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MICROLAMINATION FOR MICROTECHNOLOGY-BASED ENERGY, CHEMICAL, AND BIOLOGICAL SYSTEMS

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ABSTRACT

Microlamination is a process for fabricating micro and meso scale systems having intricate arrays of components interconnected within a single block of metal, ceramic, or polymeric material. The process begins by surface machining, or through cutting, individual laminae with patterns containing the desired structure. The laminae are often shims of a base material having desirable mechanical and thermal properties important to the functioning of the final device. Once the patterns are cut, the laminae are surface treated and stacked in a prearranged order. Bonding then takes place forming a single block of material. Some post processing of the block can be performed to dissociate internal structures if needed. This paper describes work being accomplished at Oregon State University on the microlamination process. The paper emphasizes laser micromachining of metal and polymeric laminae. Laser techniques covered include pulsed Nd:YAG-based micromachining at the fundamental and higher harmonics. Also, examples of CO_2 laser machining are presented. Process descriptions are provided and examples given of micro and mesoscale components needed for producing devices useful in the energy, chemical, and biological areas.

INTRODUCTION

Microtechnology-based Energy and Chemical Systems (MECS) are devices that rely on embedded microstructures for their function. The overall size of MECS devices places them in the mesoscopic regime, i.e. in a size range between macro objects such as automobile engines and laboratory vacuum pumps, and the intricate MEMS based sensors that reside on a silicon chip. Thus MECS, although having microfeatures, are large by MEMS standards straddling the size range between the macro- and micro- worlds. These mesoscopic systems are expected to provide a number of important functions where a premium is placed on either mobility, compactness, or point application. The internal processes of these devices rely on length scales that are much smaller than traditional systems. For thermal and chemical applications, a small characteristic size provides the benefits of high rates of heat and mass transfer, large surface-to-volume ratios, and the opportunity of operating at elevated pressures. For other more mechanically operated meso machines such as generators and motors, small dimensions imply rapid response and compact design. Furthermore, these systems can often be volume produced resulting in substantial cost reduction of each device. In the energy area, MECS will find increasingly important uses were small scale heat engines, heat pumps and refrigerators are needed. For example, the development of miniature refrigerators could provide point cooling of high speed electronics and communication equipment for enhancing performance (Little, 1990). Also, power packs based on combustion rather than electrochemistry could extend operating times of electronic devices by a factor of ten (Benson and Ponton, 1993). In the area of chemical processing, miniaturized chemical reactors could provide on-site neutralization of toxic chemicals thereby eliminating the need for transport and burial (Koeneman, et al., 1997). Because many MECS devices rely on fluidic processes, the same technology can be applied to biological applications. Miniaturized bioreactors could provide precisely regulated environments for small groups of cells to enhance their production of therapeutic drugs, or the detection of toxic compounds. Such bio-applications could range from benchtop research to large scale production facilities.

Fabrication techniques developed for IC production have been refined to the extent of supporting a multi-billion dollar industry. Chip manufacturing relies on silicon-based processing where submicron feature size is routinely used in production. MECS do not require the extremely small "line widths" needed to fabricate integrated circuits. Furthermore, for many energy applications, silicon is not the favored base material (Peterson, 1999). It has a much higher thermal conductivity than is desired for energy-based applications and the material, although strong, is brittle, expensive, and cannot always be tailored to specific environmental conditions. Other fabrications techniques (discussed in the next section) have been specifically developed for MEMS. Although many rely heavily on silicon processing (Kovacs, 1998), others can produce very small structures in metals electrodeposited on a surface or within a micromold. Again, for MECS applications, the feature size of these MEMS fabrication techniques are usually much smaller than what is needed for MECS.

Because MECS are fundamentally different than traditional ICs and MEMS, they require different materials and fabrication processes. The fabrication method discussed in this paper is microlamination (see for example, Haas et al., 1993, Haas, 1995, Wegeng et al., 1997, and Young, 1996). Although it has been used in the past, and is currently the basis for producing a commercial product (Anderson, 1989), extending the applicability of the method to MECS is being pursued by only a few groups. The method is based on micro-lamination of metals, ceramics, and polymers. The process

begins by surface machining, or through cutting, of a single lamina with a pattern containing the desired structure. The lamina is often a shim of a material having desirable mechanical and thermal properties important to the functioning of the final device. Once the pattern is cut, the laminae are surface treated and stacked in a prearranged order. The stack is then bonded together forming a single block of material. For the method to have utility, a machining method capable of fabricating structures in the laminating material is needed. The method must be versatile, easy to use, and capable of rapidly machining (with through-cuts and surface texturing) a wide variety of materials. Laser numerically controlled micromachining satisfies these requirements. Although other techniques such as through-mask electrochemical machining is applicable to shim production, this paper will emphasize the use of laser micromachining for preparing individual laminae.

LIMITATIONS OF CURRENT FABRICATION METHODS

Current microelectronic integrated circuits (IC) are predominately silicon-based. MECS, on the other hand, require the mechanical and thermal properties provided by other materials. For example, many thermally-based applications require low thermal conductivity material to reduce heat transfer (Peterson, 1998 and Peterson, 1999). Other requirements for subcomponents could be for highly fatigue resistant material for springs or magnetic steels for generator and motor cores. Clearly, current IC fabrication techniques cannot be used for constructing the major components of energy-based meso devices. Similarly, many of the prevailing MEMS manufacturing technologies (Warrington, 1995, Kovacs, 1998, and Guckel, et al., 1991), are based on silicon, polymers, or electroplated pure metals (having high thermal conductivity). Adapting these MEMS fabrication techniques for the construction of MECS would be difficult to achieve.

A second requirement for MECS construction is the need for a "vertical" fabrication method for high-aspect-ratio features. Micro channel arrays with 20-to-1 aspect ratios are commonly needed for heat exchangers and regenerators. Other MECS designs may call for a small gap between adjacent sub-components where the gap is maintained for the entire length of the structure. Other MECS requirements call for heterogeneity in fabrication materials where electrical and magnetic sections may require a metal and non-conducting sections may need a polymer or ceramic. Furthermore, electronic chips to provide processing of information or communication may be needed in the overall design of MECS. This is a significant challenge for current microfabrication techniques. Current MEMS fabrication technology has not demonstrated the capability for producing the devices envisioned here.

Finally, MECS must be able to offer geometrical sophistication at low cost in order to compete with conventional macroscale energy conversion devices. The most notable high-aspect ratio MEMS fabrication technology is LIGA (Becker, et al., 1986 and Ehrfeld, et al., 1987). In addition to being primarily a polymer forming method, LIGA is dependent upon highly capital intensive synchrotron X-ray generation. Other lower cost variants of LIGA (Paul and Klimkiewicz, 1996, Holms, et al., 1997) are being developed to address this need, but capital investment is still high. LIGA and the lower cost derivatives all use lithographic techniques for mold making and electroplating for material deposition. Weaknesses of this approach include limited material selection, limited geometric complexity (two dimensional structures), and inconsistent pattern-transferring methods (Walsh, et al., 1996). Other net-shape microfabrication techniques have been exploited including laser-beam (Ihlemann et al., 1993), electron-beam (Brunger and Kohlmann, 1992), ion-beam (Martin et al., 1996), electrochemical (Datta and Romankiw, 1989), electrodischarge (Datta, 1993), and mechanical methods (Friedrich and Kikkeri, 1995) for material removal or deposition. However, all of these approaches are either 1.) serial in nature and, therefore, lack the capability of economical mass production, or 2.) involve single layer thin film forming and, therefore, provide limited aspect ratios. No well-established micromechanical fabrication method currently exists for addressing MECS device fabrication requirements in a low-cost, high-volume manner.

Oregon State University, Pacific Northwest National Laboratory (Richland, Washington), and Tektronix, Inc. (Wilsonville, Oregon), have been developing microlamination for high aspect ratio devices. The OSU and PNNL (Wegeng, 1994 and Wegeng et al., 1996) work has concentrated on MECS while Tektronix has developed their process to mass produce ink-jet print heads (Anderson, 1989). The fabrication methods being pursued by these three groups rely on building up a microlamination of thin shims and bonding them into a composite assembly. Similar to rapid prototyping techniques, microlamination involves three steps: 1.) lamina patterning, 2.) laminae registration to form an assembly, and 3.) bonding of the assembly. Microlamination has the capacity to fabricate metal, polymer and ceramic devices with high aspect ratios in large production volumes. This has been demonstrated by the existing production capability of Tektronix. The company has fabrication lines where thousands of metal ink jet print heads are being produced for commercial use. Further development of this method with metals, and other materials such as ceramics and polymers, will require research of lamina patterning processes, bonding techniques, and the effects of non-ideal registration processes.

Table I lists the advantages and disadvantages of laser-based microlamination. The comparison is made with regard to the current state of micro and meso fabrication techniques. Although using laser micromachining for lamina patterning is an inherently serial process, for research purposes, it offers distinct advantages over electrochemical machining (an inherently batch-wise process). The main advantage is the rapid progression from design to cut laminae without the need for generating a mask. For mass production of a mature device, chemical and electrochemical processes probably have cost advantages over laser micromachining. However, with the continued improvement in the power and speed of laser micromachining, especially with the advent of diode pumped YAG lasers, this advantage may not exist in the next few years.

Table I

Advantages of Microlamination with Laser Micromachining

1.) Wide selection of material properties are available to suit a particular application. Material can be metal, ceramic, or a polymer with specific and tailored properties, e.g. low thermal conductivity, high temperature materials can be used, or steels with high magnetic permeability.

2.) Versatility in pattern design and aspect ratio. Specific lamination design can be created on a computer and then generated by numerical controlled laser machining in relatively few steps. Many laminae can be stacked to provide high aspect ratios.
3.) Quick progression from design to final device — no masking is necessary. Mask production introduces additional steps into the prototyping process.
4.) Feature size limitation well suited for mesoscopic devices. Feature sizes as small as 10 μm can be generated (dependent on the material being machined). Easy to generate large features as well.
5.) Little shape warpage during assembly and bonding. Depending on the bonding method selected, little-to-no variation in the lamina shape is observed. Majority of shape variation resides in the registration step.
6.) Hybrid structures of different materials can be assembled into a single package.
7.) Full system integration into a single block of material can be achieved thus providing a simple, but powerful technique for system development.
8.) Dissociated features can be created in the final device allowing greater versatility in developing unique functional sub-components in the final product.
9.) Although laser machining is inherently serial in cutting features, all other steps in the fabrication process can be carried out in a batch-wise manner.

Table II
Disadvantages of Microlamination with Laser Micromachining

1.) Minimum feature size is currently limited to approximately 5 to 10 μm. This is dependent on the thickness of the lamina being cut and the wavelength used. Future developments will allow smaller feature sizes.
2.) Most structures cut in single laminae are inherently two-dimensional. This can lead to design limitations in the final device.
3.) Some surface preparation is typically needed after laminae are cut thus increasing the number of processing steps.
4.) Some specialized equipment is needed, e.g. a laser micromachining system and a vacuum hot press (for bonding).
5.) Bonding techniques based on diffusion soldering and brazing require an additional plating step.
6.) Laser machining can create a heat affected zone along the cut.

LASER MICROMACHING OF LAMINAE

Laser micromachining can be accomplished with pulsed or continuous laser action. Machining systems based on Nd:YAG and excimer lasers are typically pulsed while CO_2 laser systems are continuous. Much of our experience has been with the former system using an Electro Scientific Industries model 4420. This micro machining center uses two degrees of freedom by moving the focused laser flux across a part in a digitally controlled x-y motion. The laser is pulsed in the range between 1 and 3 kHz giving a continuous cut if the writing speed allows pulses to overlap. The cutting action is either ablative, or semi-ablative depending on the material being machined and the wavelength used (either the fundamental at 1064 nm, the second harmonic at 532 nm, or the third harmonic at 355 nm). The drive mechanism for the laser is a digitally controlled servo actuator giving a resolution of approximately 2 μm. The width of the through cut, however, is dependent on the focused beam diameter.

We have also had laminae machined with CO_2 laser systems. Commercial laser machining services are available for cutting metal sheet for use in a variety of applications, especially in the testing and development of electrical machinery (motors and generators). Most of the commercial CO_2 lasers semi-ablate or liquefy the material being cut. A high velocity gas jet is often used to help with debris removal. As with the Nd:YAG systems, the laser (or workpiece) is translated in the x-y directions to obtain a desired pattern in the material. Comparative advantages of each system are that CO_2 laser systems generate more power and can cut through thicker material (upwards of several millimeters), but the Nd:YAG systems provide smaller spot sizes giving much greater capability for micromachining of thin laminae. When cutting metals, both systems benefit from post cleanup of the lamina using either a chemical wash or physical polishing to remove debris. For microlamination, it is critical that no ridging or crust remain on the laminae. Laser micromachining, in the non-ablative mode, produces some of these non-desirable features on the cut surface. Thus, post clean up of the part is necessary. However, with an ablative mechanism, such as that obtained when cutting polyimide or even some metal with UV radiation, little post cleaning is needed.

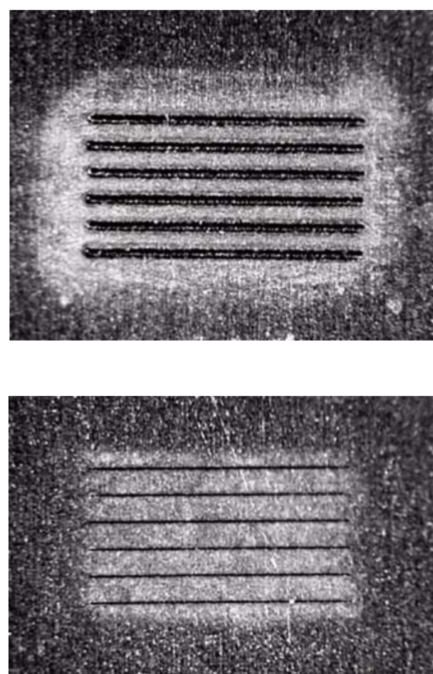

Figure 1: Laser machined lines in 90-μm-thick stainless steel. Top photo shows front side while bottom photo shows back side.

Figure 1 shows the results of using a Nd:YAG pulse laser to cut through 90-μm-thick steel shim. The front and back sides of the shim are shown in the figure. The line widths for these cuts are approximately 35 μm wide, although with steel, some tapering is observed. For the 90-μm-thick sample, three passes were made using 1 kHz pulse rate, an average laser power of 740 mW, and a distance between pulses of 2 μm. Also, the cuts were made at 355 nm. Some debris and ridging can be observed along the edge of the cut on the front side, however, this material is easily removed from the surface.

Figure 2 shows an edge structure cut at 532 nm before and after surface polishing. Average laser power and pulse rate were approximately 1 watt and 1 kHz, respectively. The material was stainless steel having a thickness of 110 µm. An example of a CO_2 laser cut shim is shown in **Fig. 3**. The part is a serpentine flexural spring used in a miniature Stirling cooler. The part has been cleaned with surface polishing to remove debris. The CO_2 through-cuts are approximately 200 µm wide and also exhibit a slight taper. The width of the CO_2 laser cut was the minimum achievable with the system used.

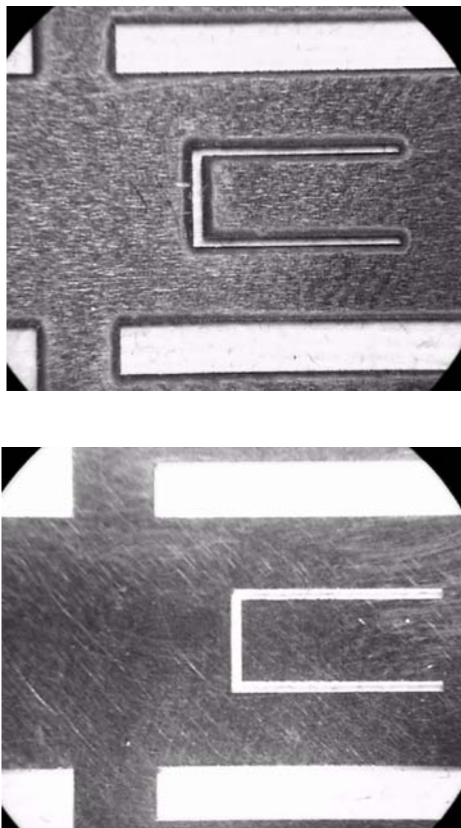

Figure 2: Laser machined laminae before (top) and after (bottom) clean-up of the part with surface polishing.

Pulsed Nd:YAG lasers have also demonstrated micromachining in polyimide material with high resolution and no debris formation. Ultraviolet wavelengths appear best for this type of work where an ablation mechanism is believed to be present. Clean, sharp-edged holes in the 25 - 50 µm diameter range have been produced.

STACKING, REGISTRATION, AND BONDING

After the laminae are cut by an appropriate method, stacking, registration, and bonding of the laminae are necessary in order to produced a completed device. As an example, consider fabricating a simple, functional structure such as a micro channel array using metal microlamination. The structure is shown in **Fig. 4** where the end use could be a heat exchanger that rejects thermal energy to the environment. **Figure 4** shows the lamination scheme for prototyping the structure. In the first step, as previous discussed, the laminae are formed by micromachining metal shims. The second step is to prepare each lamina surface by cleaning and, depending on the bonding method, plating of a thin (1.0 to 10 µm) metal layer on both sides of the lamina. Next, the laminae are stacked and registered using an alignment jig. Finally, the laminae are thermally bonded at an elevated temperature while being pressed together. This entire process produces a single block of material having embedded high-aspect-ratio features. Note that if sophisticated internal structures were needed, additional steps could be included. For example, a patterned etching for surface relief could take place before metal plating to ensure specific areas on the laminae do not bond to adjacent surfaces. Also, internal structures could be released by dissociating fixture bridges (discussed later).

Figure 3: Serpentine spring cut with CO_2 laser machining of stainless steel (after clean up). Shim thickness is 250 µm.

Once the laminae are cut by an appropriate method, it is necessary to stack and register the laminae. The stacking order is part of the design process that yields internal structures important for device operation. In advanced designs, it may be common for a hundred or more laminae to be stacked to create a high-aspect-ratio microchannel array. But in some important devices, only a few laminae are needed. For example, a float valve requiring only five laminae is discussed in the following section. Once stacked in the proper order, each lamina must be positioned precisely in relation to its neighbors. This process is called registration and is a crucial step in the microlamination process.

The precision to which laminae can be positioned with respect to one another will often determine whether a final device will function. The complexity may range from structures such as microchannel arrays which would be somewhat tolerant of misalignment, to more sophisticated devices requiring highly precise alignment. For example, a small scale device may need a rotating sub-component requiring miniature journal bearings axially positioned to within a few microns of each other. Registration can be accomplished with an alignment jig that accepts the stack of laminae and aligns each using some embedded feature — corners and edges can work as long as they are common to all laminae. Another approach incorporates alignment features, such as holes, into each

lamina at the same time other features are being machined. Then, the alignment jig can incorporate pins that pass through the alignment holes. The edge alignment approach can register laminae to within 10 microns assuming the lamina edges are accurate to this level. With alignment pins and a highly accurate lamina machining technique, micron level positioning is feasible. One other important consideration is that the alignment jig must tolerate the bonding step. Thus, in typical microlamination setups, the alignment jig is incorporated into the design of the structure that compresses the stack for bonding.

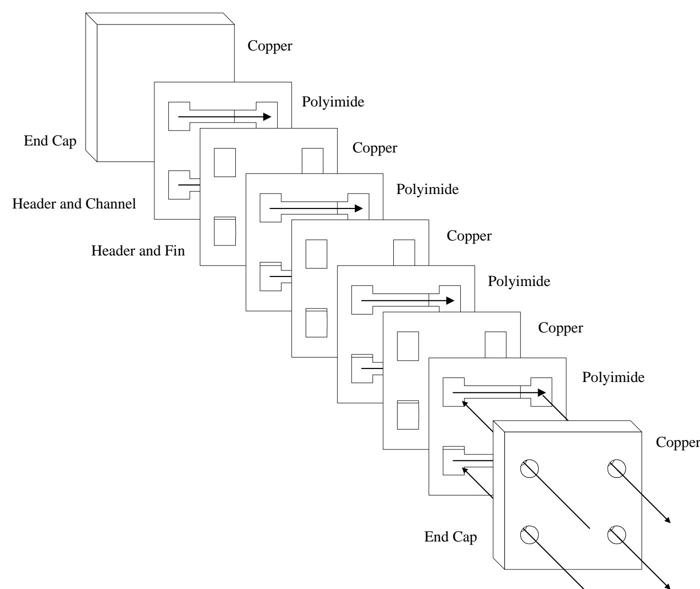

Figure 4: Microlamination sheme used to fabricate a dual micro-channel array. Arrows show direction of flow.

The laminae bonding process must form a strong, durable, and often hermetic seal between each lamina. A number of different approaches to this problem have been explored and are listed in **Table III** along with their advantages and disadvantages. One of the most promising bonding methods we are studying involves diffusion brazing and soldering.

The concept of diffusion brazing/soldering has been described previously by Jacobson and Humptson (1992). They present a number of material combinations that can be use on both base metals and on surfaces that have been metalized. Two of the more versatile combinations are tin-silver and tin-indium. These two diffusion soldering systems provide a low temperature bonding process that results in strong joints at the material interface. Another attractive feature is that the bond can take considerably higher reheat temperatures. Because of these characteristics, diffusion bonding appears ideal for producing microlaminated devices that must operate at moderate temperatures (up to approximately 500 C).

Table III
Microlamination Bonding Techniques

1.) **Polyimide Sheet Adhesive**: Polyimide is a high strength, high temperature polymer. In a special sheet formulation from Dupont called, Kapton KJ, it retains adhesive properties and can bond surfaces together when heated and compressed. This material is good for moderate strength bonds providing good sealing capability.
2.) **Diffusion Soldering and Brazing**: Requires plating of the surfaces with a low melting point metal. Tin/Silver and Tin/Indium have been used in the past for low temperature bonding. Provides a hermetic seal good up to re-heat temperatures exceeding 300 C. Best performed in vacuum hot press conditions.
3.) **Diffusion Bonding**: High strength, high temperature bonds are produced by this method. Requires high temperature, high pressure to form bond. Method can be applied to untreated (except of cleaning and oxide removal) metal surface, but techniques exist for metal plated surfaces also, e.g. stainless steel plated with gold. Often requires vacuum or reducing environments in addition to high pressures.
4.) **Micro Projection Welding**: Technique where laser machining or photolithography followed by surface etching is used to create projections on a metal surface. After laminae are stacked and bonded, electrical discharge is passed through stack heating and bonding only areas where projections make contact with adjacent parts. Can be used in air and takes place rapidly. Significant surface preparation needed.

The tin-silver system can work on any surface able to withstand moderate temperatures and capable of receiving a plating layer of the requisite metal. For many of our devices, steel and stainless steel offer a number of attractive characteristics for fatigue strength, magnetic properties, relatively low thermal conductivity (for stainless steel), and corrosion resistance. However, before the bonding can occur, the surface of each steel lamina must be prepared and plated. A typical plating process involves placing a very thin strike layer of nickel (approximately 0.5 µm) on the bare steel surface. This layer promotes adhesion of the other platable metals. Then, a copper layer 2 - 5 µm thick is plated over the nickel as a base upon which to plate either tin or silver. Copper is necessary as a bonding agent because of its ability to readily bond to both nickel and either silver or tin. Finally, a layer of tin or silver is plated 2 - 5 µm thick over the copper layer. What is desired for this last plating operation is to produce a lamina stack that will have alternating surfaces plated with either silver or tin. The two outside laminae should be silver so that the final, bonded stack does not adhere to the alignment jig. Also, our experience has shown that, if possible, non-bonded internal structures and cavities should have the silver layer on their surface. Through careful selection of which laminae to coat with tin and silver, this can usually be achieved.

The bonding takes place by momentarily raising the stack temperature above the melting point of tin (232 C) under a compression pressure of approximately 2 MPa. Careful exclusion of air (or other oxidizing atmospheres) is needed at this point to avoid the creation of tin oxides and voids. However, with the surface properly prepared, the bonding process is rapid and complete. Also, bond strength and re-heat temperatures can benefit by "cooking" the stack for a longer period of time at the bonding temperature, e.g. up to one hour. This allows tin to further diffuse into the silver and form strong

intermetallic compounds within the joint itself. Some evidence exist for ultimately forming a silver bond interspersed with intermetallic tin/silver particles yielding a high strength, moderate temperature joint. Note that indium can also be used in place of tin yielding a even lower temperature (melting point of indium is 157 C) bonding process.

SAMPLE DEVICES

In this section, a microchannel array and two types of valves are described. Each device demonstrates an important aspect of microlamination either during bonding, post-bond processing, or the incorporation of unique features into the overall design.

A.) Microchannel Arrays

As a first example of a device that can be fabricated with microlamination, **Fig. 4** shows a micro channel array. The design and stacking arrangement is shown. The device was designed to use a polymeric spacing and bonding sheet between copper micromachined shims. The bonding sheet is a polyimide material from DuPont (Kapton type KJ) that becomes active as an adhesive at temperatures exceeding 250 C. After bonding, the device has a useful service temperature under light internal pressure up to approximately 200 C. The bonding process takes place in an alignment jig using the sides and corners of the shim material as alignment features. Specific bonding conditions for the part shown in Fig. 4 was 265 C under a compression of 200 kPa. The stack is held at the bonding temperature and pressure for approximately 1 minute, then cooled. Our experience with this approach is that good, hermetic seals are formed by this method. Although clean and polished metal surfaces can be bonded together, type KJ polyimide bonds best to oxidized surfaces. Another attractive feature of this material is that under typical bonding temperatures and pressures, little flow is observed in the channel area. To date, all bonds have been accomplish in a small laboratory press surrounded by atmospheric air. We will be testing the bonding process in a vacuum press in future experiments.

The copper and polyimide laminae were cut from 100 µm-thick stock using the ESI model 4420 laser micromachining center. The output from the laser was 532 nm light from intercavity frequency doubling of the Nd:YAG fundamental. Qualitative observations were that the copper material cuts rapidly and with little debris generation on the surface. Each copper lamina was cut in approximately 45 seconds using a three pass process. This is in contrast to steel witch requires two to three times as long to cut the same thickness of material. The copper surface was physically polished to remove any debris and ridging that may have formed during the machining process. Polyimide cuts rapidly in two passes with no observable debris formation.

The final device produced after bonding was a microschannel array having 4 channels with a channel height of 100 µm, a width of 3 mm, and flow channel length of 10 mm. Headers were incorporated into the design at both ends, and as shown in the figure, top and bottom caps were used to interface the flow from a test loop to the device. Preliminary test data is shown in Fig. 5 where volumetric flow of water is plotted versus pressure head for four nominally identical devices. The theoretical curve is for laminar flow through the channels. Since the experimental curves show a slightly reduced flow rate, some influence from header design and other non-ideal flow characteristics are probably present. However, the data does suggests that laminar flow through the channel array provides a close approximation to the pressure drop.

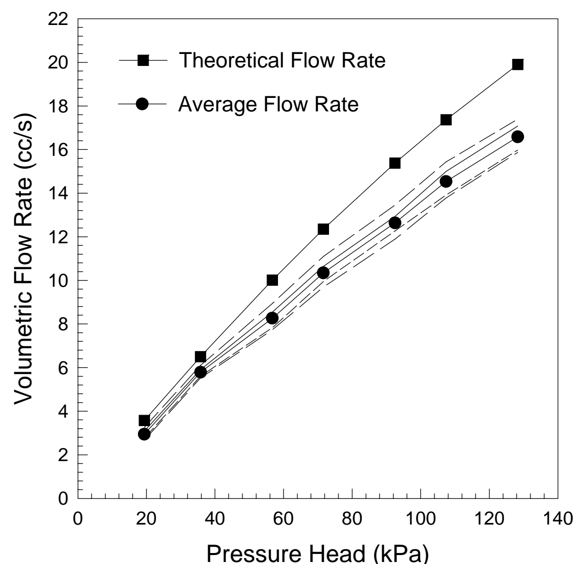

Figure 5: Flow rate vs. pressure head for four microchannel arrays. Theoretical and averaged curves also shown.

B.) Float and Flapper Valves

Two types of valves have been constructed using microlamination techniques. The major design differences between the two are shown in **Figs. 6 and 7**. The first valve was designed as a one-way float valve. It was constructed with five laminae. The design utilized an upper and lower orifice plate (laminae 1 and 5) where fluid enters and leaves the valve. The dimensions of the upper orifice was 1.5 mm in diameter while the bottom ring orifice has an outer diameter of 3 mm. In this design, the center float must be dissociated from its lamina after assembly in order for the valve to function. The second valve design was a traditional flapper assembly constructed out of two laminae. A top lamina containing the flapper was bonded to a lower orifice plate. Size of the orifice was also 1.5 mm in diameter.

The float valve design was based on a freely floating disk inside a cavity formed by two spacers, as shown in **Fig. 6**. This design calls for a special post assembly process called component dissociation which removes fixture bridging holding the float disk in place during assembly. The laminae were laser machined (532 nm output from a Nd:YAG pulsed laser) from 250 µm thick mild steel shim stock. The bonding process used in this particular design employed microprojection welding. On the back side of each lamina, a microprojection was create using acid etching through a photoresist mask. The projection formed a narrow ring around each valve component with a height of approximately 100 µm. During bonding, the lamina stack was compressed while an electric discharge was sent through the assembly. This heated and collapsed the microprojections essentially forming a weld along the length of the projections. This bonding process was accomplished in air, although future work will

investigate inert gas and vacuum conditions. Also, polyimide adhesive and diffusion soldering are being studied as possible valve bonding processes.

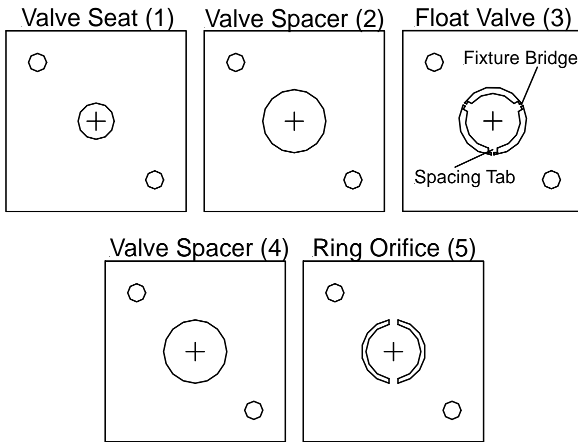

Figure 6: Lamination design for the float valve.

After bonding, the float plate is held in place with fixture bridging. Removal of this bridging can be accomplished by using a capacitive discharge process to blow the fixturing, similar to the process that a fuse undergoes when higher than rated currents flow through it. Sufficient current must be supplied to an electrode contacting the float plate (passing through the top center orifice) to vaporize the fixture bridging in one brief pulse. For the float valve results shown in **Table IV**, a 0.07 Farad capacitor bank was charged to 11 volts. With an electrode in contact with the float disk, and the body of the valve grounded, the capacitor bank was switched to connect the bank voltage to the electrode. This resulted in blowing the fixtures and freeing the float plate inside the valve cavity

Preliminary work has also been accomplished on a simple flapper valve. As shown in **Fig. 7**, a 250 μm-thick flapper plate was bonded to a 250 μm-thick orifice plate to provide the valve action. As fluid passes into the value through the bottom orifice, the flapper lifts off the orifice and provides relatively unrestricted flow through the valve. Upon flow reversal, the flapper valve seats onto the bottom plate and creates a relatively high flow resistance. The orifice diameter used in the valve was 1.5 mm. Also, the flapper was essentially a disk having a 2.2 mm outer diameter inside a larger opening having a diameter of 3 mm. To test the effectiveness of a different valve configurations, a total of 3 valves where fabricated — two having polyimide used as a seating material and one with steel-on-steel seating. Lamina material for the flapper valve was mild steel. The bonding process used for assembling the flapper valve was microprojection welding.

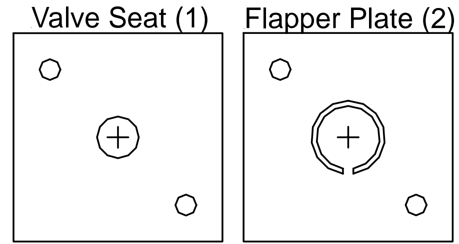

Figure 7: Flapper valve laminae showing pivoting flapper and orifice plate.

The valves were tested to asses their "diodicity", that is, their ability to restrict flow in one direction while allowing it in the other. This valve property is determined by measuring the forward and reverse mass flow rates under the same magnitude of pressure drop in the forward and reverse directions. The tests were conducted using ΔP's ranging from zero to 10.6 kPa. **Table IV** shows the performance of the flapper valve for three different valve seating configurations. The diodicity achieves values as high 6.32 for valves with polyimide on the sealing side of the flapper. Values are also given in the table for polyimide place on the valve seat, although the diodicity was not improved with this configuration. A full assessment of valve performance has not yet been accomplished and some non-ideal component effects may be present such as warpage, incomplete laminae contact after microprojection welding, and misregistration. These factors, as well as others, will need to be examined in detail before a final assessment can be done. Improvement in valve sealing, and hence diodicity, is expected once the lamina cutting, registration, and bonding steps are refined.

Table IV
Diodicity Results for Flapper and Float Valves

	Average	Maximum
Flapper Valve:		
(with Ployimide on Back of Valve)	4.08	6.32
(with Polyimide on Valve Seat)	1.22	1.78
(No Polyimide)	1.71	2.90
Float Valve:		
(No Polyimide)	11.19	17.10

CONCLUSION

The work presented here demonstrates the utility of microlamination for fabricating microtechnology-based energy and chemical systems. With the capability offered by laser micromachining, miniature devices can be rapidly moved from concept to testing on the benchtop in relatively few steps. Critical subcomponents can have feature sizes down to approximately 10 μm, although most features are currently in the 50 - 100 μm size range. Many choices exist for the bonding step required to form a device from a registered stacked of laminae. The two methods studied most so far are polyimide sheet adhesive and diffusion soldering. Both produce acceptable bonding and sealing of prototype devices.

However, further work on the registration and bonding steps is needed in order to move the microlamination method into a routine fabrication technique for MECS devices.

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