Method of mould alignment for double-sided hot embossing of microfluidic devices using kinematic constraints

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Published in Micro & Nano Letters; Received on 22nd March 2014; Revised on 26th August 2014; Accepted on 9th September 2014

Demand has increased for the double-sided moulding of microfluidic devices for a series of biochemical analyses. Accurate alignment of mould inserts is a critical aspect to transfer doubled-sided patterns on the top and bottom surfaces of a moulded part. A method of mould alignment was studied for double-sided hot embossing of polymer microfluidic devices. An alignment method was designed using kinematic constraints, and a set of three locating pins. To validate the alignment method, two brass mould inserts with fluidic reservoirs were used for the double-sided moulding of prototype microfluidic devices. The kinematic constraints were used to align the mould inserts with each other on the hot embossing machine. The misalignment of double-sided features on the moulded parts was measured using a measuring microscope. The *X*- and *Y*-magnitudes of the mismatches ranged from −28 to 118 μm along the *X*-axis of the moulded parts. The *X*- and *Y*-magnitudes of the mismatches along the *Y*-axis of the moulded parts varied from −38 to 141 μm. The results of the experiments showed that the mould alignment using kinematic constraints is applicable to the fabrication of double-sided patterns for microfluidic devices.

1. Introduction: Double-sided moulding [1–3] has significant potential for the fabrication of multilayer microfluidic systems enabling a series of biochemical analyses [4, 5]. This moulding process allows for simultaneous transfer of the functional units from two mould inserts onto both the top and bottom surfaces of a layer during a single moulding step. These functional units can be interconnected by aligning the reservoirs or channels to transport biochemical samples and reagents. The number of moulded parts of the system can be reduced by utilising both the top and bottom surfaces of the layer. This can also decrease the complexity of the alignment and assembly of multilayer microfluidic systems.

One of the most critical aspects in double-sided moulding is to have an accurate mould alignment between the top and bottom mould inserts [6]. The bottom mould insert should be aligned with respect to the top mould insert to transfer the double-sided patterns in the desired location on the surfaces of a moulded part. To meet the required performance for the biochemical analysis, minimisation of misalignment between the double-sided patterns is necessary. Reliable mould alignment is essential to achieve successful double-sided moulding.

Two prevailing alignment techniques, active and passive alignments, have been used to set components or devices in a desired relative location for the assembly or stacking of microsystems [7]. Active alignment continuously monitors the mismatch of parts during the assembly process so that the location of parts is fixed as the mismatch is minimised [8]. Mask alignment using machine vision systems for multilayer processing and silicon micromachining in UV-lithography are typical examples of active alignment [9]. The precision of the active alignment typically ranges from several micrometres to a few tens of micrometres. It provides high alignment accuracy but it requires expensive and complex feedback systems to monitor and minimise the mismatch.

In passive alignment, two or more components are located relative to each other by using mechanical structures without monitoring and feedback of the mismatch [8, 9]. Alignment accuracy depends primarily on the geometric accuracy of the structures. Passive alignment uses mechanical structures such as v-grooves and rectangular pits to constrain the location of the aligned components [7, 8]. Passive alignment can simplify alignment processes by avoiding the need for complex monitoring and feedback systems.

The development of a mould alignment method, incorporating the advantages of active and passive alignments, would be beneficial to double-sided moulding. The simplicity of passive alignment would offset the complexity associated with active alignment. The adjustability of active alignment reduces the effect of the inherent geometric variation of the mechanical structures of passive alignment on the accuracy of passive alignment. An approach is needed to take advantage of the simplicity of passive alignment and the adjustability of active alignment for double-sided moulding.

A method of mould alignment was studied for double-sided hot embossing of polymer microfluidic devices. Alignment tools were designed using kinematic constraints to constrain the relative motion between the mould inserts. Two brass mould inserts with fluidic reservoirs were used in the moulding process. The alignment tools were used to properly locate the mould inserts at the desired locations on the hot embossing machine. Prototype microfluidic devices were moulded using the mould inserts for experimental demonstration of the mould alignment.

2. Kinematic constraint for mould alignment: Kinematic constraints have been used to control the relative motions between the parts in assemblies [10]. They allow a part to be located at a desired location with respect to the mating parts by constraining its degrees of freedom. All parts in the assembly can be integrated as a complete system using the kinematic constraints. A pin, hole, v-groove and rectangular pit are typical mechanical structures used as kinematic constraints [7–8, 11–13].

Fig. 1*a* shows a schematic representation of the tool setup for double-sided hot embossing. One mould insert is mounted on the upper platen and the complementary mould insert is placed on the lower platen of the hot embossing machine. Both mould inserts have planar contacts with their mating platens, respectively. If the mould insert is fixed on the upper platen, only three degrees of freedom are needed for the complementary mould insert. Two

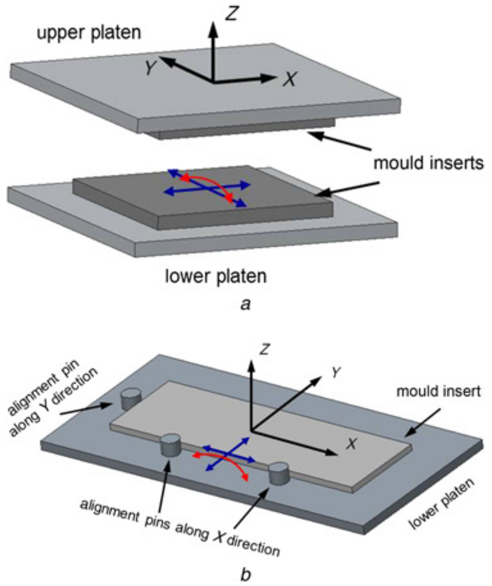

Figure 1 *Schematic representation of tool setup for double-sided hot embossing (Fig. 1a), and alignment of complementary mould insert with respect to top mould insert on upper platen (Fig. 1b)*

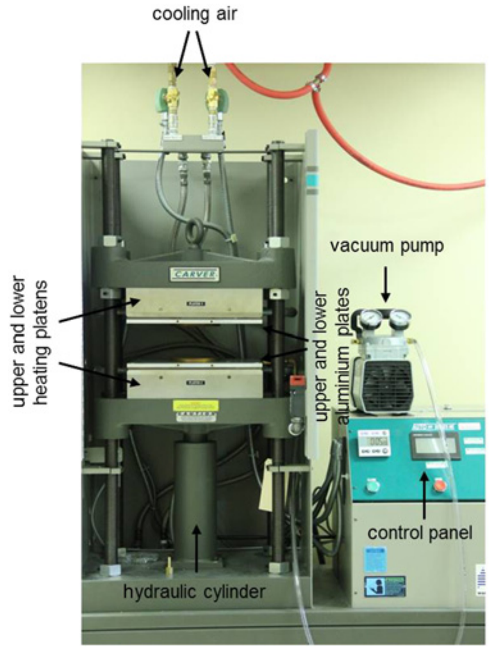

Figure 2 *Thermal hot press used for double-sided hot embossing*

translations along the *X*- and *Y*-axis and one rotation about the *Z*-axis can be considered to align both the mould inserts.

A set of three locating pins can be used as the kinematic constraints to align the complementary mould insert with respect to the top mould insert as shown in Fig. 1*b*. The top mould insert is not pictured to enable visualisation of the alignment in the Figure. Two pins in front of the platen constrain the translation along the *Y*-direction and rotation about the *Z*-direction of the complementary mould insert. The third pin constrains the motion of the mould insert along the *X*-direction. The complementary mould insert can be aligned with the top mould insert while the pins constrain the location of the mould insert.

3. Experiments

3.1. Design and fabrication: A thermal hot press (3893 4NE18, Carver Inc., Wabash, IN, USA) was used to replicate the prototype of double-sided microfluidic devices. It had heating platens, a hydraulic cylinder and a control unit as shown in Fig. 2. Two customised aluminium plates were mounted on the platens of the press. They accommodated the mould inserts and alignment tools. Vacuum was applied to hold the complementary mould insert on the lower aluminium plate.

Two alignment tools, providing kinematic constraints, were used to locate the complementary mould insert with respect to the top mould insert on the upper platen. The alignment tools consisted of a mounting plate and one or two 5–40 lead screws. The 40 threads per inch allows for 635 µm of travel for each revolution of the screw. A knob with scales was attached to the end of each lead screw. The knob had 25 equidistant marks on the face to allow for adjustments of 25.4 µm per mark. One alignment tool had a lead screw, and the other had two lead screws.

Two brass mould inserts were machined using a CNC milling machine (Minimill, Haas Automation Inc., Oxnard, CA, USA) for double-sided hot embossing. The tool paths were generated by CNC software, Mastercam (CNC Software Inc., Tolland, CT, USA). Fig. 3 shows the layout of the mould inserts. The mould inserts were 120 mm in diameter with a long flat edge on the front and two short flat edges at 90° to either side of the front. There were six bolting holes along the outer diameter of the mould inserts. They can be used to mount the mould inserts on the aluminium plates.

One mould insert contained cylindrical posts to replicate the fluidic reservoirs and double rectangular steps were added to provide a means of rapid visible detection of misalignment as shown in Fig. 3*a*. The posts were 1.5 mm in diameter with a height of 100 µm. The double rectangular steps had two rectangles, 2.5 mm long, 0.5 mm wide, 0.1 mm in height and 0.770 mm apart. The posts were located at 0, 25 and 50 mm and the double rectangular step was located 75 mm from the centre of the mould insert. The complementary mould insert with cylindrical posts and rectangular

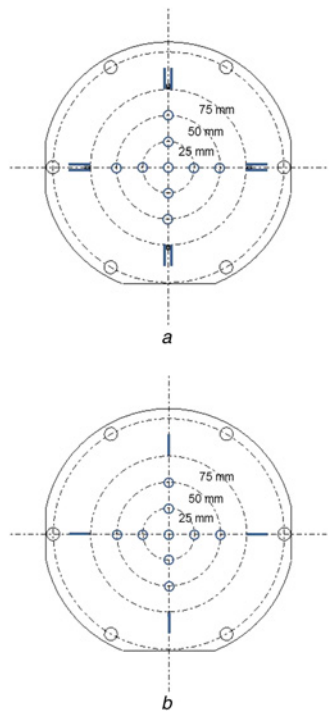

Figure 3 *Layout of top mould insert having cylindrical posts and double rectangular steps (Fig. 3a), and of complementary mould insert containing cylindrical posts and rectangular steps (Fig. 3b)*

Micro & Nano Letters, 2014, Vol. 9, Iss. 10, pp. 741–745
doi: 10.1049/mnl.2014.0134

steps had the same layout as shown in Fig. 3*b*. The posts had a diameter of 500 µm and a height of 100 µm.

Polycarbonate (PC) sheets (Lexan®, Sabic Plastics, Shanghai, China) were selected as the stock material. The thickness of the PC was 4.5 ± 0.5 mm. The PC sheets were dried in a convection oven (31-350ER-1, Quincy Lab, Chicago, IL, USA) at 121°C for 3 h prior to moulding.

3.2. Alignment and hot embossing: Two mould inserts were aligned for double-sided hot embossing to fabricate a moulded device containing fluidic reservoirs on both the top and bottom surfaces. The procedure for aligning the mould inserts is shown in Fig. 4. For the safe operation of the hot press, the alignment tools were mounted and demounted on aluminium plates while the heating platens of the hot press were in stationary positions without pressurising the liquid for a hydraulic cylinder.

The mould insert was mounted on the upper aluminium plate as shown in Fig. 4*a*. The alignment tools, having one or two lead screws, were attached to the aluminium plate to define the location of the mould insert. The lead screws of the alignment tools were moved linearly until each made contact with the flat edges of the mould insert as shown in Fig. 4*b*.

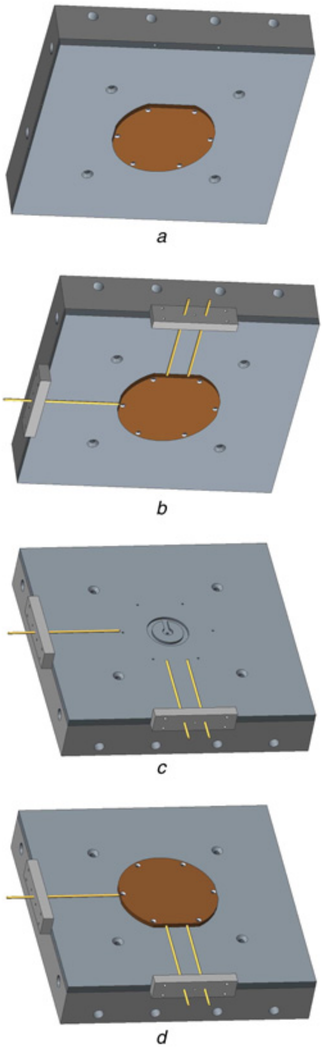

Figure 4 *Mounting of top mould insert on upper aluminium plate (Fig. 4a); three contacts of lead screws with flat edges of top mould insert to define its location (Fig. 4b); mounting of alignment tools on lower aluminium plate to constrain location of complementary mould insert with respect to top mould insert (Fig. 4c); alignment of complementary mould insert with respect to top mould insert based on position of three lead screws (Fig. 4d)*

Table 1 Moulding and demoulding parameters for double-sided hot embossing

Moulding temperature, °C	170 ± 5
Embossing force, N	300 ± 15
Holding time, s	600 ± 15
Demoulding temperature, °C	120 ± 5

By creating contact between the top mould insert and lead screws the location of the mould insert was defined by the contact with respect to the platen edges. To transfer the location of the top mould insert to the complementary mould insert, the alignment tools were demounted from the upper aluminium plate. They were remounted on the lower aluminium plate without adjusting the lead screws to align the complementary mould insert with respect to the top mould insert as shown in Fig. 4*c*. The complementary mould insert was brought into contact with the three lead screws of the alignment tools as shown in Fig. 4*d*. Vacuum was applied to provide the nesting force for the mould insert on the plate when the mould insert was located. Prior to double-sided hot embossing, the alignment tools were removed from the plate.

Nitrogen was applied on the PC sheets to remove dust and particulate matter. A mould release agent (Mold Wiz, F-57NC, Axel Plastics Research Laboratory Inc., Woodside, NY, USA) was applied to both of the brass mould inserts to assist demoulding. Hot embossing parameters, including the moulding and demoulding temperatures, holding force and hold time are shown in Table 1.

3.3. Characterisation: The locations of the fluidic reservoirs on the mould inserts and moulded parts were characterised using a measuring microscope (MM-800, Nikon, Japan) and a focus/defocus method. Based on a consistent datum point on the parts, the coordinates of three distinct points on the boundary of the features were measured. The coordinates of the centre points of the features were estimated by constructing a circle using the three points [14]. The misalignment of the double-sided features on the moulded parts was estimated, measuring the relative distances between the centre points along the *X*- and *Y*-axis on the parts.

4. Results and discussion: The locations of the reservoirs on the moulded parts were used to assess the accuracy of the alignment between the top and bottom surfaces of the moulded parts. The *X*- and *Y*-magnitudes of the misalignment were represented by the mean with error bars indicating a 95% confidence interval [7].

The locations of the reservoirs were transferred from the mould inserts into a moulded part during double-sided hot embossing, so that the location variation of the circular posts of the mould inserts is the innate variation source of moulded parts. The measured locations of the reservoirs from the centre of the mould inserts were 24.992 ± 0.007, 49.995 ± 0.003 and 74.969 ± 0.023 mm while the designed locations were 25, 50 and 75 mm.

Fig. 5 shows an optical micrograph for a typical pair of double-sided fluidic reservoirs. It was obtained by overlapping both images of the reservoirs on the top and bottom surfaces of the moulded part. The mismatch was estimated as the *X*- and *Y*-magnitude of the misalignment, ΔX_i and ΔY_i, along the *X*- and *Y*-axis on the parts. ΔX_i and ΔY_i, are evident in Fig. 5.

The mean mismatches along the *X*- and *Y*-axis in the moulded parts are shown in Fig. 6. The mismatches were measured for the reservoirs at radial locations from −50 to 50 mm at intervals of 25 mm. The *X*- and *Y*-magnitude of the mean mismatch along the *X*-axis of the parts are as shown in Fig. 6*a*. The *X*-magnitude of the mismatches ranged from 584 to 592 µm, and the *Y*-magnitude of the mismatches varied from 574 to 627 µm at the first trial for

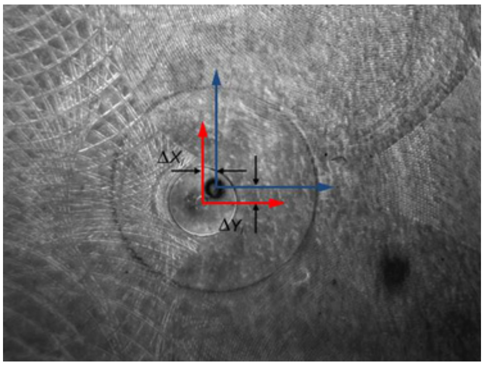

Figure 5 *Optical micrograph for typical pair of double-sided fluidic reservoirs on top and bottom surfaces of moulded part*

alignment. The *X*- and *Y*-magnitude of the mismatches along the *Y*-axis were from 553 to 627 μm as shown in Fig. 6*b*.

The physical consequences of the alignment processes, including the mounting and demounting of the alignment tools on the top and bottom aluminium plates, induced the mismatches of the first trial for the alignment. This is inevitable since the locational variation between the top and bottom aluminium plate is inherent in the configuration of the hot press. In addition, the locational variation of the reservoirs on the mould inserts also contributed to the mismatches in the replicated devices. Since the microfluidic reservoirs have a typical diameter ranging from several hundred micrometres to a few millimetres, the measured mismatches were too excessive to reliably deliver the fluidic samples and reagents into the different layers.

The adjustment of the location of the complementary mould insert was needed to compensate the measured mismatches. To determine the adjustment of the location of the complementary mould inserts, the mean of all the *X*- and *Y*-magnitude of the mismatches along the *X*- and *Y*-axis were computed. They were 598 and 556 μm, respectively. The alignment tools were reinstalled on the lower aluminium plate of the hot embossing machine. The complementary mould insert was relocated with respect to the top mould insert by adjusting the three lead screws of the alignment tools. The alignment tools were demounted from the lower platen, and subsequent microfluidic devices were moulded.

Fig. 6 also shows the mismatches of the second trial of the alignment. The *X*-magnitude of the mismatches ranged from 37 to 62 μm and the *Y*-magnitude of the mismatches were from −28 to 118 μm along the *X*-axis of the parts as shown in Fig. 6*a*. The *X*- and *Y*-magnitude of the mismatches along the *Y*-axis varied from −38 to 141 μm as shown in Fig. 6*b*. The mismatches were significantly reduced at the second trial of the alignment but a large fluctuation of the mean mismatch was observed as the radial location of the reservoir increased from the centre of the moulded part. It indicates that there was still room for improvement of the mould alignment. The mismatches in the second trial resulted from the angular effect of mould alignment, the inherent dimensional and location variation of the parts including the mould inserts, the aluminium plates and alignment tools. The thermal history of the parts, including expansion and contraction, also contributed to the mismatches.

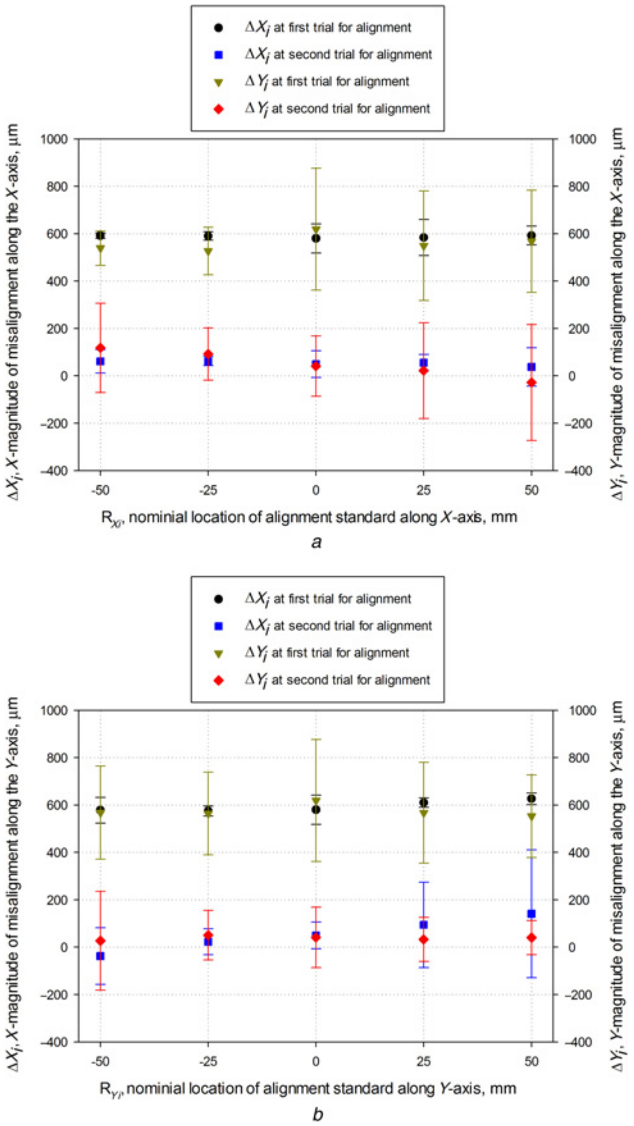

Figure 6 *X- and Y-magnitude of mismatch (ΔX_i and ΔY_i) of fluidic reservoirs along X-axis (Fig. 6a) and along Y-axis (Fig. 6b) on moulded parts*

5. Conclusions: The kinematic alignment of the mould inserts was investigated for double-sided hot embossing of multilayer microfluidic systems. The alignment tools with three locating screws were designed using kinematic constraints. An alignment process was performed for the experimental demonstration of double-sided hot embossing.

The complementary mould insert on the lower platen was aligned with respect to the mould insert on the upper platen using the three locating pins. They constrained the relative motions of the complementary mould insert for mould alignment. The *X*- and *Y*-magnitude of the mismatches ranged from 37 to 62 μm and from −28 to 118 μm along the *X*-axis of the moulded parts. The *X*- and *Y*-magnitude of the mismatches along the *Y*-axis of the moulded parts varied from −38 to 141 μm.

The proposed alignment mechanism was realised using the locating screws in a cost-effective manner. The mould alignment system is simple to implement and operate. It is applicable to the double-side moulding of multilayered polymer microfluidic systems.

6. Acknowledgments: The authors thank Mr. Shane Arabie and Mr. Ted Cera from the Department of Engineering Technology for the microfabrication support. This work was supported by the Department of Engineering Technology at the Texas State University.

7 References

[1] Skafte-Pedersen P., Sip C.G., Folch A., Dufva M.: ‘Modular microfluidic systems using reversibly attached PDMS fluid control modules’, *J. Micromech. Microeng.*, 2013, **23**, p. 055011

[2] Luo Y., Yan X., Qi N., Wang X., Wang L.: ‘Study of double-side ultrasonic embossing for fabrication of microstructures on thermoplastic polymer’, *PLOS ONE*, 2013, **8**, p. e61647

[3] Yang C.-H., Yang S.-Y.: ‘A high-brightness light guide plate with high precise double-sided microstructures fabricated using the fixed

doi: 10.1049/mnl.2014.0134

boundary hot embossing technique', *J. Micromech. Microeng.*, 2013, **23**, p. 035033
[4] Han A., Graff M., Wang O., Frazier B.: 'An approach to multilayer microfluidic systems with integrated electrical, optical, and mechanical functionality', *Sensors J.*, 2005, **5**, pp. 82–89
[5] Karlsson J.M., Haraldsson T., Carlborg C.F., Wijngaart W.: 'A double-sided micromolding process for reproducible manufacturing of thin layers and 3D microchannels in PDMS'. Proc. Micro TAS, Okinawa, Japan, 2012, pp. 659–661
[6] Dittrich H., Mehne C., Heckele M.: 'Double-sided large area hot embossing for polymer microstructures with high aspect ratio'. Proc. HARMST, Gyenogju, Korea, 2005, pp. 226–227
[7] You B.H., Chen P.-C., Park D.S., *et al.*: 'Passive micro-assembly of modular, hot embossed, polymer microfluidic devices using exact constraint design', *J. Micromech. Microeng.*, 2009, **19**, pp. 125025
[8] Bäcklund Y.J.: 'Micromechanics in optical microsystems – with focus on telecom system', *J. Micromech. Microeng.*, 1997, **7**, pp. 93–98
[9] Madou M.J.: 'Fundamentals of microfabrication: the science of miniaturization' (CRC Press, New York, 2002)
[10] Whitney D.E.: 'Mechanical assemblies: their design, manufacture, and role in product development' (Oxford University Press, New York, 2004)
[11] Slocum A.H., Weber A.C.: 'Precision passive mechanical alignment of wafers', *JMEMS*, 2003, **12**, pp. 826–834
[12] Jiang L., Pandraud G., French P.J., Spearing S.M.: 'A novel method for nanoprecision alignment in wafer bonding applications', *J. Micromech. Microeng.*, 2007, **17**, pp. S61–S67
[13] Sankar A.R., Jency J.G., Ashwini J., Das S.: 'Realisation of silicon piezoresistive accelerometer with proof mass-edge-align-flexures using wet anisotropic etching', *Micro Nano Lett.*, 2012, **7**, pp. 118–121
[14] Anton H., Rorres C.: 'Elementary linear algebra: applications version' (Willey, Hoboken, NJ, 2000)