Development of Self-Assembled Robust Microvalves with Electroform Fabricated Nano-Structured Nickel

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ABSTRACT

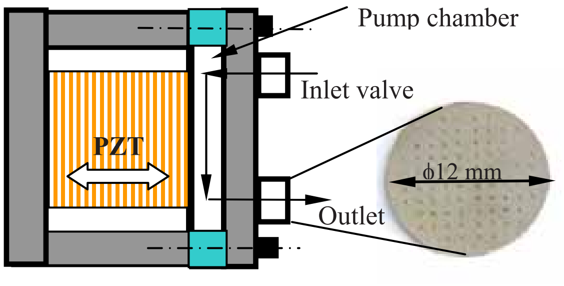
Self-assembled robust micro check valves with large flow rates (>10 cc/second, displacement related), high-pressure support ability (>10 MPa) and high operational frequencies (>10 kHz) made of nano-structured nickel were presented in this paper. The microvalve consists of an array of 80 single micro valves to achieve the required flow rates. A novel in situ UV-LIGA process was developed for the fabrication. Self-assembling was realized by guiding the electroforming process during the fabrication process. Test results show that the forward flow rate is about 19 cc/second under pressure of 90Psi. The backward flow rate is negligible. The reliability of the valve was tested by a specific loading/unloading sequence. Results show that the flow rates were repeated very well over a large range of tested pressure differences.

Keywords: self-assemble, microvalve, nano-Structured nickel, high frequency, high pressure support

1 INTRODUCTION

Hydraulic actuators, which convert hydraulic pressure into linear or rotary motions, have been used in a variety of applications. They are capable of producing large pressures/forces with compact size and high reliability. The compact robust hydraulic actuators are very important for space related applications due to their abilities in producing much larger forces/pressures per volume/mass than other existing technologies. They also play an important role in reducing the launching cost of spacecrafts, as any reduction in mass and/or power consumption for space instruments or subsystems will result in an exponential savings of the launch cost.

A compact hydraulic actuator mainly consists of a pump and inlet/outlet microvalves (Figure 1). The requirements for the compact pumping components include large pressure/force outputs, large flow rates and high working frequencies. The compact hydraulic actuators consisting of piezoelectric stacks and robust microvalves can produce power per unit volume ratio 100 to 1000 times greater than their electrostatic counterparts. The pumps (pushers) are fabricated with smart (active) materials, such as PZT, due to their simplicities in design and high power densities. On the other hand, microvalves are the key components for fluid management within the hydraulic actuator in order to meet the rigorous requirements in various space applications. The function of the microvalves is to manipulate fluid flow and to switch the flow directions (forward or backward). Obviously, the valves also have to bear the load (pressure) when they are in the closed state. Therefore, requirements for compact valves are stricter than those for the pumping components (pusher). These requirements include high flow rates (>10 cc/sec), high-pressure support ability (>10 MPa) and high operational frequencies (>10 kHz). As stated [1], active micro valves cannot fulfill all these requirements. Therefore, passive valves are promising for this application. The emerging MEMS techniques provide the opportunity to design and fabricate highly functional passive valves. Scaling laws have proven that mechanical systems could be improved greatly when the physical dimensions shrink [2], and they should apply equally to robust micro valves.



(a) (b)

Figure 1, Robust pump and microvalve.
(a) pump, (b) microvalve

Most currently developed microvalves use silicon and/or other non-metallic materials such as polymers for the structural and/or functional materials, due to the ease of fabrication. Such microvalves cannot survive without failure under severe dynamic loading conditions encountered in a robust pump (Figure 1a), due to the inherent materials' mechanical properties. Therefore, robust metallic microvalves are greatly needed for such applications since both the ultimate strength and the fracture toughness are important in these cases. Nickel is extremely suitable for the fabrication of these valves because of its high mechanical strength and ease of fabrication. The well-developed LIGA and UV-LIGA process can produce high-precision micro-scale components with vertical sidewalls that can be assembled or self-assembled to complex micro devices and systems. If properly processed, nano-structured nickel (Figure 2, right-upper corner) can be formed by the electroplating/electroforming process, which can in turn improve its mechanical performance. The authors have developed a novel mechanical tensile testing method to test the mechanical properties of the electroformed nano-structured nickel. The results are shown in Figure 2. The ultimate strength of this material can be extracted from the stress-strain curve, which is larger than 1Gpa. The Yield strength is more than 200 MPa. Using the nano-structured nickel as the building material, the authors have developed a pure nickel microvalve array, which is reported in this article.

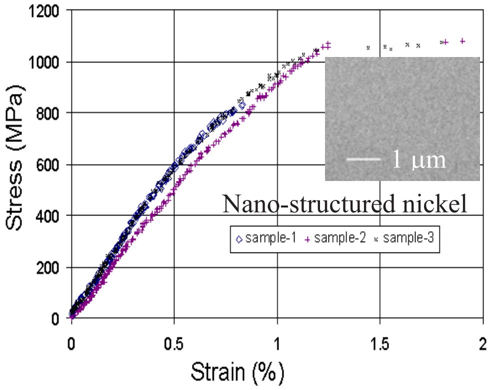


Figure 2, Tested stress-strain curve of the nano-structured nickel

2 MICROVALVE DESIGN

The design rules for the pure nickel micro mechanical passive valves are to meet the requirements of compact hydraulic actuators being developed for space applications. The concerns in mechanical design were to reduce the maximum stress of key components during the whole operation cycle. In order to match the operation of the PZT pump, the microvalve has to work at high frequencies (> 10 kHz). Therefore the natural frequencies should be much higher than 10 kHz to avoid resonance. This is insured by using the minimization. An 80-single-valve array is adopted to fulfill the flow rate requirement.

As shown in Figure 3, the designed microvalve is a normally closed micro check valve, which consists of an inlet channel, a micro nickel valve flap, and a valve stopper which houses the outlet channels. The valve flap is lifted by the pressure difference produced by the PZT pusher. Fluid is directed through the inlet channel and passes through the valve flap and leaves the valve through the outlet channels. A gap of 10 μm was designated between the valve flap and the stopper, which is used to prevent the potential tear off of the valve flap in the case of severe situation. The valve flap (Figure 3) is linked with four identical cantilevered micro beams (springs), which holds it to the valve substrate elastically. The valve returns closed by the spring force developed in the four beams, in addition to the reverse pressure difference created by the PZT's contraction (Figure 1).

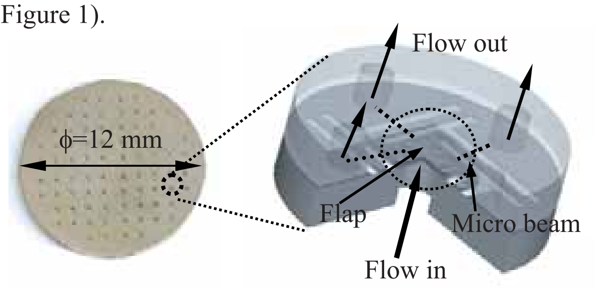


Figure 3, Concept sketch of the valve

The size of the valve-flap (square) is 300 μm by 300 μm and is held by four identical micro beams (600 μm x 50 μm x 10 μm each). The valve flap is reinforced with a cross pattern which is a15 μm thick sitting on a 10 μm membrane. The function of the cross pattern is to improve its pressure support ability in the closed state, as well as to overcome the stiction problem when the flap touches the stopper in the open state. Thick nickel layers (500 μm thick) were designed both as the supporting substrate and the stopper. All these structures are made of electroformed nickel with a novel in situ UV-LIGA process.

3 FEA SIMULATION

Static finite element simulation was performed to find the resonant frequency and to predict the stress distribution over the valve flap and the nickel substrate, both under open and closed conditions. The nickel properties used in the simulation are from the mechanical testing (Figure 2).

3.1 Resonant Frequency

The resonant frequency of the micro-beams-flap-system was predicted to be much higher than its macro counterparts due to scaling laws. Finite element simulation results showed that the system has a 1st mode resonant frequency of 18 kHz, which is much higher than the required working frequency (10 kHz). Therefore, no resonance will be induced when the valve works at 10 kHz.

3.2 Stress in the Valve Flap When Fully Opened

The stress distribution is another important concern in the design of the valve flap. Large stresses and stress concentrations need to be avoided. In the simulation (Figure 4), the ends of the micro beams were fixed, and pressure was applied over the valve flap. The stress distribution is shown in Figure 4, where the displacement of the valve flap is 10 μm, defined by the valve stopper. The maximum von misses stress is 128 MPa, located at the ends of the beams. This value is much smaller than tested strength values of electroformed nickel.

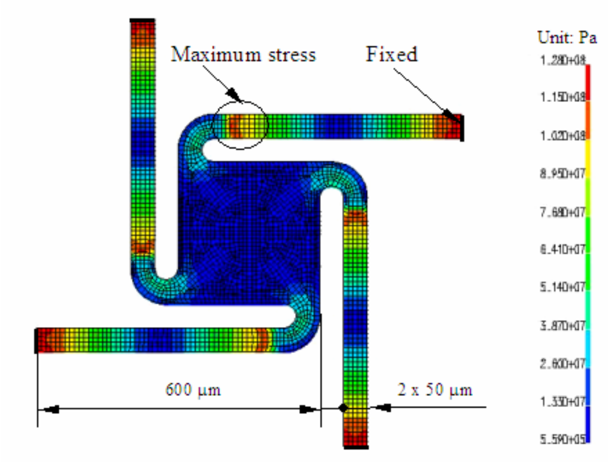


Figure 4, Stress distribution over the flap while it is fully opened

3.3 Stress in the Valve Flap When Closed

The valve flap was predicted to support high pressures (> 10 MPa) when it is closed. Therefore, finite element simulation was conducted to analyze the stress generated in this state. In the simulation (Figure 5), the ends of the micro beams were fixed and pressure was applied over the valve flap. The stress distribution is shown in Figure 5, where the applied pressure was 10 MPa. The maximum von misses stress was found to be 132 MPa, located in the center of the flap. This value is small in comparing to the strength of electroformed nickel.

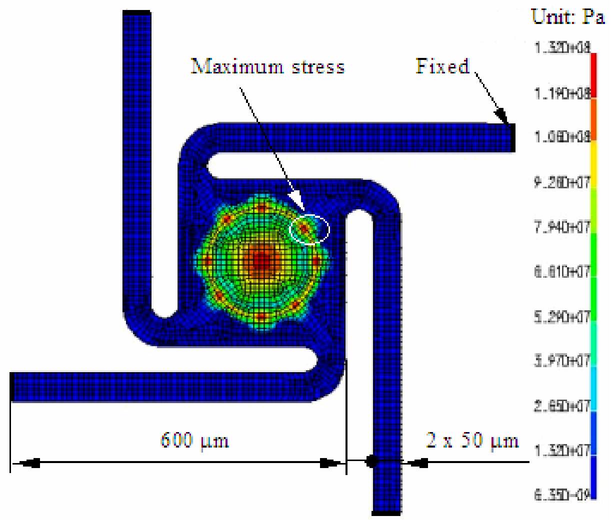


Figure 5: Stress distribution over the flap while it is closed

3.4 Stress in the Nickel Supporting Substrate

The nickel substrate (500 μm thick) needs to support large pressure, especially in the closed state. Stress analysis was performed to find the maximum stress and the distribution. The valve substrate is shown in Figure 6 (left). Thanks to geometric symmetry, only one quarter of the stress across the valve needed to be analyzed. A pressure difference of 10 MPa was applied to one side of the nickel piece. The results are shown in Figure 6. The maximum von misses stress was identified as 119 MPa. This value is in the safe range of the nickel material used. The use of nickel as the supporting substrate overcame the brittleness of the silicon substrate in the silicon-nickel valve [1]. This valve is much easier to handle, both in the process of fabrication and in the process of testing.

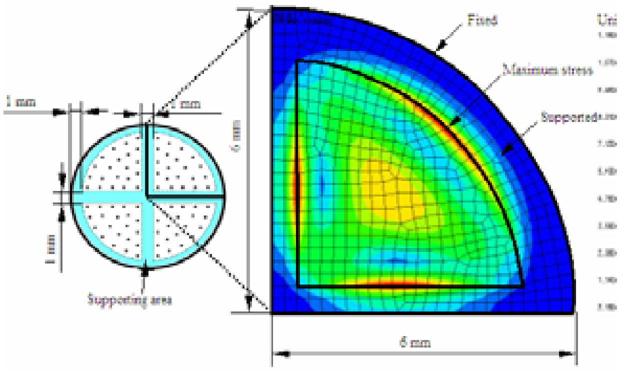


Figure 6, Stress distribution over nickel substrate under 10 MPa pressure while closed

4 FABRICATION PROCESS

The compact microvalve array had been fabricated by a newly developed innovative in situ UV-LIGA process. The valve inlet and outlet channels were defined by SU-8 molds [4] and the valve flap was defined by Photoresist molds. Chemical mechanical polishing (CMP) was applied during the fabrication. After electroforming, all SU-8 and photo resist molds were removed by using SU-8 remover and positive photoresist stripper. Finally, separated valve arrays were received. Therefore, this is a bottom–up self-assembled fabrication process. Neither etching nor bonding (or packaging) is involved during the fabrication. Figure 7 shows the fabricated valve array (80). Figure 8 shows the inlet/outlet view of the finished micro valve.

5 TESTING

To characterize the fabricated microvalve, a static fluidic test was performed by raising the pressure from low to high for both forward and backward flow. A specially designed valve holder was used to hold the valve while testing. Test results of flow rate versus applied pressure difference are provided in Figure 9. From the results, the valve's crack pressure is about 5 psi. The forward flow rate tested is approximately 19 cc/second under a pressure difference of 90 Psi, which is the largest pressure provided by the commercial air compressor used during testing. The backward flow rate is about 0.023 cc/s, which is negligible (<0.13%). It also can be seen that the measured flow rate is roughly proportional to the pressure difference applied, as predicted by Poiseuille's law. Based on Poiseuille's equation, it is reasonable to expect much higher flow rates if higher pressures are applied. On the other hand, the valve sealing is very good, as the backflow rate is negligible.

A specific loading/unloading sequence was designed to test the reliability of the valve (Figure 10). Results show that the flow rates are very well repeated over a large range of tested pressure differences. This implies that no damages or permanent deformations occurred during the test.

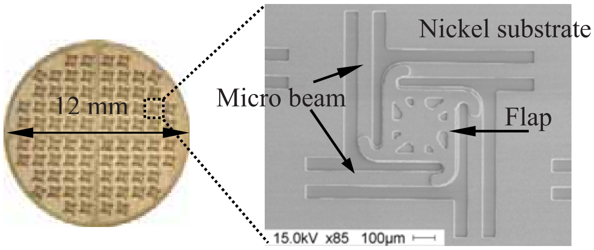


Figure 7, Fabricated micro valve array (80)

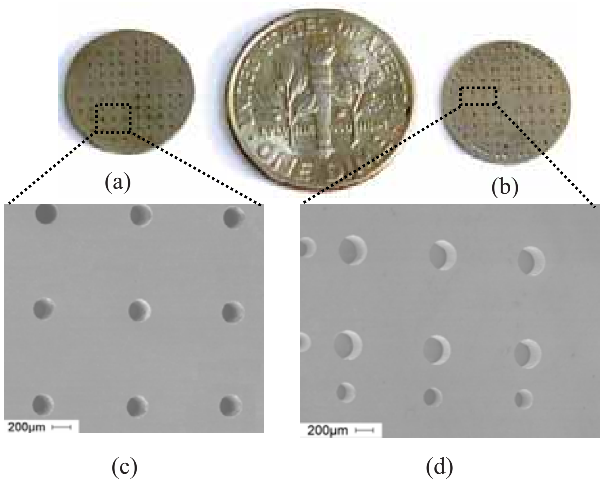


Figure 8, Fabricated microvalve. (a) Inlet view (b) Outlet view. (c) Inlet channels (d) Outlet channels.

6 SUMMARY

A self-assembled robust passive large flow rate, high-frequency and high-pressure solid nickel micro check valve has been developed for piezoelectrically actuated pumps or hydraulic actuators. The valve's reliability is assured by using a mechanically robust nickel valve stopper. Test results show that the forward flow rate is roughly proportional to the pressure applied. It is about 19 cc/s at a pressure difference of 100 Psi applied. The backward flow rate is negligible. The fabrication of the valve employed a novel in situ UV-LIGA process, where the valve stopper was self-assembled to the valve array without any additional bonding process. Therefore, this is a bottom–up self-assembled fabrication. No additional bonding (or packaging) process was involved during the fabrication.

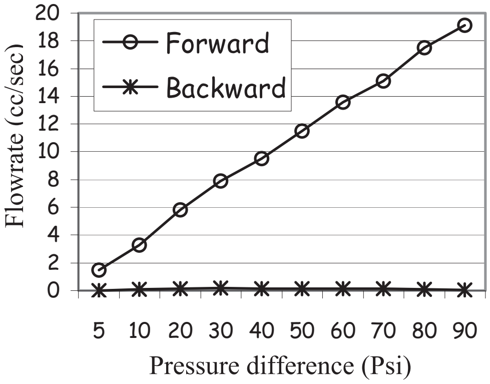


Figure 9, Tested flow rate versus pressure applied of the microvalve

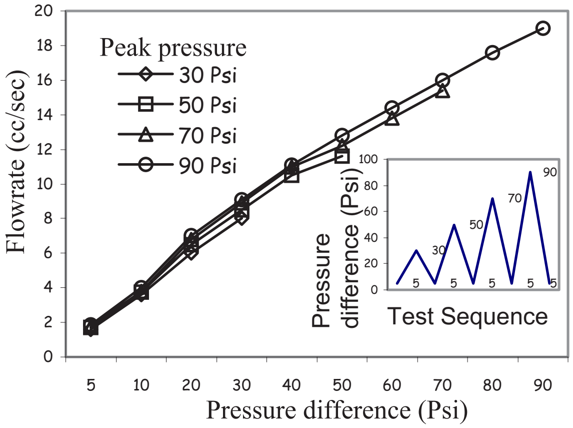


Figure 10, Repeated Test of forward flow rate under loading/unloading conditions

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