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Fabrication of Fluidic Devices through Dissolution of 3D Printed Material in PDMS Mold

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Abstract

Microfluidic devices have been used in various applications such as chemical, biological, clinical, pharmaceutical, etc. This has motivated researchers to develop inexpensive, straightforward techniques to fabricate such devices. A team of four senior undergraduate students in a microfabrication course completed a project to develop a novel method for fabricating miniature fluidic devices using dissolving a common material used in 3D printing, Acrylonitrile Butadiene Styrene (ABS) in a Polydimethylsiloxane (PDMS) mold. The students performed all development steps, including ideation, literature review, calculation, design, fabrication, assembly, testing, and writing. This paper presents the results of fabricating a complex geometry fluidic design, which was used as an example to show the effectiveness of the fabrication process. The device selected in this research is a Tesla Valve with complex features. Two device designs with different features were 3D modeled and simulated using the SolidWorks Flow module before printing to ensure functionality and guide the design process. Next, the devices were 3D printed with ABS plastic, cast inside the PDMS material, and dissolved in an acetone bath, leaving flexible PDMS fluidic channels. The design performance was tested by forcing water at two different pressures through the devices, and the time to drain volume was measured. Finally, the entire water was completely drained through the devices, proving the successful fabrication of the devices.

Introduction

Technical Concept

Microfluidics has been on the rise since the introduction of the field in the 1960s; however, the production was not the most available or optimized at the time. Some of the first and most successful microfluidic devices were created to advance Inkjet printing in the 1990s [1]. Currently, microfluidic devices are being implemented within many fields, notably the medical, research, and fuel cell fields. The medical field has begun using microfluidics in applications such as microfluidic-based protein and DNA separations [2]. Advancement in other microfabrication processes has allowed for microfluidics to be used for research purposes, including on lab-on-a-chip devices used to study cell migration and cell-to-cell interaction [3]. The increasing demand for small portable devices has created interest in microfluidic fuel cells (MFCs) [4].

Fabrication of microfluidic devices and their channels has been challenging [5, 6, 7]. Moreover, the current techniques share several drawbacks [8]. As a result, a significant amount of potential work has remained to offer better fabrication techniques other than standard microfabrication methods. In addition, other than simple structures in traditional flow devices, there is a huge demand for devices with complex geometries that mimic vital applications like the human vascular system [9, 10]. Tesla valves are among the microfluidic devices with complex geometries. They were first invented by Nikola Tesla in 1920 on a large scale [11] and needed to be fabricated on the microscale. In a Tesla valve, fluid enters one end and flows easily, yet the fluid enters experiences a large amount of opposing force due to the design of the Tesla valve, and it cannot flow in the opposing direction [12].

Research presented in this paper focuses heavily on the fabrication of Tesla valves to permit easier mass production and more customization of the design. Doug Stith, with The Physics Teacher, fabricated a Tesla valve. His model was manufactured using a router to carve a taped template of a Tesla Valve into a piece of medium-density fiberboard (MDF). His design was tested using steel balls to simulate a fluid [13]. This design differs from ours because it does not easily scale down into a microfluidic device. The design presented in this paper uses additive manufacturing via a 3D printed model, while Stith's uses a material removal process.

Researchers at the National Technical University of Athens published a paper on the design optimization of tesla valves [14]. One of our Computational Fluid Dynamic (CFD) tests were conducted using a similar design to compare our CFD findings to their tests. Acrylonitrile Butadiene Styrene (ABS) is a plastic material widely used in 3D printing applications for its toughness and resistance to wear [15]. In the scope of this research, ABS is reactive with Acetone and will dissolve when submerged in an acetone bath. In a process typically referred to as "vapor smoothing," acetone is used to remove print lines from 3D printed projects and give the part a smoother look and feel [16, 17]. Using this same principle, the 3D-printed ABS cast of the Tesla valve was cast in a PDMS mold and dissolved using acetone to leave behind a hollow channel that allows for flow through the mold. The following sections illustrate the design process and manufacturing methods used to execute this theory.

Course Structure

This paper and its associated project are major aspects of the Microfabrication course offered at the authors' institution. The course covers major microfabrication techniques from theory to practice, used to develop micro devices or components. This includes a hands-on laboratory segment of the course during which students work in groups with guidance from the instructor to fabricate MEMS (Micro-Electro-Mechanical Systems) from blank silicon wafers in a clean room. Students are expected to develop their own MEMS design and perform all lab processes on the silicon wafers, including CAD design, photolithography, doping, etching multiple layers, etc. The hands-on laboratory segment of the course provides students with a unique opportunity to work in a modern, clean room and physically perform the complex processes required to develop MEMS wafers from scratch.

As another assignment in this course, groups of students are expected to develop novel devices or processes in the microsystem. This course segment requires students to design, fabricate, test, and document a design, which is fluidic devices in this paper. There are publications from similar course projects performed in the past [18-23]. At the conclusion of this course, students are provided with a comprehensive understanding of the practical applications of MEMS devices and the processes available to manufacture these devices. This paper presents the results of a project that a group of students in the course performed to develop a novel fabrication process of complex fluidic designs.

Student learning objectives in this course are defined as a student's ability to demonstrate skills after completing the course. At the end of the course, students will be able to do the following:

1. Demonstrate the ability to design various microfabrication processes
2. Classify common microelectromechanical devices
3. Categorize common sensing and actuating methods
4. Show an ability to function in the cleanroom in a safe and deliberate manner
5. Analyze their lab data and write an effective final laboratory report

The project assignment included in this course will address the first student learning objective of "demonstrate the ability to design various microfabrication processes." The course also supports some of the student outcomes at the program level, but the outcome of "an ability to design systems, components, or processes meeting specified needs for broadly defined engineering problems appropriate to the discipline" is primarily chosen to be assessed using the project assignment in this course. It also supports the program educational objective of "can function effectively in open-ended activities involving applications, design, analysis, and implementation."

Design

This paper focuses on the fabrication process of complex geometry fluidic designs, Tesla values. Two different designs were selected as examples to show the effectiveness of the fabrication process. The device chosen in this research is a Tesla Valve that includes complex features and functions on the principle of using turbulence from the fluid flowing through the device. Two device designs with different features were 3D modeled and simulated using the SolidWorks Flow module before printing to ensure functionality and guide the design process.

Design 1

The design from the National Technical University of Athens [14] heavily inspired design 1. The design used for this project was not a novelty; however, the fabrication method is. Figure 1 shows the dimensions of Design 1. The general layout is very similar to the National Technical University of Athens' design. However, their design had no dimensions or scales, so the general shape was used for inspiration. Unlike their singular occurrence design, our design uses a pattern that occurs twice in a series. Fabricating this complex pattern aims to test the proposed fabrication technique more rigorously.

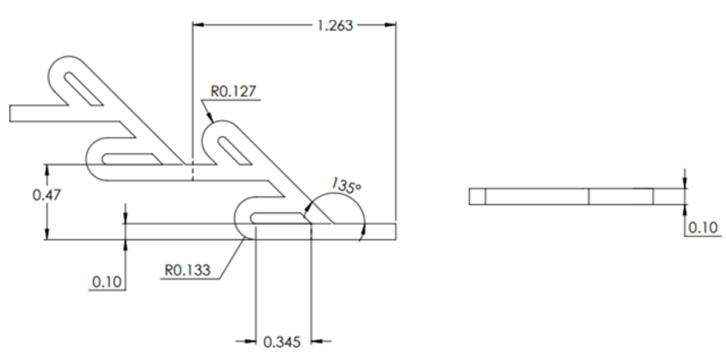


Figure 1: Design 1 layout and dimensions in inches

Once modeled, SolidWorks Flow simulation was used for all CFD simulations for the design. All CFD simulations for design 1 used an input fluid velocity of 9.8 ft/s and an output of environmental pressure. Simulations were made using water as the fluid passing through the valve. Fifty flow lines were used at the entrance of each simulation. The simulation results, shown in Figure 2, concluded that there was a great flow through the complex geometry of the channel. The advantage of first simulating the design is that there is a higher chance of success and predictability when fabricated.

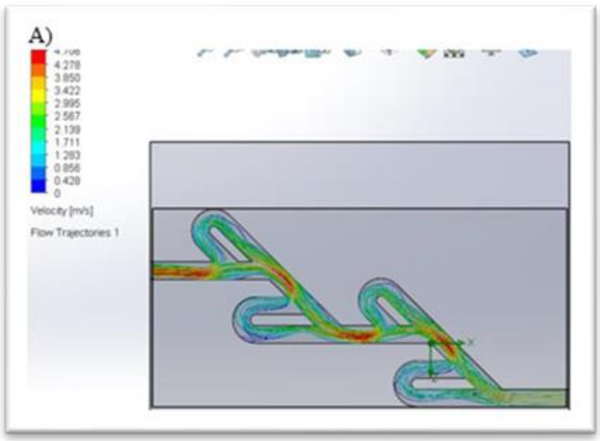


Figure 2: CFD simulation results using SolidWorks Flow for design 1

Design 2

This design, shown in Figure 3, functioned on the same principle as the Tesla valve, yet a more circular design of the eddies was used in this instance. The same CFD simulations performed on design 1 were also performed on design 2. The valve was set up with a 9.8 ft/s entry velocity of the fluid, and the boundary condition on the opposite end was left at atmospheric pressure (14.7 psi). This simulation was conducted to allow the fluid to flow both ways. Figure 4 shows the fluid flow results through the valve's flow direction. The fluid was noted to be almost unimpeded in this direction of travel, as the velocity gradient at the outlet is the same as the inlet.

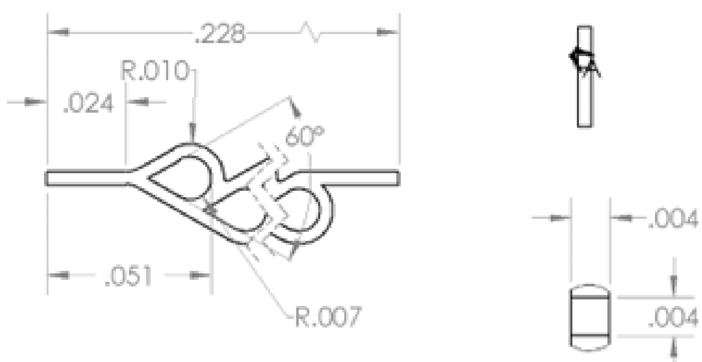


Figure 3: Design 2 layout and dimensions in inches

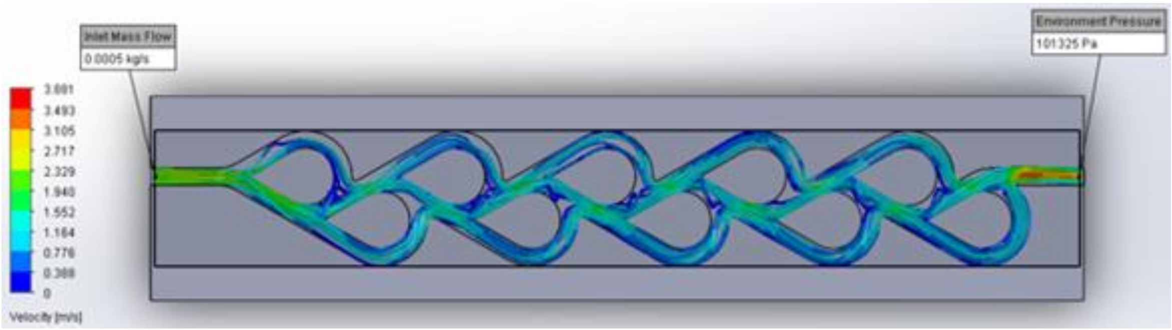


Figure 4: CFD simulation results using SolidWorks flow for the design 2

Fabrication

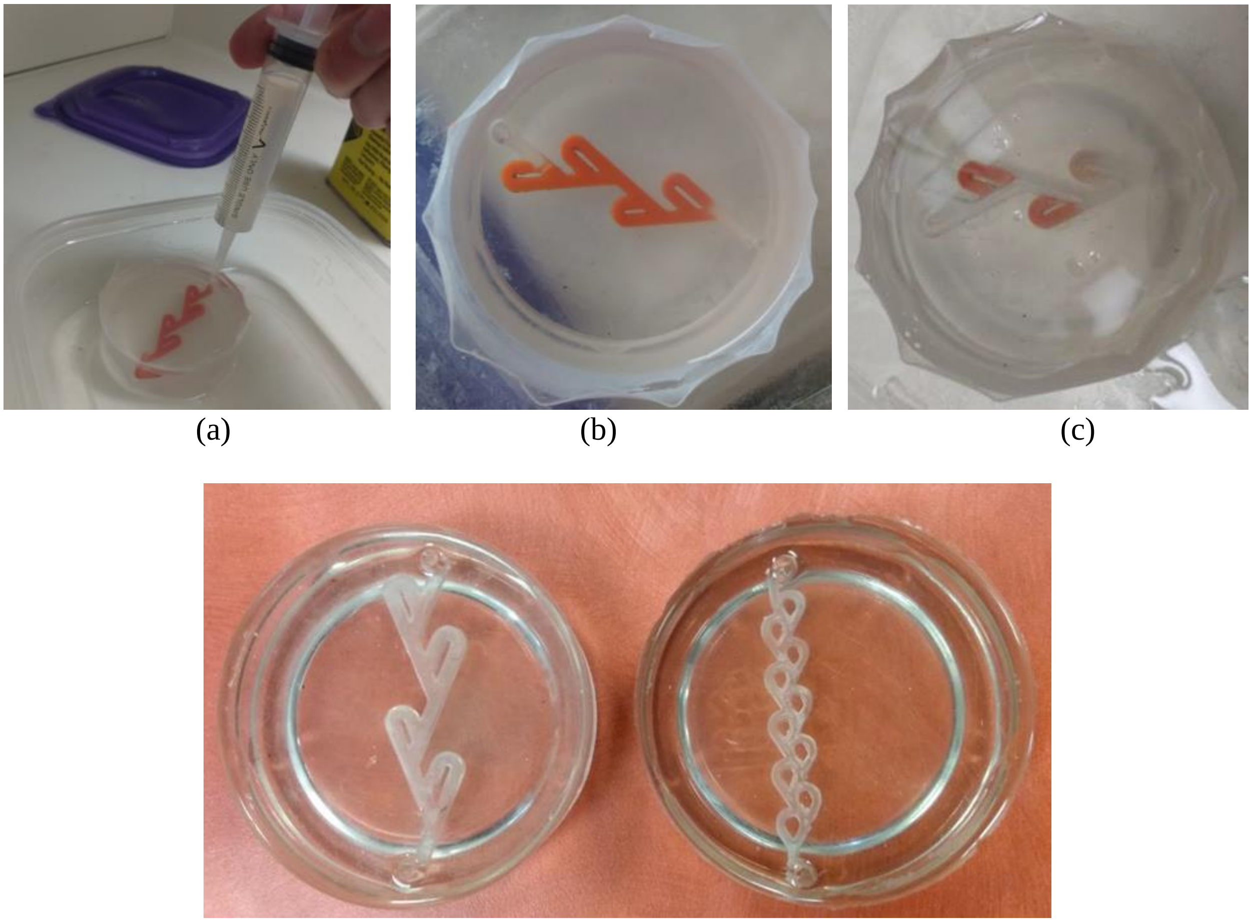
The fabrication process for the designs involved dissolving ABS inside PDMS. ABS is a material that dissolves well in acetone, while PDMS is inert to the effects of it. The Tesla valve device was printed using a 3D printer with ABS as the filament. Approximately 0.25 in PDMS was cast as a base layer so the ABS device would not sit on the bottom. The PDMS was mixed at a 10:1 ratio for parts A and B of the solution. The 3D-printed part was then suspended into the ABS.

After the part was suspended in the PDMS, it went into a vacuum chamber. This vacuum chamber, shown in Figure 5(a), created a vacuum for 5 minutes to remove any trapped gasses from the PDMS solution and get a high-quality product. The PDMS was then cured by either air overnight or by oven at 180° F for 2 hours. Design 1 was oven cured, while Design 2 was air cured. Once the parts were fully cured, the 3D print was fully embedded within the PDMS. Figure 5(b) displays the fully cured Design 1.


(a) (b)

Figure 5: a) PDMS mold in a vacuum chamber. b) Cured 3D print in PDMS mold.

Figure 6(a-c) displays updates from the acetone bath process used to dissolve the ABS. This process can be conducted by letting the acetone naturally dissolve the ABS, but for best results, periodic flushing of the channel speeds up the process dramatically. The PDMS channel flushing was conducted with a syringe filled with acetone. This removes dissolved ABS sludge and makes the ABS dissolve much faster than if it was to sit in acetone. Figure 6(d) shows the finished products of both designs after the ABS has been completely dissolved. After the ABS was dissolved, microfluidic channels left over could be used in the experimentation.



(a) (b) (c)

(d)

Figure 6: a) Acetone flushing through the PDMS channel. b) ABS removal process 48-hr progress. c) ABS removal process 96-hr progress. d) Fully completed ABS removal process for design 1 (left image) and design 2 (right image).

Results and Discussion

Technical Results

The fabrication process of the device using the PDMS was successful, and the channel created within the PDMS through the dissolving of ABS came out well. A static pressure testing method was used to test the performance of the fabricated device. The time taken to travel through the channels was recorded in the experiments of the designs. Figure 7 shows the setup used for the experimentation. First, a small container of water was placed 87 in above the device, producing a static pressure of 3.13 psi. A set volume of water was then sent through the Tesla valves in the flow direction, and the time was recorded. For another test, a small container of water was placed

30 in above the valve, producing a static pressure of 1.10 psi. A set volume of water was then sent through the Tesla valves in the flow direction, and the time was recorded.

Figure 7: Testing setup making static pressures for the device experimentation. The left image shows the small container above the channel. The right image shows the design 2 device with its input and output.

The tests were performed under two pressures of 3.13 psi and 1.10 psi. Water was used as a fluid in the experiments. The fluid was forced through both design 1 and design 2 valves in the flow direction under the two different pressures, and the time-to-drain volume was recorded. It was observed that the water was drained entirely through each valve. This proved the channels were open and, therefore, the successful fabrication of the devices. Figure 8 shows the time for the fluid to pass through the Design 1 and Design 2 valves. It is evident that the water takes a shorter time to pass through both valves at 3.13 psi than at 1.10 psi. Design 2 valve took 119 s to drain the entire fluid at 1.10 psi, while Design 1 did 65 s in the same conditions. In other words, it took 84% longer for Design 2 to drain the fluid than for Design 1 at 1.10 psi. Similarly, it took 74 s for Design 2 to drain the entire water at 3.13 psi compared with 50 s for Design 1. In other words, it took 49% longer for Design 2 to drain than Design 1 at 3.13 psi. Therefore, it can be concluded that Design 1 has a better flow structure than Design 2 for fluidic applications. Moreover, the efficiency of the two designs would be more comparable at higher pressures.

Applied Learning Results

The experience in this microfabrication course was very fruitful for undergraduate students. The opportunity to learn about MEMS and microfabrication processes in the clean room located at the authors' institution in the accelerated timeline allowed for exploring challenging developments that were not ordinarily possible for novice undergraduate students to pursue. Due to the expensive nature of the equipment and maintaining a clean room of the standard required to manufacture MEMS devices, very few institutions in the country offer hands-on experiences such as those provided throughout this course. Students were given not only a lecture-style presentation of the major aspects of microfabrication but were also able to complete supervised weekly lab sessions in the clean room, which involved step-by-step, hands-on design and fabrication of microfluidic sensing devices over the course of a semester. The course also allowed students to carry out a team-oriented project to develop a novel device or process; it was the fabrication process of fluidic devices, in the case of this paper. This included all steps of a development process, including ideation, literature review, design, fabrication, testing of a device, and rigid documentation of the entire process. The project was initiated by students with no prior experience in this field. The motivation to participate in the Microfabrication course was to explore the MEMS fabrication processes and to gain clean room experience for a job in the microsystem field.

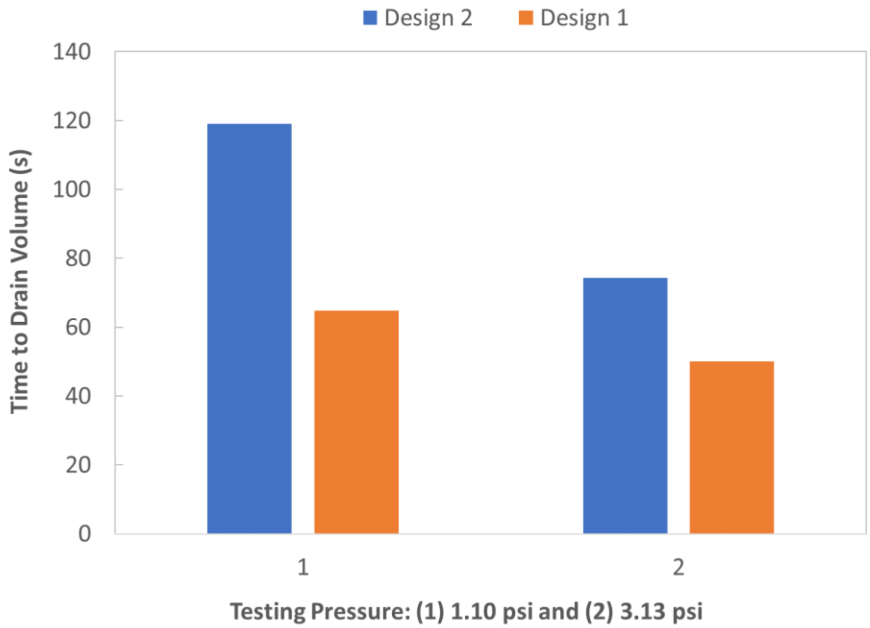


Figure 8: The time for the fluid to pass through the design 1 and design 2 valves in the flow direction with two pressures of 1.10 psi and 3.13 psi.

Groups of 3-5 students were formed at the beginning of the semester to perform the projects. The instructor introduced general ideas of the projects, and students were to conduct a literature review in Google Scholar to find a potential idea and narrow it down to a novel idea. Each group created a Gantt chart that included critical activities and milestones on the project and was designed to guarantee the completion of the project within the timelines. It included all steps of the project and allowed for redesign and refabrication per the experience from previous projects. The Gantt chart was revised based on the instructor's comments. Each group of students performed the work outside the regular class time and reported their weekly performance at the beginning of every lab session. The instructor reviewed the progress and made comments on the project. Students used CAD software, mostly SolidWorks, to design their work. Some groups of students performed a hand calculation to optimize their design, while others performed a simulation to properly design their idea before moving to the fabrication stage.

Due to the time limit within a semester, the students were supposed to find ideas that required fewer fabrication steps and used commonly available prototyping machines like 3D printers. While some groups fabricated their design in the first shot, others found flaws in their design or fabrication and needed to redesign or refabricate their work. The groups created a testing setup to validate their device. The students were provided with a workshop on research paper writing by the instructor, and they submitted their work in three stages during the semester. After each stage, the instructor left comments on their write-up, and students submitted a revision. This allowed for flawless writing within a short amount of time. Even though a semester seems short for the students to perform such a project, it was found that the microfabrication course, its components, and the teaching method proposed in this paper were successful.

Microfabrication was one of the most challenging courses in the institution's engineering curriculum. It provided students with many unique learning experiences due to the general unavailability and novelty of courses of this nature, especially when offered as an elective course within a Mechanical Engineering degree instead of being exclusive to students studying degrees in microfabrication. At the conclusion of the semester, students taking this course were provided with an opportunity to evaluate the course in both the lecture and laboratory portions of the class. Twenty of twenty-three students enrolled in the course participated in the survey, yielding an 87% response rate. Table 1 shows the questions and the results from the survey. Each of the questions dealt with a characteristic of teaching excellence. The students were asked to indicate their rating for each question by filling in a bubble number from 1 (lowest) to 7 (highest). After processing the course evaluations of every student, an overall score of 6 out of 7 was reported for this course which shows the successful conduction of the course and its components.

In addition to the quantitative survey results, the students were asked to provide qualitative feedback on two critical questions that would be helpful to the instructor as the information is used to improve the teaching style in the following years. Table 2 shows the most critical comments that the students provided. The comments indicate that the level of instruction was enough to motivate students to do their best work.

Table 1 - Student Course Evaluation Form and the qualitative results

Question	Average score out of 7
How would you rate the difficulty of this course?	4.5
1. Does the professor appear well-prepared for class?	6.4
2. How well does the professor communicate with students?	5.8
3. How well does the professor motivate students to do their best work?	5.9
4. How knowledgeable does the professor appear about the subject?	6.6
5. What is the professor's attitude toward the subject matter of the course?	6.4
6. Is the professor willing to use a variety of activities to promote student learning?	5.3
7. What was the professor's attitude toward the students?	6.4
8. How available is the professor for help outside of class?	5.8
9. How reasonable/fair are the professor's exams and/or other grading criteria?	5.8
10. To what extent are the professor's presentations generally thought provoking?	5.2
11. Feedback from the professor regarding grades is provided in a timely manner?	6.2
12. How would you rate the overall teaching effectiveness of the professor?	5.8
Average score of 12 questions	6.0

Table 2 – Qualitative Feedback from Students on the Course

What are the major strengths of the instructor and course?
• It is an interesting course and requires attention to detail. • The instructor is enthusiastic and knowledgeable on the subject; he clearly enjoys this class and the subject matter. This course is clearly the instructor’s forte. • The instructor provides interesting applications of the technologies we learn about. • The labs and projects are a new and fun experience. The lab work is helpful and attention-grabbing despite being long, clarifies instructions, and motivates us to continue research. • The instructor is always willing to work with students and give extra help in or out of class if necessary. • The instructor encourages group work outside of class, which is helpful with labs and homework. • The instructor is easily approachable about anything regarding the subject. • The instructor has a great attitude, understanding, and flexibility. • The instructor motivated students to do their best work. • The instructor offers good feedback and does his best to help students get higher grades if seeing they provide the effort. • The instructor gives fair tests. • The instructor is well-prepared for class every day. • There is a vast understanding of the process from the instructor, so it is easy to ask questions (provided they are understood correctly, however). • The instructor promotes discussion. • There are many sources for learning the topic, including lab, lecture, and project. • The instructor seems empathetic to the workload of senior students.
In what ways can this instructor improve the course?
• The projects in this course are too ambitious. • The exams could focus more on asking what specific terms mean. • It would be helpful if the important information in the lectures and labs were emphasized. • Adding more homework to the assignments would help us understand this new subject. • The lectures could be slightly better thought provoking. • Adding a review section before the test would be helpful. • Talk individually to the students failing the course. • Post the assignment instructions significantly earlier than the due date. • Due to the heavy workload in this course, move the course to a year before the senior year when senior projects are not performed.

The Microfabrication course was assessed for the student outcome of “an ability to design systems, components, or processes meeting specified needs for broadly defined engineering problems appropriate to the discipline” using the project assignment. Rubrics were created to define the expectations for the project report and shared with the students. The project report was evaluated on a 100% scale. Students must score 70% or higher for the project report to satisfy the expectations. The percentage of students receiving 70% or higher grades was calculated. The percentages of >90%, >80%, >70%, and <60% were considered exceeding, meeting, minimally meeting, and not meeting expectations, respectively. Minimally meeting and not meeting expectations required changes made or plans to do something different in the future, closing the loop for continuous improvement. The assessment for the selected outcome showed that 83% of the students received a grade of 70% or higher; therefore, the outcome was met.

Students in the Microfabrication course were challenged with the theory and lab experiences. This hands-on course is not common at the undergraduate level. The course was taught in the senior year of the mechanical engineering technology program by an instructor with several years of experience in this field. Each course component was designed to provoke students to explore new ideas. While the lecture part of the course covered processes on this advanced subject, the student used the lab component to practice the design, fabrication, and testing of microfluidic sensing devices where most of the techniques discussed in the lectures were used. This lab component of the course was performed under the direct instruction of the professor.

The project segment complemented the course by allowing the students to practice independently on novel ideas. The projects were initiated by students from scratch, starting with ideation, followed by literature review, design, fabrication, and testing. The students presented the results in class and submitted a written report. This paper is a version of one of the reports. While such a course seemed heavy for undergraduate students, it had the most promising results. Students learned an advanced subject usually taught at graduate schools, while it was completely hands-on. Students performed both independent and dependent work in the class. As a result, they obtained enough knowledge to start working in the semiconductor industry. When the instructor discussed with the experts in the industry, they stated that the industry required engineers at all levels. While engineers with a master’s or doctoral degree would work on the research and design part of such advanced devices, engineers with a bachelor’s degree are needed to produce the devices in the industry. The industry currently lacks the latter group of engineers as only a few universities prepare undergraduate students with hands-on experience in microfabrication.

Conclusions

A group of undergraduate students performed a project in the Microfabrication course to develop a fabrication process of fluidic devices. The course at the authors’ institution was one of the most challenging, advanced, and up-to-date courses that undergraduate students could take to prepare for such an in-demand industry. In addition to homework and tests, the course also included three other major segments, including lectures, labs, and independent projects. The students used the knowledge gained in the lectures and labs and performed all development steps, including ideation, literature review, calculation, design, fabrication, assembly, testing, and writing in the project.

This paper demonstrated a simple, effective fabrication process of fluidic devices. Simply put, the process was by dissolving a 3D-printed ABS material, leaving the fluidic channels inside the flexible PDMS cast. This fabrication process opened new pathways for producing fluidic devices used in any typical applications. The instructor introduced the project background to get the students up to speed as fast as possible. This project aimed to help students learn the fabrication steps of fluidic devices by developing a novel process. The instructor assisted the students with a weekly discussion of the work progress, supporting materials and equipment required, advising on methods, etc. As a result, the students were able to fabricate and test the devices within an academic semester successfully. The teaching effectiveness was evaluated using student evaluation surveys and the review of technical results. The microfabrication course and its project component presented in this paper indicate great success.

References

1) Becker, H., & Locascio, L. E. (2002). Polymer microfluidic devices. Talanta, 56(2), 267-287.

2) Abdallah, B. G., & Ros, A. (2013). Surface coatings for microfluidic-based biomedical devices. In Microfluidic devices for biomedical applications (pp. 63-99). Woodhead Publishing.

3) Shabestani Monfared, G., Ertl, P., & Rothbauer, M. (2021). Microfluidic and lab-on-a-chip systems for cutaneous wound healing studies. Pharmaceutics, 13(6), 793.

4) Wang, Y., Luo, S., Kwok, H. Y., Pan, W., Zhang, Y., Zhao, X., & Leung, D. Y. (2021). Microfluidic fuel cells with different types of fuels: a prospective review. Renewable and Sustainable Energy Reviews, 141, 110806.

5) Leester-Schädel, M., Lorenz, T., Jürgens, F., & Richter, C. (2016). Fabrication of microfluidic devices. Microsystems for Pharmatechnology: Manipulation of Fluids, Particles, Droplets, and Cells, 23-57.

6) Razavi Bazaz, S., Rouhi, O., Raoufi, M. A., Ejeian, F., Asadnia, M., Jin, D., & Ebrahimi Warkiani, M. (2020). 3D printing of inertial microfluidic devices. Scientific reports, 10(1), 5929.

7) Männel, M. J., Baysak, E., & Thiele, J. (2021). Fabrication of microfluidic devices for emulsion formation by microstereolithography. Molecules, 26(9), 2817.

8) Männel, M. J., Baysak, E., & Thiele, J. (2021). Fabrication of microfluidic devices for emulsion formation by microstereolithography. Molecules, 26(9), 2817.

9) Zhang, C., & Neelamegham, S. (2017). Application of microfluidic devices in studies of thrombosis and hemostasis. Platelets, 28(5), 434-440.

10) Ward, K., & Fan, Z. H. (2015). Mixing in microfluidic devices and enhancement methods. Journal of Micromechanics and Microengineering, 25(9), 094001.

11) Nikola, T. (1920). U.S. Patent No. 1,329,559. Washington, DC: U.S. Patent and Trademark Office.

12) Jin, Z. J., Gao, Z. X., Chen, M. R., & Qian, J. Y. (2018). Parametric study on Tesla valve with reverse flow for hydrogen decompression. International Journal of Hydrogen Energy, 43(18), 8888-8896.

13) Stith, D. (2019). The Tesla valve–A fluidic diode. The Physics Teacher, 57(3), 201-201.

14) Anagnostopoulos, J. S., & Mathioulakis, D. S. (2005). Numerical simulation and hydrodynamic design optimization of a tesla-type valve for micropumps. IASME Transactions, 2(9), 1846-1852.

15) Sudin, M. N., Ramli, F. R., Alkahari, M. R., & Abdullah, M. A. (2018). Comparison of wear behavior of ABS and ABS composite parts fabricated via fused deposition modelling. International Journal of Advanced and Applied Sciences, 5(1), 164-169.

16) Gao, H., Kaweesa, D. V., Moore, J., & Meisel, N. A. (2017). Investigating the impact of acetone vapor smoothing on the strength and elongation of printed ABS parts. Jom, 69, 580-585.

17) Torres, J., Abo, E., & Sugar, A. J. (2022). Effects of annealing and acetone vapor smoothing on the tensile properties and surface roughness of FDM printed ABS components. Rapid Prototyping Journal, (ahead-of-print).

18) Duell, T., Muehlbauer, M., Seitzinger, T., Westfall, J., & Rashidi, R. (2018, September). MEMS capacitive sensor for wound monitoring applications. In IOP conference series: materials science and engineering (Vol. 417, No. 1, p. 012040). IOP Publishing.

19) Rashidi, R., Alenezi, J., Czechowski, J., Niver, J., & Mohammad, S. (2019). Graphite-on-paper-based resistive sensing device for aqueous chemical identification. Chemical Papers, 73, 2845-2855.

20) Mbaye, A., Kreamer, C., Zink, L., Fredenburg, M., & Rashidi, R. (2018, September). 3D printed micro check valve for biomedical applications. In IOP Conference Series: Materials Science and Engineering (Vol. 417, No. 1, p. 012041). IOP Publishing.

21) Cooke, I., DeClerck, B., Hallett, J., Miller, T., Mitchell, A., & Rashidi, R. (2019, November). A Magnetic and Shape Memory Alloy Actuated Gripper for Surgical Applications. In ASME International Mechanical Engineering Congress and Exposition (Vol. 59414, p. V004T05A035). American Society of Mechanical Engineers.

22) Rashidi, R., Summerville, N. C., & Nasri, M. (2018, October). A dual-purpose piezoelectric multi-beam energy harvesting and frequency measurement device for rotational applications. In 2018 IEEE MIT Undergraduate Research Technology Conference (URTC) (pp. 1-4). IEEE.

23) Michelson, T., Rudnick, J., Baxter, J., & Rashidi, R. (2019, November). A novel ferrofluid-based valve-less pump. In ASME International Mechanical Engineering Congress and Exposition (Vol. 59445, p. V007T08A009). American Society of Mechanical Engineers.