euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
www.euspen.eu

Monitoring and closed loop feedback control of ultrafast glass welding

Karen X.Z. Yu[1], Martin R Sparkes[1], Krste Pangovski[1], and William O'Neill[1]

[1]*Centre for Industrial Photonics, University of Cambridge*

xzjy2@cam.ac.uk

Abstract

Laser based precision processing of micro and nanoscale components is a common manufacturing and prototyping production method given its non-contact nature and well defined energy delivery. However, while laser parameters are highly controllable, laser-material interactions are inherently unstable, resulting in increased rejection rates. Here, swept source optical coherence tomography (SS-OCT) is used to provide feedback control of the position, ensuring that the weld structure will successfully bridge the interface between materials. OCT is also used to monitor the glass weld cycle *in-situ,* allowing possible control of the structure size by terminating processing once desired results have been achieved. Finally, OCT is able to determine whether or not a successful weld has been created.

Glass welding, feedback and control, OCT

1. Introduction

Precision processing of micro and nano-sized objects has become increasingly more prominent in manufacturing given the drive to produce ever smaller consumer devices. In particular, ultrafast processing of glass has seen growing interest with its myriad of applications such as the creation of optical waveguides and microfluidic channels [1]. However, as opposed to more traditional manufacturing processes, a lack of monitoring and control solutions at these scales present a challenge for precise processing. One example of this is laser glass-glass welding, industrial reliability has been difficult to achieve and adhesives are applied instead [2]. We demonstrate a swept-source optical coherence tomography (SS-OCT) system combined with ultrafast processing to apply feedback to control the processing focus and validate the welds in-process.

2. Experimental Setup

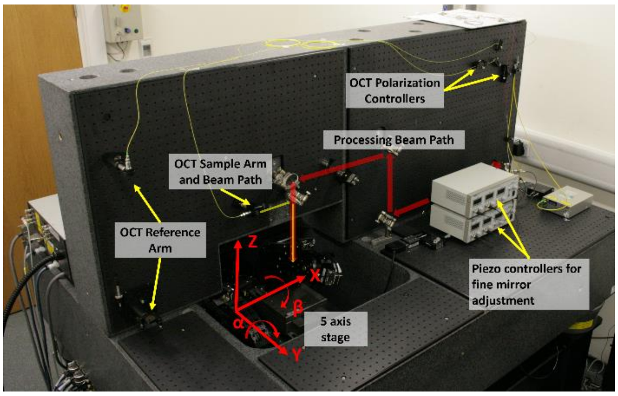

Figure 1. Set-up for OCT integrated with laser processing.

While OCT was first developed for medical examinations, recent work has shown the potential for high speed industrial inspection [3, 4]. Figure 1 shows set-up for the SS-OCT integrated with the ultrafast processing platform. The OCT source has a

centre wavelength of 1310 nm and an imaging line rate of 100 kHz.

Fused silica and microscope glass slides (borosilicate and soda-lime composite) are used as sample substrates. Processing is undertaken using a Coherent Talisker Ultra, pulse length < 15 ps, wavelength 1064 nm and a repetition rate 200 kHz.

3. Results

3.1. Focal Depth Control

During welding, OCT is used to track the focal depth of the processing beam, allowing placement of the weld to overlap the interface between glasses.

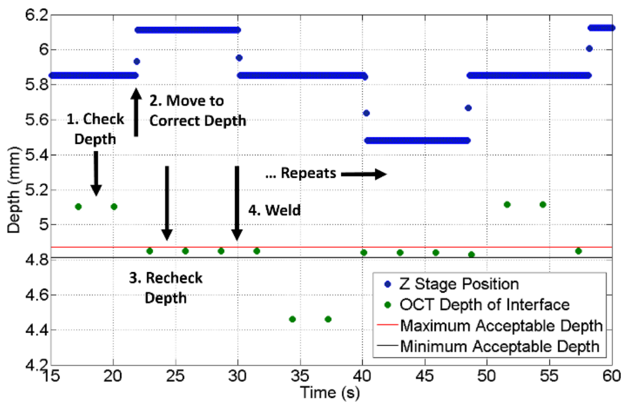

Figure 2. *In-situ* depth control data for OCT Welding.

Figure 2 shows the depth data as recorded by the OCT and stages during welding. Here, the sample is deliberately tilted by 3° and OCT is used to automatically correct for the height difference. At the start of the figure, OCT checks the depth and determines that the interface is not at the correct position (5.8 mm Z stage position). A command is sent to move to correct position, verified by OCT (6.1 mm Z stage position). Next, welding commences, followed by the stage moving back to its starting height position to avoid collision when moving to the next weld location - 6.1 mm back to 5.8 mm. The process repeats for the subsequent welds.

3.2. Weld Height Control

Figure 3 shows OCT tracking data of a welding cycle in bulk fused silica. Figure 3.a) is an OCT M-mode image, where the y axis represents depth within the sample and the x-axis represents time. In this image each pixel represents a time step of 10 µs and length step of 11 µm in the x- and y-directions respectively. Figure 3.b) is an optical microscope image of the weld, scaled to the OCT M-mode.

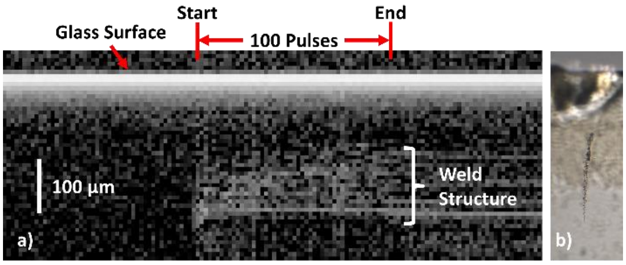

Figure 3.a) OCT monitoring of weld structure formation in bulk SiO_2 and b) corresponding microscope image of structure. The depth scale is the same for both images.

It can be seen that most of the weld is created within the first 5 – 10 pulses. After ~ 80 pulses the structure reaches saturation, Figure 4; OCT and optical microscope data also being shown to be in agreement within 80%. There appears to be an overall trend to underestimate the length by approximately 10 µm, likely due to low returning signal at the lower boundary of the structure.

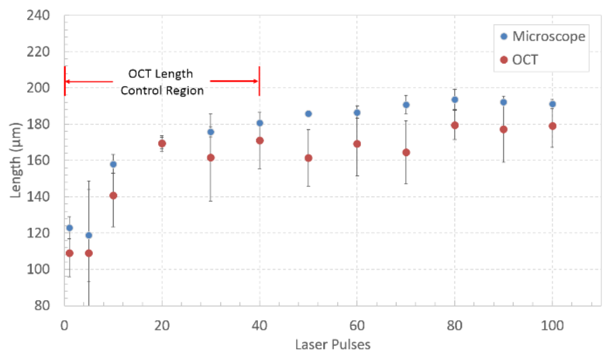

Figure 4: Length of weld structure as measured by OCT and optical microscopy as a function of laser pulses in bulk SiO_2.

3.3. Weld Validation

Processing in fused silica demonstrated detectable changes to structure measurable by OCT (Section 3.2). This was not the case in microscope slides. This incapability was shown to be a result of greater amounts of melt forming good contact with the surrounding solid glass, resulting in an interface with little change in refractive index.

Despite OCT being unable to track the length of the weld it was capable of determining when a weld bridged the interface between the two slides. Figure 5.a) shows an example where the OCT M-mode loses track of the interface between glass slides after processing. Here, the disappearing interface shows a successful weld i.e. there is no longer an air gap between the two slides. Figure 5.b) shows the fluctuation of intensity at the interface as processing occurs (due a varying melt pool) but ultimately still visible as the weld structure has not bridged both materials. Thus, during processing, OCT provides control by determining where the weld is unsuccessful and additional processing is needed at a different focal depth.

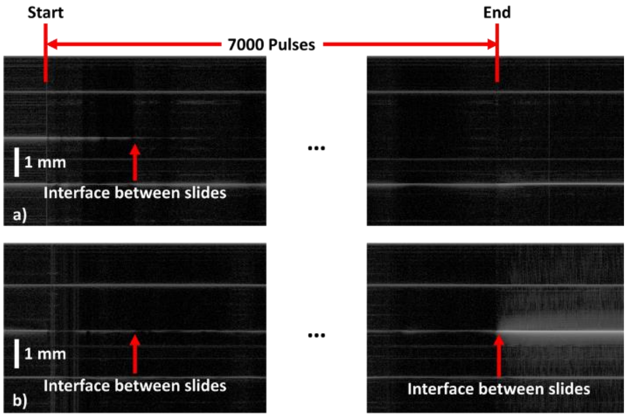

Figure 5. OCT M-modes of a) weld crossing the interface between gaps and b) not crossing the interface. Due to the long length of exposure, the middle of the images have been removed for brevity.

Figure 6.a) and b) shows top down optical microscope images of the welds seen in Figure 5.a) and b) respectively. In 6.b) the glass has been melted and re-solidified. In 6.a) the edges are clear to see as a result of material transport into the void between the sheets giving a defined edge. The OCT beam is focused to 5 µm at the centre and thus does not show information on these edge effects while coaxially aligned with the processing beam.

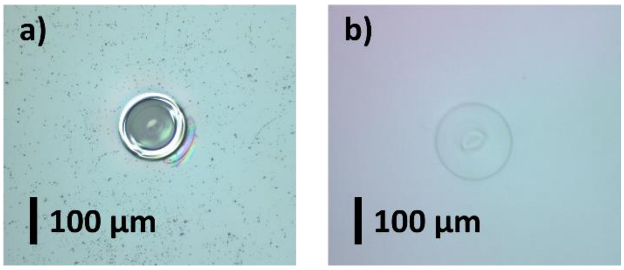

Figure 6. Top down optical microscope image of a) weld crossing the interface between gaps and b) not crossing the interface.

4. Conclusions

OCT has shown its capability for in-process monitoring of glass welds. The ability to providing position control is vital for weld placement, especially if applied to flexible materials. OCT was also able to monitor structural growth, with the potential to terminate processing and control the size. Finally, after processing, OCT is able to determine whether a weld is successful.

References

[1] Itoh K, Watanabe W, Nolte S, and Schaffer CB 2006 Ultrafast processes for bulk modification of transparent materials *J. Mater. Res* **31** 620-625

[2] Horn A, Mingareev I, Werth A, Kachel M and Brenk U 2008 Investigations on ultrafast welding of glass-glass and glass-silicon *Appl. Phys.* A **93** 171-175

[3] Huang D, Swanson EA, Lin CP, Schuman JS, Stinson WG, Chang W, Hee MR, Flotte T, Gregory K, Puliafito CA, Fuijimoto JG 1991 Optical Coherence Tomography *Science* **254**(5035) 1178-1181

[4] Webster PJL, Yu JXZ, Leung BYC, Anderson MD, Yang VXD, Fraser JM 2010 In situ 24 kHz coherent imaging of morphology change in laser percussion drilling *Opt Lett* **35**(5) 646-648