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High precision direct fabrication by laser of micromoulds in PDMS for micro-replication

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Abstract
This paper presents a direct writing technique for micro-mould fabrication for replication of high aspect ratio microfeatures in ceramics. An elastomeric block is directly 3D structured using high intensity ultrafast laser pulses to generate the soft mould without need to micromachine a master previously. This work shows the optimization of the laser parameters and the scanning strategies, to control the ablation process on the siloxane for manufacturing the target geometries, in particular high aspect ratio micropillars to produce imaging Ultrasound microtransducers. The goal is to generate pillar structures within the elastomeric mould with minimum or no debris, high quality surfaces with reduced roughness, and explore the feasible resolution, precision, and capability of the technique to produce very high aspect ratio geometries. As material for the mould, PDMS (polydimethylsiloxane) was selected, and processed with picosecond and femtosecond lasers in the visible range of the spectrum, focused through high NA (Numerical Aperture) optics. Microholes were drilled with aspect ratio over 5. Low roughness and controlled conicity allowed replication of the ablated structure through epoxy gel-casting, enabling easy demoulding without the use of demoulding agents. The microholes are produced with a wavelength at which the material is transparent. This fact, the small size and the shape of the photodisrupted volume, and the ability to fabricate relatively deep within the material, suggest that the process is exploiting a nonlinear absorption mechanism which would allow fully 3D fabrication.

Keywords: Picosecond Laser, Siloxane, microreplicarion, micropillars, micromoulds, PDMS, direct laser writing

1. Introduction

1.1. Motivation

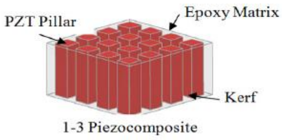
Elastomers are excellent materials for flexible and reusable moulds for soft lithography, microcasting and other microfabrication technologies. Siloxane is widely used in many replication processes such as gel casting for manufacturing of ceramic parts with high precision features. The common practice is generating the mould by replicating a master. The master fabrication is normally costly and limited in flexibility. The motivation of this work is the potential benefit of a direct writing technology on Polydimethylsiloxane (PDMS) and similar siloxanes, for direct digital production of soft elastomeric moulds in a masterless production process.

1.1. State of the art

Current commercial ultrasound systems operate under 15MHz, limited by the ability to manufacture suitable piezoelectric ceramic elements for the transducer probe. Higher frequency imaging (>30MHz) results in increased resolution images, which enable new medical applications.

Piezoelectric ceramic-polymer composites, with pillars of piezoelectric ceramic surrounded by an epoxy filler (Fig. 1), are the standard active materials in high-performance transducers that operate at conventional imaging frequencies (3-10MHz) thanks to their high sensitivity and low acoustic impedance [1].

Piezocomposites are nowadays produced by mechanically cutting deep grooves into a solid ceramic block to form thin, tall pillars upstanding from a support stock. A polymer is then cast into these grooves, and the resulting composite disc lapped to remove the ceramic base and achieve the desired thickness. The right pulse response requires a pillar height/width aspect ratio, typically 5, to maximize transduction, which adds an extra challenge to the miniaturization.



Dimension Requirements

Frequency	20 MHz	40 MHz
Pillar width	24 μm	14 μm
Kerf	20 μm	8 μm
Thickness	80 μm	40 μm

Figure 1. 1-3 piezoceramic composite structure (left) and key dimensional requirements (right).

The Applied Functional Materials (AFM) company, together with University of Birmingham and University of Aveiro, has pioneered new processing routes based in viscous plastic processing (VPP) and gel casting [2-3]. However, the problems inherent to the non optimized moulds implies the needed for further research. The actual limitation for using durable moulds comes from the cost of the mould and their ability to withstand the forces of the process. The technology presented in this paper, for direct laser writing of PDMS moulds, presents an advance in tool design and low cost toolmaking to enable a masterless process.

2. Experimental setup

A block of PDMS is prepared as a substrate using Sylgrad® 184 silicone and hardening agent, followed by degassing, casting and curing in at 80ºC for one hour. The laser processing is performed by photostructuring with highly focused visible radiation.

The laser source is a fibre-rod amplified picosecond laser (EOLITE Hegoa), emitting in IR, using harmonic extraction for generating the visible (515 nm) radiation. Typical pulse length is under 30 ps, with 40 µJ of maximum available pulse energy in the fundamental wavelength. The laser radiation is focused with a 35 mm focal length flat field optics (Theta-lens), from Sill Optics, with NA=0.15. A Newson Rhothor galvoscanner is used for relative part-laser displacement.

3. Results

The second harmonic of the HEGOA source (515 nm) was used fixing 1 MHz as the working repetition rate. Bare PDMS processing was tested, as well as polymer coated PDMS (thin acetate layer) to reduce surface damage.

The laser is delivered using a galvoscanner with 35 mm focal length optics, to produce a circular pattern. Scanner speed was set at 500 mm/s. The focal position is set fixed for all trials, 200 microns under the surface of the PDMS. Only two repetitions of the scanned circular pattern are used to produce a complete hole. The constant parameters used were 1MHz for the Repetition rate and 0.5m/s for the galvo speed, and the rest of the parameters as shown in Table 1.

Table 1. Process parameters.

	Nº.	Matrix spacing	Scan diameter	Array setup
Average power 9.6W Unprotected.	**M1**	80 µm	30 µm	25x25
	M2	70 µm	30 µm	28x28
	M3	60 µm	30 µm	33x33
Average power 8.4W Unprotected.	**M4**	80 µm	30 µm	25x25
	M5	70 µm	30 µm	28x28
	M6	60 µm	30 µm	33x33
Average power 9.6W Protected with acetate film.	**M7**	80 µm	30 µm	25x25
	M8	60 µm	30 µm	33x33
	M9	50 µm	30 µm	40x40

3. Discussion

Repetition rates around 1 MHz provide good quality and well controlled hole diameter (Fig. 2), when operated at average power rates about 8-10 W. These correspond to 10 µJ per pulse, and with a focal spot of 15 µm and 30 ps of pulse duration, leads to 0.3 MW peak power and 5 J/cm^2 fluence.

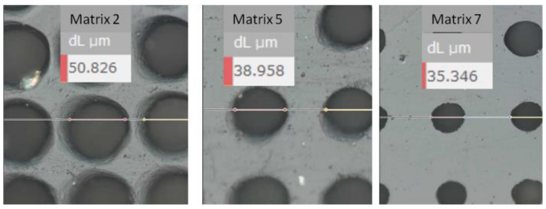


Figure 2. Entrance holes in PDMS samples for different laser process parameters. (dL (measured length): diameter in microns).

1MHz is found to be an optimal repetition rate level. For higher repetition rates, or higher pulse energies (higher average power at the same repetition rate), the laser produces widening of the micro-channel diameter, and particularly larger distortion and widening of the entrance diameter.

The dimensions of the removed volume per pulse (or voxel) for this process are strongly dependent of the applied energy and repetition rate. The hole depth is found highly dependent on laser pulse characteristics (Fig. 3). In particular, it was found that a 7 % increase in the pulse energy results in a considerable increase in the drilled depth (70 microns more), and larger dispersions in the depth values (Table 3). The bigger impact, however, is registered in the average hole diameter, and in particular in the output diameter, which is significantly enlarged with higher power.

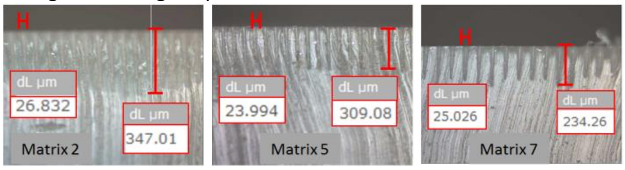


Figure 3. Cross section of different laser drilled PDMS samples.

For assessment of the channel matrix quality and correct geometry, the fabricated moulds were used for replication via epoxy gel casting of a lead zirconate titanate (PZT) ceramic slurry (0.8 µm particle size, 45% vol. solid fraction, 40% epoxy).

The obtained sintered pillars have a characteristic shape, with a cylindrical section, a sharp tip corresponding to the bottom of the laser drilled hole, and setae-like base corresponding to the opening of the hole in the surface as shown in Fig. 4.

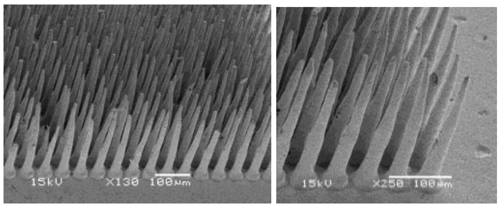


Figure 4. SEM view of the replicated PZT matrix (left) and detail (right).

Good aspect ratio (~5:1) on the PZT pillar structures was achieved. This proves that in principle a masterless approach together with the gel-casting route is possible. Large area samples have been manufactured using gel casting, thus the process may be scalable to large area samples.

4. Conclusion

Laser power, frequency, and galvo scanning speed are important factors for micro-channel fabrication by direct laser writing on PDMS. At 1 MHz repetition rate, with 10 µJ Laser pulses of 30 ps, a green laser produces high aspect ratio and high quality drilled holes with limited taper.

The results suggest nonlinear absorption and plasma mediated ablation as the mechanisms which produce slender, high aspect ratio structures by scanning the beam into the volume of the sample, with no need to perform focal spot displacement. Good productivity was achieved, being able to produce around 1000 microchannels per minute, making the process good for fast prototyping of freeform ceramic microtransducer designs.

With further work, higher aspect ratios, matching those of lithographic masters (up to 10:1), and tighter packaged pillars are targeted. This will improve the performance of the fabricated piezotransducer devices.

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References

[1] W. A. Smith: "The role of piezocomposites in ultra-sonic transducers"; *IEEE Ultrason. Symp.* **2 755-66** (1989).

[2] S. M. Olhero, et al: "An innovative colloidal approach to fabricate PZT pillar arrays"; *J. Eur. Ceram. Soc.*, **32** 1067-75 (2011)

[3] L. García-Gancedo, S. M. Olhero et al, *Journal of Micromech. Microeng,* **22** (2012) 125001 (8pp).