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Fine tuning the roughness of powder blasted surfaces

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Abstract
Powder blasting (abrasive jet machining) has recently been introduced as a bulk-micromachining technique for brittle materials. The surface roughness that is created with this technique is much higher (with a value of R_a between 1–2.5 μm) compared to general micromachining techniques. In this paper we study the roughness of powder blasted glass surfaces, and show how it depends on the process parameters. The roughness can also be changed after blasting by HF etching or by using a high-temperature anneal step. Roughness measurements and scanning electron microscopy images show the quantitative and qualitative changes in roughness. These post-processes will allow us to investigate the influence of surface roughness on the microsystem performance in future research.

1. Introduction

1.1. Powder blasting

Powder blasting is a fast and inexpensive directional machining technique for brittle materials such as glass, silicon and ceramics. It is a technology in which a particle jet is directed towards a target for mechanical material removal (see figure 1). A lateral movement ensures an evenly eroded surface while a mask, which contains the design, covers the target. Non-brittle materials such as rubbers and metals can be used as the mask material [1] to easily machine complex structures with feature sizes down to 30 μm. The removal rate depends on the particle kinetic energy, but is typically 14–25 μm min^{-1} (3 inch glass or silicon wafer, one nozzle, particle sizes between 9–29 μm). For more information on powder blasting, see [2, 3].

An unfamiliarity with powder blasting sometimes causes a hesitation to use it, especially due to the uncertainty about the effect of the rough surface on the device performance [4]. It is, for example, supposed that the roughness changes the electro-osmotic flow [5], fluidic mixing and hence the dispersion [6]. Therefore, it is important to be able to manipulate the roughness and study its effect on device performance.

Powder blasted surfaces are rough due to the nature of the erosion process. The erosion process is usually described as the sum of many single particle impacts. When a brittle material is impacted by a hard sharp particle, the contact area is deformed due to the high compressive and shear stresses. The deformation leads to large tensile stresses after the impact (relaxation) that result in one or more lateral cracks originating from the plastic zone (see figure 2). If they are large enough they will extend to the surface removing a large heap of material and creating the rough surface.

In the case of Pyrex, which is an ‘open-structure’ glass, the glass is deformed on impact by compaction of the glass, making it denser. (This is in contrast to, for example, soda–lime glass where the larger content of non-silica components results in a more plastic deformation process along slip lines [7].) Next to the lateral and radial cracks, compaction can even result in cone cracks, which are normally observed with spherical indentors and particles [8]. The erosion mechanism of a single particle impact or indentation is more thoroughly described in erosion-related papers [9–14].

1.2. Previous work on roughness

Models that explain the effect of a single particle impact have been used to predict the roughness created by powder blasting. Buijs and Pasmans [15] calculated the depth of damage due to a particle impact and related it to the roughness. Later, Slikkerveer [10] predicted the roughness by calculating the R_a of a single particle impact (based on lateral crack size). These results showed good agreement and indicated that the

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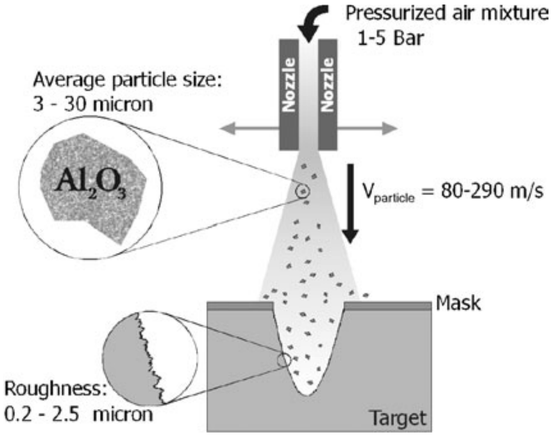

Figure 1. A schematic impression of the powder blast process.

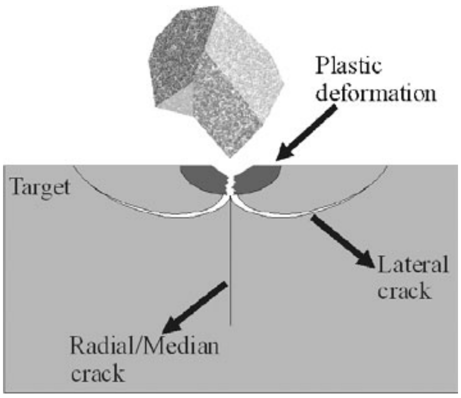

Figure 2. The erosion mechanism of a sharp particle.

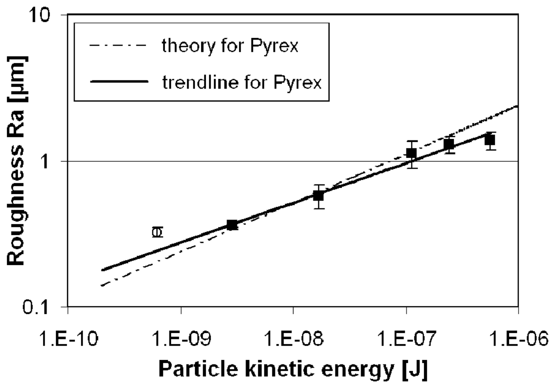

Figure 3. Surface roughness versus particle kinetic energy for Pyrex.

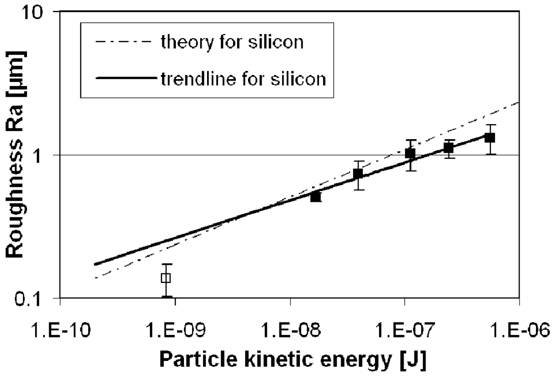

Figure 4. Surface roughness versus particle kinetic energy for Silicon.

Table 1. Material properties selected from several sources in the literature.

Material	*E* (GPa)		*H* (GPa)	
Pyrex	64	[16]	5.7 ± 0.3[1]	
Si	130–187	[17]	9.3–10	[18, 19]

[1] The measurements were made by the authors at the Cavendish Laboratory, Cambridge, UK. The hardness was measured using a microhardness tester (load 100–300 g, loading time 30 s).

roughness solely depends on the kinetic energy of the particle. The lateral crack size and depth decrease with decreasing kinetic energy so the surface roughness also decreases. At some point the kinetic energy becomes low enough to prevent lateral cracks from initiating. The absence of lateral cracks results in a much lower roughness [15].

2. Experiments

2.1. Initial roughness

Figure 3 and 4 show the surface roughness for different par- ticle kinetic energies for Pyrex and silicon, respectively. The samples for these figures have been taken from previous experiments [3]. The roughness measurement is explained in the next section.

The solid curves represent the trend lines (76.9 $U_{\mathrm{kin}}{}^{0.272}$ and 61.3 $U_{\mathrm{kin}}{}^{0.263}$ for Pyrex and silicon, respectively) and the dotted curve gives the theoretical curve [9]

$$R_a = 123\,101 \frac{E^{1/2}}{H^{5/6}} U_{\mathrm{kin}}{}^{1/3}\ \mu\mathrm{m} \tag{1}$$

where R_a is the surface roughness, E is Young's modulus, H is the hardness, and U_{kin} is the particle kinetic energy (see table 1 for the material properties used in this paper).

These are about the same values as measured and calculated by Slikkerveer *et al* [10]. The first data point was omitted from the trend line for both materials because of the low kinetic energy. In this region, lateral cracking hardly occurs and the model is not valid. The low kinetic energy did not result in a much lower roughness for Pyrex, in contrast to silicon. The cone cracks that also can be found in Pyrex might still occur at these low energies, and contribute to the surface roughness, but this point requires additional research.

We now attempt to change the roughness of the Pyrex glass samples.

2.2. Post-processes

To examine the post-processes, Pyrex glass wafers were blasted uniformly without structures using two alumina powder sizes of 29 and 9 μm with velocities of 220 and 290 m s^{-1}, respectively. The samples were taken from this wafer to perform one post-process. The surface roughness

Table 2. Roughness measurements.

Particle size (μm)/speed (m s^{-1})	9/290	29/220
R_a after blasting (μm)	1.2 ± 0.2	2.5 ± 0.6
R_a after finishing with 9 μm particles (μm)	–	2.0 ± 0.3
R_a after finishing with 3 μm particles (μm)	0.9 ± 0.2	1.8 ± 0.5
R_a after 1 h at 5% HF (μm)	1.7 ± 0.1	3.2 ± 0.2
R_a after 3 h at 5% HF (μm)	2.2 ± 0.1	3.9 ± 0.5
R_a after 1 h at 700 °C (μm)	1.1 ± 0.1	2.6 ± 0.5
R_a after 1 h at 750 °C (μm)	0.58 ± 0.1	1.8 ± 0.4
R_a after 1 h at 800 °C (μm)	0.091 ± 0.02	0.49 ± 0.3

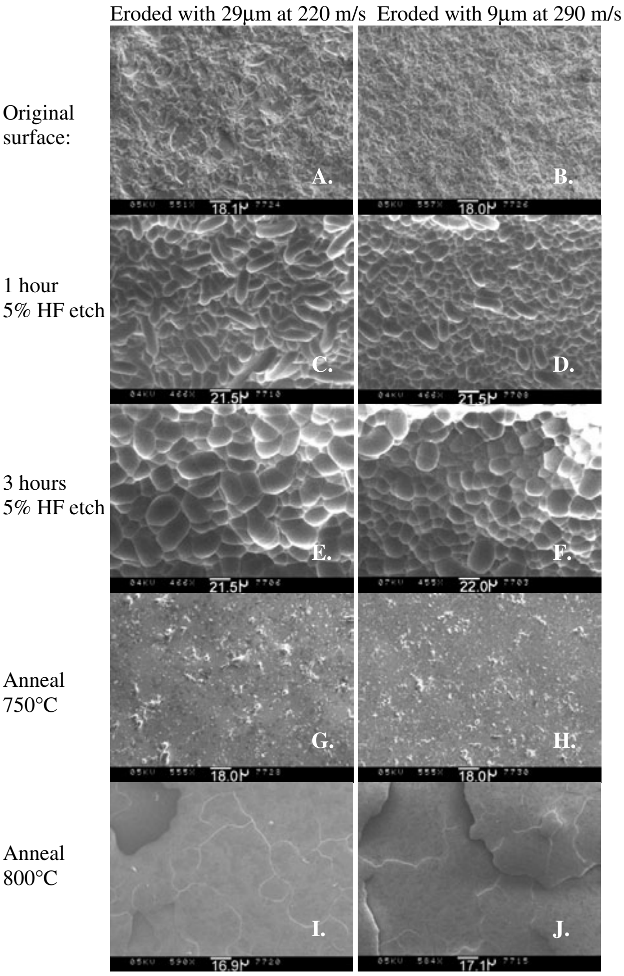

Figure 5. SEM images of the surfaces of the original and post-process samples (top view).

was determined by calculating the average R_a of five scans (by using the R_a function on the Sloan Dektak II surface profiler). The scan length was 1 mm, and the stylus tip was 2.5 μm. R_a was chosen as a first indicator for the surface roughness, and all values are listed in table 2 (the error being the standard deviation of the five R_a values). Additional scanning electron microscopy (SEM) images have been made to observe the roughness quality (see figure 5).

2.3. Post blast

The original blasted surfaces were finished with a smaller particle size, removing approximately an additional 10 μm. As table 2 shows, this reduces the surface roughness of the sample.

2.4. Post HF etch

A post HF etch increases the surface roughness quantitatively (see table 2). However, the images in figures 5(*c*)–(*f*) show that the roughness quality has also changed considerably.

2.5. Post anneal

An anneal step at a temperature $\geqslant$750 °C decreases the roughness. At 800 °C the original surface morphology is almost completely destroyed (see figures 5(*i*) and (*j*)).

3. Discussion

3.1. Post blast

Table 2 shows that finishing the sample with a smaller particle size can reduce the surface roughness. This is not trivial since the erosion process is not isotropic. An explanation would be that when impacting on an elevation, lateral cracks could more easily escape to the surface due to the vicinity of a slope. This can locally enhance the erosion rate, reducing the average roughness.

3.2. Post HF etch

The increase of R_a after a post HF etch can be explained in two ways. The powder blast process introduces many micro radial cracks (see figure 2). After particle impact, these cracks are closed and not detectable by the Dektak. However, HF etching reveals these cracks and widens them, making the surface rougher. Secondly, HF etching on a smooth wafer also increases the surface roughness. Next to silica, Pyrex also contains other metal oxides (e.g. aluminium oxide) which have a different etch rate in HF. Grains of this material will be revealed when the surrounding glass is etched away and act as a micro mask so the surface will be unevenly etched [20].

Figure 5(*c*) shows many elliptical ditches. We believe that these originate from the radial cracks that are formed during particle impact. Note that figure 2 only shows the cross section of the radial crack. The actual crack is halfpenny shaped and perpendicular to the cross section. The widths of the ellipses are rather uniform and about 12 μm wide. This is consistent with the etch rate of 5% HF, which is 6 μm h^{-1}. Vickers indentations, which are often used to predict the effect of single particle impacts, result in two radial cracks

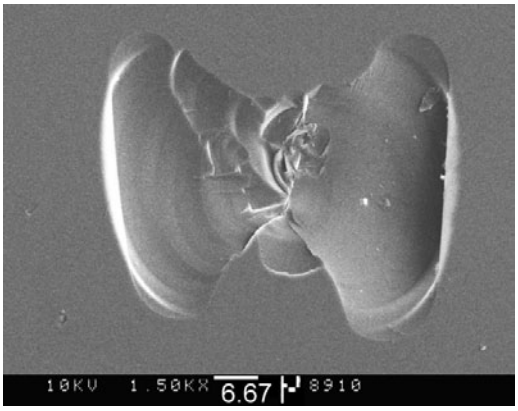

Figure 6. A single particle impact site on Pyrex (with an approximate size and velocity of 29 μm and 220 m s^{-1} respectively).

perpendicular to each other. However, when using irregular shaped particles, there can be a preferable growth direction for a radial crack, resulting in one dominant radial crack. Figure 6 shows a single particle impact site with clearly two lateral cracks and one (dominant) radial crack in between.

The ellipse effect is less clear in figure 5(*d*) because the radial cracks are not as deep when the surface is eroded with 9 μm particles. So the elliptical ditches have already become more irregularly shaped. This is also the case for figures 5(*e*) and (*f*).

3.3. Post anneal step

Table 2 shows that annealing at 700 °C does not affect the surface. A temperature of 750 °C does decrease the roughness and figures 5(*g*) and (*h*) show a smooth surface with some random irregularities. It was found that a temperature of 750 °C was still low enough to keep the integrity of a 2 mm wide and 17 μm deep channel. This is adequate since powder blasted structures in general have a feature size that is larger than 30 μm.

At a temperature of 800 °C, the surface becomes very smooth. However, this temperature is so high that any structures in the glass are ruined. Figures 5(*i*) and (*j*) show that the original surface morphology is completely destroyed. In spite of the very slow temperature ramp down, these images show small cracks. Note that the softening point of Pyrex is 821 °C [16].

3.4. Bonding

When making, for example, microfluidic devices, several process steps are involved such as wafer-to-wafer bonding. It is important to perform the tuning of the surface roughness at the correct fabrication stage, to ensure that bonding is still possible. A post-blasting naturally does not give any problems. The post HF etch makes the bonding surface rough which can cause problems with direct bonding. Additional bonding surface protection might be necessary. In the case of post annealing, we recommend its use after bonding so that it can enhance the bond strength.

4. Conclusion

The surface roughness of powder blasted surfaces was successfully changed both quantitatively (see table 2) and qualitatively (see figure 5). The surface roughness decreases rapidly at very low particle kinetic energies when lateral cracking hardly occurs any longer. Unfortunately, at this point the powder blast removal rate becomes very low. To decrease the surface roughness and preserve the high removal rate, which is one of the main advantages of powder blasting, the surface can also be finished with a smaller particle size after the fast bulk machining. Post HF etching increases the surface roughness, mainly due to micro crack widening. These cracks are also responsible for the unusual surface morphology (figures 5(*c*)–(*f*)).

A post-anneal can decrease the roughness. Especially, at 800 °C the surface becomes relatively smooth. However, at that temperature the macro shape of the glass also changes. An anneal step at 750 °C decreases the surface roughness, and at this temperature a 2 mm wide and 17 μm shallow channel still keeps its integrity.

Now that we are able to manipulate the surface roughness of a powder blasted channel, further research will be directed to the effects of roughness on device performance.

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