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Inkjet 3D printing – towards new micromachining tool for MEMS fabrication

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Abstract. Three-dimensional (3D) printing has the potential to transform science and technology by creating bespoke, low-cost appliances that previously required dedicated facilities in order to be made. An attractive and promising research field comes in the form of using 3D printing to create MEMS, including microfluidic structures. In this paper, a discussion on applicability of inkjet 3D printing (i3Dp) for MEMS fabrication is presented on the base of works carried out by a team led by the author.

Key words: inkjet 3D printing, MEMS, micromachining, lab-on-a-chip.

1. Introduction

A Micro-Electro-Mechanical System (MEMS) combines mechanical microstructures with microelectronic circuits to create very small functional systems for sensing or actuating. The MEMS micromechanical structures technology involves many well-known techniques applied to specific materials. Silicon and glass are micromachined mainly by means of wet or dry etching [1–4] while polymer microstructures are formed by means of injection moulding, hot embossing or soft lithography [5–8], and low-temperature co-fired ceramic substrates are cut and co-fired [9]. Regardless of the material and technology applied, fabrication of MEMS is a multistep process involving many technological levels (photolithography, etching, deposition, bonding, assembling etc.) that requires specialised facilities (i.e. devices and clean-rooms), trained staff and often knowledge on the applied material's properties and limits of the techniques used. Those are collected during years of experience. All these issues mean that although a single MEMS is usually a low-cost device, further decrease of cost-per-chip is difficult to achieve. This is important because some of the forecasts of established companies and institutions (including Bosch, HP, Cisco and Intel) clearly indicate that in the next decade the number of MEMS-based devices connected to the internet (Internet of Things and Internet of Everything) is going to reach the level of trillions [10]. From economical point of view, this requires a decrease of costs of the networked MEMS at least by one or two orders of magnitude. According to this concept, low prices will result in higher numbers of MEMS networked. None of the traditional technologies mentioned above is able to fulfil this requirement at this moment.

Meanwhile, 3D printing is reported to be a technique that revolutionizes today's industry and R&D works [11, 12]. Its overall concept – to create a digital virtual model of an object and then print it as a fully functional real object – caused 3D printing to not only become a tool for rapid prototyping but also an interesting tool for low-series customized products made of plastic, glass, metal or ceramics. It also opens new possibilities in R&D works because there is almost no limit to the geometry of the element developed. Additionally, it is possible to print objects from several metres in dimension down to micro- and nanoscale, depending on the material and printing technique applied. A review of the current fields of 3D printing applicability on the base of hype cycle (Fig. 1) shows that this technology is present in many fields of everyday life, research and industry.

Thus a natural tendency is to combine MEMS and 3D printing technologies to create new technology that enables low-cost, rapid and high throughput fabrication of fully functional MEMS devices solely on the basis of a computer design and by using a printer. That is the ultimate goal and that is also

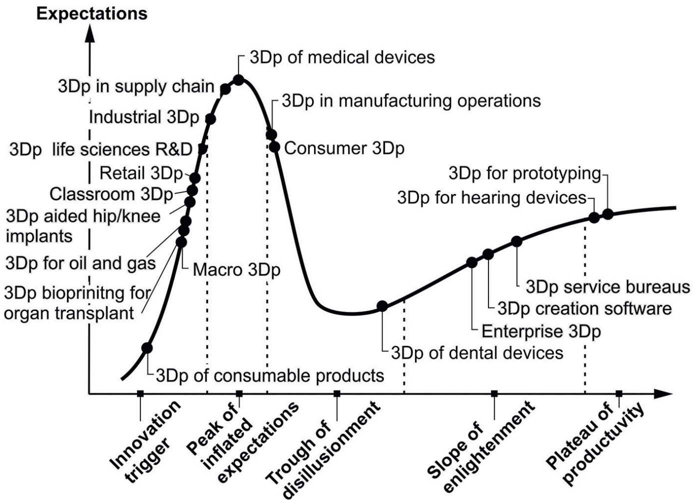

Fig. 1. Hype cycle of 3D printing (on the basis of [13])

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the challenge. The question remains of how far the 3D printing technology is from reaching its goal. Printing of MEMS requires printing of some electronic and mechanical components. One promising method that is used to print electronics circuits and sensors is inkjet printing. Many reviews on the applicability and technology of printed electronics are available and they discuss the state of the art deeply. Examples include [14–17], and they do not need to be analysed here. Less attention is paid to investigations of inkjet 3D printing as a tool for fabrication of micromechanical structures that are important parts of many MEMS.

In this paper a discussion on applicability of inkjet 3D printing (i3Dp) to MEMS technology is presented. Special attention is paid to fabrication of mechanical microstructures, based on the author's experience in the field. A brief review of the author's comprehensive works on main features of inkjet 3D printing (geometrical and mechanical optical ones as well as biocompatibility) is presented. Examples of various 3D printed microstructures are shown. First simple structures such as microfluidic channels used in lab-on-chip technique are described and utilized in a disposable chip for genetic material analysis of on-chip gel electrophoresis. Next, a check microvalve is described as a microfluidic component with a micromechanical element. Some simple mechanic micro- and sub-millimetre components are presented, e.g. beams and gears. The beams can be actuated by using an integrated magnetic-polymer composite. Finally SWOT analysis of i3Dp technique from the point of view of micromachining for MEMS technology is presented and discussed. In conclusion some main remarks on i3Dp properties as well as limits and potential directions of 3Dp development for MEMS are presented.

2. Inkjet 3D printing as micromachining tool

Inkjet 3D printing refers to the layer-by-layer technique of creating structures by selective applying droplets of light curable resin (building material, e.g. VisiJet M3 Crystal by 3D Systems Inc., USA) [18]. The empty spaces in the virtual structure geometry are filled with a support material in the real printings process (e.g. VisiJet 300 by 3D Systems Inc., USA). The support material is then removed in the post-printing process. Due to the micrometre size (e.g. 70 μm) of the deposited droplets determined by the diameter of the outlet hole in the printings nozzle (e.g. 50 μm), it is possible to build several-micrometre-thick layers (16–32 μm) with hundreds of dots per inch resolution and 25–50 μm accuracy [19]. Thus i3Dp seems to be a very attractive choice when tenths of micrometre and sub-millimetre structures are required as mechanical parts of MEMS. Detailed studies of Walczak et al. on the selection of the inkjet printer fulfilling the requirements of microfluidic structure fabrication led to a number of conclusions [20]. It has been found that the minimum dimension (width or depth) for a properly printed microfluidic structure was 200 μm for ProJet3510SD by 3D Systems Inc. (USA). Although nominal resolution of the printers was one order of magnitude better, smaller microchannels were not printed at all (Fig. 2).

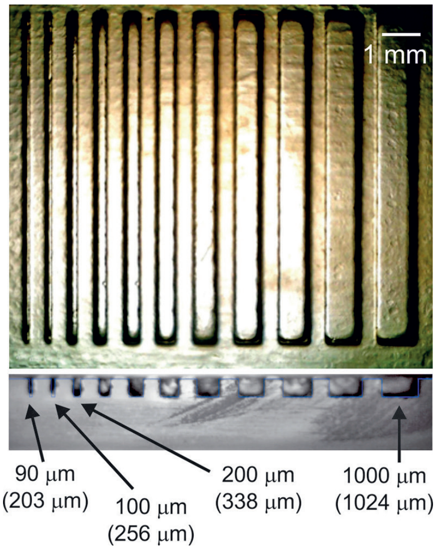

Fig. 2. Test board (top and cross-section views) for inkjet 3D printing microchannels accuracy of mapping. Measured and designed (in brackets) widths are shown

The surface roughness of the best printouts was comparable to precise micromilling and better than the roughness obtained by the use of stereolitography or fused deposition modelling as reported in the literature [21–23]. A simple method for correction of the mapping error was also proposed. It allowed for significant decrease of the difference between the designed and real dimension to drop below 5%. It was concluded that real planar resolution of the printer was worse than the nominal one due to the spread of the deposited droplets and reflow of the pattern during final planarization of the printed layers. Last but not least, a critical step of post-printing processing is the support material removal (e.g. melting away at 60°C, followed by warm oil bath with ultrasonic agitation). An example of the microfluidic channel (500 μm in diameter and 30 mm length) with properly removed support material is presented in Fig. 3. Although decrease of the microchannel diameter is possible down to around 200 μm, efficient removal of the support material is very difficult. It is also the reason for limited length of the microchannels.

Aside from the geometrical properties of inkjet 3D printing, mechanical properties of the building material applied also constitute an important issue in designing and operation of mechanical structures. In a series of independent experiments, tensile test specimens were tested according to ISO standards (ISO 527–1, 527–2). Tests were carried out to determine tensile strength, elongation at break and Young's modulus, and to observe the influence of the test structure printing orientation (parallel PR and perpendicular PP to the force applied later) on these parameters (Fig. 4). Significant differences were found between the values measured and the values declared by the manufacturer [24]. The tensile strength determined was almost two times lower in comparison to the data sheet (23–26.1 MPa vs 42.4 MPa), elongation at break was more than two times higher (11.2–19.2% vs 6.93) and Young's modulus was almost

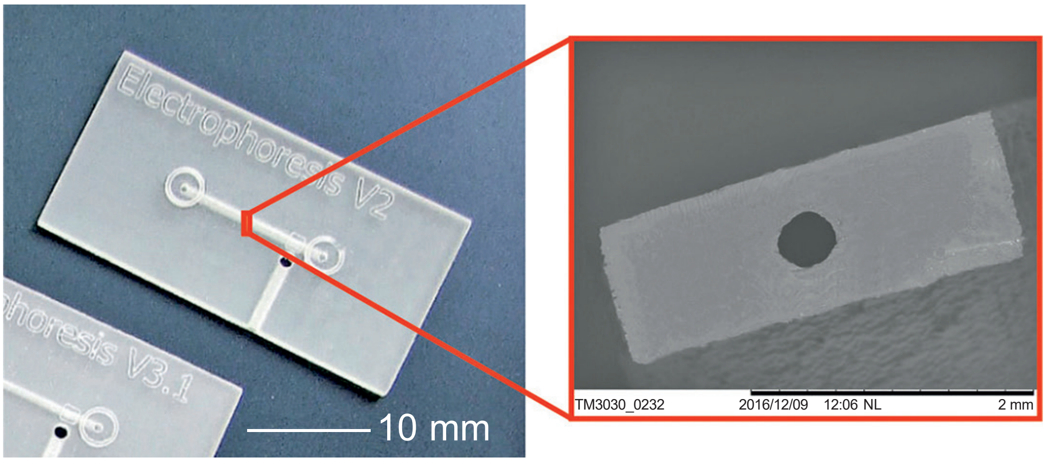

Fig. 3. Inkjet 3D printed microfluidic channel – view and cross-section (SEM image×50) after support material removal.

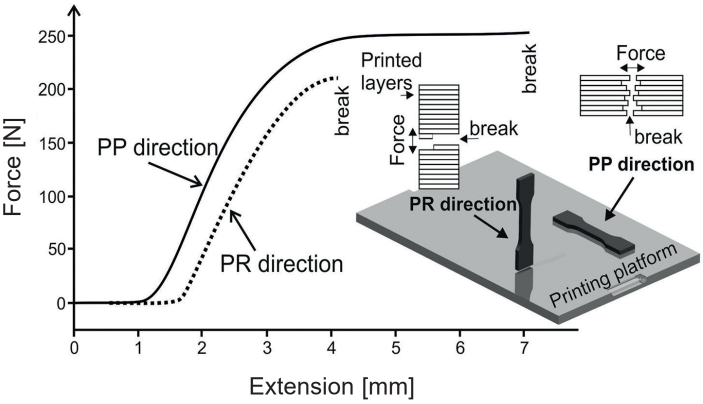

Fig. 4. Extension-force curve of the inkjet 3D printed test samples printed in PP and PR directions

three times lower (478–508 GPa vs 1463 GPa). The differences noted indicated that the real structures were more flexible that it had been assumed based on the manufacturer's data. Similar differences in mechanical properties depending on printing orientation and the different values of real parameters in relation to the declared ones have also been observed for other printed materials [25–27].

Optical properties of the printed microstructures were also studied because visual inspection or detection is often applied in the MEMS technique. Thus optical transparency and autofluorescence were examined [28]. It was found that the printed microstructures were semi-transparent. The highest transmittance (61%) was noted for λ = 650 nm and a 64 μm thick layer printed with layer orientation parallel to light propagation direction (Fig. 5). The transmittance decreased almost linearly down to 20–30% for the 320 μm thick layers. Although theoretical minimum thickness of a single printed layer could be 32 μm, the many defects and perforations observed resulted in the minimum thickness of properly printed layers being two times higher. The autofluorescence of the polymer was investigated for three most commonly

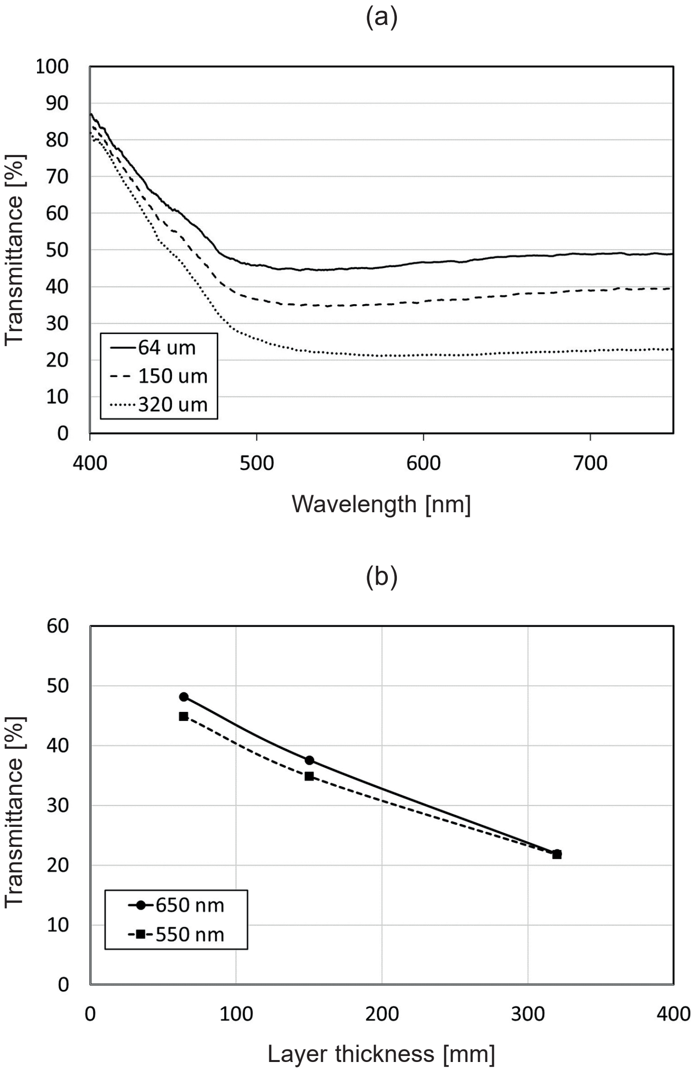

Fig. 5. Optical transmittance of the inkjet 3D printed test samples: a) spectral characteristic for various printed layer thickness, b) transmittance as function of the layer thickness for 650 nm and 550 nm

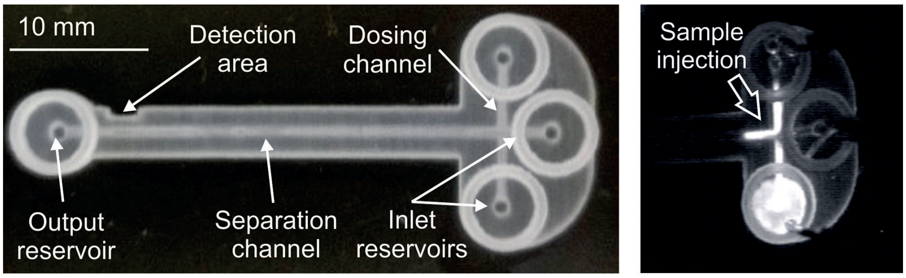

Fig. 6. Inkjet 3D printed chip for genetic material analysis by means of on-chip gel electrophoresis – view of the chip after post-printing processing (left) and during injection of the fluorescence sample into separation microchannels (right)

used fluorescence-inducing wavelengths (488 nm, 532 nm and 635 nm, light power 5–25 mW). Autofluorescence was not observed. Thus thin layers of the printed structures may be used as parts of optical detection systems in labs-on-a-chip or other MEMS where optical detection (including fluorescence) is involved.

Due to operation of some MEMS (e.g. labs-on-a-chip) with organic materials, biocompatibility of the building material was also examined, both in the author's works and by other groups [28, 29]. Zhu et al. investigated long-term 72 h influence of various materials on viability of living zebrafish embryos [29]. The main conclusion in the case of VisiJet M3 Crystal was that the embryos were dead after 72 hours of growth in the presence of the investigated material.

Described by Walczak et al., cytotoxity tests were performed according to ISO 10993–5:2009 with Jurkat cells [28]. Long (72 h) growth in the presence of the polymer samples examined (discs with $\phi = 6$ mm and 1 mm thickness) was fostered and followed by cells counting (Bürker's method) in each growth reservoir. Initial concentration of cells was 10^5. The experiment was repeated five times to obtain statistically valuable data. After the growth period, the cell number in the control group (no building material) was $3.1 * 10^6 \pm 0.13$ whereas in the sample group it was from $1.1 * 10^6 \pm 0.11$ to $2.1 * 10^6 \pm 0.14$. A difference was observed between reference and test growths but it was not as huge as it was expected on the base of Zhu's work [29]. Results of both groups show that short-term interactions are negligible and more specific longer-term studies need to be performed for ascertaining their biocompatibility. It seems that in spite of the polymer composition also post-printing procedures (support material removal, cleaning, sterilization) must be taken into account as parameters influencing cytotoxity of the printed microstructures.

3. Examples of i3Dp MEMS structures

Collected knowledge on geometrical, optical, mechanical and biocompatibility properties of the i3Dp enabled development of various microstructures that are fully functional MEMS or parts of MEMS. A brief review of selected examples is presented below.

A novel application of i3Dp consists in fabricating a disposable chip for on-chip gel electrophoresis of DNA [30]. The lab-on-a-chip is printed in a single process and cleaned according to the optimum procedure developed (Fig. 6a). The chip contains dosing and separation microchannels 500 μm in diameter and 10/23 mm in length, respectively, four microreservoirs for buffer and sample introduction (10 μL volume each) and a fluorescence detection area with thinned walls at the end of the separation microchannel (Fig. 6). Successful separation of the DNA 50–800 bp ladder in POP-4 gel (A&A Biotechnology, Poland) with the fluorescence readout method developed earlier [31, 32] was achieved in less than 10 minutes. The theoretical number of separation plates achieved for the developed chip was in the order of 10 000. It was significantly lower than the result obtained in an all-glass chip (up to 600 000 of plates for the 30 μm deep, 500 μm wide and 25 mm long separation channel) but printed microchannels were one order of channel magnitude larger in diameter [31].

Mechanical properties as well as the designing rules developed were used to create the check microvalves [24], a set of gears and microbeams. Two types of the check microvalves were fabricated (Fig. 7a). They were printed in a single process

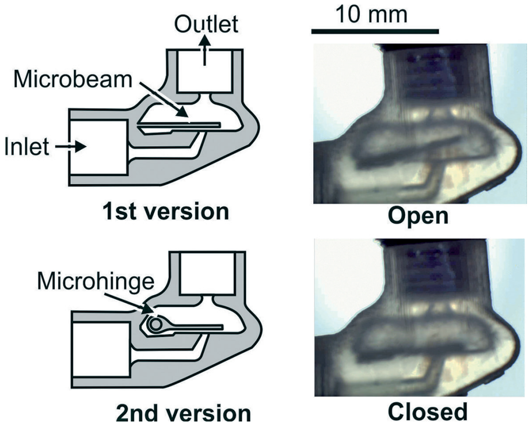

Fig. 7. Inkjet 3D printed check microvalves – schematic cross-sections of two versions (left) and internal view of the microvalve while open and closed (right)

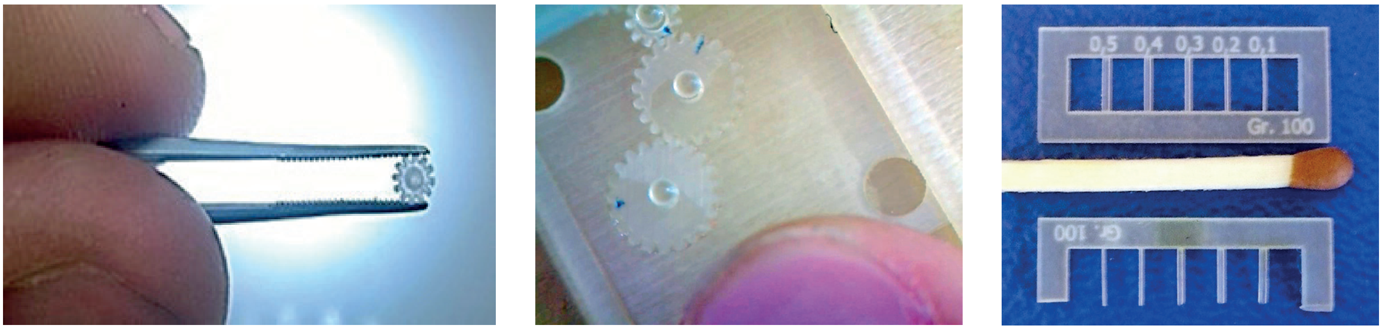

Fig. 8. Inkjet 3D printed micromechanical elements: a) single microgear with 3 mm diameter, b) set of gears with diameter from 2.5 to 6 mm on the substrate, c) microbeams and microbridges

without post-printing assembling. The first version contains a flexible microbeam (203 μm or 305 μm thick) fixed to the valve body that tights the microvalve yoke, while the second version has an integrated 305 μm thick microbeam with a microhinge. Proper operation of the microvalves for forward and backward flows (for pressure of up to 500 kPa) was observed. The backward to forward flow ratio was in the 0.005 to 0.015 range, depending on microbeam thickness and microvalve version. Similar values were reported for other micromachined check valves made from different materials [33].

The miniature gear ($\phi = 3$ mm, 500 μm thick) and a set of gears were printed as discrete elements (Fig. 8a) or located on the carrier platform (Fig. 8b). The net of gears was driven by an external electric engine. Thus it was shown that a fully functional micromachine can be inkjet 3D printed. In further works also microbeams and microbridges were printed. Dimensions of the microstructures presented in Fig. 9 are 100 μm in thickness, 5 mm in length and 100 μm to 500 μm in width (Fig. 8c).

The beams can be magnetically actuated. The pure VisiJet M3 Crystal material is dielectric and non-magnetic yet addition of Fe powder (diameter of the grains below 1 μm) to the non-cured polymer causes the UV-cured composite to acquire magnetic properties. Deposition of a small portion of the composite at the end of the beam (10 mm long, 3 mm wide and 100–500 μm thick) enables controlled deflection of the beam in the presence of a magnetic field (Fig. 9). The magnetic field generated by neodymium magnets was measured with a magnetic field meter (Extech MF100, USA).

The above examples confirm that i3Dp can be used to develop various microstructures with dimensions well below 1 mm. It was also concluded that the minimum dimension of the printed microstructures was around 200 μm in the case of microchannels and 100 μm for standalone microstructures with thickness controlled even down to tenths of micrometres.

4. Discussion and conclusions

Results of carried out works form a box of parameters (geometrical, mechanical and optical ones) that can be used to design and print micromechanical structures for MEMS. Without doubt, the strongest feature of i3D printing is its 3D capability, turn-around time and integration of moving elements without post-printing assembling. Main disadvantages include the res-

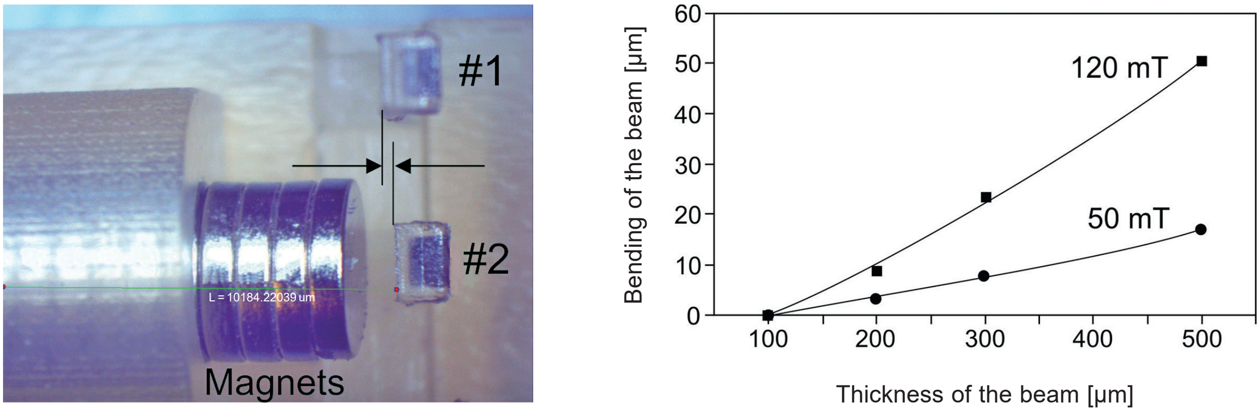

Fig. 9. Inkjet 3D printed microbeams with magnetic composite actuation – view of two beams with magnetic composite container. Beam No, 2 is magnetically actuated (left). Bending of the beam as function of beam thickness for 50 mT and 120 mT magnetic field intensities and 200 μm thick microbeam (right) is presented

olution, post-printing processing and lack of multimaterial (functional) printing. SWOT analysis of the i3Dp technique from the point of view of micromechanical structures fabrication for MEMS (Table 1) summarizes the current stage of i3Dp development.

Table 1
SWOT analysis of inkjet 3D printing for MEMS micromachining

Strengths:	– on-demand digital manufacturing from computer design to real structure – truly 3D capability – high microstructure complexity – reduction or lack of assembly work – fabrication in standard laboratory (no clean-room required) – relatively low cost for low-series chips – acceptable optical transparency and lack of autofluorescence (optical detection/observation possible) – acceptable mechanical properties (mechanical elements integration possible)
Weakness:	– limited resolution/accuracy in comparison to other microengineering techniques – time consuming and non-automated post-printing procedures (support material removal, cleaning, surface finishing) – support material removal limits geometry of the embedded microstructures – biocompatibility issues – lack of multimaterial (multifunctional) printing – training required especially in post-processing procedures – setup and material costs too high for home applicability
Opportunities:	– development of functionally integrated designs in one step – high manufacturing flexibility – local customer-oriented production enabled
Threats:	– intellectual property rights limitation, – relatively easy copying of the designs – missing quality standards

Inkjet 3D printing is a promising alternative to other microengineering techniques and it breaks the limits of other techniques in the fields of 3D capability and designing flexibility. It is very useful when monolithic, submillimetre micromechanical structures must be developed in a low to average number of copies with hours-counted time from computer design to real structure. These features are strongly applied in the development of lab-on-a-chip devices.

Improvement of printing resolution towards fabrication of real micrometre range structures is a technical problem (new printing heads, modified/new building/support materials etc.) [34]. A comparison of two main parameters (resolution and automation) of various 3D printings techniques in relation to well-established photolithography-based or direct laser writing techniques, that define shapes/dimensions of the microstructures and are applied in fabrication of today's MEMS, is shown in Fig. 10. Inkjet 3D printing ensures high automation with reasonable resolution.

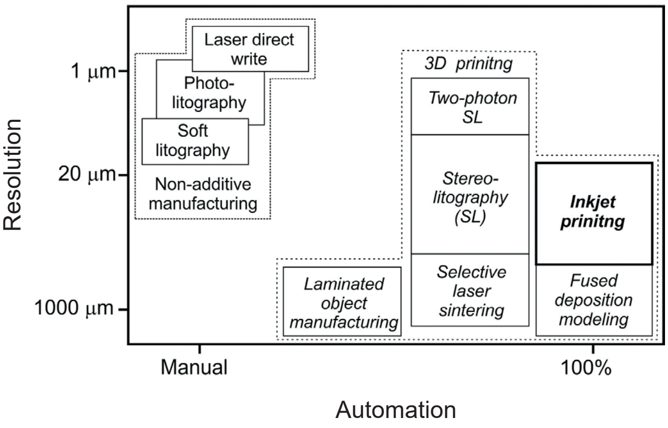

Fig. 10. Resolution vs automation for non-additive manufacturing techniques applied in MEMS technology and 3D printing techniques, on the basis of [34]

It is predicted that that new technical solutions (microfluidics-oriented printers) could be developed if fabrication of i3Dp MEMS structures will be truly economically justified. For example, the first microfluidic-oriented 3D printer utilizing fused deposition modelling is already available [36]. Yet there are other two important challenges that require deeper insight if i3Dp is going to be useful for MEMS – throughput of i3Dp and multimaterial printing.

From tenths to hundreds structures can be printed in a single printing batch but all of them require post-processing: support material removal and cleaning. At this moment, these procedures are done manually. This takes minutes at least for a single element. Post-processing without automatization is a bottle neck that limits throughout of the i3Dp process if large scale fabrication and, consequently, low cost per item are considered. Thus simultaneously to the development of 3D printers dedicated to MEMS fabrication, automatized systems for post-processing should also be considered.

Aside from fabrication of the structures directly from computer design that is without doubt the added value of 3D printing, the next breakthrough step in i3Dp proliferation (and that of other 3D printing techniques, too) can be printing at the same time with materials with different properties and functions (multimaterial printing). As it was mentioned earlier, inkjet printing is widely used to print conductive, resistive and sensing (e.g. strain or pH) layers but on planar surfaces (glass, foil, metal, paper etc.) [37, 38]. Deposition of layers on non-planar surfaces requires special techniques (e.g. aerosol jet printing or piezo-actuated printing). With these techniques, conductive nano-particle inks, micron scale inks, adhesive/dielectrics and biological reagents can be accurately deposited

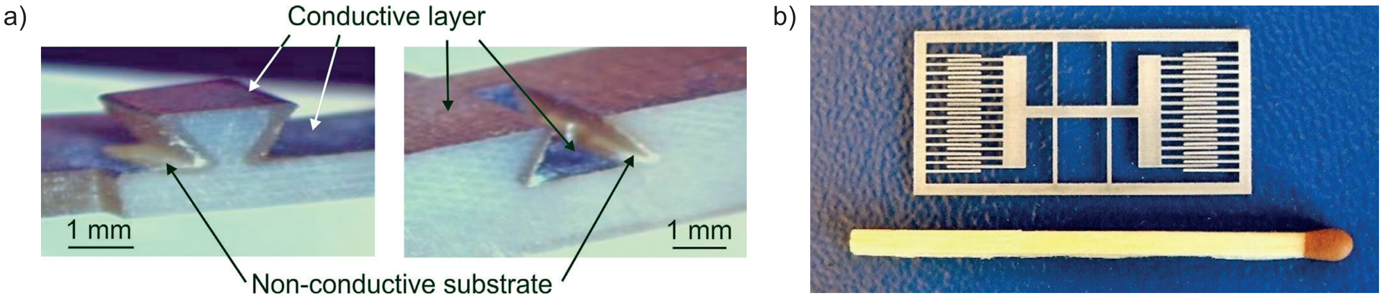

Fig. 11. Metallisation of inkjet 3D printed elements: a) geometrically separated conductive paths (cooper layer, 1.2 μm thick), b) comb-drive actuator

onto complex-shaped non-planar substrates [39, 40]. However, this is still an emerging technique without finally confirmed usefulness in the case of MEMS.

Some preliminary works carried out by the author showed also that it is possible to optimize parameters of the magnetron sputtering process to deposit conductive layers of 3D sub-millimetre structures to form geometrically and electrically separated conductive paths or a comb-drive actuator (Fig. 11).

In conclusion it can be pointed out that ten years ago inkjet 3D printing was a very expensive technique with properties far away from MEMS requirements. Today 3D printers are present in many laboratories involved in development of one of MEMS types, i.e. microfluidic structures [39–46]. This is because these microstructures have relatively simple geometry and do not require multimaterial printing. Works of the author confirmed also that it is possible to print micromechanical structures. The next milestone is 3D printing of functional materials. Thus 3D printing of polymers in combination with 3D printed electronics and functional materials seems to be nearest future core production technology for the next generation of MEMS.

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