Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition
IMECE2013
November 15-21, 2013, San Diego, California, USA

IMECE2013-65788

MEASUREMENT AND PROCESS CONTROL IN PRECISION HOT EMBOSSING

Maia R. Bageant
Laboratory for Manufacturing and Productivity
Massachusetts Institute of Technology
Cambridge, MA, USA

Prof. David E. Hardt
Laboratory for Manufacturing and Productivity
Massachusetts Institute of Technology
Cambridge, MA, USA

ABSTRACT

Microfluidic technologies hold a great deal of promise in advancing the medical field, but transitioning them from research to commercial production has proven problematic. We propose precision hot embossing as a process to produce high volumes of devices with low capital cost and a high degree of flexibility. Hot embossing has not been widely applied to precision forming of hard polymers at viable production rates. To this end we have developed experimental equipment capable of maintaining the necessary precision in forming parameters while minimizing cycle time. In addition, since equipment precision alone does not guarantee consistent product quality, our work also focuses on real-time sensing and diagnosis of the process.

This paper covers both the basic details for a novel embossing machine, and the utilization of the force and displacement data acquired during the embossing cycle to diagnose the state of the material and process. The precision necessary in both the forming machine and the instrumentation will be covered in detail. It will be shown that variation in the material properties (e.g. thickness, glass transition temperature) as well as the degree of bulk deformation of the substrate can be detected from these measurements. If these data are correlated with subsequent downstream functional tests, a total measure of quality may be determined and used to apply closed-loop cycle-to-cycle control to the entire process. By incorporating automation and specialized precision equipment into a tabletop "microfactory" setting, we aim to demonstrate a high degree of process control and disturbance rejection for the process of hot embossing as applied at the micron scale.

INTRODUCTION AND MOTIVATION

The term "microfluidics" embodies a suite of technologies that take advantage of the physics present at small volumes of fluid to quickly and at low cost accomplish typically complex, expensive, or time-intensive tasks (1). Many breakthrough designs for processes from PCR to cell sorting to assays testing for various diseases have been developed and verified in laboratory situations. These devices are typically fabricated by casting polydimethylsiloxane (PDMS), a cross-linked elastic polymer, onto a lithographically-patterned master. The PDMS negative is then bonded to a glass backplane, forming enclosed channels (2). PDMS, though a suitable material for device design and research, has several key flaws, including permeability to certain solvents and biological molecules, as well as unstable material properties with age (3); but transferring these soft-polymer designs into mass-manufacturable hard-polymer designs presents further obstacles, and transitioning these research technologies into products widely available on the market has proven to be a challenge.

Several existing technologies have been applied to the production of microfluidic devices in hard polymer form. Micromilling and laser ablation are flexible processes capable of manufacturing devices individually, but exhibit low throughput due to the fact that they are serial processes (2). Nanoimprint lithography shows promise in patterning large areas with micro- or nano-scale features, but has yet to be demonstrated as a suitable manufacturing scale technique (2). Ultraviolet nanoimprint lithography, in which a fluid polymer is cast using UV light onto a mold, is another promising technique; however, to achieve microscale features, the mechanical and manufacturing demands are similar to that of conventional lithography, making it a relatively expensive process (4).

Injection molding is a high-throughput process well-optimized for the hard thermoplastics of interest, but fabricating microscale features with adequate fidelity poses greater challenges; careful process optimization is required for microscale features to fully fill before the liquid thermoplastic freezes in narrow channels. The time and capital investment for tooling and optimization can be large, making injection molding a less attractive solution for low-volume device production and design iteration (5).

Precision hot embossing occupies the space in between these two techniques, providing a flexible, scalable, low-cost manufacturing process. Embossing equipment requires less mechanical complexity and capital investment than injection molding equipment, and can be scaled to right-sized needs to control cost as well as operated in parallel to increase throughput. The process offers comparable feature fidelity to injection molding (features down to 25nm have been successfully replicated (6)). Both embossing and injection molding are subject to significant de-molding stresses that must be considered in both the tooling material and device geometric design (8). However, embossing causes large deformation only at the embossed surface, creating smaller residual stresses. This results in lessened damage to tooling and makes embossing suitable for applications sensitive to residual stresses in the plastic, such as optical waveguides (7).

To this end, this project seeks to apply hot embossing to precision polymer fabrication techniques, and to develop precise process control in order to ensure high part quality output and production rate even when subject to disturbances.

PROCESS PHYSICS OF HOT EMBOSSING

The hot embossing process is one in which permanent plastic deformation is imparted to a polymer substrate using a heated, micro-featured stamp. The polymer is heated above its glass transition temperature, decreasing its elastic modulus and promoting essentially purely plastic flow when a tool is imprinted even at low pressures (13). Once flow is complete, the polymer is then cooled below its glass transition temperature, and the tool is removed, leaving permanently formed features in the polymer.

One important fact for the design of industrial equipment is that the hot embossing process is a threshold process. Given sufficiently high temperatures and pressures, the micro-features will form to a high degree of fidelity, and any increased force or temperature will not significantly improve quality. However, excessively high temperatures and pressures will cause the polymer substrate to exhibit bulk flow, distorting the substrate and preventing subsequent registration for further finishing steps (14).

It was determined, then, that to successfully accomplish precision micro-embossing on an industrial scale, that temperature and applied pressure needed to be tightly controlled, and that precise parallelism between forming platens as well as precisely repeatable linear motion was required to control variability.

EQUIPMENT NEEDS AND STATE OF THE ART

Once embossing was selected as the process of interest, the next question was to understand what areas of the process required precise experimental control, and whether existing commercially available solutions were capable of meeting these requirements.

Industrial hot embossing presses are commonly available for low-precision, low-cost applications, such as embossing patterns into leather, foils, and polymers (9), but are unsuitable for precision microscale embossing. Laminating machines have been shown to be effective but slow, requiring a full hour to produce one device (10). Specialized solutions intended for automatic or semi-automatic embossing are available from sources such as EV Group, but are high-cost solutions (4), though they do outperform more primitive presses significantly (11).

EXPERIMENTAL EQUIPMENT

Thus, it was identified that no suitable low-cost, high-throughput, high-precision option was available for precision microscale embossing production, and that custom equipment would need to be constructed. Previous work completed by Hale demonstrated that the design and construction of a simple, fast-cycle, low-cost embossing machine was feasible (14). However, this work also demonstrated a need for enhanced control over forming parameters and for mechanical precision and repeatability. To reduce variability and achieve the desired higher level of precision, the new generation of equipment detailed in this document was developed. In addition, this undertaking presented the opportunity to outfit the equipment with a sensor package to monitor and investigate quality and process physics in-cycle during production. The result is experimental equipment capable of both industrial-level production and of experimental process monitoring and control.

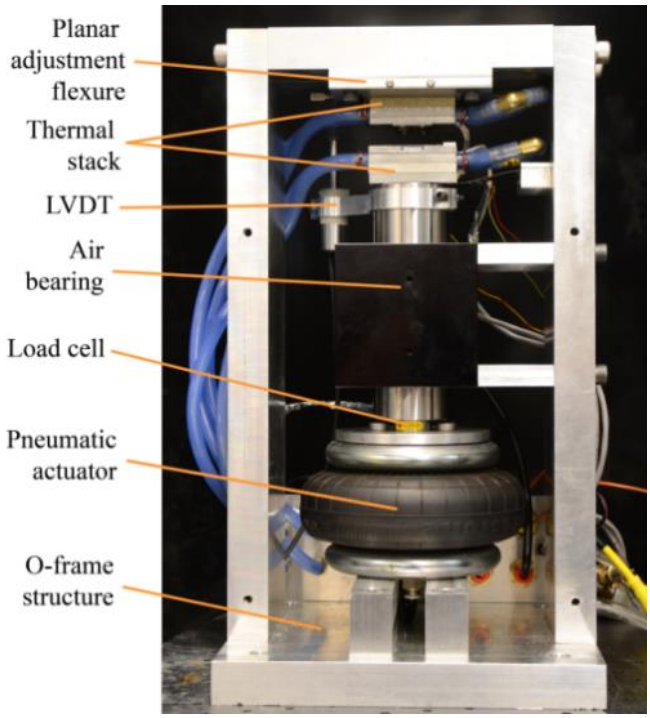

FIGURE 1. EXPERIMENTAL EQUIPMENT WITH KEY FEATURES LABELED.

An image of the equipment with key features labeled in shown in Figure 1. The equipment is supported in a rigid O-frame structure. On the roof of the structure, the tool is

mounted on a stack consisting of an active thermal mass and a reinforced insulating slab. On the base of the structure, a pneumatic bellows vertically displaces a blade flexure-guided shaft held in an air bushing to move the lower forming platen, also consisting of an active thermal mass isolated from the machine structure, upwards to bring the substrate in contact with the tool. The combination of the pneumatic bellows with the air bushing allows for completely stiction-free movement and force application, and thus allows for precise linear control of both force and position. The repeatability of the linear motion of the platens relative to each other, due to the rigidity of the O-frame structure and the precision of the air bushing, is measured to be better than 5μm. This machine has been demonstrated to produce parts of good quality with cycle times of 90-120 seconds (15).

One key challenge was to allow tooling features to be aligned with existing features on substrates. A kinematic alignment system consisting of three fixed pins combined with an industrial pick-and-place robot arm allows placement of substrates into the embossing machine to a repeatability of 25μm (12). In addition, the tool is mounted on a planar flexure which allows the tool position to be calibrated to match the pins. This flexure can be loaded with the full force required for embossing without deformation. The kinematic alignment pins and planar adjustment flexure are shown in Figure 2, in which the embosser structure has been opened to take a photograph.

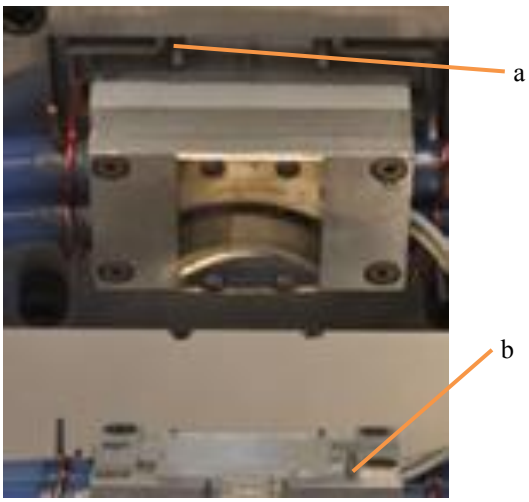

FIGURE 2. IMAGE OF KINEMATIC ALIGNMENT PINS (A) AND PLANAR ADJUSTMENT FLEXURE (B).

Another key challenge was to carefully control the forming parameters in order to ensure their precision and the repeatability of each cycle. Internal sub-loops within the heater controllers and the pressure controller maintain the temperature and pressure setpoints. An enclosing force loop consisting of a feedforward and discrete proportional-integral controller allows attainment of force setpoints to within the sensor resolution of 5N. The temperature control loops allow the temperature setpoint to be controlled to within 2°C, despite slight physical differences in heater output power between the two heating units. Given the precise control of forming parameters, repeatability of the cycle is ensured, and the input parameters may be finely and reliably adjusted to control quality.

SENSOR CAPABILITIES

In addition to providing a platform suitable for studying the precision embossing process, the experimental equipment provides a platform to investigate the process physics real-time and in-cycle. An LVDT measures displacement between the lower platen and the upper platen, and is capable of resolving 0.5μm displacements over a range of 1mm. A load cell measures force transmitted through the structural stack and can resolve forces down to 5N over a 2000N range. These two measures provide both force and displacement, and built-in thermocouples in the heaters provide a measure of temperature. These sensors allow both the thermal and mechanical state of the material to be estimated during the process.

One important measurement related to part quality that can be made is the measurement of bulk deformation. When substrates are exposed to insufficient temperature or pressure, the microchannels do not fully form. When substrates are exposed to excess amounts of temperature and pressure, however, the microchannels exhibit high fidelity to the master, but the substrate displays bulk deformation around its unconstrained edges, making the finished product aesthetically displeasing and difficult to register for finishing steps. When optimal pressure and temperature are applied, the channels may be well-formed without the bulk deformation on the edges. A visual depiction of under-formed, well-formed, and over-formed devices is shown in Figure 3.

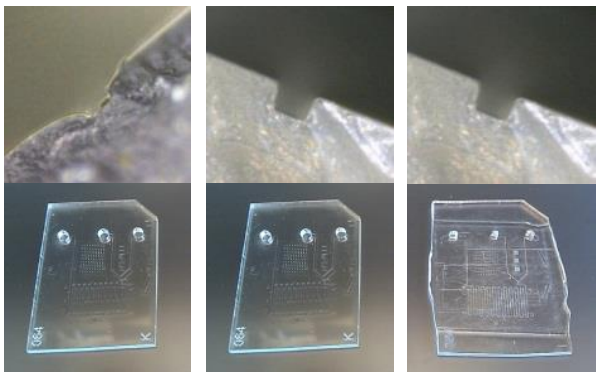

FIGURE 3. IMAGES OF UNDER- (LEFT), WELL- (CENTER), AND OVER-FORMED (RIGHT) DEVICES.

Thus, the ideal formation parameter set point is to achieve the minimum temperature and pressure suitable to ensure channel formation while still staying within a determined threshold of acceptable macroscale deformation. By measuring the displacement of the platens during forming, the bulk thinning of the substrate can be monitored. Assuming that under the conditions of constant force and temperature, the

deformation consists mostly of plastic flow with relatively conserved volume, this measurement should be an indirect indicator of the degree of macroscale area deformation of a finished product. Obtaining this measurement in combination with measurement of the quality of channel formation then defines total quality of a produced part.

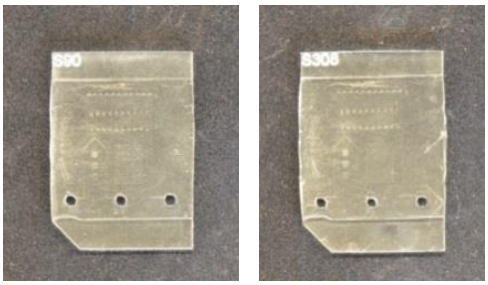

FIGURE 4. EXPERIMENTAL DEVICES WITH LOW DEGREE OF OVERFORMING (LEFT) AND HIGH DEGREE OF OVERFORMING (RIGHT).

To this end, a set of experiments was performed, in which macroscale deformation was intentionally created to various degrees. The displacement during each production forming cycle was measured at constant temperature and force. After formation, an image under constant lighting and focus conditions of each product was captured. Each image was taken at 300dpi resolution, so that the device occupied an area of approximately 0.7 megapixels in each image. Sample images prior to analysis are shown in Figure 4. By applying a threshold filter to the image, removing particles, and filling holes in the remaining large particle, the area of the product could be measured, and changes in area from pre- to post-embossing on the order of 1% could be measured, with natural variation of the imaging technique estimated at 0.7% of the total area. The measurement noise derives from the ambient-light optical imaging technique, which is very sensitive to even small variations in light and shadow.

The result, plotted in Figure 5, showed a strong correlation between the optically measured area and measured displacement. The strong quadratic correlation, expected under incompressible conditions owing to the relationship $\Delta A \propto (\Delta z)^2$, provides evidence for the indirect measurement is sufficient to detect macroscale deformation in-process.

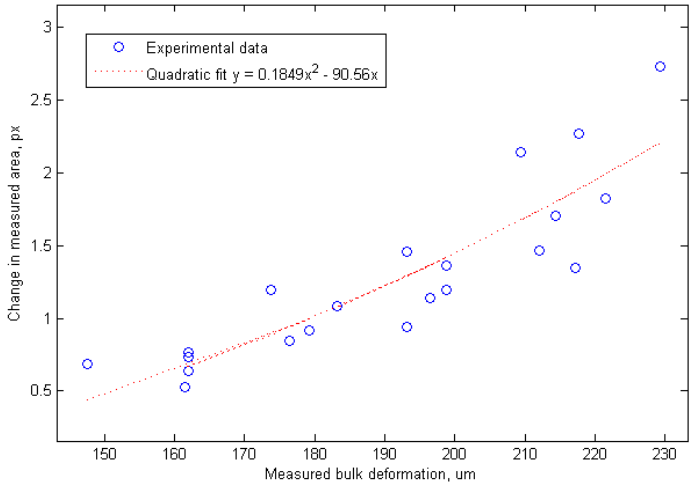

FIGURE 5. CORRELATION OF AREA MEASUREMENT TO MEASUREMENT OF DISPLACEMENT DURING FORMING.

Another important measurement to make in-process is the initial thickness of the blank. The planar geometry of the blanks is very consistent, but great variation has been found in the material thickness. This variation affects the heating rate of the blank, which can be taken into account to adjust the temperature or the length of the pre-heating period in order to minimize cycle time. In addition, it is important for later registration for measurement and finishing steps; and, by detecting a "zero-thickness" blank, the equipment is capable of detecting a materials handling error and aborting an erroneous cycle.

To complete this measurement, the equipment simply records the displacement at which a nonzero force is first detected and thus contact with a blank is first made, and subtracts out a known physical offset between the LVDT tip and contact surface. To corroborate this measurement, before forming, the blank is measured using a micrometer, and then an offset for estimated thermal expansion is added. The comparison of these two measurements shows that the initial blank thickness can be accurately measured within 5% with an average error of 2.45%, as demonstrated in Figure 6.

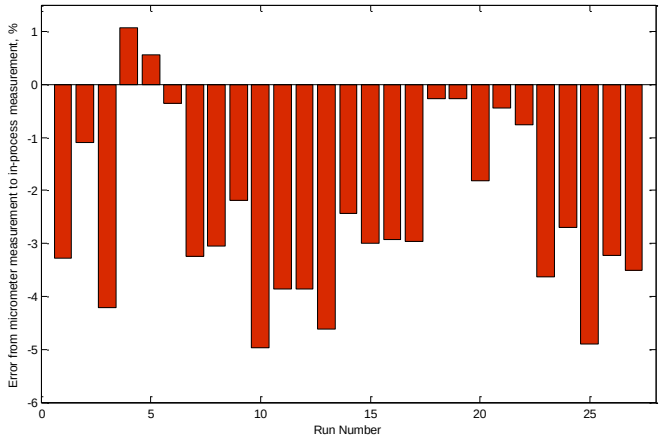

FIGURE 6. PERCENTAGE ERROR BETWEE MICROMETER THICKNESS MEASUREMENT AND IN-PROCESS THICKNESS MEASUREMENT.

The consistent bias toward measuring substrates to be thinner than expected is believed to be due to a low sampling rate relative to the rate of compression. This allows for some compression of the substrate to occur in each trial after contact is initiated but before contact is detected. By improving the sampling rate, it is believed that the thickness measurement error could be detected.

The in-process measurement can also be combined to estimate the glass transition temperature of the material in real-time. For polymer materials, the glass transition temperature is marked by a change from elastic to visco-elastic or plastic properties, and is measureable as a sudden drop in elastic modulus (13).

Assuming constant geometry, structural stiffness in compression is then a surrogate for elastic modulus. Under the conditions of constant force application, ramping up of temperature, and subtraction of thermal expansion, a change in stiffness should manifest as a displacement. Thus, by measuring displacement during the pre-heat portion of the cycle in which these conditions are found, changes in stiffness as a function of temperature should follow the same pattern as the elastic modulus. The expectation is then that the stiffness will rapidly decrease to a plateau when graphed against temperature, and this fact can be automatically detected to compute glass transition temperature.

That is, an effective stiffness may be computed as

$$K_{eff}(T) = \frac{F}{\delta(T) - \delta_a(T)},$$

Where δ_a is the total estimated thermal expansion of the equipment and the substrate. In practice, the effective stiffness shows a positive slope, followed by a sharp inflection at the glass transition temperature, as shown in Figure 7. It is theorized that the positive slope is caused by a combination of unmodeled thermal expansion as well as an effective change in stiffness as the tool features sink into the substrate and the tool encounters bulk contact instead of point contacts.

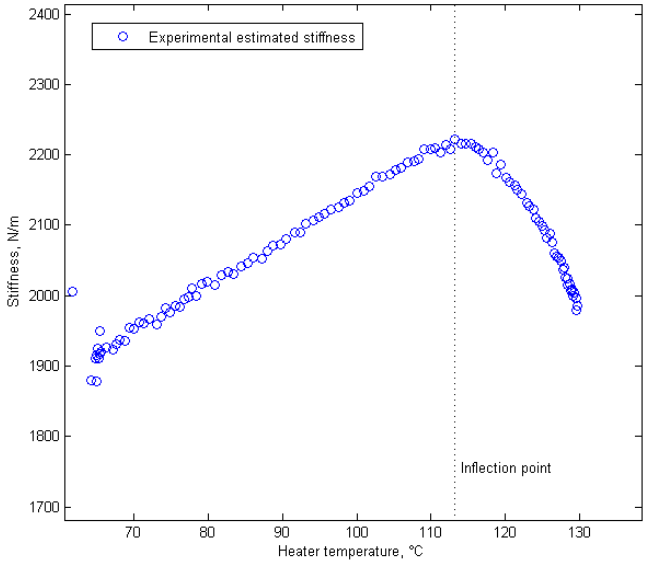

FIGURE 7. EFFECTIVE STIFFNESS VERSUS TEMPERATURE MEASUREMENT, IN WHICH A CLEAR INFLECTION POINT MARKS A STEEP DROP IN STIFFNESS.

It is expected that by detecting changes in slope or local optima, the glass transition temperature can be estimated automatically and in-process, and small adjustments to forming parameters could be automatically made in real-time to compensate.

CONCLUSION AND FUTURE WORK

This paper has presented both a novel equipment design for hot micro embossing and the use of in-process measurements to monitor the state of the product in real-time. The equipment was designed both to be of low enough cost and cycle time to be commercially viable and to have the necessary precision for micro-scale feature embossing. By combining this precision with sensor information, estimates of the thermal and mechanical state of the polymer from temperature, forces and displacement has been demonstrated. These states were then shown to correlate well with off-line measures of substrate thickness, total bulk deformation, and variations in glass transition temperature. Knowledge of these factors is key to controlling the process and maintaining consistent quality in a production environment.

This equipment is now being integrated into an automated production cell that can produce and test a functional device at rate of approximately 30 units per hour. Once the equipment is part of this system, the goal is to use both process and product quality feedback to reduce variation, to allow for rapid product changeover, and to recover quickly from expected material and process disturbances.

ACKNOWLEDGMENTS

This work was conducted under the generous support of the Singapore-MIT Alliance, Manufacturing Systems and Technology Programme

REFERENCES

[1] Whitesides, G. M. "The origins and the future of microfluidics." *Nature* 442 (2006) 368-373.

[2] Kang, Shinill. *Micro/Nano Replication: Processes and Applications.* New Jersey: John Wiley & Sons, Inc, 2012.

[3] Regehr, Keil J., et. Al. "Biological implications of polydimethylsiloxane-based microfluidic cell culture." *Lab on a Chip* 9 (2009): 2132-2139.

[4] EV Group. "Nanoimprint Lithography Systems." Web. Accessed May 2013.

[5] Park, S. H. et. Al. "Injection molding micro patterns with high aspect ratio using a polymeric flexible stamper." *eXPRESS Polymer Letters* 5.11: 950-958.

[6] Chou, Stephen Y., Peter R. Krauss, and Preston J. Renstrom. "Imprint Lithography with 25-Nanometer Resolution." *Science* 272 (1996): 85-87.

[7] Heckele M. and W.K. Schomburg. "Review on micro molding of thermoplastic polymers." *Journal of Micromechanics and Microengineering* 14 (2004) R1-R14.

[8] Dirckx, M.E. and Hardt, D.E., "Analysis and Characterization of Demolding of Hot Embossed Polymer Microstructures", , J. Micromech. Microeng. 21 (2011) 085024

[9] Stamprite Machine Company. "The VT-Series Hot Stamp Press." Web. May 2013.

[10] Jeon, Jessie S., et al. "Hot embossing for fabrication of a microfluidic 3D cell culture platform." Biomedical Microdevices 13.2 (2010): 325-333.

[11] Pelzer, Rainer, et al. "Nanoimprint Lithography -- Full Wafer Replication of Nanometer Features." Proc. of SPIE Vol. 5650.

[12] Zarrouati, N. (2008). *A Precision Manipulation System for Polymer Microdevice Production.* (Master's thesis). Retrieved from MIT DSpace. (http://hdl.handle.net/1721.1/61927).

[13] Srivastava, Vikas et al. "A Thermo-mechanically-coupled Large-deformation Theory for Amorphous Polymers in a Temperature Range Which Spans Their Glass Transition." *International Journal of Plasticity* 26.8 (2010): 1138-1182.

[14] Hale, M. (2007). *Development of a Low-Cost, Rapid-Cycle Hot Embossing System for Microscale Parts*. (Master's thesis). Retrieved from MIT DSpace. (http://hdl.handle.net/1721.1/50565)

[15] Bageant, M. (2011). *Development of Precision Hot Embossing Machine with In-Process Sensing.* (Master's thesis). Retrieved from MIT DSpace.

[16] D Hardt, B Anthony, S Torr, "A teaching factory for polymer microfabrication –μFac," *Int. J. Nanomanufacturing,* **6** (1/2/3/4) 2010, p. 138.