to 180MPa. **Figure 8 (a)** obviously shows that pulse repetition rate between 0.5MHz and 2.0MHz has successfully created molten lines with minimum strength declination of about 30MPa compared to the non-irradiated specimens.

Comparing those three graphs, it could be concluded that molten zones strength would decrease with the increment of feed rate. The range of applicable pulse repetition rate became narrower with the increment of feed rate. In case of feed rate v=200mm/s, the applicable pulse repetition rate was only at 2MHz with average breaking load of approximately 130MPa. Therefore, it is considered that proper setting of processing parameters would has the possibility as a high reliable fusion welding of glass without the fatal decrease of mechanical strength.

4. Conclusions

In this study, molten zone of glass welding by ultra-short pulsed laser were evaluated. Main conclusions obtained are as follows.

1) Polarization did not bring any serious changes to the molten zones shape and size of both borosilicate and fused silica glasses.
2) Increasing the feed rate led to the reduction of molten zone size.
3) Pulse repetition rate is the important factor to reduce crack generation. Cracks generated outside the molten zones extend downward with bigger size with decreasing pulse repetition rate. In contrast, higher pulse repetition rate leads to the crack generation in the molten zones.
4) Three points bending test proved that slow feed rate of 20mm/s is preferable in order to obtain a strong fusion welding zone compared to higher feed rate of 200mm/s. The applicable region of pulse repetition rate becomes wider under lower feed rate conditions.

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