Advances in LIGA-based post-mold fabrication

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ABSTRACT

The establishment of a process to allow planarization of deep x-ray lithography based microfabricated metal components via diamond lapping has enabled examination of three additional microfabrication issues. The areas of improvement that are discussed include materials, microassembly and packaging, and multilevel fabrication. New materials work has centered on magnetic materials including precision micromagnets and surface treatments of electrodeposited materials. Assembly and packaging has been aided by deep silicon etch processing and the use of conventional precision milling equipment combined with press-fit assembly. Diffusion bonding is shown to be a particularly important approach to achieving multilevel metal mechanisms and furthermore shows promise for achieving batch assembled and packaged high aspect-ratio metal micromechanics.

Keywords: LIGA, MEMS, magnetic materials, permanent magnets, assembly, packaging, diffusion bonding

1. INTRODUCTION

LIGA-based processing or deep x-ray lithography based mold fabrication and subsequent additive processing has demonstrated the ability to extend precision machining limits to the millimeter part regime while maintaining tolerances of 1 part in 10^4 . The unique processing feature that enables this result is the high precision mold obtained by exposing a photoresist material with highly collimated and long absorption length x-rays combined with accurate masking, development and subsequent mold filling. The prismatic geometry that results is further defined by precision lapping to control thickness¹.

Growing interest and use of deep x-ray lithography² (DXRL) has led to improved storage-ring access to the point where it may be acquired as a foundry-like service. Exploitation of high-energy x-ray flux has further shown sufficient cost efficiency to support direct deep x-ray lithography and mold filling processing without mold replication³. Additionally, improved stability of the x-ray photoresist, namely PMMA, has resolved many issues with respect to maximum mold aspect ratio, ultimate structure height, and minimum feature size⁴. The resulting high molecular weight PMMA mold material has proven to have sufficient mechanical integrity to withstand single level processing and is able to be readily dissolved subsequent to mold filling and planarization with organic solvent. The mold filling materials have most commonly been readily electroformable metals such as nickel and alloys of nickel including nickel-iron, nickel-cobalt, and nickel phosphorous, and copper, silver, and gold. This list of electroplatable metals which is expanding and also includes electroplated composites⁵ is sufficient for many applications. More material choices are still needed in particular for magnetic devices and high temperature devices. Work in powder metallurgy and plastic injection molding has given an indication of what additional materials are possible^{6,7}.

To further advance deep x-ray lithography based additive processing, three areas of processing are receiving attention: the areas include material base expansion, assembly and packaging techniques, and multi-layer processing.

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2. MATERIALS

Several means to incorporate new materials into deep x-ray lithography based molding while maintaining the same mold precision have been investigated. A large effort is directed at improved magnetic materials including soft (high permeability) and hard (permanent magnet) materials. Soft magnetic material may be achieved with an electroplated 78/22 nickel/iron or 78 Permalloy alloy with initial permeability of 2000 and a saturation magnetic flux density of 1.0 Tesla. More recently a higher percentage of iron has been implemented at a 45/55 nickel/iron composition with a sulfamate base electrolyte. The advantage of this composition is its similar high permeability with an increase in saturation magnetic flux density to 1.6 Tesla. The higher saturation induction yields an increase in the magnetic pressure that may be achieved in a magnetic actuator by a factor of 2.5.

The incorporation of a permanent magnet material in MEMS has received comparatively little attention^{8,9}. This is the situation despite the attractive MEMS feature of a permanent magnet which is that its magnetization remains independent of scale. Electromagnetic coils, on the other hand, are constrained during scaling due to current density limits. Superconductors also suffer this limit, which results in a reduction of magnetic field that may be produced from a coil of decreasing dimensions due to a scaling dependence on length.

The best magnets available today in terms of maximum energy product, which is the figure of merit important for actuator performance and volume efficiency, are rare-earth based permanent magnets with available energy products over 40 MGOe (Mega-Gauss-Oersted, $1 \text{ MGOe} = 100/4\pi \text{ kJ/cm}^3$). Implementing fully dense rare-earth based permanent magnets requires high sintering temperatures that are not compatible with precision molding due to volume shrink. It is possible, however, to incorporate rare-earth magnet powder with a binder to make bonded or composite magnets. A reduction in magnet material density results in a reduced remanence and energy product that still far exceeds that possible in non rare-earth based magnets. It is this bonded form of rare-earth permanent magnet which has been used for molding into DXRL defined PMMA. The $\text{Nd}_2\text{Fe}_{14}\text{B}$ intermetallic has been used primarily with various powder particle sizes less than 20 micron and an epoxy binder. A preferred process has been the incorporation of the unmagnetized powder/binder matrix in a low viscosity state into a PMMA mold via calendaring and pressing. The resulting substrate containing a multitude of permanent magnet geometry is batch magnetized in a preferred orientation with a field of at least 35,000 Oersted. An epoxy composition of 20% by volume has been found to yield a micro-magnet with sufficient mechanical strength to be handled and a maximum energy product of 10 MGOe. The PMMA mold material may be dissolved without affecting the binder material and the magnets may be released by undercutting a suitable sacrificial material. An M-H loop of a magnet $900\mu\text{m} \times 900\mu\text{m} \times 120\mu\text{m}$ is shown in Fig. 1. Example micro-magnet geometry is depicted in Fig. 2 along with close-up views of sidewall reproduction.

Fig. 1 M-H loop for bonded micro-formed permanent magnet with $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder and 20% epoxy binder measured with the use of a SQUID magnetometer.

In order to increase the maximum energy product, incorporation of anisotropic $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder is under investigation which has been reportedly used to achieve energy products of 19 MGOe. This material requires processing in a magnetic

field to orient the powder particles. In the pursuit of fully dense rare-earth magnets, MnZn and NiZn ferrite materials have successfully been formed using DXRL defined molds followed by their release and sintering. This approach, however, is only appropriate if volume reduction can be tolerated. Hot pressing methods that may alleviate this dimensional shift for prismatic geometry are also being pursued.

a)

b)

c)

d)

Fig. 2 SEM views of bonded and molded micro-magnets with $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder particle size less than 10 microns. The partial arrow-shaped tabs on the structures in a) are patterned to indicate easy identification of magnetization direction after release. The thickness of these particular magnets is 30 microns.

Another means to fill DXRL molds with different materials has been with thermal spray techniques. In this approach, molten metal droplets are sprayed against a substrate where they coalesce and solidify. Substrates covered with DXRL defined PMMA molds have been tested with the use of a subsequent lapping step to remove the overspray. Initial results are shown in Fig. 3 with the material Kirksite (3.5%Cu, 4% Al, 0.04% Mg, bal. Zn). No observable perturbation of the PMMA mold occurred and vertical sidewall replication is apparent. The variation in density as a function of aperture size is also readily apparent and suggests a classic wetting phenomenon. Additional study is being carried out which if successful would yield a deposition speed far surpassing electroplating rates with the incorporation of an extremely broad material base.

Fig. 3 SEM photographs of thermal spray result with Kirksite in a screen geometry. The PMMA mold material has been removed.

Methods to improve the mechanical properties of electroformed metals are also receiving attention. Since nickel and copper are easily electrodeposited with low stress with reasonably fast rates they are preferred materials from the standpoint of processing. Their mechanical use could be expanded if a suitable batch treatment was available to improve their surface properties. One such approach has been demonstrated with electroformed nickel by using implantation of titanium and carbon to increase its yield strength and hardness¹⁰. The result is an amorphous near surface layer extending 100 nm into the nickel surface. Characterization by finite-element modeled nano-indentation reveals a yield strength of 6 GPa, hardness of 16 GPa, and an elastic modulus of 400 GPa in the amorphous region, all of which far exceed bulk or as-electrodeposited material values. The result is a substantial reduction in wear and a 50% decrease in the friction coefficient¹¹. An additional attribute of this surface is its anti-corrosion character and reduced surface chemical activity that has significant implications for long term static friction or "stiction" concerns.

Because implantation treatments are "line of sight" processes, the ability to treat all geometry including narrow apertures may present accurate implementation issues. A conformal technique removes this difficulty and has been demonstrated with PECVD (Plasma Enhanced Chemical Vapor Deposition) silicon carbide films deposited directly on a substrate decorated with LIGA nickel structures. A silicon carbide film 900 angstroms thick on electroplated nickel has demonstrated hardnesses of nearly that of the implant treatments and has an added potential benefit of forming an insulating layer.

3. ASSEMBLY

To date, the majority of MEMS implementations of LIGA based fabrication have been accomplished by assembly of individual LIGA parts. The assembly substrate is commonly decorated with LIGA fabricated assembly geometry such as locating and assembly pegs or shafts, guide posts and other fixed geometry. This substrate is then used to assemble components via pick and place assembly which are held captive by retaining clips and springs. This approach is particularly sensitive to two processing concerns of adhesion and internal strain. The example of an assembled gear on a shaft to implement a journal bearing reveals the problems. Electroplating a shaft on a substrate typically involves at least two interfaces: one interface exists between the plating base and the substrate and the other exists between the plating base and the electrodeposited material. At each of these interfaces, a concern for adhesion exists. The necessary minimum adhesion is complicated by several factors. Lapping and assembly operations create shear stresses acting on the top surface of the electrodeposited structures. For high aspect-ratio geometry, this stress is magnified by a resulting lever arm thereby creating large tensile stresses at the substrate interfaces. In addition, any residual strain in the electrodeposit adds to the burden on the interfaces.

Two approaches are being pursued to eliminate the interface adhesion problem. One approach involves the use of press-fit pins which are sunk into either a LIGA fabricated peg-board or a pre-drilled substrate. This transfers the adhesion problem into a material strength problem. The trade-off is an increased reliance on assembly. The assembly in Fig. 4 demonstrates this capability. The aluminum substrate was drilled with locating holes using a precision mill capable of 0.000020" positional accuracy. Pins were made from tool steel gauge pin stock that in this case were 0.0059" in diameter and cut to 0.033" lengths which after being press fit into the 0.020" thick substrate provided a 330 μm high pin. The gear train was assembled by first fitting a collar with a key on each shaft and then two gear thicknesses were used to assemble a gear train with a 450:1 transmission ratio coupled into a rack (see Fig. 4.a). The large pin located in the front of the gear train pictured in Fig. 4.c) is

a)

b)

c)

Fig. 4 SEM photographs of a two-level gear train assembled on a press-fit pin array. The substrate material is aluminum, the pins are tool steel, and the gears are LIGA fabricated from nickel.

used to align an output gear from a miniature motor to couple into and drive the mechanism. A flat plate that covers all assembly pins is placed over the mechanism to keep it captive.

Another means that has been pursued to eliminate interface adhesion limitations and expand packaging and system assembly possibilities is to create an assembly substrate monolithically. By taking advantage of precision high aspect-ratio silicon etching multi-level silicon alignment structures may be fabricated by etching into a standard silicon substrate that may be used to assemble LIGA fabricated components. The results are shown in Fig. 5 for the same gear train mechanism

a)

b)

Fig. 5 Two-level nickel gear train assembled into high aspect-ratio silicon etched substrate. The silicon pins are $150\mu\text{m}$ in diameter and $330\mu\text{m}$ tall.

described previously. A glass plate was bonded on top of the etched silicon die to provide for packaging during testing. The mechanism was run for several days indicating that silicon is a reasonable material to be used with metal LIGA components.

This is the first step in demonstrating the use of silicon as a packaging material for LIGA components which allows the pursuit of further system integration. Integrated silicon microelectronics may be resident on the same assembly substrate and connected to the electromechanical assembly with electrical vias. Also, a complementary etched silicon substrate may be used to bond with the assembly substrate to serve as a cover and enable batch packaging.

Furthermore, the array of silicon assembly die provides a basis for batch assembly of LIGA components via wafer-to-wafer transfer and batch release. In this assembly sequence a silicon wafer is deep RIE etched to form assembly geometry and alignment pegs. A complementary substrate with suitable sacrificial layer is fabricated with first level LIGA components, aligned to the silicon assembly substrate with which it engages, and finally a sacrificial etching step releases the components onto the assembly substrate. This batch assembly process has been successfully tested for one level and is expected to provide a technique suitable for multi-level LIGA batch assembly.

4. MULTILEVEL FABRICATION (DIFFUSION BONDING)

The ability to construct 3-dimensional micromechanisms with planar-based processing continues to be a challenge with ever increasing complexity. In the area of high aspect-ratio processing considerable advancement has occurred via deep silicon etching, novel polysilicon processing, and LIGA-like fabrication. Process integration issues for high aspect-ratio structures, however, lead to many complications for extending this type of processing to multiple levels in batch form. One example of the problem is evident with a simple journal bearing several hundred microns in length. In order to maintain a reasonable bearing tolerance ($<1\mu\text{m}$) subtractive fabrication by assembly of two closely dimensioned parts has proven to be a suitable albeit cumbersome technique. The relatively recent capability of accurate thickness control of electroformed structures in LIGA processing with precision diamond lapping and polishing has brought a significant improvement and expansion to LIGA-based device implementations. Additional obstacles remain in establishing a multi-level process with batch assembly and packaging.

Previous work to incorporate multilayer LIGA structures has used successive electroplating upon electroplating sequences¹². The main concern in this approach is photoresist stability that in the case of the DXRL photoresist of choice, PMMA, is prone to crazing and adhesion loss when subjected to multiple liquid exposures and temperature cycles. Plating base complications also constrain geometry and lead to consideration of electroless deposition⁷ which has further complications due to deposit stress and limited thickness.

The multilevel technique to be discussed takes advantage of the unique qualities of DXRL-based fabrication including the attributes of additive processing to develop a new concept in metal microfabrication of MEMS. Use is made of diffusion bonding (or diffusion welding, or solid-state bonding) to develop a process for the batch fabrication of multilevel LIGA components. The ability to planarize LIGA structures is a critical enabler of such a process since it allows two substrates decorated with LIGA components to be placed face-to-face in close contact across an entire substrate. Diffusion bonding possesses many attributes ideally desired for a multilevel precision micromachining process. Bonding takes place by definition without any material melting thereby retaining the precision of the microcomponent definition. The time-temperature-pressure trade-off may be used to advantage by conceding time for temperature and pressure. This is reasonable for batch part microfabrication where several hour bond times are allowable and additionally many wafers may be processed simultaneously as opposed to more conventional single part diffusion bonding where bond times are excessive if greater than tens of minutes. In addition, it is possible to obtain a diffusion bonded component using only a single material.

Initial tests for diffusion bonding electroformed nickel to itself have shown successful bonding at temperatures surprisingly as low as 450 degrees C at a pressure of 7 ksi (~50 MPa). This is well less than half (590 deg. C) the absolute melting temperature of nickel. A possible reason for this low temperature result may include the very fine grain size associated with as-electroplated nickel. Electroplated metals in general have this fine-grain character. During the diffusion bonding temperature cycle grain growth encourages coalescence of grains at the bond interface. Also, careful surface preparation included chemical removal of the nickel oxide and highly flat, parallel and polished components resulting from

diamond lapping. Bond strength testing was performed with a Sebastian adhesion tester and a sample geometry outline in Fig. 6. A nail head pull test peg was bonded to the individual diffusion bonded discs which could be gripped and pulled in the adhesion tester. Temperatures between 450 deg. C and 600 deg. C and pressures between 7 ksi and 10 ksi were used with bond times of 6 hours. All bonds exceeded the capacity of the pull tester which for the smallest geometry resulted in a maximum load of ~ 15 ksi. The indication is that the temperature and pressure may be further reduced. Photographs revealing the diffusion bond interface metallography are depicted in Fig. 7. The bond line is difficult to see until a grain boundary etch is carried out.

Fig. 6 Preparation of diffusion bond test specimens.

Fig. 7 SEM photographs of nickel-nickel diffusion bond interface. Fig. a) shows the as polished bond line indicated by the arrows and Fig. b) shows the interface after a grain boundary etch.

One result is shown in Fig. 8 for a nickel multiple layer stacked component that was diffusion bonded in one step at 500 deg. C and 10 ksi for 6 hours. No observable deformation occurred near interface edges which is a sign of insignificant creep. The proposed batch diffusion bonding sequence is shown in Fig. 9 which incorporates a suitable sacrificial layer that is expected to be copper and a precision alignment technique utilizing similar gauge pins to those used in the assembly shown in Fig. 4.

a)

b)

Fig. 8 SEM photographs of 7 layer diffusion bonded all-nickel component. Alignment of the stack was achieved with two copper wires press fit through all seven layers. This particular component may be diffusion bonded in one step since all interfaces have the same overlap area. Such a situation will not be true in general for a batch wafer scale bonding process.

Fig. 9 Batch diffusion bonding procedure.

In order to more accurately assess the diffusion bond strength a method to allow measurement of local shear strength across a substrate has been devised using a milli-scale torsion tester. The specimen geometry is depicted in Fig. 10 and includes a scalloped ring geometry which accepts coupling to a circular array of six pins that extend from the end of a torsion arm. The pins are located with a LIGA fabricated part fit into the pin housing part of the instrument depicted in Fig. 11.

Fig. 10 SEM photograph of distributed array of 3mm diameter torsion shear test rings. The measurement bar indicates 5 mm and there is some distortion occurring due to the low magnification SEM image.

The milli-torsion testing has just been initiated and it is evident that the ability to test other types of LIGA adhesion concerns in this fashion is also accommodated.

Further extensions of microfabrication by diffusion bonding include the use of a patterned sacrificial layer for eventual partial part release and fully integrated metal micromechanisms. Since diffusion bonding takes place in a high vacuum, batch vacuum packaging and packaging in an inert ambient are also possible extensions.

a)

b)

Fig. 11 Photographs of torsion shear test instrument showing x-y-z substrate mounting stage, lever-arm mounted to 6-pin fixture and in background: motorized micrometer, load cell and LVDT. Fig. b) shows a close-up of partial pin engagement with the scalloped ring specimen.