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Deep x-ray lithography for micromechanics

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ABSTRACT

Extensions of the German LIGA process have brought about fabrication capability suitable for cost effective production of precision engineered components. The process attributes allow fabrication of mechanical components which are not capable of being made via conventional subtractive machining methods. Two process improvements have been responsible for this extended capability which involve the areas of thick photoresist application and planarization via precision lapping. Application of low-stress x-ray photoresist has been achieved using room temperature solvent bonding of a preformed photoresist sheet. Precision diamond lapping and polishing has provided a flexible process for the planarization of a wide variety of electroplated metals in the presence of photoresist. Exposure results from the 2.5 GeV National Synchrotron Light Source storage ring at Brookhaven National Laboratory have shown that structural heights of several millimeter and above are possible. The process capabilities are also well suited for microactuator fabrication. Linear and rotational magnetic microactuators have been constructed which use coil winding technology with LIGA fabricated coil forms. Actuator output forces of 1 milliNewton have been obtained with power dissipation on the order of milliWatts. A rotational microdynamometer system which is capable of measuring torque-speed data is also discussed.

Keywords: LIGA, precision machining, microactuators, deep x-ray lithography, microfabrication, PMMA, dynamometry

1. INTRODUCTION

Demand for mechanical components with ever decreasing dimensions and tolerance requirements has pushed the limit of what is achievable with conventional mechanical machining. Generally regarded as the most accurate material removal machining process available, single point diamond turning is capable of achieving dimensional accuracies on the order of 1 part in 10^5 to 10^6 [1]. Limitations exist in machining ferrous materials, however, and as with any mechanical material removal process material machinability is an issue. Processes such as electrodischarge machining (EDM) and laser machining [2] avoid problems associated with difficult to machine materials such as very hard materials but are not capable of the same accuracies as diamond turning with achievable accuracies on the order of 1 part in 10^3 or 10^4. For micromechanical components with dimensions ranging from 1000μm to 10μm maintaining such tolerances becomes increasingly difficult and implies levels of dimensional accuracy well into the submicron range.

Precision micromechanical components will have a large impact on high volume markets if they can be fabricated cost effectively. Cost effectiveness in this sense is usually realized by batch fabrication methods where many components are produced in parallel. The aforementioned machining processes are serial based and therefore material removal rate becomes the critical parameter in determining throughput and thus cost effectiveness. Another important issue in mass fabrication of precision componentry is repeatability. Assuming this is not set by the resolution of the process, repeatability limits arise from inherent or environmentally induced machine offsets.

Micromachining based on LIGA processing, an acronym coined by its founders at the Karlsruhe research center (FZK) in Germany [3,4,5], has demonstrated the capabilities required for the future generation of precision mechanical componentry. The acronym LIGA represents the three process steps of deep x-ray lithography (DXRL), electroplating, and injection molding replication. The lithography step uses synchrotron radiation generated by an electron storage ring to expose an x-ray sensitive photoresist, typically polymethylmethacrylate (PMMA). The properties of synchrotron radiation include high collimation and large absorption length into PMMA, resulting in the ability to expose component definitions into thick layers of photoresist (several hundred microns or more) with lateral dimension run-out of less than 0.1μm per 100μm of photoresist thickness. The exposed component definition in the photoresist is subsequently developed down to a plating base thereby forming an electroplating mold. Following electroplating the prismatic metal components may be used a primary mold form and replicated via injection molding. The resulting process not only addresses the above precision machining issues, but extends fabrication capability to component dimensions and geometries which were previously unattainable.

Several other processes are being pursued for the fabrication of high aspect ratio microstructures. They may be broadly defined as photoresist based and silicon based. A variety of thick photoresist layers combined with UV exposures are used by a variety of researchers to create electroplating molds [6, 7, 8, 9, 10]. Reactive ion etching is also used to etch both polymers [11, 12] and silicon [13, 14, 15] thereby either creating electroplating molds or silicon based structures directly. These processes are limited to a thickness of 150μm to 300μm with maximum aspect ratios of 15:1 as compared to 1000:1 or better for LIGA defined structures.

The particular attributes of the LIGA process, furthermore, lend themselves well to microactuator construction. Such devices profit from the properties of precision micromechanical components. Actuator positional accuracy, for one, is improved. Since inertia diminishes rapidly as component dimensions decrease, actuator bandwidth and acceleration increase. A batch-mode, integrated circuit-like fabrication sequence allows inexpensive high volume manufacturing.

Many current microactuator performance requirements demand mechanical output forces of the order of 1 milliNewton and above with travel of several hundred microns. Applications which hinge on such requirements include magnetic disk head positioning, microrelays, micro-fluidic handling, optical fiber switching, and micro-surgical instruments. Regardless of the means of actuation, whether it is electrostatics, electromagnetics, or fluidics, actuator forces are generated by changes in stored energy. Such output forces may be represented as changes in output energy, ΔW_{out}, as,

$$\Delta W_{out} = \rho_E \cdot \Delta V_{work} \tag{1}$$

where ρ_E is the energy density present in the actuator working volume V_{work} and is assumed to be constant. The maximum value of ρ_E depends on the type of energy storage which may be limited by electric breakdown or magnetic saturation for example. For prismatic actuator geometries eq. (1) may be further described with actuator dimensions as,

$$F_{out} = \rho_E \cdot h \cdot \frac{dA}{dx} \tag{2}$$

where h is the height of the working gap, A represents the area defined by the gap length and the length of the actuation stroke and x is the direction of actuator motion. For actuators with large travel the gap length across which the field is established typically does not change. As a result, the ability to produce force in a prismatic actuator for a given excitation has a geometrical dependence on height and the efficiency with which the gap area is distributed or equivalently the filling fraction of the actuator geometry. Realizing this, for reasonable actuator die areas of several mm on a side, actuator heights of several hundred micron and above are desired.

A further micromechanics fabrication need is the availability of a large variety of materials. For example, materials with high yield strength are required for springs and ferromagnetic materials are needed if magnetics is to be considered. Examples of two magnetic microactuators, a linear and rotary device, will be discussed in this paper which show the flexibility which fabrication based on LIGA processing has.

DISCLAIMER

2. DEEP X-RAY LITHOGRAPHY BASED MICRO-FABRICATION

2.1 Photoresist application

The LIGA process begins with one of the most troublesome problems in thick photoresist processing, namely that of application of thick photoresist to a plating base covered substrate. Multiple layers of spun-coated photoresist are commonly used for UV based processing[7]. Layers up to 150μm thick have been demonstrated. Greater thicknesses become impractical as the solvent must be baked out after each layer which limits the thickness of each layer and introduces photoresist strain. In the original German LIGA process PMMA is cast and polymerized with cross-linking on a plating base covered substrate. This procedure avoids solvent problems, although a large volume reduction which occurs during polymerization causes adhesion problems with the substrate and results in a strained photoresist layer that limits practical film thicknesses to about 500μm. The strain may be lessened somewhat through anneal cycles, but an application method to nearly entirely eliminate photoresist strain has been achieved[16]. The method uses commercially available high-purity, pre-cast linear PMMA sheet of high molecular weight. Typical sheet thicknesses of from 1mm and up are available which may be annealed as a free sheet to relieve strain after cutting the sheet to a shape which conforms to the desired substrate. A plating base covered substrate is spun with a thin PMMA layer a few microns thick and baked. The thick PMMA sheet is then solvent bonded to the thin spun-on layer and left to cure at room temperature. Use of a precision diamond fly-cutting machine enables thinning of the PMMA to a desired thickness within a few microns.

The resulting low-strain bonded PMMA layer process has been responsible for stabilizing the entire deep x-ray lithography process. Minimum design rules have decreased as a result and furthermore the PMMA remains well intact through electroplating steps. This has allowed the use of PMMA as a structural material. Mechanical components comprised wholly of PMMA as well as composite PMMA/metal have been successfully made as a result[17].

2.2 X-ray exposure

Before proceeding to x-ray exposure of the PMMA resist, a suitable mask is required. Depending on the available x-ray spectrum the required x-ray mask may take different forms in order to achieve sufficient contrast. At the 1.0 GeV Aladdin storage ring at the Synchrotron Radiation Center (SRC) in Stoughton, WI, the x-ray spectrum is such that a membrane of a low atomic number material is needed. A 1.0 μm thick low strain silicon nitride film is typically used for the absorber carrier. A high atomic number x-ray absorbing layer of 5.0μm thick electroplated gold provides sufficient contrast to expose several hundred microns of PMMA with the Aladdin source. Patterning of this gold layer is done using a bi-layer photoresist process described in [18]. The situation changes for a higher energy spectral source such as the one available from the 2.5 GeV storage ring at Brookhaven National Laboratory. Due to the higher energy photons available the x-ray mask carrier may simply be an unthinned silicon wafer which considerably simplifies x-ray mask construction. A gold absorber layer of 50μm is necessary, however, to maintain contrast for these higher energy x-ray exposures. A two step x-ray mask fabrication process involving deep x-ray lithography is thus required for patterning 50μm thick gold patterns. Such an x-ray mask has a further benefit of being much less fragile than membrane based x-ray masks.

The desire in thick photoresist exposure is to uniformly expose the photoresist throughout its thickness with the minimum amount of energy necessary. Because of material absorption properties, however, this is difficult to achieve. Plotted in the graph of Fig. 1 is the absorption length of PMMA as a function of photon energy. The graph indirectly identifies the PMMA thickness which may be exposed with a given x-ray source. Because overexposure is undesirable, filtering of the continuous synchrotron radiation spectrum is necessary to remove the lower energy spectral regions which contribute only to surface dose. This filtering is typically accomplished with Be and results in an x-ray energy at peak power output shown in Fig. 1 for the SRC and Brookhaven (BNL) storage rings. The absorption length at the peak power photon energy of about 4 keV at SRC is near 100μm which in turn allows PMMA exposure depths of several hundred microns. The corresponding absorption length for 20 keV photons at BNL is near 1 cm which follows the cubic law dependence of absorption length on energy. The long absorption length available at BNL has yielded extreme structural heights such as are

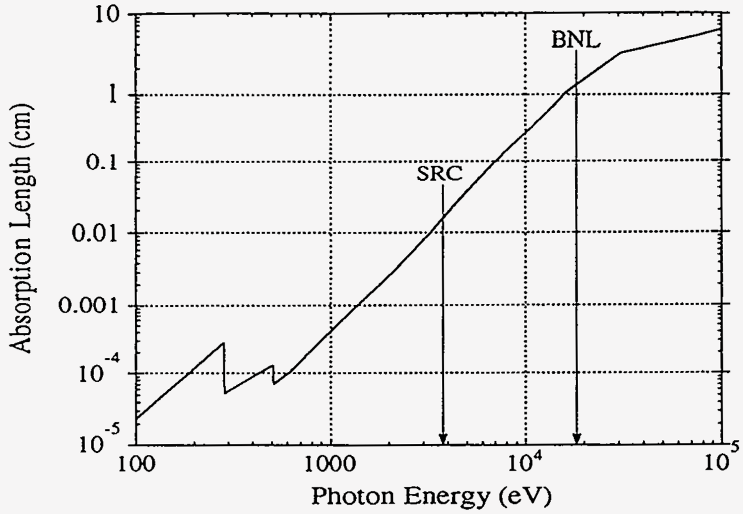

Fig. 1 Plot of PMMA absorption length as a function of photon energy. The SRC line identifies the energy at maximum intensity after filtering the Aladdin 1.0 GeV produced radiation spectrum through a 250μm Be filter. The maximum intensity energy of 3850 eV results in an absorption length of the order of 100μm. The BNL line corresponds to a maximum intensity energy of 18500 eV resulting from 1mm Be filtering of the 2.5 GeV spectrum and yields an absorption length of the order of 1cm.

Fig. 2 Developed PMMA test structures 3.2 mm thick exposed with 2.5 GeV synchrotron radiation at the National Synchrotron Light Source of Brookhaven National Laboratory.

shown in Fig. 2. Using 35 keV photons, 11 cm (4.5 inches) of PMMA was successfully exposed and developed at BNL [19]. The availability of radiation with such large absorption length allows one to expose many stacked thinner sheets of PMMA simultaneously. This resulting throughput advantage leads to substantial reductions in exposure costs which may offset the need for synchrotron independent injection molding replication techniques.

2.3 Development and electroplating

In order to maintain the nearly perfect vertical sidewall definition afforded by synchrotron exposure, a developing system which does not attack the unexposed photoresist is necessary. An aqueous PMMA developer formulated through research efforts in Germany [18] serves this purpose which has nearly infinite selectivity of unexposed to exposed PMMA. The resulting developed PMMA may be used directly for plastic components or as is more typical, used for an electroplating mold.

Electroplating, being an additive process, does not have the machinability problems associated with material removal processes. Many metals, including alloys which have a wide range of mechanical material properties, may be electroplated. Electroplating rates of several microns per minute are feasible for the structural thicknesses of interest. The low capital equipment cost of an electroplating bath also makes it feasible to use many baths in parallel or alternatively a large bath for large batches of substrates may be used. Of particular importance to actuators is the availability of an electroplated magnetic material. A variety of other materials have been demonstrated to be moldable through the use of LIGA processing including thermoplastics, various resins, and ceramics [20].

2.4 Electroplating thickness control

A problem which has hindered product implementation of LIGA fabricated precision components is that of electroplated metal thickness control. Thickness non-uniformity in electroplating arises primarily due to current crowding as a result of field concentrations in the electrolyte. Thickness variations across a single component as well as across an entire substrate area are possible. A greater than desired surface roughness of the electroplate is also typically present and can be as high as a few microns. Methods to planarize the electroplate via precision diamond lapping have recently been investigated. Fig. 3 shows a lapping test result for nickel. Optically smooth and flat surfaces have been produced with this method. Lapping of electroplated metal in the presence of the PMMA mold, furthermore, is accomplished without undercutting of the softer PMMA plastic. The planar metal-plastic composite surface may therefore readily accommodate a second PMMA layer to use for definition of a second electroplated layer. This procedure may subsequently be repeated for additional multiple layers.

2.5 Further process extensions

Processing which incorporates a sacrificial layer is used to fabricate free and partially free DXRL defined parts. In order to fabricate devices with greater three-dimensionality, free prismatic components may be assembled into more complex structures. Micro-assembly also solves the problem of maintaining intercomponent tolerances for high aspect ratio micro-scaled components. Journal bearing gap tolerances of 0.25μm have been achieved by fabricating a shaft diameter of 100.0μm and separately fabricating a gear with a corresponding diameter of 100.5μm. The gear is released on a separate substrate and assembled onto the shaft. Direct patterning of a 0.25μm photoresist structure with several hundred micron thickness is not practical for two reasons. Defining a 0.25μm geometry in a mask appropriate for DXRL exposures is not trivial, but moreover, the resulting photoresist structure would not be mechanically stable due to extreme sensitivity to strain and adhesion loss. The assembly of such precision mated DXRL components also provides data concerning the steepness of the sidewall which is difficult to measure directly. By measuring the gap distance in the journal bearing with the assembled

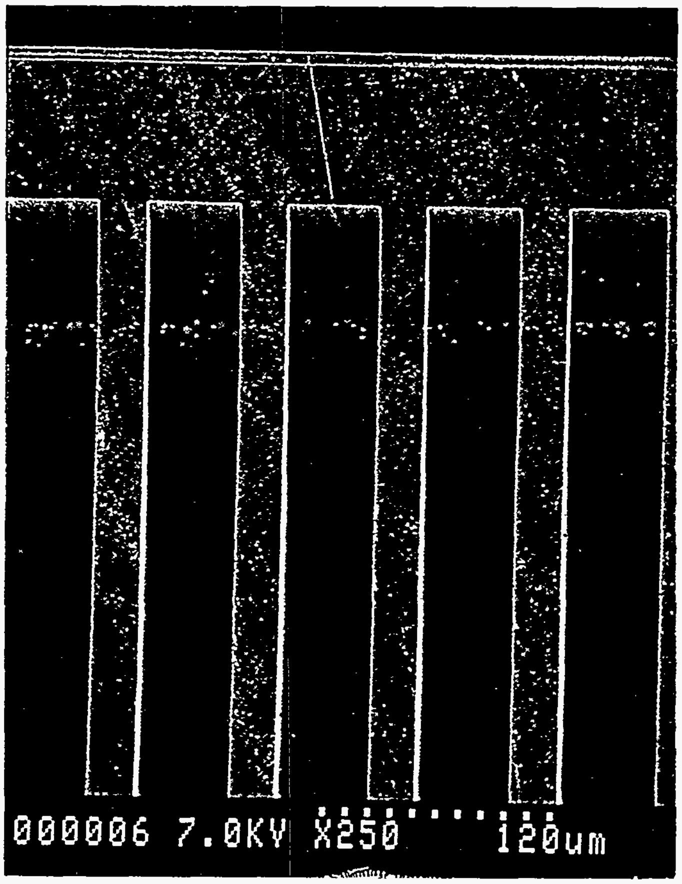

Fig. 3 Diamond lapped nickel test structure. Most notable is the absence of smearing at the edges of the top surface.

component inserted in its two possible orientations as well as whether the part is capable of being assembled in both orientations yields a measure of sidewall slope.

Since the processing steps of DXRL and electroplating fabrication do not involve high temperatures with maximum process temperatures less than 200°C and typically less than 50°C, process integration with prefabricated integrated electronics is readily possible. This capability has been demonstrated by using an arrangement of silicon photodiodes underneath an integrated rotational motor for use as a shaft encoder. Real time rotor position data may thus be acquired and used for dynamic parameter extraction as well as for feedback control.

3. RESULTS

Results for individual components defined by DXRL have proven the unique capabilities of this process. Gears, for example, have been fabricated with tooth widths of 5μm as shown in Fig. 4. Other mechanical components which have profited from DXRL processing include precision dies, microsurgical instruments, ink-jet nozzles, and gratings.

Two types of microactuators have been pursued using DXRL based fabrication including linear and rotary magnetic microactuators. Before magnetics can be considered, two major issues must be addressed [21]. A soft ferromagnetic material

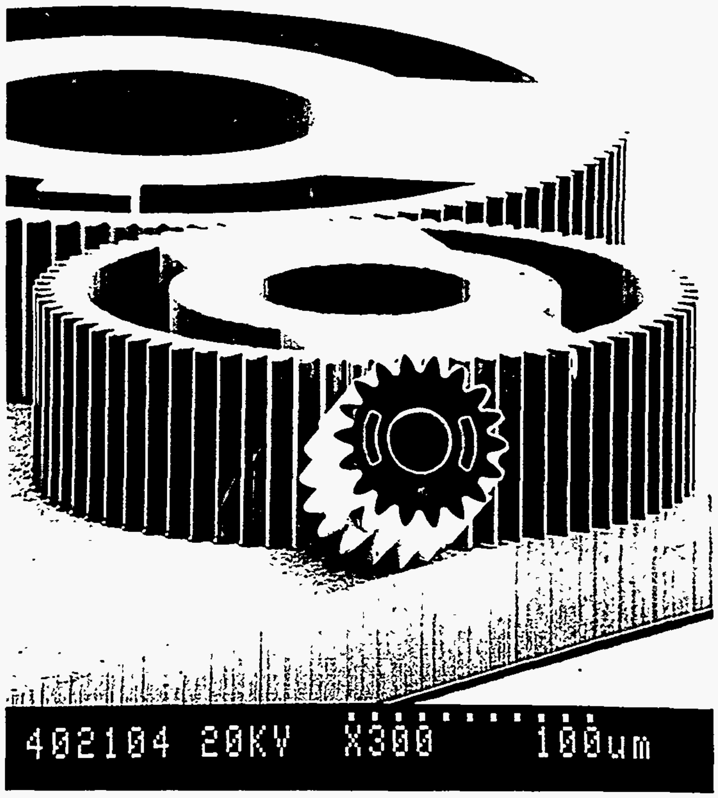

Fig. 4 SEM photograph of released nickel gears fabricated by DXRL and electroplating. The smallest gear has a 70µm diameter with 100µm thickness.

is required as well as the ability to construct coils. The magnetic material has been satisfied by using electroplated 78/22 Ni/Fe or 78 Permalloy. Such material has a magnetic saturation flux density of 1.0 Tesla and a measured initial permeability of 2000. These properties are entirely sufficient for magnetic circuit construction. Coil implementation has been approached in two steps. Initial coil fabrication was directed at only establishing a functional coil and utilized an integrated approach which consisted of a bottom layer of patterned metallization, vertical extensions incorporated into the DXRL layer, and bonded top crossovers. The resulting planar coils suffer form a low coil winding density and high power dissipation. For a given required magnetomotive force (mmf) the dissipated power in a coil is reduced by 1/n where n is the number of coil turns. Making use of coil winding technology with 25µm diameter magnet wire appropriate coil forms have been fabricated using DXRL and electroplating. Coils were thus improved from tens of turns to several hundred turns with corresponding power dissipation reduction from Watts to milliWatts.

A generic magnetic linear microactuator design has been pursued which is capable of generating milliNewton output forces with 250µm travel [22]. Such a microactuator is depicted in Fig. 5 which has been implemented with a wound assembled coil. The actuator consists of three parts. A spring constrained plunger is used to avoid friction during plunger motion, a magnetic circuit with pole faces and coil inserts provides a medium for magnetic flux from coil to plunger, and a

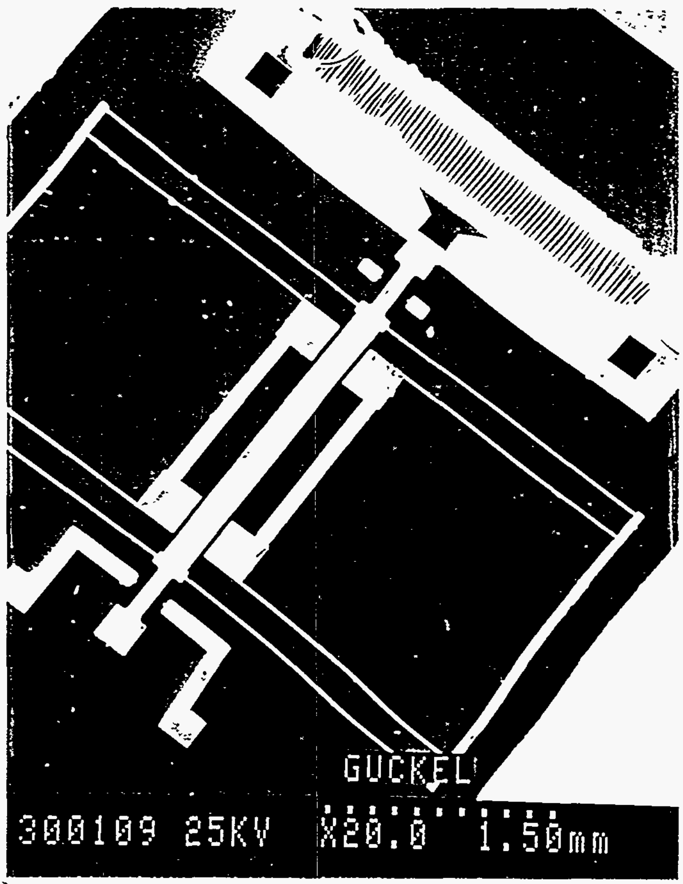

Fig. 5 SEM photograph of completed linear magnetic microactuator with 80μm thick assembled spring, 150μm thick magnetic circuit, and 400 turn coil. The spring constant of the crab leg fixture in the compliant direction is 3.5 N/m Plunger displacements of 300μm, therefore, show that forces near 1mN are produced.

wound coil is fabricated separately and assembled using spring clamps into the magnetic circuit. Two mask levels are needed for the linear microactuator construction including one for the fixed magnetic circuit definition and spring support posts and one for the free spring and coil form components. All parts are fabricated with electroplated 78 Permalloy which has proven to be a suitable spring material with high yield strength and very fine grain structure. Operation at resonance at a frequency of 361 Hz with a vibration amplitude of 250μm is sustained with a dissipated power of 200 microWatts. Coil inductance in the milliHenry range allows the position of the plunger to be monitored through inductance changes. The measured position sensitivity is near one microHenry per micron of plunger travel.

Two directions have been pursued for rotational microactuators. The first area makes use of the large reduction in rotational inertia which occurs for microscaled rotational elements. Fig. 6 depicts a rotational variable reluctance micromotor with 150μm diameter rotor and integrated coils. A shaft encoder is also implemented with prefabricated silicon photodiodes which lie underneath the rotor area. Real time position data is therefore available. Measured rotational speeds up to 150,000

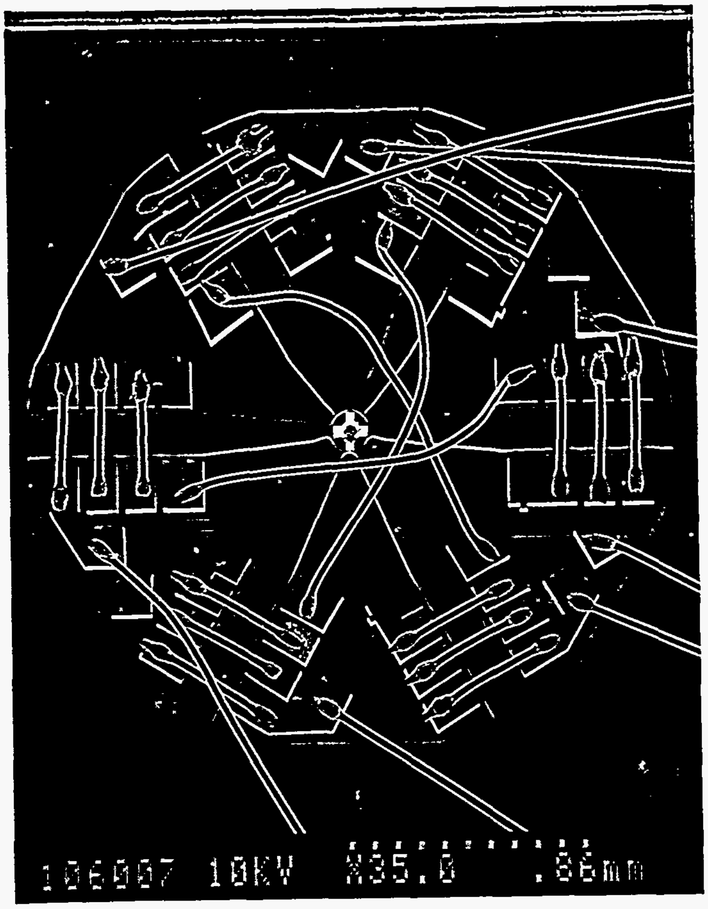

Fig. 6 Integrated magnetic variable reluctance micromotor with shaft encoder. A bonded coil implementation was used here. The rotor and stator are fabricated from electroplated 78 Permalloy. Metallization runners to the shaft encoder underneath the 150μm diameter rotor are apparent.

rpm have been demonstrated in air. These micromotors have been operated in excess of $3(10)^9$ cycles and do not reveal any lifetime problems. Speed limitations occur due to stepping instabilities and may be remedied via closed loop control which is possible with the available shaft encoder signals. A vertical magnetic suspension has been incorporated into this micromotor by fabricating a rotor thinner than the stator. Rotational speeds of 10^6 rps are being pursued at which point the potential exists for several sensing applications such as vacuum pressure gauging.

The second rotational microactuator area of concern involves the generation of a sufficient level of output torque necessary to be useful in order to drive micromechanical loads. Torque outputs of 1μN-m and above are required. Methods to directly measure such output torque levels are also required. A system which is aimed at these goals is shown in Fig. 7. The system consists of a 3-phase variable reluctance stepping micromotor coupled through a planar gear train to a variable reluctance electromagnetic brake. Fig. 8 shows a close-up of the gear coupling. By varying the amount of applied brake current an electrically controlled variable mechanical load is established thereby providing dynamometry measurement

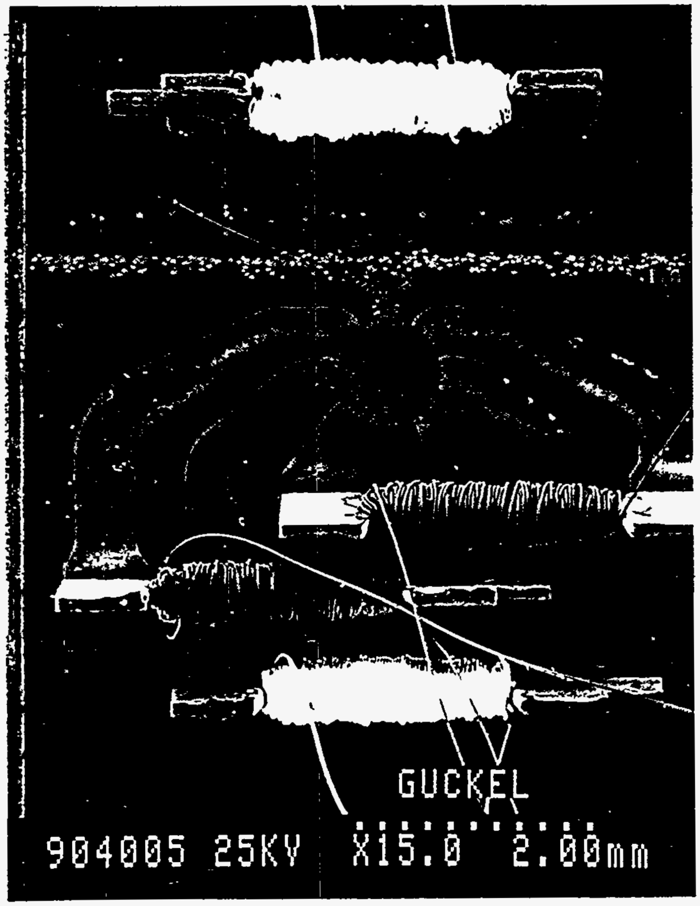

Fig. 7 SEM photograph of a variable reluctance stepping microdynamometer system fabricated with DXRL, electroplating, and microassembly fabrication. The driving rotor radius is 500μm and has a thickness of 150μm. The stator thickness is 180μm and is furnished with 3 assembled coils with 400 turns of 50 AWG magnet wire. A brake coil with 600 turns is used to drive the single phase magnetic brake.

capability. Torque calibration of the brake gear is required and is done with beam bending measurements. Output torques in excess of 0.3μN-m are measured at input power levels of 20 mW. Minimum input power necessary for rotor rotation alone is 52μW and increases modestly when loaded by the gear train which indicates a relatively low friction existing between 78 Permalloy components. Dynamometry measurements reveal a torque speed behavior common to variable reluctance stepping motors and a maximum motor output power of 20μW. The behavior exhibited by this electromagnetic system makes evident possible extensions to micro generators and micro servo mechanisms.

4. CONCLUSIONS

Deep x-ray lithography and electroplating based processing provides a powerful and flexible tool for fabrication of the next generation of precision mechanical components. Arbitrary geometries may be accommodated with 0.1μm accuracy and precision lapping and polishing allows for thickness control. This processing is also well suited for microactuator construction when microassembly is exploited.

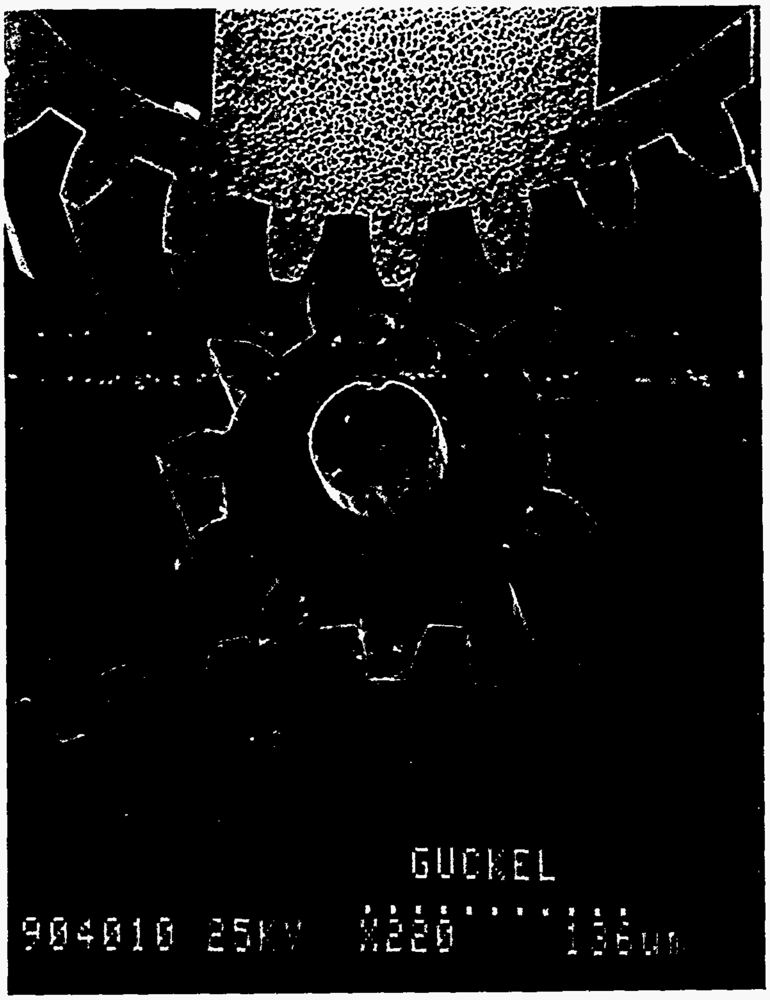

Fig. 8 Close-up of gear train coupling in variable reluctance microdynamometer.

5. ACKNOWLEDGMENTS

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