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Powder blasting for three-dimensional microstructuring of glass

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Abstract

We report on powder blasting as a promising technology for the three-dimensional structuring of brittle materials. We investigate the basic parameters of this process, which is based on the erosion of a masked substrate by a high-velocity eroding powder beam, using glass substrates. We study the effect of various parameters on the etching rate, like the powder velocity and the mask feature size, which induces geometrical effects to the erosion process. We introduce oblique powder blasting and investigate, in particular, sidewall effects of the micropatterned structures. A few examples of devices micromachined by powder blasting are also presented.

Keywords: Sand blasting; Powder blasting; Microfabrication; Erosion; Etching

1. Introduction

Erosion is a phenomenon that we can observe in lot of hydrodynamic applications. It generates serious damage to objects in contact with eroding particles present in an air or liquid flux. In order to minimise or avoid erosion-linked damages, particle erosion processes have been studied with an increasing interest [1]. Erosion behaviour depends both on the particle morphology and on the properties of the target material. Ductile metal erosion has been studied using both macroscopic hardened steel spheres [2] and microscopic particles [3]. The erosion mechanisms of brittle materials like ceramics and glass by the impact of hard and sharp eroding particles has been mainly studied and were shown to be very similar to what is known from quasi-static or scratching Vickers-indentation measurements. When a particle arrives at the target surface having a certain velocity, it induces a local material deformation. When its energy is higher than the fracture threshold of the material, cracks are generated and some parts of the target material are removed [4,5].

During recent years, powder blasting technology has been developed to pattern large glass surfaces for flat panel display applications. This technique has been considered to be economically the most appropriate for this kind of application [6–8]. Moreover, this application has triggered advanced study and modelling of the powder blasting process [9,10]. Recently, we proposed to utilise the powder blasting process for the microstructuring of brittle materials for sensor applications [11]. In this paper, we want to focus on fundamental parameters and characteristics governing the powder blasting process. Traditionally, glass patterning is realised using aggressive wet etching schemes (HF-based), limited to produce microstructures with isotropic etching profiles. The powder blasting technique allows to get complex and controlled shapes of the eroded structure. Moreover, the erosion rate of the powder blasting process is typically several hundreds of micrometers per minute, which is much higher than what is obtainable by standard wet or dry etching processes. This makes the powder blasting technology very appropriate for fast and complex three-dimensional microstructuring without any geometrical size upper limits.

In Section 2, we present our experimental set-up and discuss the system that we use to measure the particle velocity. In Section 3, we discuss the experimentally measured powder velocity, which is mainly determined by two parameters: the applied pressure and the nozzle–substrate distance. We also discuss the influence of pattern size on the etching rate and the influence of the impact angle of the powder beam on the glass surface. In Section 4, we present a few possible applications of the powder blasting technology, showing its interest in microstructure fabrication. Finally, in Section 5, we present our conclusions.

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2. Experimental set-up

All the erosion experiments were performed using a Texas Airsonics abrasive jet machine, type HP-2. The powder is constituted by 30-μm-size alumina sharp particles (Al_2O_3), which is injected in a compressed air flux to the nozzle through a rubber tube. As represented in Fig. 1, the nozzle is mounted on an arc-shaped support. This system allows to change easily the incidence angle θ of the powder beam to the target. The distance d from the nozzle to the target can be varied up to 9 cm. In order to uniformly expose the whole target surface to the powder beam, we use an x-axis translation stage for the substrate and a y-axis translation stage for the nozzle. To erode selectively, the surface of the substrate, a 0.5-mm laser cut iron mask containing the desired structures is fixed on the surface of the substrate with an Apiezon® wax seal. During powder blasting, the exposed seal is immediately removed by the first incoming particles and does not influence the erosion process of the substrate. The glass wafer is also maintained on a table substrate by a magnetic coupling between some hard magnets biased in the table and the iron mask.

3. Experimental characterisation of the erosion process

3.1. Powder velocity

It has already been shown that the erosion rate E_{rate}, defined as the ratio of the removed weight to the incoming particle weight, is strongly dependent on the indenting particle velocity [9,10], which makes this parameter an essential one for the characterisation of the micro-particle erosion process. We have measured the particle velocity by positioning a double disk system underneath the static nozzle. The two horizontal disks are parallel and the upper disk has a 1-mm-diameter hole permitting the particles to pass through in a very narrow beam. These particles erode a glass target fixed on the 1.5-mm-distant lower disk. In each case, we compare the static impact profile (disks not rotating) on the glass target with two erosion profiles corresponding to two different disk rotation speeds ω. The three erosion profiles (one static and two dynamic measurements) are then linearly scanned using an Alpha-step 500 profilometer. One dynamic spot is separated from the static one by a linear distance l. The particle velocity is now given by

$$v = \frac{\pi r e \omega}{30 l} \qquad \text{if } l \ll r \tag{1}$$

where r is the distance from the 1-mm hole to the disks rotation axis (4 cm in our case) and e is the air gap between the 1-mm hole on the upper disk and the glass target on the lower disk. As an example, we obtain a particle velocity $v = 191$ m/s with a nozzle pressure $p = 3$ bar and a nozzle–substrate distance $d = 4$ cm.

Many different particle velocity measurements have been performed using varying two parameters: the air pressure p and the distance d between the nozzle and the glass target. Fig. 2 shows the influence of these parameters on the particle velocity. We can observe a decreasing particle velocity with an increasing distance d. The kinetic energy of the particles is $E_k = 1/2mv^2$, with $m = 0.45$

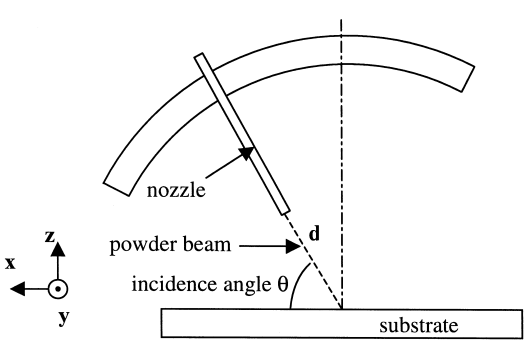

Fig. 1. Schematic view of the used powder blasting system configuration.

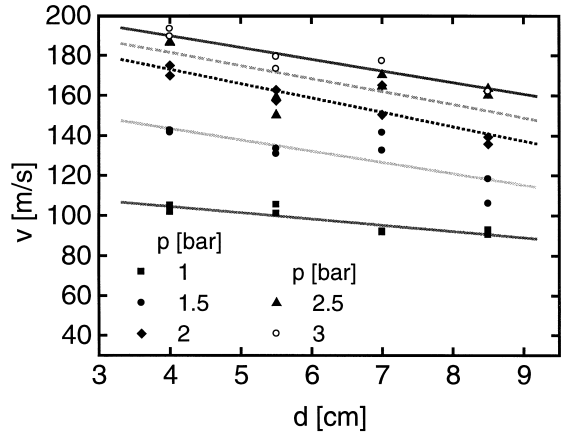

Fig. 2. Influence of the distance between the nozzle and the substrate on the particle velocity for different air pressures.

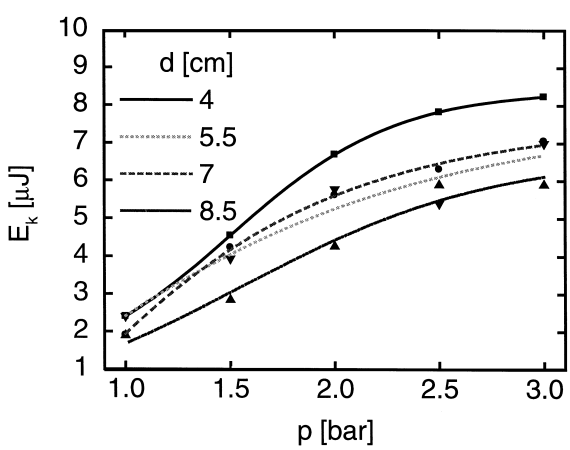

Fig. 3. Variation of the incoming particle kinetic energy, which is proportional to the square velocity, as a function of the beam pressure for different distances from the target to the nozzle.

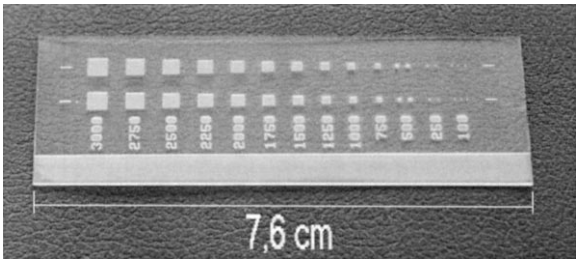

Fig. 4. Powder-blasted glass sample with different mask pattern sizes.

μg, the mean mass of a single particle. The particle is assumed to be spherical with a diameter of 30 μm. Fig. 3 presents the evolution of E_k with increasing applied air pressure. We can note that the increase of the kinetic energy with the pressure tends to saturate at higher pressures.

3.2. Geometrical effects on etching rate

We have studied the influence of mask feature size on the etching rate using a 0.5-mm-thin iron mask with many square holes, ranging in width from 0.1 to 3 mm. The applied pressure and the distance from the nozzle to the target are fixed to respectively 3 bar and 7 cm, and the incident angle is maintained constant at normal incidence. After the uniform exposition of the whole substrate surface to the powder beam, we have measured the erosion depth of each hole structured in the glass substrate shown in Fig. 4, using an optical microscope. Fig. 5 presents the erosion depth measurement results for two different glass samples etched at two different etching times differing by a factor of 3.2. We obtain a good consistency between the two etching times used. We can see that for mask opening sizes above 1.5 mm, the erosion depth is approximately constant and independent of the mask size. In the 0.5–1.0 mm range, one can observe a slight increase of the depth while it strongly decreases for smaller opening mask size. This decrease connects to the difficulty for the particles to enter and to leave the small hole mask opening compared to the particle size, giving rise to a possible particle accumulation inside the structure and to a decrease of the etching rate.

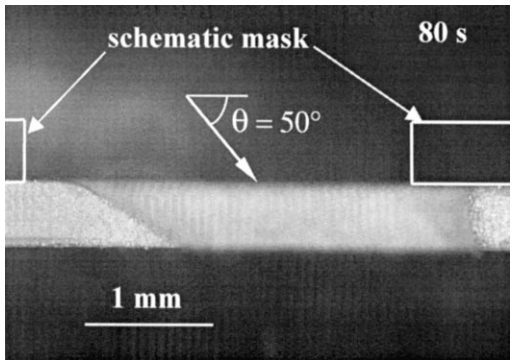

Fig. 6. Profile of an oblique powder-blasted hole in glass using an eroding beam with an incidence angle $\theta = 50°$. The position of the mask during erosion is schematically indicated.

The noticed small bump in the curves for mask sizes between about 0.5 and 1 mm is a geometrical effect due to incoming particles reflecting on the mask wall or on the wall of the already etched structure. These rebounding particles have the particularity to give a smaller erosion contribution than primary particles, due to the energy loss at the reflection impact, but their indenting sites are situated at a certain distance from the mask or structure wall, giving locally an additional erosion contribution [1,12]. For a given mask size, the erosion effects from the particles reflecting on the whole mask or already etched structure walls, add constructively, thereby increasing the etching depth.

3.3. Oblique powder blasting

The standard mode of operation of the powder blasting nozzle is using a powder beam at normal incidence ($\theta =$

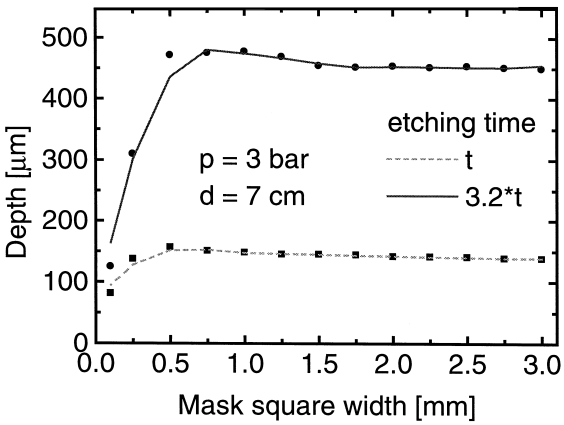

Fig. 5. Etching depth as a function of the mask pattern size for two powder-blasted glass samples during two etching times differing by a factor of 3.2.

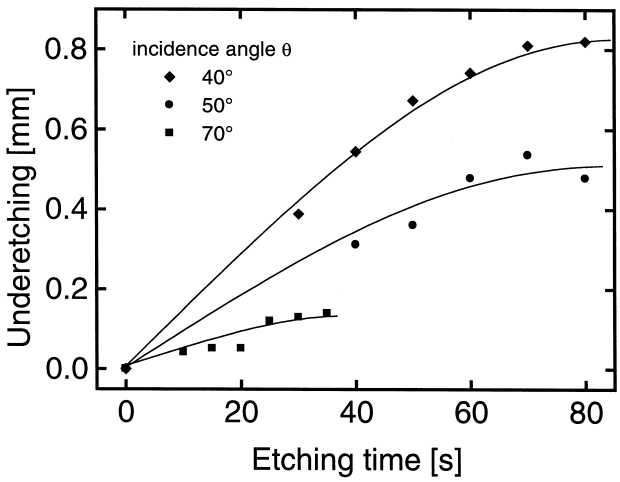

Fig. 7. Mask underetching as a function of the etching time for different incidence angles.

90°). As already shown in Fig. 1, we also have the possibility with our set-up to vary the incidence angle θ of the particles. This opens new interesting perspectives for mask underetching and three-dimensional-like microfabrication. Fig. 6 shows a typical erosion profile obtained with a 0.53-mm-thick Pyrex wafer and an incidence angle $\theta = 50°$. The position of the metal mask during the erosion experiment is schematically indicated. We observe a strongly different erosion process between the two wall sides of the eroded hole. Moreover, the right-hand side of the hole structure is characterised by in important mask underetching effect. This phenomenon has been measured for several hole profiles corresponding to different incidence angles and is presented on Fig. 7. We observe that it is more important for small impact angles. The curves first increase linearly and then show a beginning of saturation at an etching time corresponding to the time necessary to etch through the complete wafer. This indicates a contribution of secondary impact particles to the underetching phenomenon, due to incoming particles, which rebound on the bottom of the already etched structure, reaching and eroding the wall of the glass structure under the mask.

To further quantify the oblique powder blasting process, we have investigated the wall slope evolution as a function of the etching time by measuring the wall inclination angle θ_{wall} at different etching times and for different incidence angles θ, as shown in the first picture of Fig. 8 with $\theta = 50°$. As we could see in Fig. 6, the sidewalls of the powder blasted holes are not perfectly parallel to the powder beam, but present a different slope. We have measured the initial wall slope for different etching times and deduced the related angle θ_{wall} on the left side of the hole, which is only exposed to primary incoming particles. Fig. 9 shows the inclination angle measured on hole structures etched with different incidence angles, as a function of etching time. We clearly see that the wall

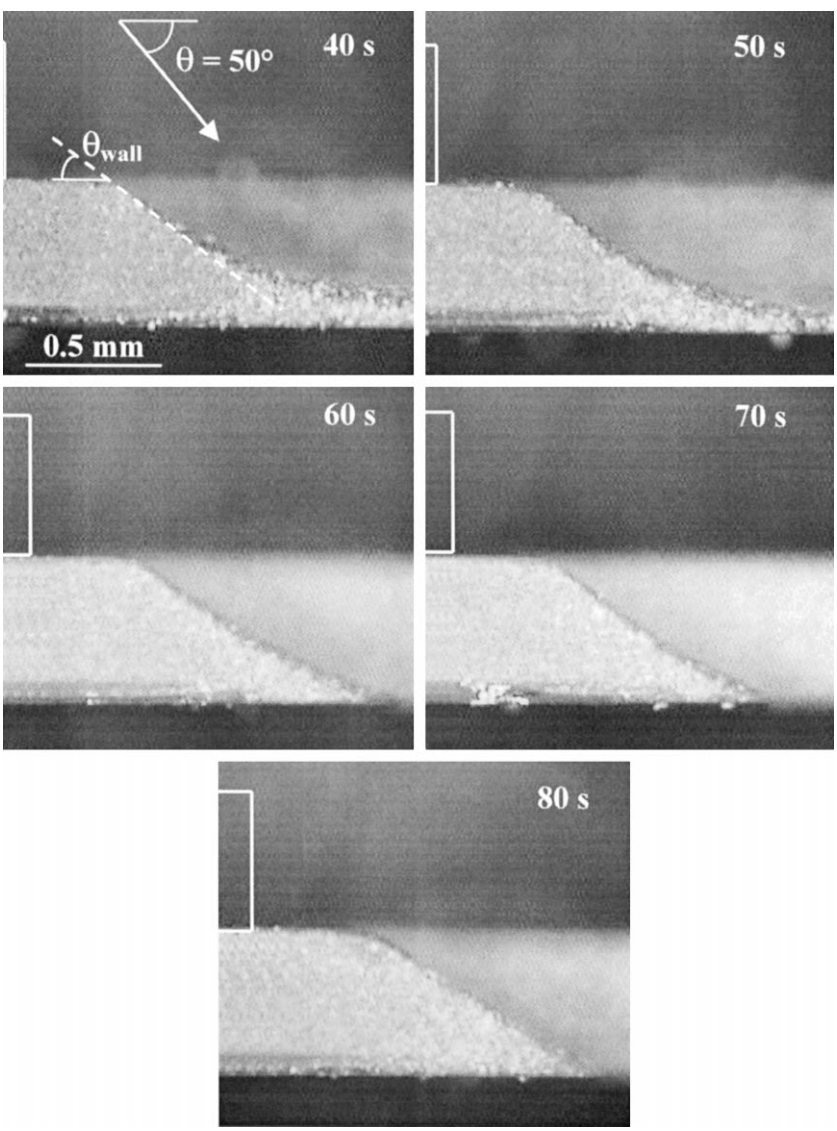

Fig. 8. Hole profile evolution with an incidence angle $\theta = 50°$ at different etching times. The position of the mask during erosion is schematically indicated.

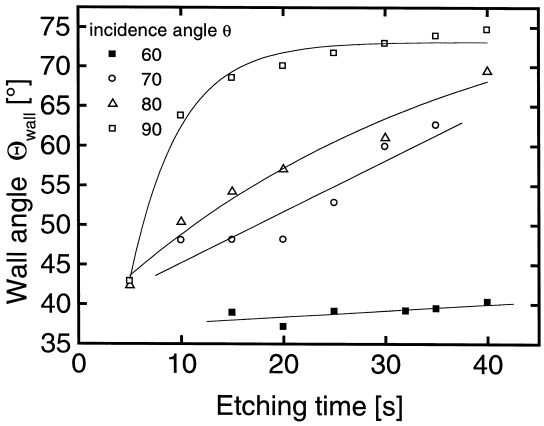

Fig. 9. Wall profile angle θ_{wall} relative to the wall slope of Fig. 8 for different incidence angles.

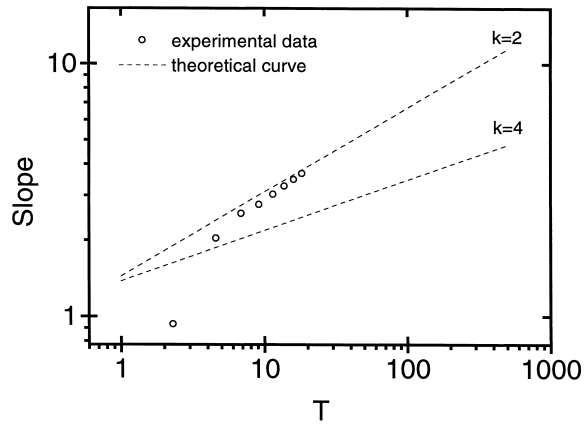

Fig. 10. Comparison between our experimental wall slope results and the mathematical model proposed by P.J. Slikkerveer [12].

angles tend to saturate at a value about 10–20° less than the corresponding incident angle θ.

The wall slope evolution during the erosion process has been a subject of theoretical research and an analytical model has been developed for erosion at normal incidence ($\theta = 90°$) [1,12,13]. It has been proposed that the erosion profile results mainly from the different erosion rates for different angles of incidence of the particles on the target surface. The substrate near the edge of the mask is less exposed to erosion as a consequence of the finite size of the impacting powder particles, thereby initiating the non-uniform erosion rate. The evolution of the surface of the hole in the vertical direction z during the erosion process can be modelled by the following relation [12]:

$$\frac{\partial z}{\partial t} = E_{\mathrm{eff}} \frac{\frac{1}{2}\phi_{\mathrm{jet}} v_{\mathrm{jet}}^2}{\rho_t} \left(\frac{1}{\sqrt{1 + (\partial z/\partial x)^2}} \right)^k \tag{2}$$

where E_{eff} is the already introduced erosion efficiency, ϕ_{jet} the mass flux of powder, v_{jet} the particle velocity, ρ_t the specific mass of the substrate and k a constant correlated to experimental measurements of E_{eff} with different particle sizes. As defined, the value of k should be between 2 and 4 [12]. In our case, an approximate value of k will be determined based on our experimental slope measurements. To express the slope relation in dimensionless units, it is necessary to introduce a dimensionless time parameter T defined as

$$T = \frac{E_{\mathrm{eff}} v_{\mathrm{jet}}^2 \phi_{\mathrm{jet}} t}{2 W \rho_t \delta} \tag{3}$$

where t is the experimental etching time, W the mask opening size and δ a dimensionless parameter defined as equal to d_{m}/W, with d_{m} representing the distance from the mask edge where the particle etching contribution is reduced due to their finite size. In our case, we attribute to d_{m} the value of the particle size (30 μm). Since our opening mask size W is 3 mm, we obtain $\delta = 0.01$.

The slope $\partial z/\partial x$ in the limit of $|\partial z/\partial x| \gg 1$ is then given by [12,13]:

$$\frac{\partial z}{\partial x} = \left(-(k+1)T \right)^{\frac{1}{k+1}} \tag{4}$$

Dotted lines of Fig. 10 show two asymptotic theoretical values of $\partial z/\partial x$ $(= \tan(\theta_{\mathrm{wall}}))$ for $k = 2$ and 4, respectively, calculated using Eq. (4). We have correlated these theoretical curves with our experimental slope measurement results obtained on a pyrex substrate with an incidence angle $\theta = 90°$. As we can see, there is a good agreement between our experiments and the mathematical erosion model, from which we deduce a value of k tending to be equal to 2 with increasing etching time. Physically, this value for k reflects an erosion efficiency E_{eff}, which is independent of the particle energy [12], in agreement with our experimental results.

4. Powder blasting applications

The high etching rate and the good control of eroded profile slopes make the powder blasting technology a very promising technique for the realisation of microstructures

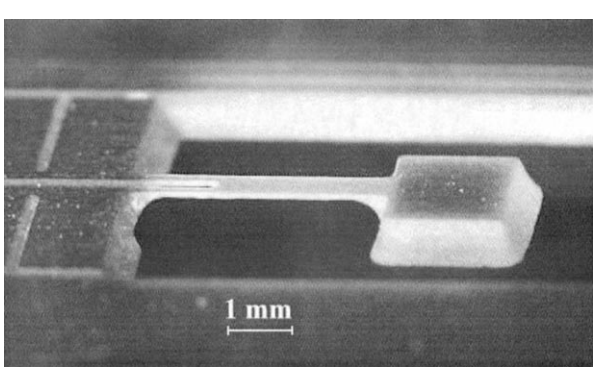

Fig. 11. Glass cantilever beam realised by powder blasting for inertial sensor applications.

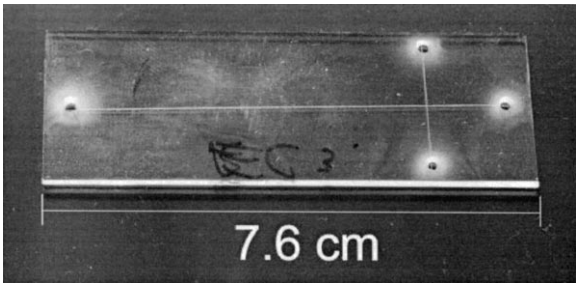

Fig. 12. Microfluidic chip obtained by the powder blasting of two glass substrates. This device is used for electrophoresis applications.

ranging in size from a few hundreds of microns up to a few centimeters or more. Some of the microstructures realised by powder blasting in different types of brittle substrates are presented here. Fig. 11 shows a 100-μm-thick cantilever beam supporting a mass and realised for inertial sensor applications. It has been realised in a 550-μm-thick glass substrate by a two-step powder blasting process, respectively, to create the whole structure and to thin the cantilever beam to reach a defined resonance frequency. The beam deflection detection of such an inertial sensor can be done by the use of a previously deposited piezoresistive thin layer or by a capacitive detection system composed by a deposited metallic thin layer on the seismic mass and on a counter electrode [11].

A second possible application of the powder blasting technology is the realisation of microchannels in glass, pyrex of quartz substrates for microfluidic applications [14]. Fig. 12 shows such a device composed by two fusion-bounded soda lime rectangular substrates. On the upper one, four through-etched holes have been made by powder blasting, while two 100-μm-wide and 20-μm-deep cross channels have been eroded on the lower substrate. Fig. 13 is a picture of the crossing point of the two channels.

Another possible application of the powder blasting technology is the microstructuring of ferrite substrates. Fig. 14 presents a matrix of 4-mm-wide *E*-cores, structured in a 1-mm-thick ferrite substrate for magnetic device applications like microtransformers. In this case, powder blasting proved to be not only the most appropriate, but also a very fast and cheap way to get such structures.

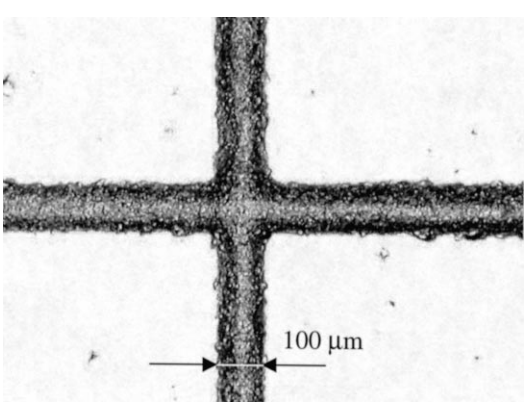

Fig. 13. Enlarged view of the crossing of microchannels of Fig. 12.

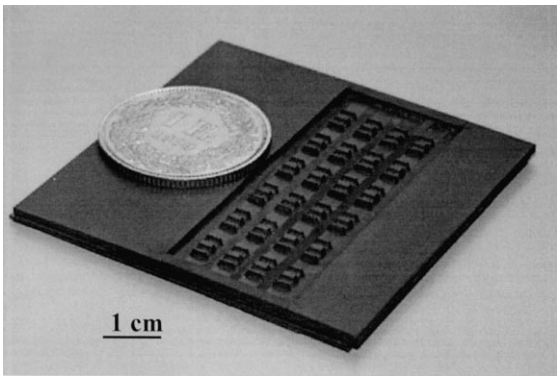

Fig. 14. Miniaturised *E*-cores microstructured by powder blasting in a 1-mm-thick ferrite substrate for magnetic device applications.

5. Conclusions

We have presented powder blasting technology as an interesting option for the three-dimensional microfabrication of brittle materials. We have used a pressurised nozzle for projecting abrasive 30-μm Al_2O_3 particles to such masked substrates. First, we studied the basic parameters of the powder blasting erosion process, like the particle velocity varying with the applied air pressure and the distance from the nozzle to the substrate. Also, we have studied mask opening size influences on the etching rate. We introduced powder blasting at a variable angle of incidence, opening the way to new underetching effects and perspectives in the three-dimensional microfabrication. We have compared the experimental etching profiles of the perpendicular powder blasting process with a recent mathematical model and found a good agreement between the theoretical and experimental results. Finally, some possible applications of the powder blasting technology have been proposed, showing the high potential of this process for the realisation of miniaturised structures.

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References

[1] P.J. Slikkerveer, F.H. in't Veld, Model for patterned erosion, Wear 233–235 (1999) 377–386.

[2] I.M. Hutchings, N.H. Macmillan, D.G. Rickerby, Further studies of the oblique impact of a hard sphere against a ductile solid, Int. J. Mech. Sci. 23 (1981) 639–646.

[3] M. Dundar, O.T. Inal, J. Stringer, The effect of particle size on the erosion of a ductile material at the low particle size limit, Wear 233–235 (1999) 727–736.
[4] G.P. Tilly, W. Sage, The interaction of particle and material behaviour in erosion processes, Wear 16 (1970) 117–165.
[5] M. Buijs, Erosion of glass as modeled by indentation theory, J. Am. Ceram. Soc. 77 (1994) 1676–1678.
[6] T.S. Baller, G.G.P. van Gorkom, N. Lambert, E.A. Montie, P.H.F. Trompenaars, S.T. de Zwart, Construction and physical processing of Zeus panels, Philips J. Res. 50 (1996) 463–474.
[7] H.J. Ligthart, P.J. Slikkerveer, F.H. in't Veld, P.H.W. Swinkels, M.H. Zonneveld, Glass and glass machining in Zeus panels, Philips J. Res. 50 (1996) 475–499.
[8] T. Hirose, K. Kariya, M. Wakitani, A. Otsuka, T. Shinoda, Performance features of a 42-inch diagonal color plasma display, Fujitsu webpage information, www.fujitsumicro.com, 1997.
[9] P.J. Slikkerveer, P.C.P. Bouten, F.H. in't Veld, H. Scholten, Erosion and damage by sharp particles, Wear 217 (1998) 237–250.
[10] M.A. Geltink-Verspui, Modelling Abrasive Processes of Glass, PhD Thesis, Eindhoven University of Technology, 1998.
[11] E. Belloy, S. Thurre, E. Walckiers, A. Sayah, M.A.M. Gijs, The introduction of powder blasting for sensor and microsystem applications, Sens. Actuators, A (2000) in press.
[12] P.J. Slikkerveer, Mechanical Etching of Glass by Powder Blasting, PhD Thesis, Eindhoven University of Technology, 1999.
[13] P.J. Slikkerveer, J.H.M. ten Thije Boonkkamp, Mathematical modeling of erosion by powder blasting, Surv. Math. Ind. (1999) submitted for publication.
[14] A. Sayah, D. Solignac, T. Cueni, M.A.M. Gijs, Development of novel low-temperature bonding technologies for microchip chemical analysis applications, Sens. Actuators, A (2000) in press.

Biographies

Eric Belloy was born in Geneva, Switzerland, in 1972. He received his diploma in microengineering in 1997 from the Swiss Federal Institute of Technology of Lausanne (EPFL). His diploma work was the study, realisation and characterisation of microtips on Si and glass substrates in use for the detection of the electrical activity of nerves cells. Since April 1997, he works as a research assistant in the Institute of Microsystems at EPFL. He has first developed the technology process for a new magnetic sensor based on the Hall effect. Then, he has developed a new technology based on flex-foil patterning and assembling in order to realise magnetic devices. His actual research area is on the etching by micro-sandblasting.

Abdeljalil Sayah received his degree in physics in 1988 from University Mohammed V, Rabat, specialising in solid state physics. From 1993 until 1996, he worked as a research assistant in the CNET-Bagneux (Paris) Laboratory where he received a PhD degree for the thesis entitled "Realisation of Silicon-based dielectrics Optical Waveguide on InP by Photochemical Deposition". In 1996, he joined the Applied Optics Institute (IOA) of the Swiss Federal Institute of Technology in Lausanne (EPFL) as a postdoctoral researcher. His research interests included the study and characterisation of optical fiber tips for scanning near field optical microscopy by protection layer liquid-phase etching. He participated on the characterisation of Bragg gratings produced in optical fibers by UV lasers. He is now with the Institute for Microsystems (IMS) at EPFL. His current research interests are in inertial sensors (gyroscope), bio-sensors, and fabrication technologies.

Martin A.M. Gijs received his degree in physics in 1981 from the Katholieke Universiteit Leuven, Belgium, and his PhD degree in physics from the same university in 1986. He joined the Philips Research Laboratories in Eindhoven, The Netherlands in 1987. Subsequently, he has worked there on micro- and nano-fabrication processes of high critical temperature superconducting Josephson and tunnel junctions, the microfabrication of microstructures in magnetic multilayers showing the giant magnetoresistance effect, the design and realisation of miniaturised motors for hard disk applications and the design and realisation of planar transformers for miniaturised power applications. He joined the Swiss Federal Institute of Technology Lausanne (Ecole Polytechnique Fédérale de Lausanne) in 1997 as a professor in the Institute of Microsystems of the Microengineering Department, where he is responsible for the Microsystems Technology group. His main interests are in developing technologies for novel inductive-type devices, new microfabrication technologies for microsystems fabrication in general and the development and the use of microsystems technologies for biomedical applications in particular.