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The formation of moulds for 3D microstructures using excimer laser ablation

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Abstract Fabrication by the 'Laser-LIGA' process of three-dimensional structures for micro-fluidic devices is investigated. Polymer moulds are formed by projection ablation using an excimer laser operating at 248 nm wavelength. The moulds are replicated by electroforming – as in conventional X-ray LIGA – to produce fixed and freely moving nickel microturbine parts with heights of 150 μm, wall angles of 1.5° from vertical and surface roughnesses below 100 nm.

1
Introduction

Recently there has been growing interest in low-cost LIGA processes in which X-ray lithography is replaced by a cheaper alternative technique. These processes are aimed at applications for which the extreme precision of the conventional LIGA process is not required, and for which the cost of access to a synchrotron source cannot be justified. Two processes in particular have been reported, based on UV photolithography [Löchel et al. (1993), Engelmann et al. (1992), Frazier et al. (1994)], and deep reactive ion etching [Juan and Pang (1994)]. UV photolithography can produce resist images with depths of up to around 100 μm (limited by optical absorption), but has several drawbacks. In particular, control of linewidth and side-wall profiles is difficult, and high aspect ratios cannot be achieved. Reactive ion etching offers much better linewidth control, and can also achieve moderately high aspect ratios ($>10:1$), but the process tends to be rather slow, at least for conventional reactive ion etching. This situation is changing with the application of faster etching processes [Shimokawa et al. (1991)].

A third method for producing deep resist moulds is to use excimer laser ablation. In this process the resist is etched directly by intense pulses of UV radiation, usually at 248 nm or 193 nm wavelength. Three-dimensional relief is produced either by scanning a shaped beam over the resist surface, or by projecting a mask pattern through suitable optics. The excimer laser approach has a number of attractive features. Firstly, unlike UV photolithography, there is no depth limitation due to absorption. This is because ablation always occurs at the surface of the partially formed structure, with the material exposed by each pulse being ejected before the next pulse arrives. Secondly, complex three-dimensional surface profiles can be produced in the resist, either by varying the scanning speed and beam shape in a serial system, or by means of variable transmission (grey-scale) masking in a projection system. This feature is not available with X-ray lithography or reactive ion etching, although it can be achieved with UV projection lithography [Wagner et al. (1994)]. Thirdly, a very wide range of polymer materials can be ablated, increasing the potential both for multi-level processing and for integration with other microengineering processes.

Excimer laser ablation studies were first undertaken at RAL in the early 1980s [Davis et al. (1983)], when much effort was concentrated on understanding the basic ablation parameters and developing high fluence lenses for 248 nm and 193 nm optical wavelengths [Goodall et al. (1990)]. In recent years this technology has been used to form the precision micromoulds from which a low cost LIGA-like excimer laser technology has been developed [Lawes (1993)]. A full Laser-LIGA process based on 193 nm ablation using a scanning shaped beam was reported previously [Arnold et al. (1995)]. Here we present results obtained using the alternative approach of mask projection ablation at 248 nm wavelength. Using this method we have fabricated deep resist moulds in polymethylmethacrylate (PMMA), which we have subsequently replicated by electroforming to produce both fixed and freely moving nickel microturbine parts.

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Experimental

The laser ablation method is generally limited to aspect ratios of the order of 10:1. Consequently, fabrication of rotary micro-actuators by conventional sacrificial layer processing (i.e. where all parts are made in-situ) is not feasible, because

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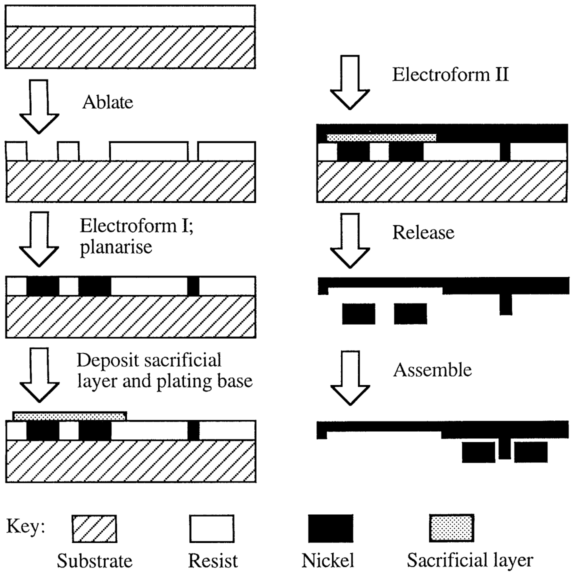

Fig. 1. Modified sacrificial layer process used to fabricate microturbines by Laser-LIGA

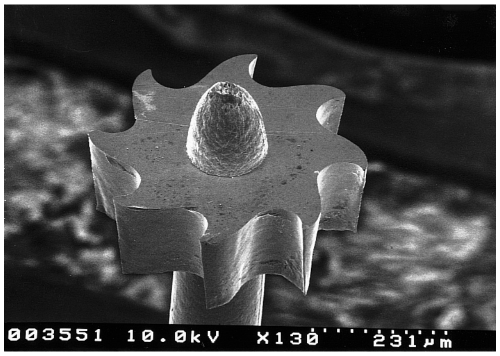

Fig. 2. Nickel microturbine rotor (outside diameter ≈ 470 µm; height 150 µm) fabricated by Laser-LIGA

the clearances between the fixed and moving parts cannot be made small enough. Instead it is necessary to fabricate component parts separately, and then assemble them. Our approach to this problem is shown in Figure 1. First, the moulds for the rotors and stators were defined in different areas of a single resist layer, and replicated in nickel by electroforming. The sample was planarised by lapping with silicon carbide (to 4000 grade finish), and a polymer sacrificial layer was deposited over the rotors. A sputtered nickel seed layer (300 Å thick) was then deposited over the entire sample, followed by a 500 µm thick electrodeposited nickel backing plate. Finally, the structures were separated from the substrate by thermal shock, and the resist and sacrificial layer removed by dissolution.

The resist used in this work was cross-linked PMMA. This is the standard resist for the conventional X-ray LIGA process, and consequently techniques for producing the necessary thick films are well established. From the point of view of laser micromachining, PMMA is a reasonably good resist in as much as it can be etched without significant melting of the surrounding material, and re-deposited ablation debris can be removed quite effectively by ultrasonic cleaning after exposure. The etch rate at 248 nm wavelength is around 1 µm per pulse (or 20 µm per sec at 20 Hz rep rate) at a fluence of 1 J/cm^2. Thick films of PMMA were cast onto solid titanium substrates which had previously been oxidised to improve adhesion. After annealing the films to minimise internal stresses, the resist was machined to a thickness of 170 µm, and then lapped to a final thickness of 150 µm.

Exposures were performed using a Lambda Physik LPX 305i laser operating at 248 nm wavelength and 20 Hz repetition rate. This laser delivers a beam of nominal cross-section 23×8 mm^2 (FWHM), with 'top hat' and Gaussian profiles in the long and short axes respectively. The raw laser beam was used to illuminate a standard chrome-on-quartz mask, which was imaged onto the resist surface using a 5X reduction lens (0.1 NA refractive). Chrome exhibits a finite etch rate at the fluences required for polymer micromachining, but we have found the lifetime of a standard mask is of the order of 10^6 pulses, which is quite acceptable. No beam-forming optics were included in the system, so there was inevitably some variation in etch rate across the exposed field (2×2 mm^2 at the workpiece). This, together with the lack of any off-axis component in the illumination, meant that long exposures were required to achieve steep side-walls at all points. Each field was exposed for between 3000 and 5000 pulses. The fluence at the centre of the field was set to 1.5 J/cm^2, corresponding to an etch rate of around 1.6 µm per pulse.

Electroforming was performed using a commercial nickel sulphamate bath (Schloetter type MS), excluding any brighteners or levelling agents. Low stress deposits were obtained with a temperature of 50 °C and a deposition rate of around 10 µm per hour. Continuous recirculation with filtering to 1 µm was employed.

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Results

Figure 2 shows a 150 µm high microturbine rotor fabricated by the above route. This component provides a good illustration of the potential of the Laser-LIGA method. The central hole has a diameter of 104 µm at the top surface, compared to a design value of 110 µm. The source of this error is not clear at present. The hole diameter increases to 112 µm at the bottom, indicating a wall angle of 1.5 degrees. The outside diameter measurements show slightly more taper (467 µm at the top, decreasing to 453 µm at the bottom), due to the blade profile. Surface roughness measurements made using a Tencor surface profilometer indicate that the RMS roughness of the side-walls is below 100 nm. The rotor was placed on a tapered shaft as shown for SEM inspection purposes.

Figure 3 shows an assembled prototype microturbine, comprising a rotor and a stator. The clearances are rather large on this device, primarily because the finite wall angle was not included in the mask design; more recent designs take this factor into account. Note that the surface finishes of the rotor and stator are different. This is because the rotor was flipped over before being placed in the stator. Thus while the top surface of the stator is a replica of the original titanium substrate, the top surface of the rotor has been lapped during the fabrication process.

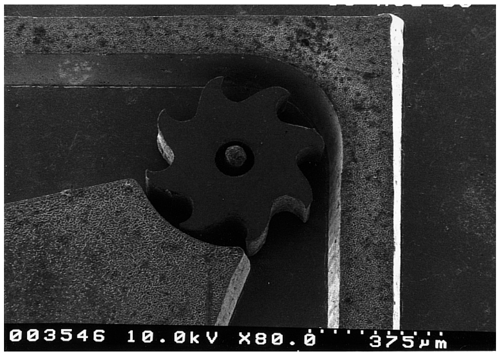

Fig. 3. Assembled prototype microturbine, fabricated using process shown in Fig. 1

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Discussion

The preliminary results presented here indicate for the first time that the Laser-LIGA process is capable of producing high quality nickel structures with heights in excess of 100 µm. We are currently developing the technique to allow the realisation of stepped multi-level structures with complex surface profiles. These types of structures will be essential for the realisation of useful micro-actuator devices.

Multi-level structures may be built up by depositing a number of resist layers, with each layer being patterned and filled with metal before application of the next. This type of multi-level LIGA process has already been demonstrated using UV photolithography [Lorenz et al. (1995)]. However, it is less straightforward in the case of Laser-LIGA, because it is difficult to ablate each layer without damaging the underlying material. At present we are investigating the use of intermediate metal 'blocking' layers as a solution to this problem. The generation of complex surface profiles in resist by projection ablation using grey-scale masks has been reported previously [Holmes et al. (1995)]. We are currently working to integrate this technique into the Laser-LIGA process in order to produce microturbine rotors with profiled surfaces. This involves performing Laser-LIGA on a substrate with a surface layer of resist which has previously been patterned by grey-scale exposure. As with the multi-level LIGA process, suitable blocking layers need to be identified.

Both of the above developments will require identification of alternative resist materials, since casting of PMMA on surfaces other than oxidised titanium tends to result in adhesion problems. We are currently investigating the use of laminated dry film photoresists in this application [Zhu et al. (1996)]. These resists, which are well-established in the printed circuit industry, offer ease of application, good thickness uniformity, good adhesion to a range of metals, and conformal coating of non-planar surfaces.

In conclusion, we have fabricated nickel microturbine components using a Laser-LIGA process based on projection ablation at 248 nm wavelength. Structures with heights of 150 µm, surface roughnesses of the order of 100 nm and near-vertical side-walls were produced.

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