Mechanical Evaluation of 3 D Printed Polymers - a New Lab Design

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Abstract

A new laboratory experiment for junior mechanical engineering students was developed involving testing the mechanical properties of 3D printed polymers. Additive manufacturing technique is attractive for polymeric materials due to its versatile use and cost effectiveness. Students were required to design 3D printed polymer samples following specific dimensions resulting from ASTM requirements and according to available mechanical testing equipment capabilities. After manufacturing the samples, mechanical properties (i.e. ultimate tensile strength, stiffness, ductility, hardness) were characterized by performing ASTM compatible mechanical testing. Students were required to search different methods to improve the mechanical properties of 3D printed polymers by using different temperatures and times for heat treatment of the structures or by using micro particles imbedded in the polymers for reinforcement. The new laboratory is creating an environment that is enhancing the students' ability to develop and conduct appropriate mechanical testing evaluations, analyze and interpret data, draw conclusions, and based on acquired data to offer suggestions for materials properties improvement.

Keywords

3D Printing, Tensile Testing, Heat Treatment, Particle Reinforcement

Introduction

The junior mechanical engineering laboratory have been encountered with increasing number of students during past years. A new lab was developed to accommodate for larger student groups while introducing novel concepts according to new technologies and materials. The objective of the lab is to investigate the mechanical properties resulting from tensile testing of 3D printed polymers by constructing standardized stress-strain diagrams and to propose methods of improving the 3D printed polymers mechanical behavior. There is a recent increase in global production of polymeric based products due to their low cost, low weight and easy manufacturing process. The additive manufacturing technique, or 3D printing is a cost efficient, fast manufacturing method attracting recent interest in many industrial fields, medicine and research as it can offer high quality, high precision polymeric products. During their service, the parts made from 3D printed polymers are subjected to forces and experience different amounts of mechanical and environmental stresses, therefore their mechanical behavior is an important factor for different applications. The new lab provides students with the opportunity to apply theoretical knowledge acquired in the classroom, to explore and solve real-world engineering problems through hands-on experiences.

The manufacturing processes of polymeric materials are affecting the mechanical performances of the final products [1-3], with molded parts tending to have more desirable mechanical properties as compared to 3D printed parts. This is because 3D printed samples are anisotropic and can have premature failure at the raster terminations (where the printer's raster direction changes) as well as poor layer adhesion that limits the transverse strength and stiffness [4]. Therefore, features such as filament orientation and build direction can affect the mechanical properties of the final parts [4-7]. Improvements to the mechanical properties of these polymers have been shown through various processes. Polymers can be reinforced with other materials, such as particles and fibers that can improve their final mechanical properties [8]. Recent studies have shown that heat treatments can improve the mechanical properties of some polymers (e.g. Polyether ether ketone (PEEK) and Polyphenylene Sulfide (PPS)) by improving layer adhesion and relieving internal stresses resulted during the manufacturing process [9, 10].

It is important for students to recognize the capabilities of 3D printed polymers and predict their performance under different loading conditions. The American Society for Testing Materials (ASTM) is providing general standardized testing methods for analyzing materials' deformations, strengths, fracture, and mechanisms of failure; however it is not providing specific testing methods for additive manufactured polymers. According to ASTM D638-02a [11] tensile testing can be employed to understand the performances and limitations of polymeric based materials. The results of the testing are the stress-strain curves that can be used to obtain the yield strength, tensile strength, strain, and ductility behavior. Further analysis of the curves are necessary to determine the resilience and fracture toughness or impact resistance of the materials.

The new lab experiments for junior mechanical engineering students is designed to address the ABET requirements by offering students the "ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgement to draw conclusions". Students are required to design and perform ASTM compatible and reliable tests using the existing equipment and report the mechanical properties such as: hardness, stiffness, yield and ultimate tensile strength. They are required to analyze different perspectives and theories about 3D printed polymers mechanical properties and possibilities of improvement, to propose solutions related to heat treatment cycles (corresponding temperatures and times), and choices of particle embedment to improve the mechanical properties. The lab is responding to ABET outcome concerning development of students' "ability to function effectively on a team whose members establish goals, plan tasks, meet deadlines, provide leadership and create a collaborative and inclusive environment". Students are implementing basic research methods to address materials properties improvement based on existing methods and research. At the end of the labs, students are writing reports including the testing procedures, results and methods developed for properties improvement.

Experimental Methods

The standard requirements and tensile testing equipment capabilities are used to determine the size of the samples in order to test the mechanical properties of 3D printed polymeric materials. Based on calculations students must recommend the appropriate sample dimensions for the available Mark-10 ESM303 Motorized Test Stand. The equipment is a single-column force tester for tension and compression measurement applications with a maximum 300 lbf (1.5 kN) capability, with selectable speed setting and USB output of force versus time or force versus travel distance. Students are investigating the literature for the available strength recommendations for the polymeric materials. For example, most manufacturers are reporting strengths values of 40 +/- 10 MPa for PLA (Polylactic acid, an environmental friendly material) with higher values for particle reinforced PLA. Students are using the anticipated polymer strength values in order to determine the critical cross-sectional area that will result in polymer total fracture during the tensile testing. A safety coefficient was considered and the maximum force for calculations was below the available maximum force (1.3 kN). According to calculations and standardized dimensions resulting from ASTM D638 2a, only types IV and V samples may be used for performing the test. Similar calculations were performed for other polymers selected for testing: Nylon and ABS (acrylonitrile butadiene styrene, a biocompatible polymer) and for the composite polymers: copper nanoparticles and carbon fiber reinforced PLA in order to find the anticipated load at failure. Due to the fact that type IV sample size offers a smaller cross-sectional area, the type V sample was finally selected and recommended for further manufacture and testing. The general samples dimensions according to standards are: 9.53 mm (0.375 in) length, 3.18 mm (0.125 in), with a gage length of 7.62 mm (0.3 in).

In order to manufacture the polymeric samples, a 3D model of the standardized sample was generated using Solid Works and then 3D printed using the available printing equipment. Two different colors were used for printing the PLA samples to distinguish samples with a longitudinal pattern (white samples) from samples with transversal pattern (orange samples). Some of the manufactured PLA samples were exposed to heat treatments. Students searched existing literature for possible heat treatment conditions and recommended cycles consisting of different temperatures and times. Each group of students had a final choice of two heat treatments that were performed in available Lucifer furnaces. For example, the procedures were performed at temperatures of 71 ^{0}C (160 ^{0}F) or 85 ^{0}C (185 ^{0}F), with times of exposure: 30, 60, or 90 minutes. The variation of temperatures and times enabled the study of heat treatment influence upon the mechanical properties. The other polymeric materials (Nylon and ABS) and polymer composites (copper filled and carbon fiber reinforced PLA) were also manufactured using the 3D printing equipment with similar final dimensions. Students measured the manufactured samples dimensions to confirm they were within the tolerance ranges required by standard. After the samples preparation, mechanical tests were conducted according to ASTM D638 2a standards. The MTS Mark-10 provided data for force as a function of displacement, from which a stress-strain relationship was obtained using the known dimensions of samples.

For the final report students analyzed the collected data by plotting the stress-strain diagrams for tested samples and determined the average elastic modulus, ultimate tensile strength and yield strength for each polymer and polymer composite type. They calculated and commented on the resilience, fracture toughness and ductility of the selected polymers and composites and modes of fracture. The results were correlated with hardness measurement, observing the influence of the pattern directions and the influence of particle reinforcement on the mechanical properties. The influence of different cycles of heat treatment using different temperatures and times on the mechanical properties enhancement was also analyzed. Students are using and applying knowledge acquired in previous classes (i.e. Statics and Strength of Materials, Materials Engineering) in a more complex setting of a lab containing hands on experience and research components. The lab is simulating the real world application and understanding of the new classes of materials as a good preparation for the future workplace. It is responding to the outcome related to the “ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics”. They are working for designing and testing polymers that are environmentally-friendly and/or have biomedical applications.

Results and Discussion

The 3D printed polymeric based samples were tested in order to observe and characterize the effects of the manufacturing procedure, different heat treatment cycles and particle reinforcement upon the mechanical properties. The tensile testing was performed on all samples and the resulted stress-strain curves were analyzed to reflect the improvement effects. The mechanical properties of samples with transversal and longitudinal raster orientations during the sample manufacturing were initially compared. The general trend for PLA showed a higher strength recorded in the case of transversal printed samples. An example of the stress-strain curve is represented in Figure 1 and is showing that the properties of both samples were similar at lower values of stress; however, with stress increase, the transversal raster orientation PLA had higher performance while the longitudinal samples suffered an early failure.

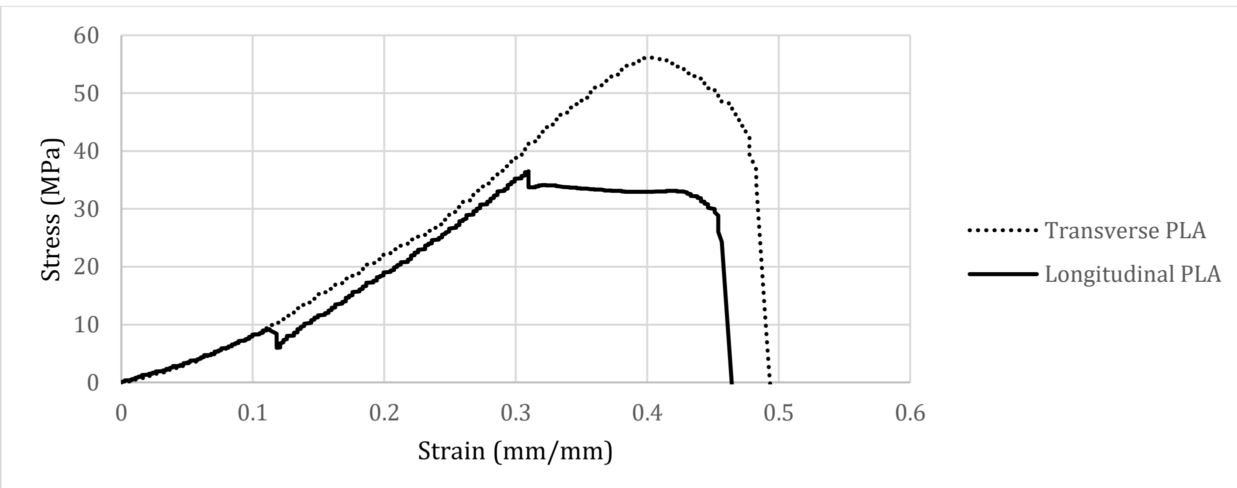

Figure 1: The stress-strain relationship showing the effects of raster orientation during the 3D printed PLA manufacture on the mechanical properties

Due to the fact that transversal printed PLA had a better mechanical behavior, the effects of different heat treatment cycles on the mechanical properties was further analyzed using the transversal manufacturing method. It was observed an improvement in the ductility of the samples due to heat treatment with no significant changes in strength. Both the duration and the temperature magnitude of heat treatment procedures were parameters that affected ductility. For example, an increase in ductility was recorded for shorter exposure times and lower heat treatment temperature cycles (e.g. 30 minutes and 160 ^oF). The higher temperature cycles (e.g. 185^oF) showed ductility improvements over non heat treated samples, but with longer exposure times, ductility decreased. The general trends of the stress-strain curves showing the heat treatment cycles influence on PLA samples are represented in Figure 2.

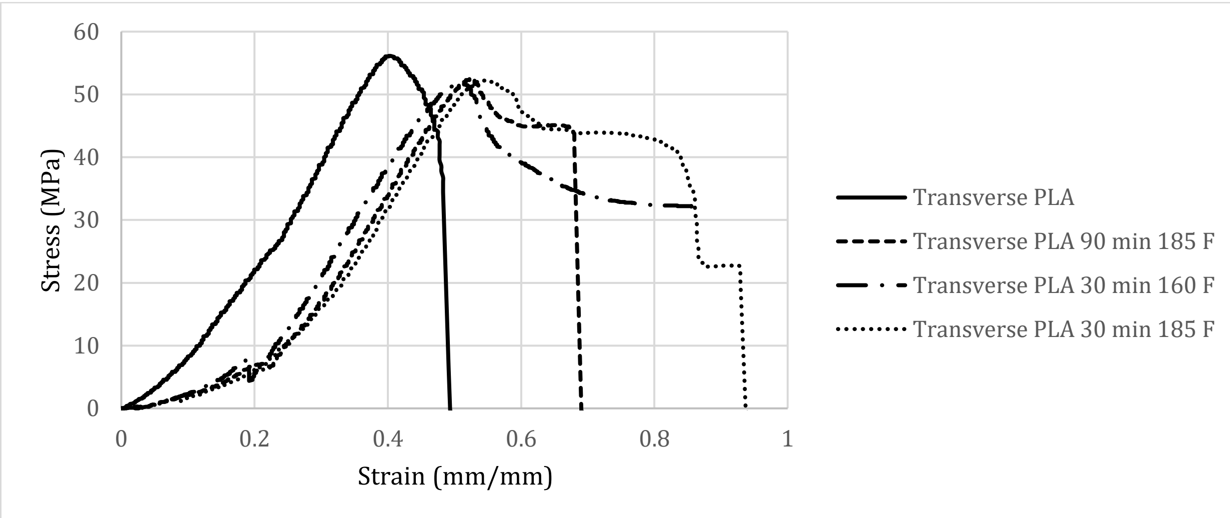

Figure 2: The stress-strain relationship showing the effects of heat treatment cycles on the mechanical properties of 3D printed PLA

Further on, it was observed that particle reinforcement had minor effects on the mechanical properties. The carbon fiber (CF) reinforced PLA had a higher strength when compared to simple (unreinforced) PLA while the copper (CU) filled PLA had lower performance than simple PLA. The ductility was not affected by the reinforcement or by the type of the particles reinforcing the sample. Figure 3 shows a typical stress-strain curves for reinforced and simple PLA samples.

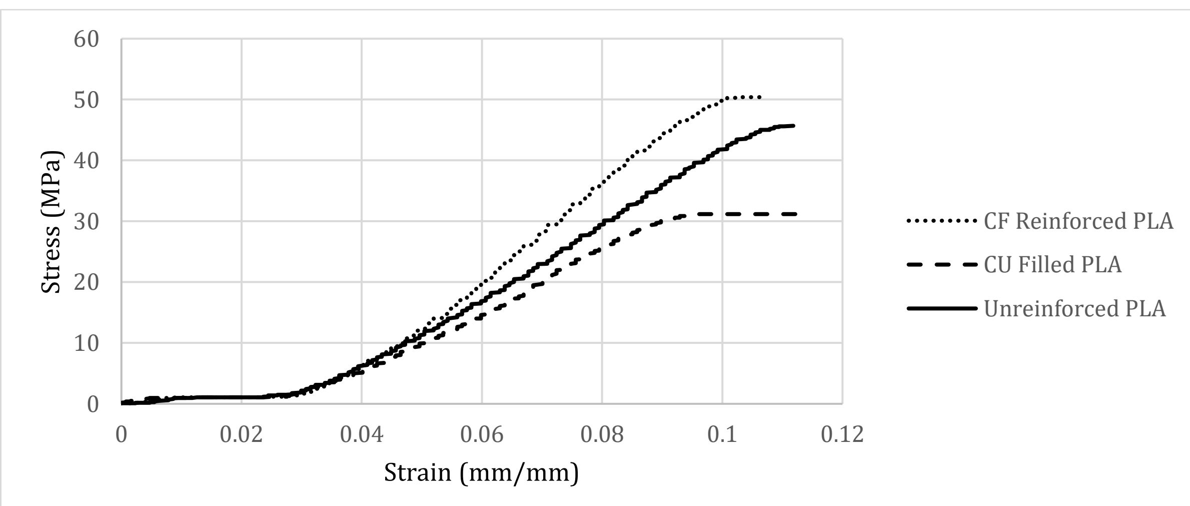

Figure 3: The stress-strain relationship showing the effects of particle reinforcement on the mechanical properties of 3D printed PLA

The changes in strength and ductility of transversal raster oriented 3D printed PLA samples after different heat treatment cycles is represented in Figure 4. The chart shows significant changes in ductility after different heat treatment procedures, but little improvement in tensile strength due to temperature and time variations. For example, it was observed that the ductility increased and almost doubled the initial values for 185 ^{0}F and 30 minutes heat treatment.

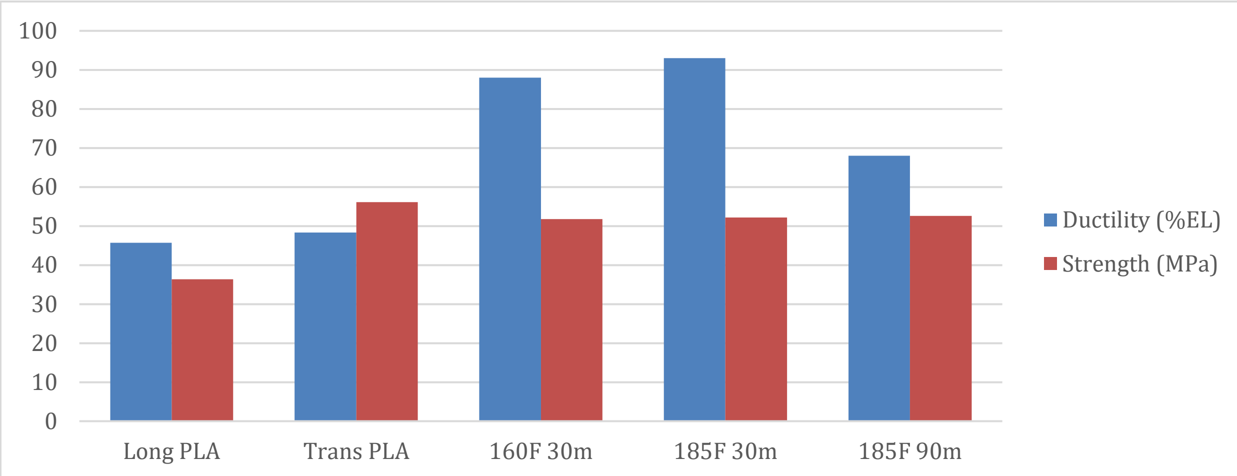

Figure 4: Ductility (%) and Strength (Mpa) for different heat treatment cycles for 3D printed PLA

The changes in the mechanical properties: ductility and strength for simple PLA, copper filled and carbon fiber reinforced PLA are represented in Figure 5. It was observed that the strength of PLA increased with carbon fiber reinforcement, but decreased for copper filled PLA. The ductility of all samples was similar, showing no improvement with particles addition.

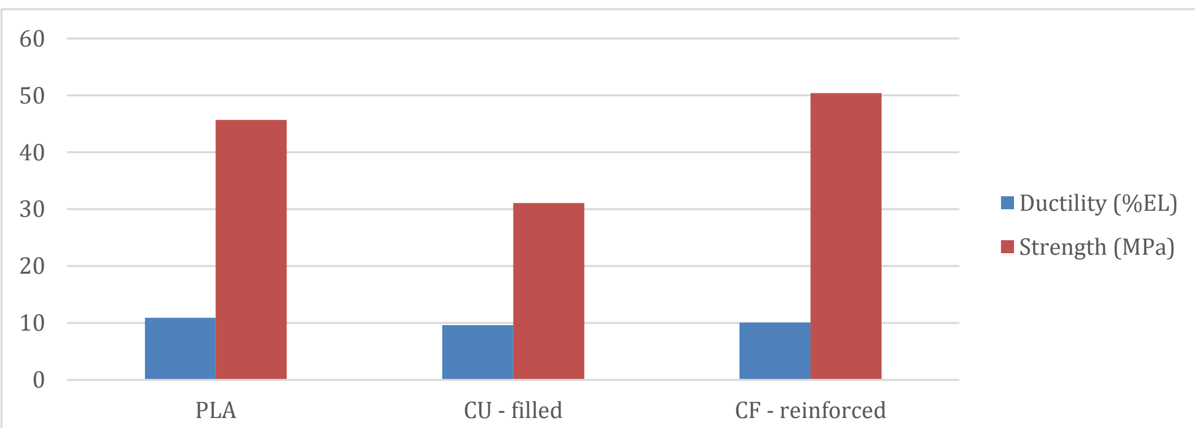

Figure 5: Ductility (%EL) and Strength (Mpa) for PLA, copper (CU) filled PLA and carbon fiber (CF) reinforced PLA

The lab offered students the opportunity to learn about biodegradable polymers (i.e. PLA), their importance for preserving the environment and to elaborate ethical reasoning related to the subject. They are also learning about biocompatible polymers (i.e. ABS) and the possibility of creating biomedical structures. The lab setting is responding to the ABET outcome referring to the "ability to apply engineering design to produce solutions that meet specified needs with consideration for public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" and to the outcome referring to the "ability to recognize ethical and professional responsibilities in engineering situations and make informed judgements, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts".

Conclusions

A new lab was developed for mechanical engineering students involving 3D printed polymers specimen design and mechanical testing. The testing was performed according to standardized requirements and available equipment. The students had the possibility to develop experiments, analyze and interpret data and draw conclusions through "hands on" experiences. They analyzed existing resources on mechanical properties of 3D printed polymers and searched for methods of improving the properties by using heat treatment cycles with different temperatures and times of exposure and by using particle embedment for reinforcement purposes. The lab offered students the possibility to function within a team with collaborative and creative environment, to establish goals and corresponding plans to achieve the goals. Students had the opportunity to relate the theoretical knowledge with experimental learning. The lab showed the differences in mechanical properties of 3D printing polymers depending on the manufacturing processes, the possibility of improving the ductility by performing heat treatments and the strength by using carbon fiber or other particles for reinforcement. They've learn about the importance of environmental friendly materials. The students' final reports include the testing procedures, the results and the methods developed for improvement of mechanical properties.

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