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Pop-up book MEMS

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Abstract

We present a design methodology and manufacturing process for the construction of articulated three-dimensional microstructures with features on the micron to centimeter scale. Flexure mechanisms and assembly folds result from the bulk machining and lamination of alternating rigid and compliant layers, similar to rigid-flex printed circuit board construction. Pop-up books and other forms of paper engineering inspire designs consisting of one complex part with a single assembly degree of freedom. Like an unopened pop-up book, mechanism links reside on multiple interconnected layers, reducing interference and allowing folding mechanisms of greater complexity than achievable with a single folding layer. Machined layers are aligned using dowel pins and bonded in parallel. Using mechanical alignment that persists during bonding allows device layers to be anisotropically pre-strained, a feature we exploit to create self-assembling structures. These methods and three example devices are presented.

1. Introduction

Many machines realize greater performance and economy if made smaller. However, when shrunk to millimeter and micron sizes, new challenges arise in their construction. Monolithic fabrication must replace traditional methods, enabling efficient batch processing while eliminating the onerous assembly and handling of individual components. Integrated circuit technology has strongly influenced and informed this monolithic approach. Fabrication techniques include optical lithography, physical and chemical vapor deposition, spin coating of polymers, electroplating, thermal treatment, chemical and plasma etching, abrasive polishing and laser machining. Micro-devices with a variety of electrical and mechanical functions manufactured using these (and other) techniques are named microelectromechanical systems (MEMS). Many MEMS devices have found wide commercial success, including miniaturized accelerometers, gyroscopes, displays, electrical and optical switches, scanning mirrors and pressure sensors [1]. The success of these devices is due not only to the increased performance and reduced costs associated with miniaturization and batch fabrication, but to their tolerance of the limitations imposed by monolithic fabrication using integrated circuit techniques.

Most MEMS devices are made using surface micromachining [2]. Material is deposited onto a substrate, masked and then etched. These steps are repeated to build up layers. As most methods of deposition are isotropic, chemical-mechanical polishing is often used to planarize each layer. Free-standing mechanical structures are created by removing sacrificial material or etching undercuts. When multiple materials are used, earlier layers must survive later deposition, etching and thermal treatment steps, potentially limiting the combinations of materials that can be used. Complex MEMS devices may have several material layers and require hundreds of sequential process steps. This highly serial nature compounds the impact of defects introduced at each step. To achieve economical device yields, it is then necessary to reduce the number of layers and shrink the size of the individual devices. Most commercially successful MEMS devices are not hindered by a restriction to planar structures, material limitations or increasing miniaturization. Indeed, many of the devices previously listed consist of a silicon structural element oscillating at high speed along a single axis. These requirements are well met by tiny, planar silicon components. Silicon has excellent specific stiffness and low thermal distortion, and processing methods therefore are well developed [3].

There is strong interest in constructing non-planar miniature devices that do not conform to traditional MEMS processing. These devices—which include motors, transmissions, linkages, linear and rotary servo elements, micro-robots and complex three-dimensional structures—are challenging to create using surface micromachining. There are practical limitations on the types and thicknesses of material that can be deposited by vapor deposition, spin coating and electroplating. It is not practical to use more than a few device layers, but within these restrictions, surface-machined gears, motors and other mechanical devices have been made [4]. Bulk machining—a technique in which multiple substrates are machined separately and then bonded together—is an alternative MEMS process which eliminates the need for sequential planarization and allows layer substrates to be processed in parallel. Bulk machining enables thicker layers and allows for a wider range of layer materials. It has been used to create a variety of structurally complex miniature devices, including gas turbines [5], multi-axis force sensors [6] and microfluidic devices [7].

To overcome planar limitations inherent to MEMS, there has been much effort to create three-dimensional structures through folding. Surface-machined pin-and-staple hinges [8] and polymer flexures [9] are two common methods used to create folding linkages. Schemes to exploit deposition stresses [10] or solder/polymer surface tension during reflow [11] are common ways to induce folding. Co-fabricated assembly actuators [12], though bulky, allow for a highly controlled fold sequence. If latching mechanisms are present, stochastic assembly through simple agitation might also be used.

2. Design and fabrication methods

In this paper, we present a new method for making threedimensional MEMS devices and microstructures, based on the folding of multilayer rigid-flex laminates. Essentially, we are combining the surface-machining methods of folding and self-assembly with the simplicity and material flexibility of bulk machining. These ideas have been strongly influenced by printed circuit board (PCB) fabrication. In particular, we have adopted adhesive bonding, mechanical layer alignment and parallel lamination—all common PCB fabrication methods.

2.1. Printed circuit board techniques

Bulk-machined multilayer MEMS devices are constructed by machining individual layers (typically using deep reactive ion etching or chemical wet etching), followed by lamination using wafer bonding. Alignment accuracy of 1–5 μ m is typical for direct bonding methods, although successive bonding in a multilayer device leads to accumulated error. For methods that use an intermediate bonding material, such as adhesive, glass frit, eutectic or solder bonding, alignment accuracy is degraded by flow and thermal expansion of the bonding agent. There has been effort to integrate mechanical alignment features into layer substrates (typically silicon wafers) to prevent them from shifting during the bonding cycle. Surfacemachined aluminum disks were used as friction pads to improve post-bond alignment by an order of magnitude for benzocyclobutene adhesive bonding [13]. Bulk-machined post-and-trench alignment features have also been used, not only to improve alignment, but to achieve it by mechanical, rather than optical means [14]. Adoption of PCB alignment and bonding techniques is a natural extension of these efforts.

Multilayer PCBs use precision dowel pins to maintain alignment during lamination. Alignment holes are punched or laser-drilled in each layer. The laminate is placed between precision die plates with relief holes for the alignment pins and then bonded in a heated press. Multiple layers are easily aligned and bonded simultaneously. Since mechanical alignment persists throughout the bonding cycle, misalignment from adhesive shearing and layer migration is largely eliminated. The challenges of achieving high bond strength, low adhesive flow and high accuracy alignment are well understood, and a wide array of highly optimized materials, tools and techniques are commercially available to support high-accuracy parallel lamination.

2.2. Laminate fabrication

Our process begins with the production of multilayer laminates. Individual layers are first bulk machined to define part geometry. Layers-post machining-must remain contiguous to preserve structural integrity of the layer and provide a stable mechanical connection from each device component to the alignment pins. Usual practice is to machine features while leaving small tabs or 'bridges' connecting parts to the surrounding bulk material, similar to break-off tabs in panelized circuit boards. After lamination, a second round of machining, the 'singulation' step, will free the individual parts. Any method of machining that is sufficiently accurate and compatible with the layer materials can be used. For our research purposes, we use laser micromachining for its maskless nature and compatibility with a wide range of materials. We employ a diode-pumped Nd:YVO₄ laser, q-switched and frequency tripled to 355 nm. Maximum average power is 1.5 W, which we find sufficient for machining layers in the 1–150 μ m thickness range. The beam is focused to a spot approximately 8 μ m in diameter using a telecentric objective lens. Full-range accuracy and repeatability of beam/part positioning is 2 μ m or better. With this system, adhesive and polymer layers for all devices presented took a few seconds to machine, and metal and carbon fiber layers took a few minutes each. Layers were 25-50 mm in size.

After each layer is machined, optional steps-such as electropolishing, ultrasonic cleaning and plasma treatmentmay be performed to prepare each layer for lamination. In flex circuit construction, circuit layers are usually bonded with acrylic sheet adhesives. PCB sheet adhesives are highly engineered materials with tailored thermal expansion properties, and they exhibit very little flow during the bonding cycle. We use Dupont FR1500, a commercially-available acrylic sheet adhesive, 12.5 μ m thick. The adhesive is used in two ways: it is either machined with alignment holes and included as a free-standing layer, or it is tack-bonded to an adjacent layer. For either technique, laser machining is used to pattern the adhesive. Other adhesives or methods of adhesion could certainly be used, but we find the combination of properties present in this type to be suitable for our purposes.

Figure 1 illustrates the alignment tooling used during lamination. This alignment and bonding configuration is typical of PCB lamination. After stacking the layers, the layup and tooling are placed in a heated press for bonding. The typical lamination cycle used was 1 h at 190°C with 400 kPa of pressure. Alignment accuracy is determined by several factors: alignment hole and pin accuracy, coefficients of thermal expansion for each layer material, bonding temperature and the laminate dimensions. For alignment, we use precision



Figure 1. Exploded view of the alignment tooling used to align and bond multiple layers in parallel. Release/conformal layers, shown in red, sandwich the part layers. After stacking layers onto the alignment pins, the part and tooling are placed in a heated press for bonding.

dowel pins (1/16in); layer material permitting, alignment holes are undersized by a few microns to exploit elastic averaging. In practice, post-lamination alignment is better than 5 μ m. The exact accuracy is difficult to measure since the material uniformity and edge roughness of our current materials and machining process are of a similar scale.

We first demonstrate these methods by making a complex part from a relatively simple layup: with just two rigid layers, separated by a single adhesive layer, we can form a linked chain. Figure 2 illustrates the design and process with a simple two-link version. The resulting 549 link chain is shown in figure 3. The rigid layers are a pre-cured carbon fiber laminate, 95 μ m thick; each layer is composed of three plies of unidirectional carbon fiber (33 g m⁻² fiber areal weight per ply), arranged in a 0–90–0 layup and impregnated with a cyanate ester resin. This material is very strong, stiff and light. It laser-machines easily and has a low coefficient of thermal expansion. After lamination and singulation, the chain is simply lifted out of the frame.

2.3. Pop-up book folding

The chain, though a toy example, demonstrates a complex topology using just two layers and selective adhesion. While adding more layers will allow devices of greater complexity, this '3D printing' approach has several limitations: as part thickness grows, it is increasingly difficult to make singulation cuts deep in the part, excess supporting material must be removed and structural elements aligned normal to the working



Figure 2. Layer design and fabrication process for a simple two-link chain. The adhesive layer is machined so as to prevent bonding between the rigid layers at the points of overlap. All three layers are laser-cut, laminated and then released with a second round

of laser machining ('singulation').



Figure 3. A monolithically fabricated 549-link carbon fiber chain, made using the methods shown in figure 2. After singulation, the completed chain is pulled from the frame in one continuous motion. Each circular link has an internal diameter of 1 mm and an annular width of 200 μ m.

plane are weakened by interleaved adhesive layers. To address these shortcomings, we have explored folding as an alternative method for making 3D structures.

To form patterned folding layers in our process, we machine 'links' out of a rigid material, separated by narrow gaps bridged with a flexible material. These flexures may serve as either assembly or mechanism folding joints. The primary challenge with folding is assembly; when working with a single folding layer, forming complex shapes either requires many sequential folds (origami) or the handling and assembly of many separate parts. Assembly would ideally occur using a single complex part with just one assembly degree of freedom. A motivating example is a pop-up book,



Laminate Index

Layer CF 3 Laser Toolpath

Figure 4. The model Wright Flyer is made of 95 µm carbon fiber laminate (CF), Dupont FR1500 sheet adhesive (A) and 7.5 µm polyimide film (PI). Examples of bridge and access port features are shown on layer CF 3. The folding mechanism for the front and rear stabilizers is similar to the wing box/fuselage mechanism shown. After lamination, the lower wings are opened like a book.



Figure 5. Top: 1:900 scale 1903 Wright Flyer model after lamination and singulation. All layers are bonded in a single lamination cycle. Bottom: the model after folding, held with tweezers above a US quarter. The wing span is 14 mm, the wings are separated by 2 mm and the vertical wing spars are 100 μ m \times 100 μ m in cross section.

where a single rotation results in the folding and assembly of many interconnected components.

Using our laminated fabrication process, we can make 'pop-up book' structures monolithically; multiple rigid-flex folding layers are stacked and selectively bonded together. Four-bar linkages, spatial linkages and other complex closedloop mechanisms can be formed without assembly, an idea previously explored in surface-machined MEMS [15]. As a demonstration, we constructed a miniature model of the 1903 Wright Flyer, at 1:900 scale. As shown in figure 4, this model consists of 15 physical layers: 6 rigid layers (carbon



Figure 6. Electron micrographs of layer CF 3 after laser-cutting, ultrasonic cleaning and tack bonding and patterning of adhesive layer A 4 (shown in blue false color).

fiber, as before), 7 adhesive layers (Dupont FR1500) and 2 polymer flexure layers (7.5 μ m polyimide film) which are shared by adjacent rigid layers to form 4 rigid-flex folding layers. The folding layers are connected together to form a series of parallel four-bar linkages. Figure 4 also shows the laser tool path for a rigid layer (CF 3) and a portion of folding mechanism employed. After the layers are laser-cut and laminated, the model is released by trimming each bridge connecting linkage elements to the bulk material. Bridges on lower layers are exposed by 'access ports' on layers above. After releasing the model, assembly proceeds in a single motion by opening the wings like a book. Figure 5 shows the Wright Flyer before and after folding. A small under-wing brace and cyanoacrylate adhesive were manually applied to fix the model in its folded state.

To create complex multi-layer folding mechanisms, small patches of adhesive form 'mechanical vias' connecting adjacent layers, analogous to electrical vias connecting conductive layers in PCBs. Requiring a contiguous freestanding adhesive layer to make these connections can be an onerous restriction; if the adhesive layer is free standing, bridges of adhesive must connect each via patch, but these bridges lead to large areas of unwanted bonding between folding layers. To mitigate this problem, we employ one of two methods to 'tack bond' adhesive patches to neighboring rigid layers. In the first method, sheet adhesive is tacked (using low heat and pressure) to a pre-machined rigid layer. The adhesive is then laser-skived, leaving the required patches. In the second method, sheet adhesive is kiss-cut at low laser power while still on its release paper backing. Alignment holes are then machined into the backing, allowing mechanical alignment when the adhesive is transferred to an adjacent rigid layer by tack bonding. Figure 6 shows rigid layer CF 3 of the model after initial laser machining and ultrasonic cleaning. Adhesive layer A 4 has been tack bonded to the top surface and then patterned; the remaining adhesive is shown false colored in blue.

While inter-layer alignment was consistently within 5 μ m, comfortably below the minimum feature size for the device, occasional yield losses resulted from material defects. Fiber gaps, such as those visible in figure 6, can ruin a part if they overlap critical bonding regions. While rejected parts due to material defects were not common, the assembly step proved tricky. Assembly of this part does truly consist of a single rotational fold, but grasping and handling the device with tweezers is a delicate operation. The miniature flexures are easily torn with a small slip or tremor of the hand. Customized assembly jigs would certainly make this process easier, but their use dilutes the advantages of a monolithic structure. If practical devices are to be successfully mass-produced, they must interface with simple external assembly actuators or they must include a mechanism for self-assembly.

2.4. Self-assembly

When dealing with miniature, batch-fabricated devices, selfassembly is highly desired, but rather difficult to arrange. In the absence of external manipulation or energy input, assembly will only proceed spontaneously if the laminate is not at its minimum energy state when released. To establish this condition in our laminates, we can introduce a pre-strained elastic layer; in particular, we use common spring steel shim-stock, laser-cut into flat springs. Materials used for springs must have a high yield strain, high toughness and must not anneal during the bonding step. This spring-pattern layer is stretched and held under tension during bonding. Persistent mechanical alignment is critical to establishing and maintaining accurate anisotropic pre-strain within the laminate.

As a demonstration, we created self-assembling hexagonal prisms. Our method and demonstration structure are partially inspired by previous work in recreational paper engineering which achieved spontaneous folding using prestretched rubber bands [16]. Figure 7(a) illustrates the structure and its folding mechanism; the hexagonal ends are bisected, allowing the device to flatten, effectively creating a one degree-of-freedom Sarrus linkage. Opposing fold joints, labelled j_1 , are connected by a flat spring. Figure 8 shows the part layup and illustrates the folding mechanism. Layup materials are the same as those in the chain and Wright Flyer examples, with the addition of a 75 μ m spring steel layer. The alignment holes for this layer are shifted inward along the spring axis; the layer must be stretched to fit onto the alignment pins.

After lamination, the ends of the springs are lasercut, releasing the parts. However, this particular device is laminated into a singular configuration, since the j_1 and j_2 hinges are co-planar. To initiate assembly, the structures were dipped into an ultrasonically agitated water bath. They 'popped up' into form immediately. The design could be modified to move the j_2 hinges outward with respect to the central layer, resulting in immediate buckling and assembly after spring release. The disadvantage of such a design is the potential for premature release of one spring end during the release cut.

This structure demonstrates the viability of self-assembly using a pre-strained layer. Many practical devices will require high-accuracy assembly folds. We expect this can be achieved through kinematic fold stops and a spring layer designed to provide positive closing action after assembly. In addition to a positive-acting spring, 'snap-fit' latches might be employed to prevent unfolding of the device.

3. Discussion and future work

These techniques cannot easily compete with surface micromachining in terms of layer thinness and feature resolution. As a bulk-machined process, these properties are limited by handling and stability requirement for each layer and characteristics of the adhesive method used. The methods presented in this paper hold promise for devices at a scale just above traditional surface-micromachined devices, and MEMS devices which require complex mechanical structures or specialized materials.

Using standard PCB processing facilities will require pre-machining of device layers or the availability of onsite laser machining or other systems appropriate for bulk machining. While the type of laser used in this work is commercially employed for laser-drilling electrical vias (especially in high-density flex circuits), they would need to be configured for machining and singulation as well. Achieving the degree of accuracy reported here will require special attention to panel size (thermal effects) and the layout density of alignment pins. Larger devices with tolerances in line with current PCB practices can be produced without As circuit traces and material thicknesses modification. shrink below 25 μ m, and advanced packaging techniques proliferate, commercial production will become more practical.

Some aspects of paper engineering, such as a pop-up book design, have provided a source of initial folding strategies for monolithic devices; however, general design principles for folding and assembly of these structures have not been established. Our designs are currently hand-drafted—20 or



Figure 7. (*a*) Illustration of the folding mechanism used for the hexagonal prism structures. (*b*) Electron micrograph of a self-assembled device. (*c*) A spring layer used in part layup, including alignment pin holes. The springs follow a serpentine path, 65 μ m wide.



Section B-B

Figure 8. Layup and folding mechanism for self-assembling hexagonal prisms. Layer materials are 95 μ m carbon fiber laminate (CF), Dupont FR1500 sheet adhesive (A), 7.5 μ m polyimide film (PI) and 75 μ m spring steel (SS).

more device layers are not uncommon. This process is extremely tedious and error prone; unlike PCB and integrated circuit design, no process-specific software layout tools are currently available.

Our ongoing work is focused on using and expanding these principles to design functional microsystems. While the devices presented in this paper are purely mechanical, adding electrical components and circuitry is a simple extension due to the PCB-based methods employed, analogous to the natural integration of MEMS and integrated circuits. Addition of electronic circuit elements, actuators and other discrete components is envisioned through the use of standard circuit board processing techniques, such as pick-and-place population and reflow soldering. From a research standpoint, the advantage of a simple, flexible and fast manufacturing process cannot be overstated. To provide some perspective, note that turnaround times for prototype PCBs are measured in days and MEMS devices in months.

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