DESIGN AND TESTING OF AN ORTHO-PLANAR MICRO-VALVE

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Abstract This paper presents the production and testing of an ortho-planar one-way micro-valve. The main advantages of such valves are that they are very compact and can be made from a single flat piece of material. A previous paper presents and discusses a micro-valve assembly based on a spider spring. The present paper focuses on the valve assembly process and the valve performance.. Several prototypes with a bore of 0.2 mm have been built using two manufacturing techniques (µEDM and stereo-lithography) and tested for pressures up to 7 bars.

1 Introduction

Micro-valves are one of the most important components of micro-pumps which exist in hundreds of configurations [1]. They exist in various working principles and designs as presented in [2-4]. One of the smallest check valves available commercially is from the Lee Company which is a poppet-type and has a diameter of 3.2 mm and a length of 13.2 mm. A list (non exhaustive) of commercial miniature valves is given in Table 1.1.

Table 1.1. Industrial check valves

manufacturer	principle	diameter	length	-
Check-all Valve	Poppet-type	22 mm	60 mm	[5]
Clippard minimatic	Poppet-type	9.5 mm	19 mm	[6]
Command controls corp.	Ball	14.2 mm	25 mm	[7]
Deltrol Fluid Products	Ball	11.2 mm	24.5 mm	[8]
Halkey-Roberts	Ball	7.3 mm	21.6 mm	[9]
Lee Company, The	Poppet-type	3.2 mm	13.2 mm	[10]
O'Keefe Controls Co	Ball	8 mm	11.6 mm	[11]
Sterling Hydraulics	Ball	19 mm	27.2 mm	[12]

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Most of these commercial miniature valves are either poppet-type or ball-type valves. These two principles are illustrated in Figure 1.1. The forward flow is left to right. Note that in these versions there is a spring to maintain the ball or the cone on its seat at zero or very low negative pressure. One can see in Table 1.1 that industrial check valves are big regarding micro-pumps. This paper discusses on a small valve that can be built from a single flat piece of material.

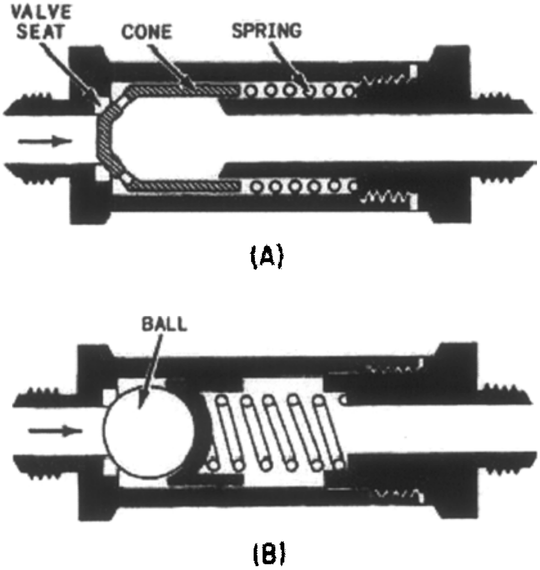


Fig. 1.1. Valve principles: (A) poppet-type valve, (B) ball valve (by courtesy of Integrated Publishing [13])

A previous paper [14] presents and discusses a micro-valve assembly based on a spider spring. It discusses the advantages of ortho-planar springs, and describes a new analytical model of the particular spider spring. The model is validated by a FEM and by measurements. The present paper focuses on the valve assembly process and the valve performance.

The first section (section two) of the paper sums up the situation with respect to the previous paper and presents the second ortho-planar spring realization. In section three, the valve assembly is presented and analysed. Section four presents the sealing tests and the flow rate measurements for low and high pressures.

2 Spider spring manufacturing

This section recalls and summarizes what had been presented in [14] concerning the spring realisation. The spider spring is produced using a micro electro discharge machining (μEDM) milling machine; the clamping system is presented in figure 2.1. The stainless steel foil is 10 μm thick and the cutting electrode has a diameter of 150 μm.

The second technique of manufacturing that was used is SU8 lithography. This process is presented and characterized in various papers [15, 16]. The main limitation of this method concerns the mask needed to manufacture the parts.

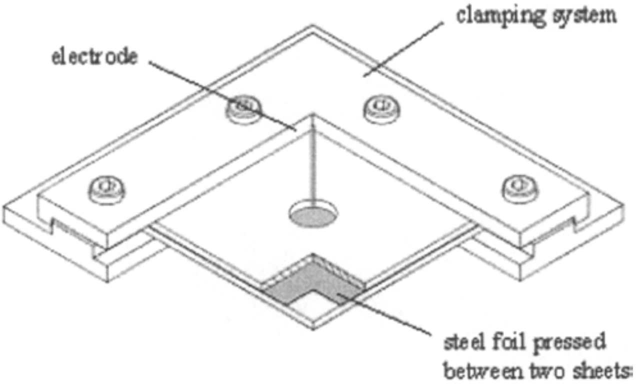


Fig. 2.1. Clamping system for EDM manufacturing

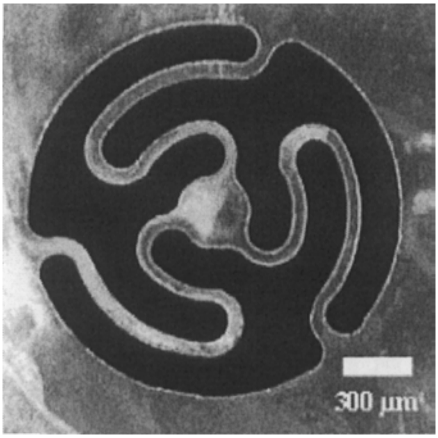


Fig. 2.2. Valve spring manufactured by EDM (150 μm electrode)

The resolution of this mask, which depends on the method used (laser, ink-jet printing), will directly influence the accuracy of the final spider spring. An example of a mask is shown in Figure 2.3. This shows an array of spider springs, which consist of a central disc connected to an outer ring (1) via spider spring arms. The outer ring is connected to plate (3) via break-away beams (2). Figure 2.4 presents some realizations of spider springs made from a resin epoxy-type material called SU8.

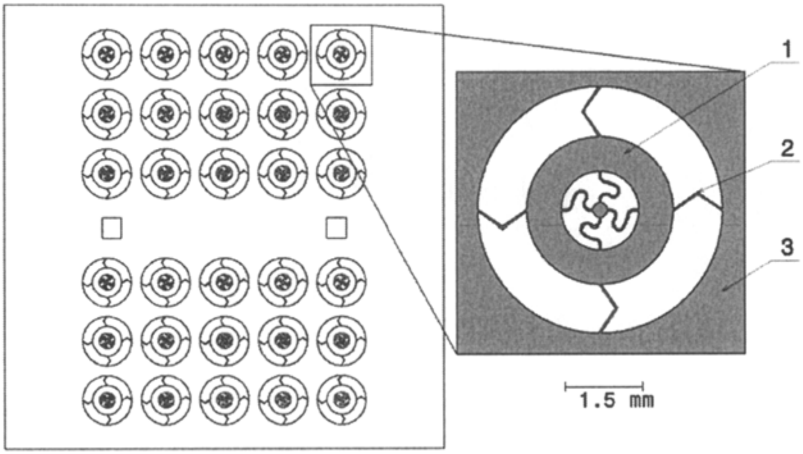


Fig. 2.3. Mask for lithography process

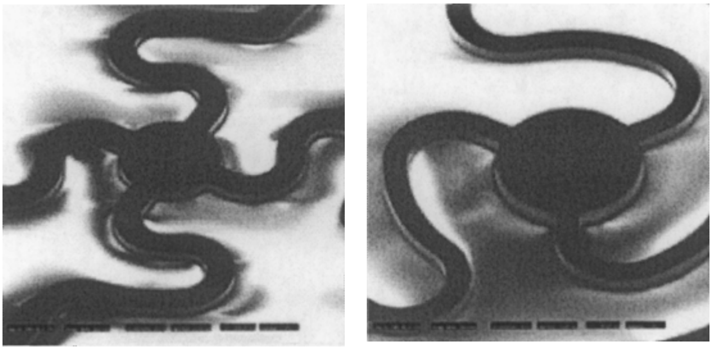


Fig. 2.4. SU8 end products (mask accuracy 2 μm)

This method has several advantages:

- it uses materials with **lower** Young's moduli (compared to materials used with the EDM technique), in particular epoxy type - i.e. SU8: E = 4 GPa,
- possibility to manufacture an **array** of spider springs in one step,
- possibility to manufacture a **multi-layered** spider spring. By varying the thickness of the spider spring along the diameter, it is possible to pre-stress the valve (see figure 2.5).

The advantage of pre-stressing the valve is to prevent backflow (so to enhance sealing) at very low pressure. As shown in Figure 2.5, there are two main methods to pre-stress the spider spring: either to modify the seat, or to modify the spring. So, the possibility to manufacture a multi-layered spider spring leads directly to the pre-stress of the valve.

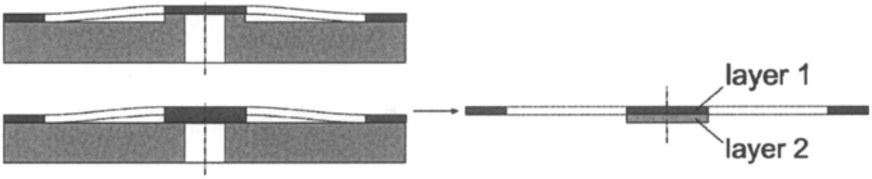


Fig. 2.5. Valve pre-stress principle (lateral view)

3 Assembly of the micro-valve

This section presents all the parts included in the valve and the assembly of all these elements. Figure 3.1 illustrates the principle of the valve (not to scale). The inlet of the valve is at the bottom and outlet at the top. The spider spring (3) is placed on the aluminium seat (5): since the central disc is over the input hole, an o-ring (2) is placed on top of the spring and an aluminium ring (4) is placed around the spider and the o-ring. The role of the o-ring is to uniformly distribute the force over the external part of the spider spring. Finally, a lid (1) is placed on top of everything. The reason for separating parts 4 and 5 is that in that way, the top surface of part 5 (i.e. the seat of the valve) can be easily polished to obtain a better quality surface. The crucial point of this assembly is to correctly align the spider spring (3) and the seat (5). In the first version of the valve, the spring is aligned visually (using a microscope) with the seat, and then the o-ring is placed on the spring. This operation is quite difficult because of the small dimensions of the spring.

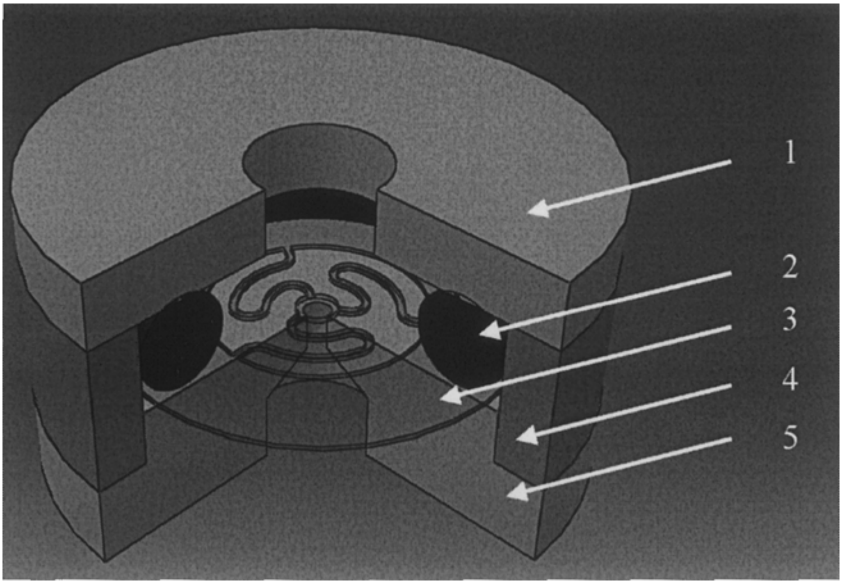


Fig. 3.1. Principle of assembly of the valve

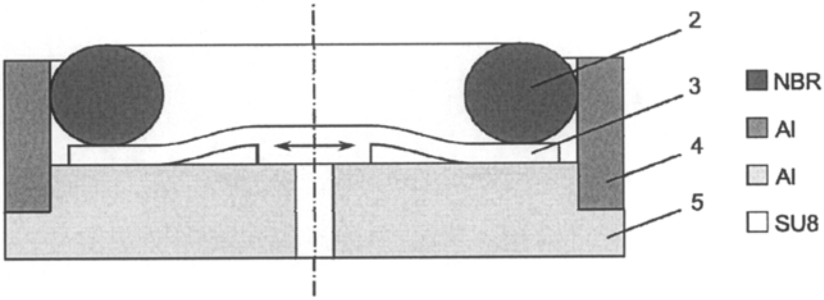


Fig. 3.2. Spider spring placement

All the parts are held together using screws (not represented on the diagrams) passing through parts 1, 4 and 5. Another solution would have been to glue all the elements together but in that case, we would have to realise as many complete valves as springs to be tested.

Starting from theoretical considerations, we can find rules for design for manual assembly at classical dimension in [17]. These are listed in decreasing order of importance:

1. reduce part count and part types,
2. strive to eliminate adjustments,
3. design parts to be self-aligning and self-locating,
4. ensure adequate access and unrestricted vision,
5. ensure the ease of handling of parts from bulk,
6. minimise the need for reorientation during assembly,
7. design parts that cannot be installed incorrectly,
8. maximise part symmetry if possible or make parts obviously asymmetrical.

For our application, we will discuss rules 3 and 4. In the design presented in Figure 3.2, part 3 is not self-locating on part 5 (rule 3 is not respected). Furthermore, due to the clearance between part 3 and 4, adjustment of part 3 has to be made through the o-ring (2). This decreases the access and restricts the vision. A simple way to improve the situation is to design part 3 to be self-aligned. In That way, we will try to provide parts with leads, lips, tapers, chamfer, etc. so that alignment is built into the design. However several limitations should be considered:

- tapers or chamfers are not possible in our stereo-lithography process
- lips on the seat makes the polishing of the seat difficult
- pilot on spider should be deep, but manufacturing time increases with the deepness of a layer and a layer is limited in thickness...

Several solutions were considered. These impose the need to either modify the spider spring, or to modify the seat or to manufacture an extra intermediate part.

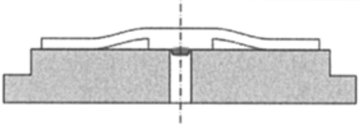
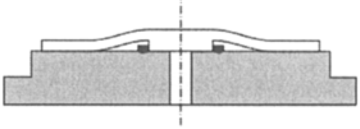
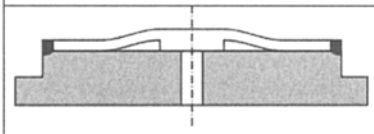
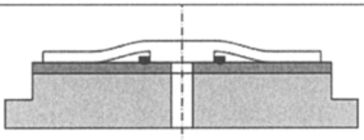
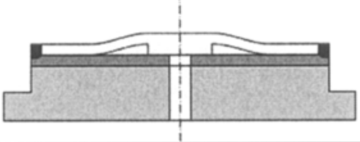
name	Part modified	Schemes	Advantages/drawbacks
pilot	spider		- chamfers not possible to manufacture - 3 layers means very long manufacturing time -risk of wedging
lips	seat		- requires precision micro-milling machine - polishing of the upper surface of the seat not possible anymore -risk of wedging
			- requires precision micro-milling machine - polishing of the upper surface of the seat not possible anymore
	Extra part (PDMS)		+ Better surface finish of the upper surface of the seat - risk of wedging
			+ Better surface finish of the upper surface of the seat ✓

Fig. 3.3. Solutions for alignment problem

The adopted solution presented on figure 3.4 has two advantages: the first is to allow an accurate centering of the spider spring, and the second one is to improve the surface quality of the seat.

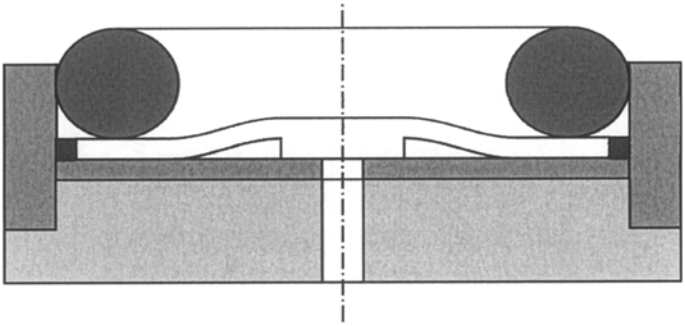


Fig. 3.4. Drawing of principle of the solution adopted for the micro-valve

4 Valve tests

This section presents the flow rate measurements as a function of the pressure difference. Two test beds were realised, the first one for low pressure measurements, where the pressure is generated by a water column, and the second one, where a pressurised tank is added. In both cases, the flow rate is measured using a graduated tube and a chronograph.

4.1 Low pressure tests

The tests bed is presented in Figure 4.1. Several spider springs were tested using this test bed. The maximum pressure was 0.1 bar (a water column of 1 meter). Measurements for spider spring with no pre-stress are very bad (high leakage in backflow) and are not presented here. Figure 4.2 presents results for pre-stressed spider springs. The main characteristics of these springs are presented in table 4.1. There is practically no backflow and we see that, in general, the flow in the forward direction is higher when the stiffness of the spring is smaller.

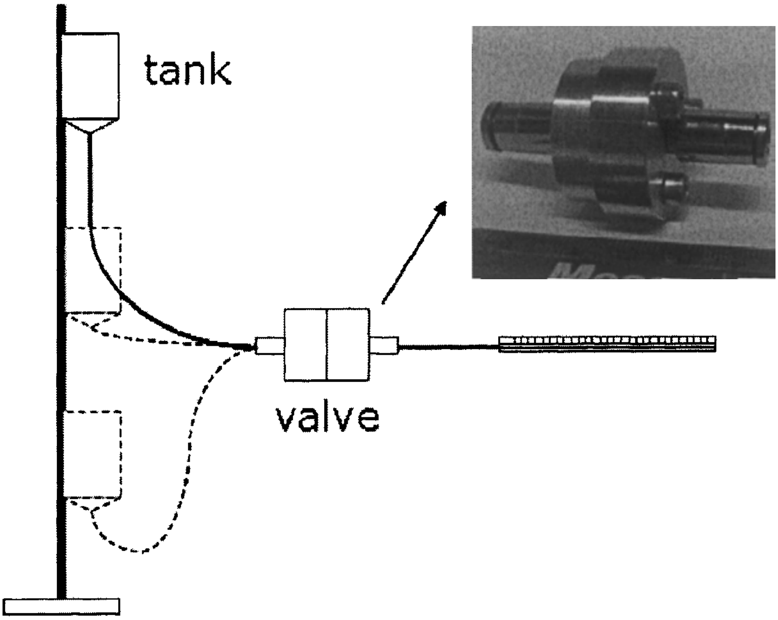


Fig. 4.1. Test bed for flow rate measurements

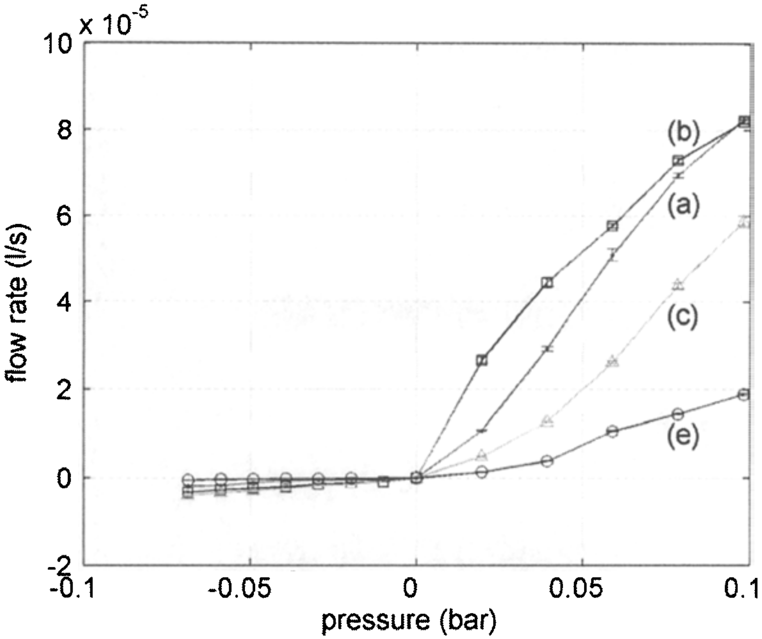


Fig. 4.2. Flow rate measurements for the parameters presented in table 4.1

4.2 High pressure tests

To test the valve under higher pressures, we used a tank with two compartments. One side is filled with air and the other with water. A pump was used to increase the air pressure (and hence the water pressure up to 5 bars). Flow rate measurements are presented in Figure 4.3. The dotted line represents the theoretical behaviour of the same test bed without any spider spring. The conclusion of that graph is that, for higher pressures, the behaviour is quite similar for the various spider springs. At these pressures, all the valves are fully open and the presence of the spider spring introduces an additional pressure drop with respect to the free circulation dotted curve.

Table 4.1. Parameters for spider springs

-	a	b	c	d	e
material	SU8	SU8	SU8	SU8	SU8
Nbr of arms	3	3	4	4	4
Sheet thickness	30 μm	30 μm	30 μm	30 μm	30 μm
b_{width}	50 μm	60 μm	40 μm	50 μm	80 μm
$Angle_1$	65°	65°	35°	35°	25°
$Angle_2$	46°	46°	16°	16°	6°
Stiffness	9 N/m	12 N/m	19 N/m	24 N/m	44 N/m

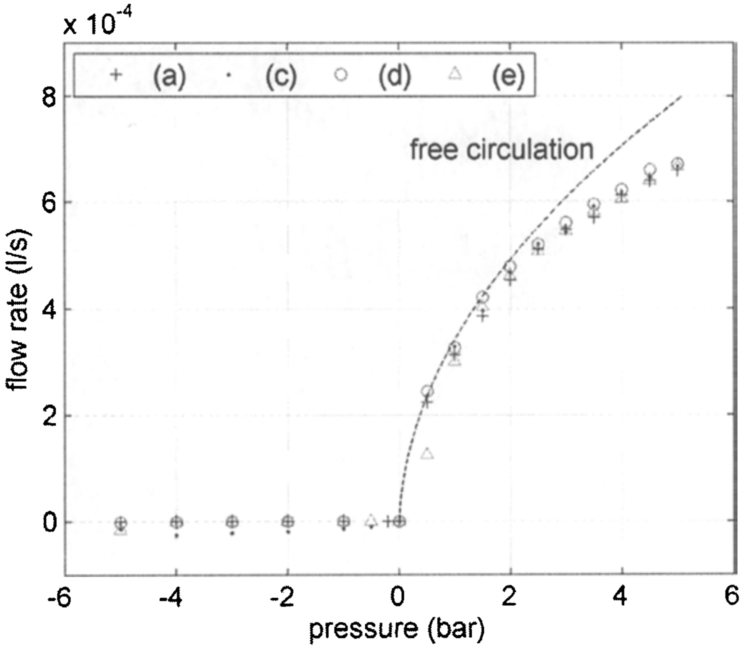


Fig. 4.3. High pressure tests for the parameters presented in table 4.1

5 Conclusion

This paper presents two manufacturing techniques for ortho-planar springs. It emphasises the importance of a pre-stress on the valve in order to improve sealing and prevent backflow. It discusses the micro-valve assembly regarding classic DFA rules. The chosen solution to align and correctly locate the spider spring is an extra part made of PDMS. Finally it gives a full characterization of ortho-planar valves for low and high pressure tests.

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