High Strength Fused Silica Flexures Manufactured by Femtosecond Laser

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ABSTRACT

Flexures are mechanical elements used in micro- and precision-engineering to precisely guide the motion of micro-parts. They consist of slender bodies that deform elastically upon the application of a force. Although counter-intuitive at first, fused silica is an attractive material for flexure. Pending that the machining process does not introduce surface flaws that would lead to catastrophic failure, the material has a theoretically high ultimate tensile strength of several GPa. We report on high-aspect ratio fused silica flexures manufactured by femtosecond laser combined with chemical etching. Notch-hinges with thickness as small as twenty microns and aspect ratios comparable to aspect ratios obtained by Deep-Reactive-Ion-Etching (DRIE) were fabricated and tested under different loading conditions. Multiple fracture tests were performed for various loading conditions and the cracks morphologies were analyzed using Scanning Electron Microscopy. The manufactured elements show outstanding mechanical properties with flexural strengths largely exceeding those obtained with other technologies and materials. Fused silica flexures offer a mean to combine integrated optics with micro-mechanics in a single monolithic substrate. Waveguides and mechanical elements can be combined in a monolithic devices opening new opportunities for integrated opto-mechatronics devices.

Keywords: flexures, femtosecond lasers, fused-silica, mechanical properties of glass.

1. INTRODUCTION

Flexures are mechanical elements used in micro- and precision-engineering to precisely guide the motion of micro-parts. They consist of slender bodies that deform elastically upon the application of a force. As such they can be considered as friction-less joint between two solid-parts that constraint certain degree-of-freedoms in order to precisely guide the relative motion of two connected parts. The table below summarizes the main differences between a traditional mechanical joint and a flexure.

<table>
<thead>
<tr>
<th>Mechanical joint</th>
<th>Flexure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembled</td>
<td>Monolithic</td>
</tr>
<tr>
<td>Geometrical surfaces</td>
<td>Elasticity of material</td>
</tr>
<tr>
<td>Large range motion possible</td>
<td>No backlash / no play</td>
</tr>
<tr>
<td>Backlash / play</td>
<td>Range motion limited</td>
</tr>
</tbody>
</table>

One of the early examples of an elastic element to guide a motion is the clock that Christiaan Huygens built in the XVIIth century. This famous clock revolutionized the time keeping, offering a precision never obtained before. Flexures have also been used for decades in scientific instruments, as well as other devices.

While they were first confined to the niche of precision instruments (an illustrative example of these developments is the optical slit proposed by R.V. Jones [1]), there are now much more broadly used with the general trend for miniaturization. They are extensively used in MEMS-design (an illustration can be found in [2]). In fact, the majority of MEMS with movable parts operate with flexures. In this paper, we investigate the use of fused silica as a material for miniaturized flexure and more specifically, the mechanical properties of femtosecond laser micro-fabricated flexures.

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2. **LONG-TERM OBJECTIVE: MONOLITHIC INTEGRATION IN FUSED SILICA**

The last decades have seen the emergence of micro-/nano- systems with diverse functionalities (see Figure 1). Starting from integrated circuits in the 70s, followed by micro-mechanical systems in the 80s-90s, photonics and fluidics in the 90s-2000s and recently the addition of organic material and bio-molecules, micro-/nano- systems are becoming complex machines performing sophisticated tasks.

Significant progress and breakthroughs are expected with the integration of these functionalities on a common platform. While the merger of electronics and micro-mechanics on a common platform (MEMS) is showing some significant success, a true integration of photonics, micro-mechanics and fluidics on a common platform has yet to be successfully demonstrated and implemented. This is especially true when working with non-planar (i.e. 3D) devices. Despite undisputable successes - vivid examples are accelerometers or inkjet printer heads, the number of successful microsystem applications (i.e. that get out of the lab) remain limited and well below its perceived potential. Cost-effectiveness and reliability issues still prevent a broader acceptance.

Our long-term research interest is to explore novel approaches to system integration at the micro-/nano- scale and in particular, methods for monolithic integration.

![Fig. 1 – Integration at the micro- / nano- scale. Starting from the electronics in the 70s, integration of functionalities has rapidly progress toward systems with functionalities as diverse as micro-mechanics, photonics, fluidics or recently biological material.](image)

To reduce the fabrication complexity and to increase the performance and reliability of microsystems, we have focused our research on monolithic integration based on a concept of “system-material”. Rather than building up a device by combining and assembling materials, this concept consists in turning a single piece of material into a system by locally tailoring its properties in selected locations. The material is no longer just an element of a device but becomes a device on its own. This approach has many advantages. It can be a single process approach; it reduces microsystems assembly steps (a common source of cost, inaccuracy and reliability issues); and it opens new design opportunities.

In that context, the use of ultrafast laser to process fused silica (the amorphous form of SiO₂) is of particular interest. Femtosecond laser beam can locally increase the refractive index [3][9], enhance the etching rate [4][10], introduce sub-wavelength patterns [5], create voids [6] or change the thermal properties [8] of fused silica. By scanning the laser through the specimen volume, one can distribute, combine and organize these material modifications to form complex patterns to be used for instance as waveguides or fluidic channels.

With this technique, instead of building up a device by combining layers of materials as common practice, the microdevice structure and function are directly “printed” into a single piece material. Note that thanks to the non-linear nature of the laser-matter interaction, laser-induced material modifications can be introduced not only at the material surface but also anywhere in the bulk where the laser is focused.
To explore the potential of fused silica as a system-material, we not only need to explore its capability as a platform for integrated optics but also the use of the material for micro-mechanics components. As part of this broader objective, this study specifically aims at investigating femtosecond-laser micro-machined structures as mechanical components.

In the next paragraph, we describe the test structure we have used and the fabrication process associated with it. Then, we present experimental results performed on a batch of fifteen flexures. We finally discuss these preliminary results as well as the potential of fused silica flexures not only in the context of micro-instruments but also as a tool to investigate the strength of silica glass at the micro-scale.

### 3. FABRICATION METHOD

#### 3.1 Test structure

The test structure used in these experiments is shown in Figure 1. It consists of a monolithic structure cut out of a 1mm-fused silica substrate. The fabrication process is further detailed in the next paragraph.

The structure is made of a slender body itself consisting of a thin part (the notch hinge) and a thicker beam. The test structure also has a protective frame to prevent possible damage during the fabrication process (in particular the etching step) and features like reference surfaces and mounting hole for handling and fastening.

![Fig. 2. Schematic (CAD drawing) of the test structure used in these experiments. The part is cut out of a 1mm-thick fused silica wafers. It consists of a slender part (the hinge) in the lower right corner, a protective frame, reference surfaces and mounting hole in the upper left corner. A contact pin moving along the Y-axis is used to load the hinge in bending.](image)

![Fig. 3. Test specimen dimensions. The thickness of the notch hinge is set variable between specimens.](image)

Test structures are mounted under a microscope and loaded by pressing a contact pin translating along one axis (the Y-axis in Figure 1) against the thicker element of the slender beam. As the contact pin touches the beam, it applies a force that deforms elastically the structure. Since there is no joint between the contact pin and the beam and considering that the pin is guided along the Y-axis, the contact points just slides along the beams as it deforms. The pin-beam contact is...
dry and no lubricant is used. Nevertheless the pin diameter is sufficiently large compared to the glass roughness to prevent chattering and eliminate unwanted forces along the X axis.

During the experiments, a video of the deformed beam is captured and later analyzed using image processing techniques. Stationary features (such as the edge cut at 45 deg in the middle of the structure) are used as reference to measure the angular deflection of the beam. The loading case corresponds to a pure bending mode. We calculate the maximum stress in the beam using standard modified equations for flexures on which a pure moment is applied.

3.2 Fabrication process

We used a fabrication method that was described in ample details in a previous paper [10]. Here, we only summarize the main aspects (see Figure 4).

In a first step, we use a femtosecond laser (RegA, Ti-Sapphire with 100fs pulse-length at 250 kHz, the focusing objective is a 50X objective with a NA of 0.55) to locally modify the glass structure. We use low-pulse energy. At this energy level, the material is not ablated but locally densified [13]. During this “exposure” step, the specimen is translated under the laser focusing objective using high-precision moving stages (Aerotech) with sub-micron resolution.

Figure 4 shows a scanning electron microscope image (SEM) of a micromachined hinges (left) and a schematic of two steps of the machining process we used to produce the parts.

![Figure 4](image)

**Fig. 4.** Left: micro-machined flexure / Right: schematic of the two-step micromachining process. The fused silica material is first exposed to the laser beam and then subsequently etched in a low concentration HF bath.

![Step 1](image)

**Step 1 – Femtosecond laser exposure (Ti-Sapphire, ~100fs pulses, 250 kHz rep-rate, low-pulse energy <1 μJ) – “Exposure”**

![Step 2](image)

**Step 2 – Etching in a low concentration HF bath (2.5 to 5%) “Development”**

Although the surface roughness is rather good for a laser-based machining process, it remains in the few hundreds of nanometer (RMS). Figure 5 shows an image of the edge of a micro-machined hinge and a roughness measurement measured at the edge of a slab cut using the same process parameters [11].

![Fig. 5](image)

**Fig. 5.** Scanning Electron Microscope (SEM) pictures of the cut edge of a flexure. The RMS roughness (measured at the edge) is about 300 nm, down to nearly 200 nm in the middle.
Fused silica follows a brittle mechanical behavior. It does not exhibit any plasticity (at least at the scale we are considering). These materials are characterized by an asymmetric mechanical characteristic. While they can be submitted to high compression stress level, they are weak while submitted to tensile stress.

Although glass materials have a high theoretical elastic limits (estimated at 15GPa or greater), they tend to break at much lower stress (typically a few tens of MPa) due to presence of surface flaws that act as possible crack nucleation sites [7]. When a crack forms, it rapidly propagates through the structure leading to catastrophic failure.

The tensile stress elastic limit dominates the flexure design as it defines the maximum possible excursion for a given hinge thickness, and ultimately governs how compact a flexure can be. As an example, 400-500 MPa are typical value used as limit when designing flexures of materials such as common steels.

For fused silica flexures machined by femtosecond laser, it is of prime importance to evaluate these elastic limits as a function of various experimental conditions to qualify fused silica as a flexure material of interest.

**4. RESULTS & DISCUSSION**

### 4.1 Bending experiments

Figure 6 shows a notch hinge (with a notch thickness of 40 microns) being loaded in bending. The pin sliding on the beam surface can be seen on the first four images (from left to right). This series of images is a video footage and the deformation shown in Fig. 6 was reversible. The maximum angle achieved there was 62 degree.

This is quite remarkable for a glass material and demonstrates the potential high resistance to tensile stress of these micro-machined hinges.

![Fig. 6. Illustration of a bending experiments on a flexure. The flexure is 40 microns thick in its thinnest part.](image)

To quantify the performances of these micro-machined structures, we have performed several breaking tests. The test consists in loading the flexure in pure bending (like shown above) until it breaks. Although the loading rate conditions (that may affect the results) were not very accurately controlled, comparable loading rates were applied to all the specimens considered in this study.

Using the video of the experiments, we extracted the last image before the structure collapse. These images look similar to the rightmost image in Figure 6. We then used image processing to measure the deflection angle with respect to reference surfaces. Knowing the bending angle we can then evaluate the load and the corresponding maximum tensile stress.

In a first approximation, we assumed small deformations to compute the maximum stress. Although the deflection is quite spectacular for some specimens, the hinge radius of curvature versus the hinge thickness remains in the acceptable limit of validity for the small deformation assumption (i.e. a radius of curvature at least ten times greater than the beam thickness). We also make the assumption that the hinge cross-section aspect ratio remains nearly unchanged by the etching. This is equivalent to neglect the rounding of the edges. The estimated stress level values could be refined by using a more sophisticated deformation model and also by taking into account possible changes in the second moment of inertia induced by the etching.
4.2 Experimental results

The calculated maximum tensile strengths (UTS) for various specimens are shown in the figure below. The left graph on Figure 7 shows the results as a function of the etching time. Here the etching time corresponds to the time spent by the specimens in the etchant and not the exposure time to HF for the glass surface of the hinge. The latter is more complex to define since the glass edges defined during the laser exposure are progressively exposed to HF as the etchant progressed through the material. Note that it takes about 8h (at 5% HF) to free the parts from the substrate.

The diamonds symbols correspond to specimens that were etched in a 2.5% HF concentration bath (after being freed from the substrate) while the circles are for specimens etched in a 5% HF concentration bath after being freed from the substrate. The right graph on Figure 7 shows the maximum tensile strengths for the same specimens but this time as a function of the hinge thickness.

![Graph showing calculated maximum strength for specimens etched for increasing period of time. The maximum strength is also shown as a function of the thickness. The circles correspond to specimens etched in a 5% Hydrofluoric (HF) solution while the diamonds symbol refer to specimens etched in a 2.5% HF solution.]

We caution that to be fully conclusive and considering the probabilistic nature of the glass fracture (it typically follows a Weibull distribution), we would need a larger number of specimens. This series of experiments was limited to 15 specimens due to machining constraints.

Nevertheless, we can make the following observations:

- The etching time clearly enhances the maximum strength of the flexure. This fact is not surprising and has been reported in the past [7]. A way to enhance the maximum strength of a glass is to etch its surfaces in HF.
- With the exception of one specimen, all the specimens exhibit UTS at least above 500 MPa.
- The UTS limit seems to linearly increase with the etching time. We note a difference of UTS increase rate for specimens etched in a 2.5% solution.
- UTS as high as 2.5 GPa are observed for specimens etched for a long period of time.

To further investigate the effects of the HF on the fused silica roughness, we measured the topography of four specimens etched respectively for 8, 14, 20 and 26 hours using an AFM. The results are shown in Figure 8.
Fig. 8. Topography as seen with the AFM for specimens etched for various amount of time in a similar composition HF bath (5\%). Specimens 1 to 4 were etched respectively for 8, 14, 20 and 26 hours. The scanning area is the same for the four specimens.

The RMS roughness is not dramatically modified by the etching time. However, we note that the spatial frequency of pits and edges seems to be reduced. Taking the first derivative for a line taken across an AFM topography map, we note the smoothing effect on the curves (as can be seen in Figure 9). This indicates that specimens etched for a longer time see their profile varying with lower spatial frequency and are less prone to sharp changes. These observations are consistent with a reduction of surface flaws density that would increase the UTS limit.

Fig. 9 – First derivative of the topography profile lines taken across an AFM topography map.
5. CONCLUSIONS & PROSPECTS

In this paper, we have briefly shown that femtosecond laser machined flexures can exhibit high ultimate tensile strength, exceeding 500MPa (measured on a collection of 15 specimens). These observations show that the material can successfully be used for fabricating all-optical devices with opto-mechanical functions. We demonstrated a micro-displacement sensor that integrates waveguides and a complex flexure set [12]. In that design, we limited ourselves to UTS lower than 450MPa which is rather conservative if we consider the results outlined in this paper. Therefore, there is room for further miniaturization and new design principles.

The fracture behavior of silica specimens at the micro-scale is not fully understood; in particular scaling effects are untested at this point. In these types of studies, the fabrication of suitable test specimens is challenging. Here, we have shown that femtosecond laser offers an efficient fabrication method to create test specimens of any arbitrary shapes with somewhat reasonably limited influence on the bulk material properties itself.

REFERENCES