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The Use of 3D Printing to Introduce Students to ASTM Standards for Testing Tensile Properties of Acrylonitrile-Butadiene-Styrene (ABS) Plastic Material

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Abstract

In a freshman introductory plastics course at a mid-western state university and a technical college, students were introduced to several metal and plastic materials properties and were taught how some of these properties could be determined using testing procedures described in the American Society for Testing and Materials (ASTM) standards. One such standard is designated D-638-14, titled "Standard Test Method for Tensile Properties of Plastics," which states that "test specimens shall be prepared by machining operations, or die cutting, from materials in sheet, plate, slab, or similar form. Specimens can also be prepared by molding the material to be tested." Missing from the list of test specimen preparation methods are 3D-priting techniques. In this study, students prepared test specimens of Acrylonitrile-Butadiene-Styrene (ABS) plastic material by 3D-printing according to ASTM D638 Type 1 specimen specifications. These test specimens were compared to specimens prepared from ABS sheets by laser cutting to determine if 3D printing had a significant effect on the tensile properties of ABS test specimens. The test specimens prepared by laser cutting served as the control test specimens; this option replaced the use of injection molded specimens as the control test specimens because of the higher costs of the latter specimens. The fused-deposition-modeling 3D-printing machines used in this study were Makerbot™ Replicator 2x, Lulzbot™ TAZ 5, and Stratasys' Dimensions™. The Instron materials testing machine, model 5967, was used in testing the tensile properties of the ABS specimens.

The objectives of this study were

(1) To introduce students to the use of ASTM Standards in testing material properties using 3D printing as a motivation.
(2) To determine if 3D-printing is a viable option, both technically and financially, for preparing test specimen for testing the tensile properties of plastic material in accordance with ASTM standards.

Assessment:
Students' knowledge of ASTM standards and their use will be assessed before and after the project using a survey and class quiz as the assessment instruments. The results will be shared in the ASEE conference presentation. Also, the comparability of the test specimen preparation methods, laser cutting and 3D printing, will be presented at the conference.

Introduction

Students majoring in mechanical engineering technology at a mid-western state university and a technical college were introduced to engineering materials which include metals, ceramics, plastics, and composites in two 100-level courses. Primarily, the contents of these courses consisted of topics such as the nature of materials, structure-property relationships, manufacturing methods, and techniques of determining engineering materials' properties according to industrial procedures described in the standards such as those of the American

Society for Testing and Materials. These same students, according to their academic plans, were required to take a freshman technical design graphics course, where they are introduced to 3D printing. Thus, it seemed reasonable to synergistically utilize the skills acquired from two to three freshman courses in a project-based learning endeavor as illustrated in Figure 1. Secondary to this goal was the convenience of inexpensively preparing tensile test specimens according to ASTM D 638-14 specifications. Prior to this endeavor, tensile test specimens were out-sourced for both plastic and metal materials. As is shown in Table I, the cost of out-sourced injection molded plastic specimens are relatively expensive compared to other methods for making ASTM D 638 Type I tensile test specimens. Therefore, specimens prepared by laser cutting of ABS sheets were used as the control test specimens.

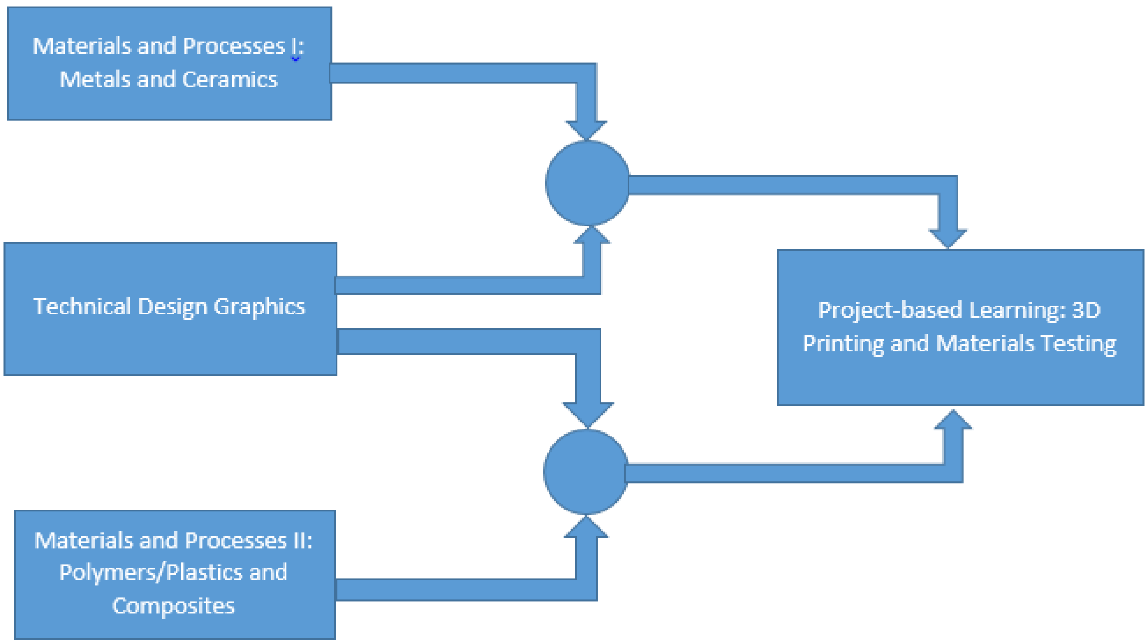

Figure 1. A schematic of courses used for project-based learning incorporating 3D Printing

Table I. Cost comparison for making ASTM D 638 Type I Tensile Specimens

Methods	Quantity	Material	Out-Sourced Cost	Unit Cost
Injection Molding	30	ABS generic	USD 470	USD 15.67
Laser Cutting	30	ABS generic	USD 103.45	USD 3.45
3D – FDM: Dimension	20	ABS M30	CAD 232.19	CAD 11.61
3D – FDM: Lulzbot TAZ 5	10	ABS generic	USD 32.50	USD 3.25

In addition to its cost savings and convenience advantages, the use of 3D printing (also known as additive manufacturing, AM) in manufacturing activities is rapidly growing; therefore, it seemed logical to continuously provide our students with opportunities to acquire the skill set needed to be successful in the additive manufacturing industry. According to a recent report,[1] it was claimed that Wohlers Associates estimated that the 3D printing industry has been growing at an annual rate of 25% for the past 25 years, and suggested that the market for the industry would reach $10.8 billion by 2021. To meet the growing demand of the 3D printing industry, it appears that many technologies have been developed to address the various needs of the industry. Table II lists available 3D printing technologies and their comparative advantages and disadvantages[2].

Table II. Comparison of additive manufacturing technologies (Melchels et al. 2012)[2]

Technique	Accuracy (µm)	Materials	Advantages	Disadvantages	Refs
Inkjet printing (thermal or piezo-electric)	20–100	Liquids, hydrogels	Use of existing cheap technology, multiple compositions	Low viscosity prevents build-up in 3D, low strength	Wilson & Boland, 2003; Boland et al. 2003; Xu et al. 2007
3D printing	50	Polymers, ceramics	Multiple compositions	Requires powder, cell-unfriendly environment	Giordano et al. 1996; Seitz 2005
Stereolithography (incl. two-photon polymerization)	0.5–50	Hydrogels, polymers, ceramic-composites	High accuracy	Single composition, requires photo-curable material	Arcaute et al 2010; Lu et al. 2006; Melchels et al. 2010; Chan et al. 2010
Laser direct writing	20	Cells in media	Single cell manipulation	No structural support, scalability	Odde & Renn, 1999
Direct writing	1	Polyelectrolytes	High accuracy	Requires solvents, cell-unfriendly environment, scalability	Gratson et al. 2004; Ghosh et al. 2008
Melt extrusion (including FDM)	100	Thermoplastics, composites	Technologically simple	Requires strong filament and high temp.	Hutmacher et al 2001; Zein et al. 2002
Robotic dispensing	100	Hydrogels, polymers, ceramic-composites	Multiple compositions	Relatively low accuracy	Censi, 2011; Pescosolido et al. 2011
Selective laser sintering	50	Polymers, ceramics		Requires powder, cell-unfriendly environment	[Antonov et al. 2005; Williams 2005
Biolaserprinting	10	Liquids	High accuracy at high speed	Low viscosity prevents build-up in 3D	Barron et al. 2004; Guillemot 2010
Robotic assembly	5	Rigid solids	No heat, light or reaction required	Expensive machinery	Zhang 2005

In this paper, the authors used fused-deposition-modeling (FDM) machines to print ASTM D 638-14 Type-1 tensile test specimens. Figure 2 shows a 3D drawing of an ASTM Type-1 tensile test specimen while Figure 3 shows a schematic diagram of the FDM technology[3]. Essentially, a plastic filament is fed into a heating chamber where the plastic is melted and extruded through a nozzle and laid on the build-platform layer by layer. The height of the layer ranges from 100 micron (100 x 10^{-6} meter) to 250 micron (250 x 10^{-6} meter). Turner et al.[4,5] has written excellent reviews of the FDM process while Jaksic[6] described many applications of 3D printing in novel experiential learning practices in engineering education. For this study, the FDM machines used were Makerbot® Replicator™ 2X, Lulzbot® TAZ 5, and Stratasy's Dimension™ (out-sourced), and the plastic material was generic acrylonitrile-butadiene-styrene (ABS). For the Lulzbot TAZ 5 machine the recommended filament size was 3.00-mm in diameter while it was 1.75-mm for the Makerbot machine. The control tensile test specimens were prepared by laser cutting extruded ABS plastic sheets. Injection molded tensile test specimens were rather expensive, and were not used in this study. There are plans to use them in future studies.

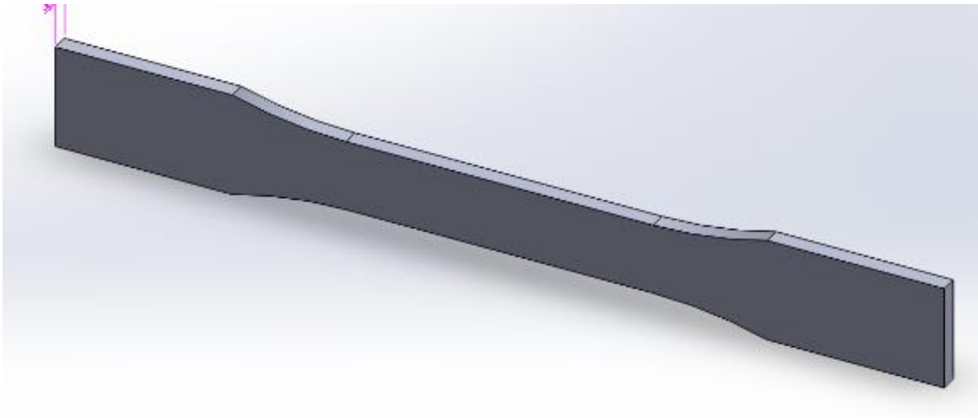

Figure 2. ASTM D 638 Type 1 Tensile Test Specimen

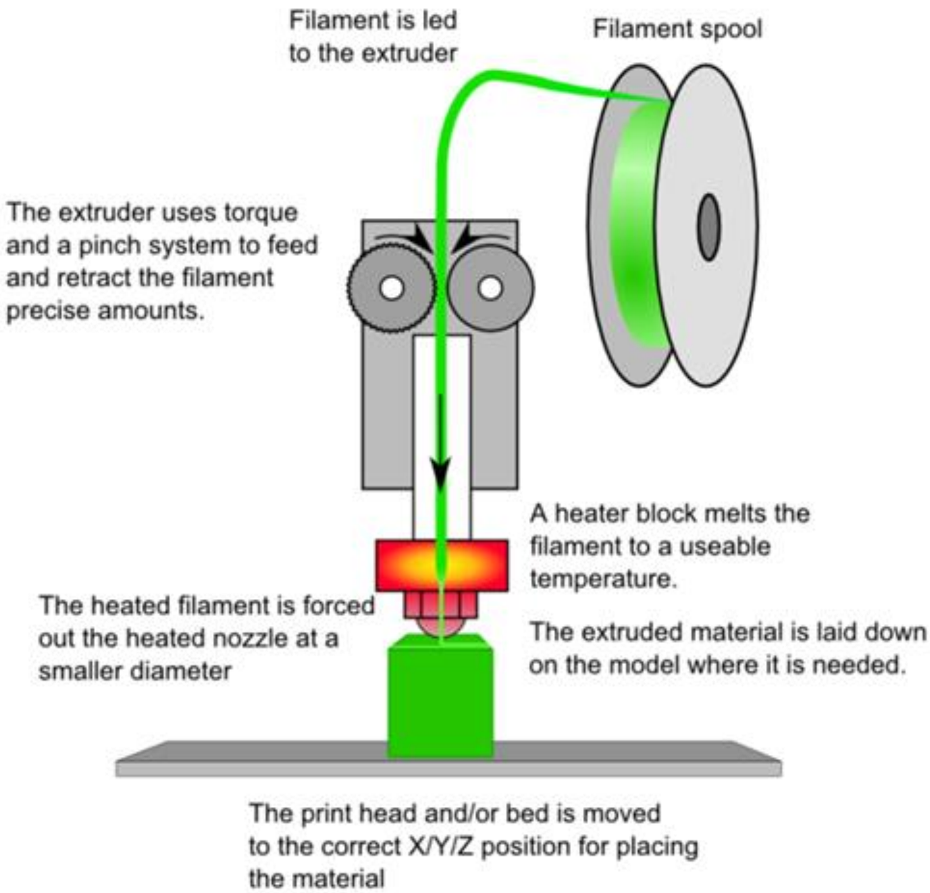

Figure 3. Schematic diagram of the FDM process[3]

Experiment

The tensile test specimens were designed using 2014 Solidworks® Education Edition CAD software. The part files were imported into the 3D printing machine as STL files. Figures 4 and 5 show the Makerbot® and Lulzbot® machines used in printing the tensile test specimens. Even though these machines were easily accessible to the students, they had to be trained on how to run them by the laboratory technician. Figure 6 shows some of the tensile specimens that were 3D printed and tested. All tensile test specimens were 3D printed at 100% fill with ± 45º raster angle. After 3D printing the specimens, they were conditioned for over 40 hours at room temperature and at ~50% relative humidity, according to the standard practice for conditioning plastics for testing described in ASTM D 618-14. Following the conditioning of the specimens, an Instron materials testing machine, model 5967, was used in performing the tensile testing of the specimens. The testing speed was 5 mm/min (0.2 in/min) and all test specimens broke within the recommended range of 0.5 – 5.0 minutes, on the average about 50 seconds.

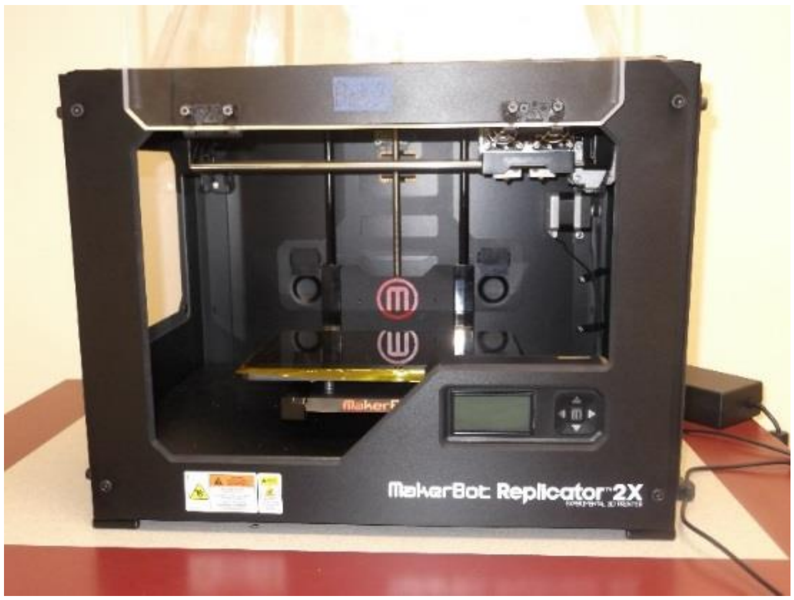

Figure 4. Makerbot® Replicator™ 2X used in printing ABS tensile specimens

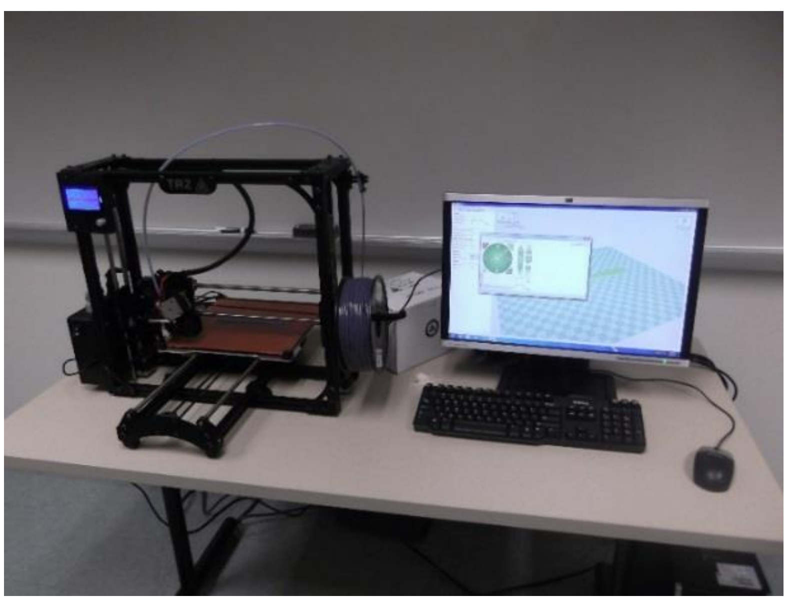
Figure 5. Lulzbot® TAZ 5 used in printing ABS tensile specimens

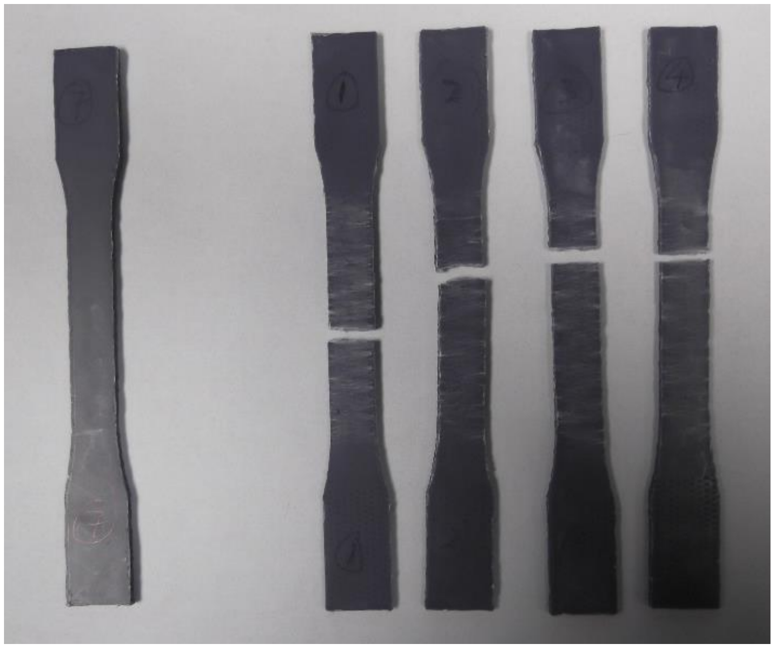

Figure 6. Tensile test specimens prepared by 3D printing with Lulzbot TAZ 5

Results

Tables III – VI and Figures 7-10 show that the results of the measured tensile properties of the ABS specimens prepared by laser cutting and the different 3D printing machines were not significantly different one from another. Therefore, it seems reasonable in terms of costs and convenience to use 3D printing to prepare tensile test specimens of plastic materials such as ABS.

Table III. Modulus of elasticity of ABS specimens prepared by laser cutting (control) and 3D printing

Modulus of Elasticity (MPa)				
Specimen #	Laser Cutting	Makerbot	Dimension	Lulzbot
1	1780	1760	2040	2060
2	2220	1790	2020	1960
3	2010	1830	1850	2100
4	2140	1800	1990	2880
5	2000	1790	2020	1960
Mean	2030	1794	1984	2192
Std. Dev.	167	25	77	390

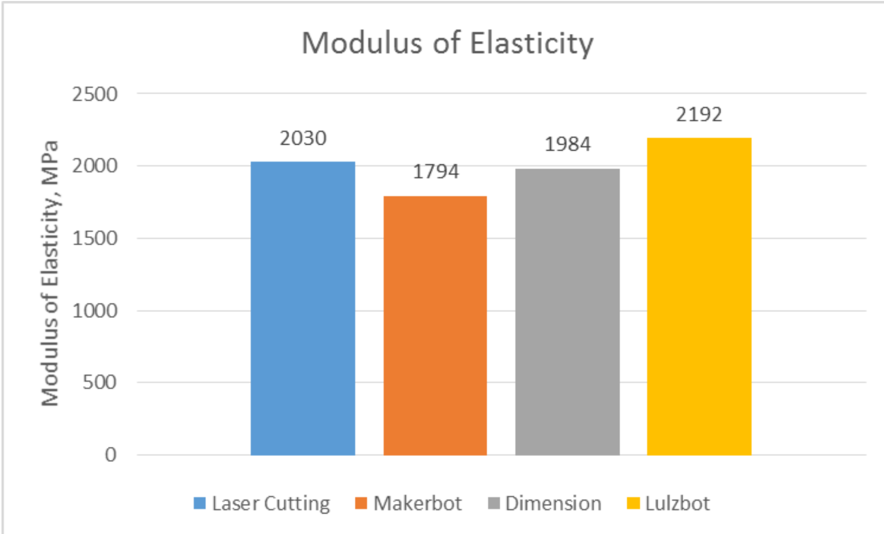

Figure 7. Comparison of modulus of elasticity of ABS specimens prepared by laser cutting and 3D printing

Table IV. Tensile strength at yield of ABS specimens prepared by laser cutting (control) and 3D printing

Tensile Strength at Yield (MPa)				
Specimen #	Laser Cutting	Makerbot	Dimension	Lulzbot
1	30.5	29.4	29.3	35.2
2	30.7	29.5	30.5	29.8
3	31	29.5	28.7	31.9
4	30.9	29.8	30.3	30.8
5	30.8	30	30.9	31.3
Mean	30.78	29.64	29.94	31.8
Std. Dev.	0.19	0.25	0.91	2.05

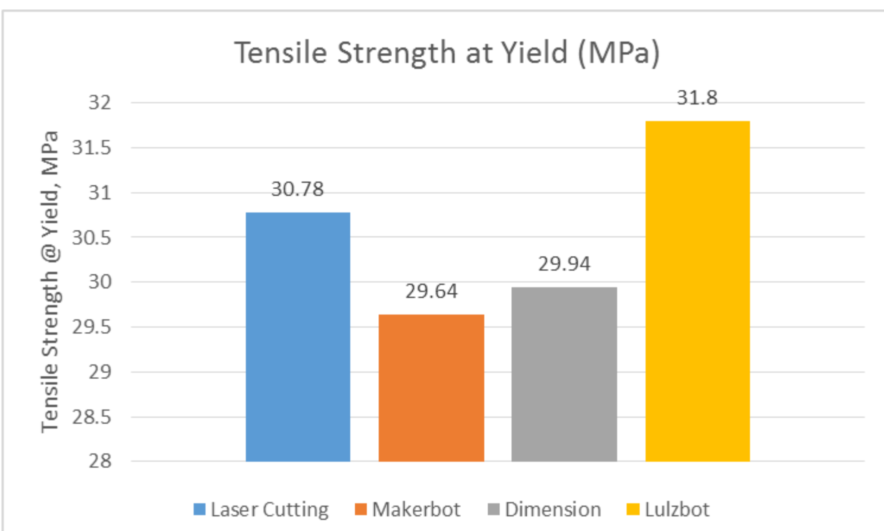

Figure 8. Comparison of tensile strength at yield of ABS specimens prepared by laser cutting (control) and 3D printing

Table V. % Elongation at yield of ABS specimens prepared by laser cutting (control) and 3D printing

Percent Elongation at Yield (%)				
Specimen #	Laser Cutting	Makerbot	Dimension	Lulzbot
1	2.17	2.40	2.11	2.16
2	1.87	2.39	2.09	2.10
3	1.94	2.32	1.95	2.08
4	1.86	2.36	2.09	2.38
5	1.98	2.46	2.12	2.02
Mean	1.96	2.39	2.07	2.15
Std. Dev.	0.13	0.05	0.07	0.14

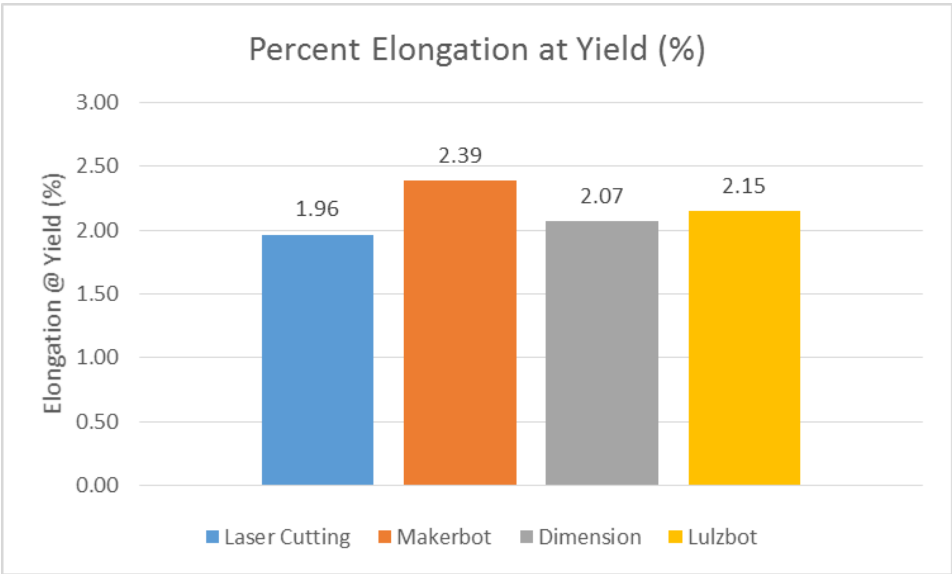

Figure 9. Comparison of Percent elongation at yield of ABS specimens prepared by laser cutting (control) and 3D printing

Table VI. Tensile strength at break of ABS specimens prepared by laser cutting (control) and 3D printing

Tensile Strength at Break (MPa)				
Specimen #	Laser Cutting	Makerbot	Dimension	Lulzbot
1	26.5	27.4	26.1	30.9
2	26.2	27.3	26.2	27.8
3	27.5	28.1	24.9	29.2
4	28.2	27.4	25.5	28.7
5	27.1	27.9	26.8	29
Mean	27.1	27.62	25.9	29.12
Std. Dev.	0.80	0.36	0.72	1.13

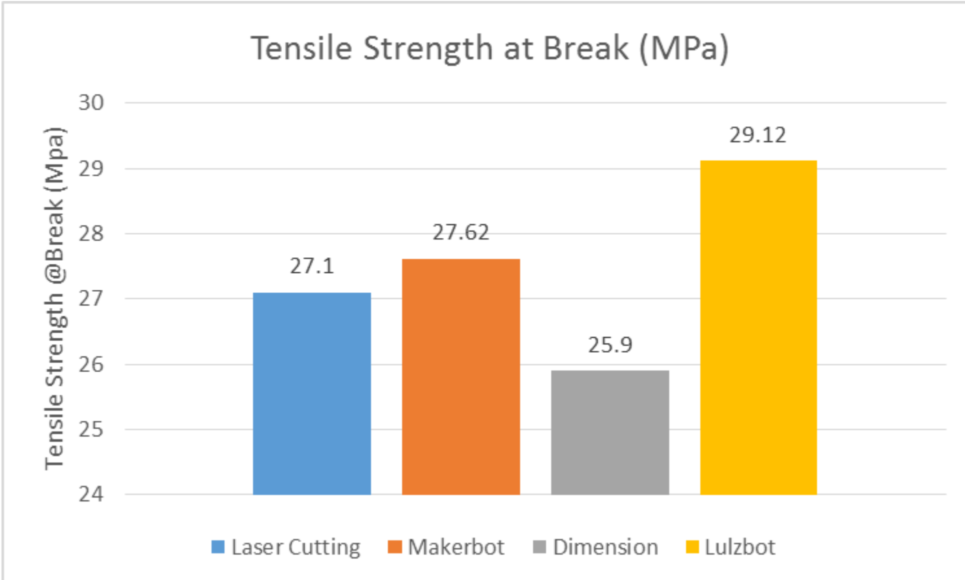

Figure 10. Tensile strength at break of ABS specimens prepared by laser cutting (control) and 3D printing

Assessment

The authors used two methods, namely survey and quiz instruments, to assess students learning outcomes in this study. In both methods, the instruments were given before and after the topics of materials' tensile properties and measurements were covered in class lectures. Students were formally introduced to the FDM machines after the subject of tensile specimen preparations was covered in class even though 83% of the students had prior familiarity with these machines. Table VII shows the results of the survey and quiz. The difference in the results between the survey and quiz may have been caused by the requirements of the survey and quiz. With the survey instrument, the students were instructed not to write their names on the survey sheets while their names were required for the quiz, because their scores on the quiz would be a component of their course grades. The "before" survey and quiz were given on separate days while the "after" survey and quiz were given on the same day.

Table VII. Determining extent of learning outcomes of using 3D Technologies to introduce ASTM Standards

Learning Outcome	Survey		Quiz	
	Before	After	Before	After
Pass rate	43.8%	57.1%	52.5%	79.5%

Table VIII. Determining improvement in learning outcomes of using 3D technologies to introduce ASTM Standards

Learning Outcome	Quiz		
	Before	After	Difference
Knowledge of ASTM D 638 (for plastics)	33%	83%	50% improvement

Knowledge of ASTM E 8 (for metals)	17%	100%	83% improvement
Knowledge of 3D Printing Technology	100%	100%	None
Problem solving skill. For example, determining the tensile stress in a bar subjected to a force	20%	92%	72% improvement
Problem solving skill. For example, using Hooke's Law to determine the tensile strain in a rod subjected to a force.	0%	62%	62% improvement

The results shown in Tables VII and VIII demonstrate an improvement in learning outcomes particularly with respect to the results of Table VIII. However, the proportion of the observed improvement that could be attributed to the use of 3D printing technologies in this study is not entirely clear. What was certain in this study was that students appeared motivated to explore the use of 3D printing to make tensile test specimens. A definite assertion of the percent contribution of the use of 3D technologies to the learning outcomes shown in Tables VII and Table VIII would require more studies.

Conclusion

The results of this study show that 3D printing is a viable option to prepare ASTM tensile test specimens of ABS plastic materials, at least, in a 100-level university and college materials' courses, because the measured tensile properties of ABS prepared by 3D printing were not significantly different from those prepared by laser cutting ABS plastic sheet. Furthermore, the lower costs and convenience of preparing tensile test specimens by 3D printing make using the technology attractive. Assessment of the learning outcomes of incorporating the use of 3D printing tensile test specimens for measuring materials' tensile properties may have improved students learning outcomes because of the motivation of students to explore new technologies in traditional courses.

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