Ultrafast laser microwelding for transparent and heterogeneous materials

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Outline

- *Introduction to filamentation*
- *Ultra-fast laser micro-welding of glass with filaments*
- *Ultra-fast laser micro-welding of heterogeneous materials*
Filamentation

Normal Focusing

Nonlinear Medium

Lens

Filamentation

High-Intensity Pulse

Self Focusing

(Optical Kerr Effect)

Filament

Plasma Formation

3
**Filamentation**

- balancing between self-focusing and defocusing by plasma -

Scattering or luminescence from filament

Micrograph of the resultant index change

Magnified micrograph

(a) 200 µm

(b) 200 µm

(c) 50 µm
Formation of single filament

NA of focusing lens : 0.1
Exposure time : 5 min.
( 300,000 pulses )

- Multiple filaments

- Scattering damages

Core diameter : ~ 2 µm
Applications of filamentation

- Waveguide writing
  Waveguides*¹, WG Couplers*²

- Writing optical elements
  Mirrors, Lenses*³, Optical devices*⁴

- Welding transparent materials

- Ultra-fast laser micro-welding of glass with filaments

Scanning the filament

Low repetition source
Fast scanning

Low repetition
Slow scanning

High repetition source

~ Gap

~ Accumulation of heat

~ No gap
Optical setup

- Wavelength: 800 nm
- Pulse duration: 130 fs
- Repetition: 1 kHz
- Incidence energy: 1.0 µJ/pulse
- Numerical aperture: 0.30
- Irradiation area: 100 µm x 100 µm
- Translation speed: 5.0 µm/s
Welding flat samples

(a) Samples

(b) Jig for welding

(c)
Micrographs

Top view

Side view
Joining strength (Same material)

15 MPa ~ 150 kgf/cm²

Usual adhesive ~ 50 kgf/cm²

(kgf: kilogram force)
Optical transmittance

- Fused silica glass: 87 ~ 89 %
  - Theoretical limit: 92 %
- Borosilicate glass: 81 ~ 87 %
  - Theoretical limit: 93 %
Effects of Annealing

Annealing makes welded part invisible.
(Implication of disappearance of defects or stress.)
## Enhancement of joining strength & optical transmittance

<table>
<thead>
<tr>
<th></th>
<th>Joining strength</th>
<th>Optical transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before annealing</td>
<td>After annealing</td>
</tr>
<tr>
<td>Borosilicate</td>
<td>15 MPa</td>
<td>33 MPa</td>
</tr>
<tr>
<td>Fused silica</td>
<td>15 Mpa</td>
<td>33 Mpa</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td>(336 kgf/cm(^2))</td>
</tr>
</tbody>
</table>

Before annealing:
- Joining strength: 15 MPa
- Optical transmittance: 88% (Theoretical limit: 93%)

After annealing:
- Joining strength: 33 MPa
- Optical transmittance: 92% (Theoretical limit: 93%)

Before annealing:
- Joining strength: 15 Mpa
- Optical transmittance: 87% (Theoretical limit: 92%)

After annealing:
- Joining strength: 33 Mpa
Enhancement of optical transmittance by annealing

<table>
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<tr>
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<th>Borosilicate glass</th>
<th>Fused silica glass</th>
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<td>Before annealing</td>
<td>88 %</td>
<td>87 %</td>
</tr>
<tr>
<td>After annealing</td>
<td>92 %</td>
<td>91 %</td>
</tr>
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</table>

(Theoretical limit: 93 %) (Theoretical limit: 92 %)
- Ultra-fast laser micro-welding of different glass
**Heterogeneous welding:**

*dissimilar kinds of glass*

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**Geometry**

- **Borosilicate glass**
  - $39 \times 10^{-7}/°C$
- **Fused silica glass**
  - $5.9 \times 10^{-7}/°C$

*Thermal expansion coefficient*

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Joining strength and transmittance

**Joining strength**

*Pulse Energy [µJ/pulse]*

- 15.3 MPa
- 15.2 MPa
- 14.9 MPa

*Scanning Speed [mm/s]*

- 0.1
- 1

**Optical transmittance**

*Pulse Energy [µJ/pulse]*

- 71.5 %
- 71.8 %
- 88.3 %

*Scanning Speed [mm/s]*

- 0.1
- 1

- 73.2 %
- 73.6 %
- 73.4 %

Values:

- Joining strength:
  - 15.3 MPa: 71.5 %
  - 15.2 MPa: 72.6 %
  - 14.9 MPa: 88.3 %

- Optical transmittance:
  - 71.8 %
  - 73.4 %
  - 73.6 %
**Heterogeneous welding:**  
**dissimilar kinds of materials**

<table>
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<tr>
<th>Material</th>
<th>Fused silica glass 5.9 [$\times 10^{-7}/^\circ\text{C}$]</th>
<th>Borosilicate glass 39 [$\times 10^{-7}/^\circ\text{C}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polymer</strong></td>
<td>PMMA 700 [$\times 10^{-7}/^\circ\text{C}$]</td>
<td>14.9 MPa</td>
</tr>
<tr>
<td><strong>Semiconductor</strong></td>
<td>Silicon 28 [$\times 10^{-7}/^\circ\text{C}$]</td>
<td>15.0 MPa</td>
</tr>
<tr>
<td><strong>Metal</strong></td>
<td>Cupper 183 [$\times 10^{-7}/^\circ\text{C}$]</td>
<td>14.9 MPa</td>
</tr>
<tr>
<td><strong>Alloy</strong></td>
<td>Stainless steel 175 [$\times 10^{-7}/^\circ\text{C}$]</td>
<td>14.9 MPa</td>
</tr>
</tbody>
</table>

*Thermal expansion coefficient

**Wide range of heterogeneous welding**

Geometry:
- Glass
- Other material
Ultra-fast laser micro-welding of glass and metal
Ultra-fast Laser Micro-welding of Glass and Copper

Realizing tight contact between glass and copper
Optical Setup
Optical microscope images

(a) Side view

(b) Top view

(c) Whole image

Laser source: Regenerative Ti:sapphire laser (Spectra Physics, Spitfire)

Central wavelength: 800 nm
Pulse duration: 130 fs
Repetition rate: 1 kHz
Pulse energy: 4 μJ/pulse
Scan speed: 1 mm/s

Joining strength: 23 MPa
Joining Strength

- Glass plate (5 × 10 × 0.7 mm³)
- Small glass plate (5 × 5 × 0.7 mm³)

Average: 21.5 MPa

0.38 µJ
No crack nor gap was observed.
But, some bumpy irregularity presents.
Summary

- Ultra-fast laser micro-welding of glass with filaments
- Ultra-fast laser micro-welding of homogeneous and heterogeneous welding, such as silica and borosilicate glass, silica glass and metals

average joining strength: 21.5 Mpa

( ~220 kgf/cm^2 )
Welding with High Repetition Laser Pulses

Wavelength: 1558 nm
Pulse duration: 947 fs
Repetition rate: 500 kHz
Input energy: 0.8 \( \mu \)J/pulse
Translation speed: 20 \( \mu \)m/s
Objective lens: 0.40-NA (Numerical aperture)

Samples: Borosilicate glass
Joint strength: 9.87 MPa @ 100 \( \mu \)m/s
6.81 MPa @ 200 \( \mu \)m/s
Conventional and ultra-fast laser micro-welding

Conventional laser micro-welding:
- Glass
- Other material
- Femtosecond pulses
- Local heating
- Glass and other material

Wide heating:
- Expansion due to temperature rise

Cooling with cracks:
- Contraction due to cooling

Cooling without cracks:
- Cooling without cracks
Application of Ultra-fast Laser Micro-welding to Metal Package (Glass & Kovar)

(a) Birds-eye view

(b) Top view
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Osaka University

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Konica Minolta Opto, Inc.