ADDITIVE MANUFACTURING OF SOFT AND COMPOSITE PARTS FROM THERMOPLASTIC ELASTOMERS

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Abstract

Thermoplastic elastomers (TPEs) are low-durometer materials that can support large strains without breaking, making them attractive materials for producing 3-D printed soft components. However, prefabricated TPE filament, especially those with low hardness, cannot be used in typical filament feed extrusion mechanisms that are popular in material extrusion-based 3-D printers today.

Therefore, we have developed a mini-screw extruder, small enough to be incorporated on a typical 3-D printer system, and capable of extruding various TPE formulations directly from commercially available pellets. This paper presents the design and thermal analysis of the mini-extruder, experimental testing of the 3-D printing process for TPEs with nominal hardness in the range of 5 – 52 Shore A, and compression and tension tests of the properties of printed parts. By combining 3-D printing of soft TPEs with rigid thermoplastics, the new system also opens up new possibilities in additive manufacturing of soft and hard composite parts.

Introduction

Thermoplastic elastomers (TPEs) are materials that can support large strains without breaking (several hundred percent or more) and have good mechanical strength (typical tensile strength 10 – 21 MPa) [1]. TPEs can be readily found in hardness ranges from 95 to 5 Shore A, making them attractive materials for producing 3-D printed soft, rubber like components.

Nevertheless, low hardness prefabricated TPE filaments cannot be used in typical filament feed extrusion mechanisms that are popular in material extrusion-based 3-D printers today. Consequently, 85-98 Shore A is the typical range of hardness for the commercially available products [2]. Other additive manufacturing methods, such as Stratasys Polyjet, use UV-cured liquid photopolymers and can combine rigid and rubberlike materials to simulate nine Shore A values from Shore 27 to Shore 95 [3, 4]. However, the mechanical properties of these materials are usually lacking compared to TPEs, with typical tensile strength in the range of 1.5 – 10 MPa, and elongation at break between 35 – 130%.

The paper presents the design and thermal Finite Element Analysis (FEA) of a novel mini-extruder capable of extruding TPE formulations in a wide hardness range, directly from commercially available pellets. The mini-extruder has been incorporated on a custom additive manufacturing system and standard specimens for tensile and compression tests have been fabricated. The experimental results for the force-elongation measurements and stress-strain curves are presented for three elastomers spanning the hardness range from 5 to 52 Shore A. Lastly, several multi-material parts 3D-printed from soft TPEs and rigid thermoplastics are presented.

Extruder Design

Industrial screw extruders, such as the Killion LX-4, can produce TPE filaments with relative ease. However, prefabricated TPE filaments with low Shore hardness tend to buckle under the axial stress when fed into the hot-end extrusion blocks prevalent in today's Fused Deposition Modeling (FDM) 3D printers. In addition, because of their large elasticity the TPE filaments are hard to grip by the feeding rollers or gears [5].

Therefore, our goal was to develop an extruder capable of working with TPE formulations in a wide range of hardness, and compatible with a typical 3-D printer system from the size, geometry, and control and operation perspective. Specifically, the extruder was intended to function with commercially available 5 - 90 Shore A elastomer pellets, and to be incorporated in the Fiber Encapsulation Additive Manufacturing (FEAM) printer, recently developed by LAMRA [6].

We have selected a *smooth bore - single screw* configuration for its compactness and ease of manufacturing. The steel barrel is mounted at 45° to vertical and the elastomer pellets are fed distally through a custom hopper 3D-printed from ABS (see Fig. 1a). The hopper can swivel about the extruder longitudinal axis for filling and emptying the pellets, and is equipped with a vibrator that facilitates pellet flow into the feed section of the screw. The Ø9.3×170 mm constant pitch screw (length-to-diameter ratio, L/D = 18) feeds the pellets through the transition (melting) section of the extruder barrel, which is maintained at the set temperature by a Ø20×25 mm, 45 W collar heater as seen in Fig. 1b. A Ø6×20 mm, 75 W cartridge heater is used to control the temperature of the hot end block. The temperature is sensed using a bolt-on washer thermocouple (Omega WTJ-8-36) mounted laterally on the hot-end block and is controlled by a CN142 universal temperature process controller (Omega, Stamford, CT).

The hot end block is equipped with a vertically oriented Ø500 µm brass extrusion die (Quintessintal Universial Building Devices [7]) that is utilized as a print nozzle (see Fig. 1b). The extrusion rate is controlled using a high torque 23HS30-2804S-PG47 geared stepper motor (StepperOnLine Motors & Electronics, Nanjing, China) connected to a spare axis of the FEAM printer motion controller (DMC4183, Galil Motion Control, Rocklin, CA). The melt feed rate is calibrated based on the screw's volumetric capacity and the print nozzle diameter. Extrusion can be stopped quickly by stopping and driving the motor in reverse for a prescribed angle based on the TPE used in extrusion.

The mini-extruder is assembled on the base plate using a bolt-on solid aluminum mounting bracket. The bracket cap is equipped with fins and acts, together with the base plate, as a heat sink. In conjunction with the collar heater this design creates the appropriate temperature distribution along the extruder barrel to insure proper melting of the polymer material at the lower extremity, while the upper regions are maintained cool enough to prevent pellet aggregation in the hopper. The base plate mounts on the existing vertical plate of the FEAM printer Z-stage through a XY fine adjustment mechanism.

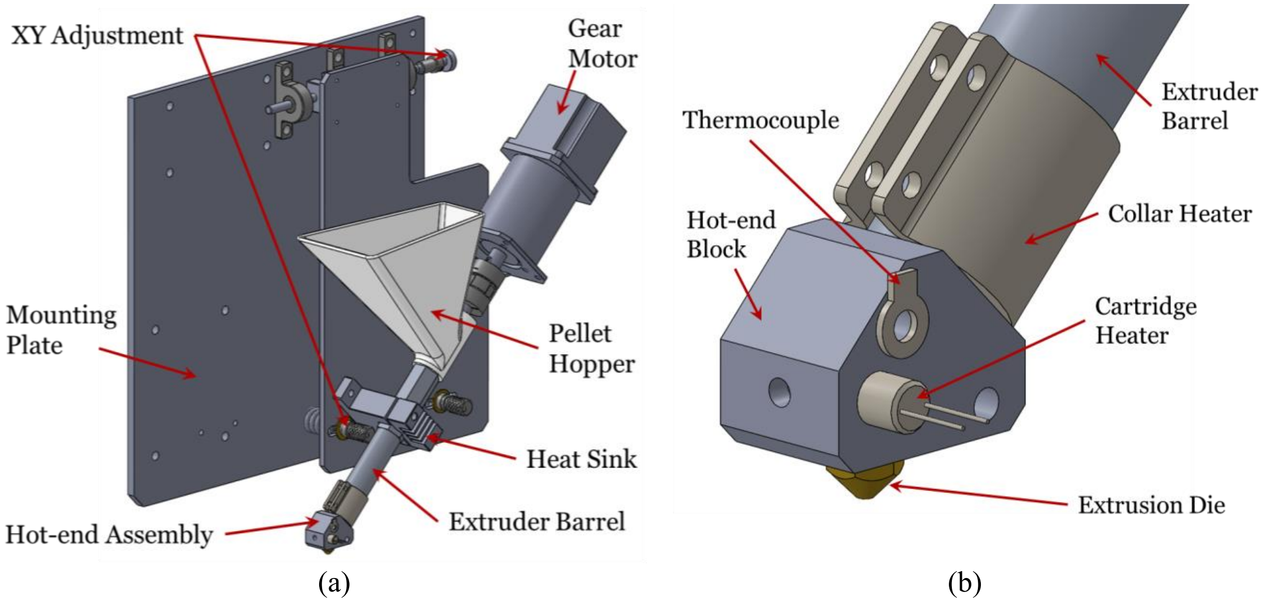
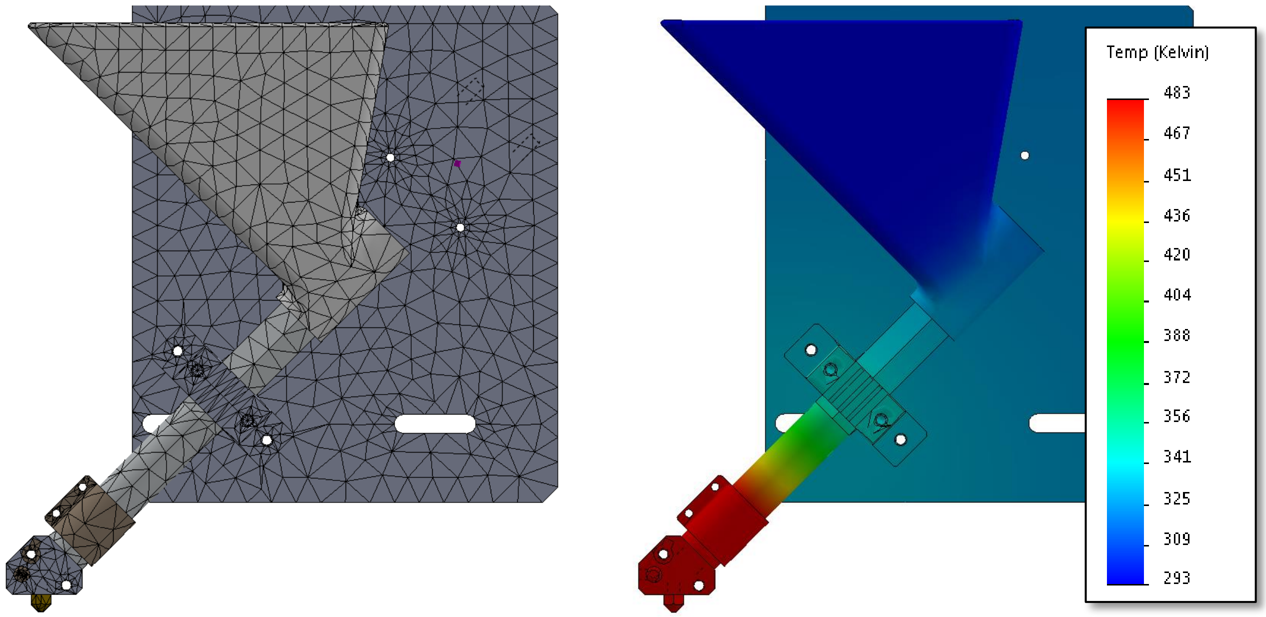


Figure 1. CAD representation of the mini-extruder with mounting and adjustment system for integration in the FEAM system (a); detail of the hot-end assembly (b).

Thermal Analysis of the Mini-Extruder Design

For the mini-extruder to function properly it is necessary to produce and maintain a relatively constant temperature at the printing nozzle, high enough to produce easy flow of the elastomer through the extrusion die and to insure intra and inter layer adhesion of the extrudate to the printed material. A high temperature gradient is necessary along the extruder barrel such that the elastomer material is transitioned from close to ambient temperature at the feed section to a temperature higher than the TPE's melting temperature in the transition and metering sections of the screw. Moreover, the collar heater has to be able to produce sufficient heat to completely melt the elastomer during fabrication.

To test the feasibility of the design we constructed a FEA model of the extruder using the Simulation module from SolidWorks 2014 package (Dassault Systèmes SOLIDWORKS Corp., Waltham, MA, USA). The 3-D CAD assembly file was imported as a Thermal Study with global component contact set to "Bonded". To speed up the analysis the gear motor assembly was excluded from the analysis, its contribution to the temperature of the working sections of the extruder being minor. Material properties were assigned from the software library or according to the manufacturers' specifications. The temperature of the cartridge and collar heaters was set as "Constant Temperature" at the desired working value of 483 K (210 °C) used for the temperature controller. Convection and radiation boundary conditions were set for all exposed surfaces with a convection coefficient of 5 W/m^2 K and emissivity 0.07. The ambient temperature was set to 293 K (20 °C). The model was discretized using a tetrahedral solid mesh with 15,978 elements, 30,373 total nodes and maximum element size of 10 mm, as shown in Fig. 2a. A Dell OptiPlex 7010 workstation with 3rd Gen Intel Quad Core i5-3470, and 16 GB DDR3, 1600 MHz RAM was used to run the FFEPlus iterative solver to obtain the steady state solution.



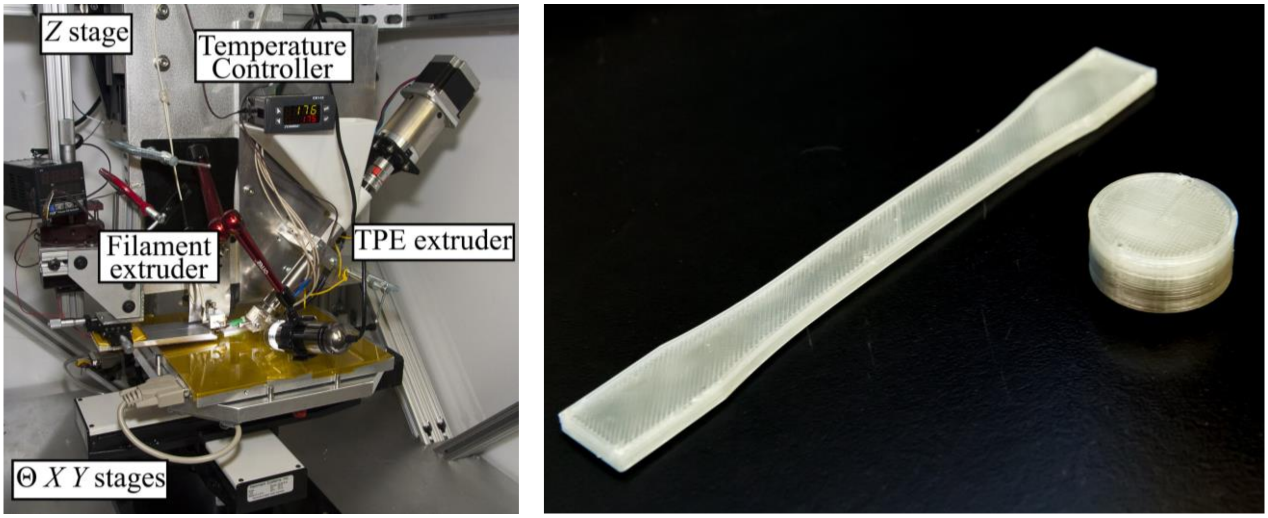
(a) (b)

Figure 2. Solid mesh of the relevant components of the mini-extruder model with 15,978 elements and 30,373 total nodes (a); FEA results for the temperature distribution for 483 K working temperature (b).

The results shown in Fig. 2b show the temperature distribution on the components under analysis. The temperature of the hot-end block is relatively uniform with only 2 K (2 °C) variation in its entire volume. The temperature at the printing nozzle was calculated as 481 K (208 °C), which was deemed adequate for reliable adhesion of the extrudate to the previously deposited material. The power required to maintain the working temperature in steady state was 35.25 W, well within the capabilities of the heaters. Distal from the collar heater the temperature gradient along the extruder barrel exceeded 3,000 K/m. Thus, the maximum estimated temperature at the pellet hopper was 332 K (59 °C), sufficiently low to prevent material softening as well as pellet aggregation.

Fabrication of Specimens for Experimental Testing

Based on the design presented in the previous sections, a prototype of the TPE mini-extruder was manufactured and integrated in the FEAM additive manufacturing system under development by the Laboratory for Additive Manufacturing, Robotics, and Automation (LAMRA) in the Department of Mechanical Engineering, Southern Methodist University, Dallas TX [6]. The process is an extension of Fused Deposition Modeling (FDM) in which both a fiber (e.g., metal wire, or non-metallic fiber) and the matrix (e.g., a thermoplastic polymer) are deposited simultaneously (see Fig. 3a). In this system the printing hardware (nozzle, extruder, wire feeder, etc.) remains fixed in the XY plane while a *Z* positioning stage allows the deposition of successive layers in the vertical direction, generating a three-dimensional part [6, 8].



(a) (b)

Figure 3. Photograph of the FEAM additive manufacturing system equipped with the TPE mini-extruder (a); Test specimens manufactured using the mini-extruder for tensile (ASTM D638-02a) and compressive (ASTM D575-91) testing of material properties (b).

In order to assess the mechanical properties of the elastomers, two types of tests have been selected: tensile testing using the ASTM's Standard Method for Tensile Testing of Plastics (ASTM D638-02a) [9] and compression testing following ASTM's Standard Test Methods for Rubber Properties in Compression (ASTM D575-91) [10]. Accordingly, two types of test specimens were modeled in SolidWorks 2015. The parts were exported to STL file format, and KISSlicer 1.4.5.10 x64 (http://www.kisslicer.com) was used to slice the geometry and generate GCode tool paths. The layer thickness was set to 0.254 mm and the trace width at 0.45 mm. The infill was set as solid with 3 skin layer loops, with 45° raster and direction alternating each layer. A custom script was used to convert from GCode to GalilCode, the language the GalilMC DMC4183 controller employed in the FEAM system. The motor controller was operated using the linear interpolation mode with the magnitude of the velocity vector held constant.

Three materials, spanning a wide hardness range were selected for the test specimens. Kraton G1643 M and D1161 P are clear, linear triblock copolymers based on styrene and isoprene, with polystyrene content of 20% and 15% respectively (Kraton Polymers, Torrance, California). The third selected material was ChronoPrene 5A (AdvanSource Biomaterials, Wilmington, MA), which is a biocompatible TPE based on styrenic olefinic rubber and hydrogenated isoprene. Table 1 presents the relevant mechanical properties of these materials as specified by the manufacturers.

Table 1. Manufacturer specified mechanical properties of selected TPEs

Property	Unit	Kraton G1643 M	Kraton D1161 P	ChronoPrene 5A
Hardness	Shore A	52	32	5
Elongation at Break	%	>600	1300	700-900

Tensile Strength	MPa	10	21	0.34-0.69
Specific Gravity	g/cc	0.90	0.92	-
Styrene / Rubber ratio	-	20/80	15/85	-
Melt Flow Range	g/10min	12.50-25.00	-	2-26

It was found that the Kraton G1643 M and D1161 P TPEs extrude well in the mini-extruder at the working temperature of 483 K (210 °C), and extrusion velocities of 18.2 and 16.4 mm/s respectively. Good quality parts from ChronoPrene 5A were obtained at lower extruder temperature, 468 K (195°C), and lower extrusion velocity (15.3 mm/s). The dimensions prescribed by the standards and the actual dimensions for the fabricated tensile and compression specimens are shown in Tables 2 and 3.

Table 2. Prescribed and actual dimensions for the ASTM D638-02a Type I specimens

Dimension, mm	*L*	*D*	*LO*	*WO*	*T*	*W*
Standard	57	115	165	19	3.2	13
Tolerance	0.5	5	-	6.4	0.4	0.5
D1161 PT	57	115	164	19	3.2	12.6
G1643 MS	57	114	164	19	3.4	13
ChronoPrene 5A	57	116	165	19	2.6	12.8

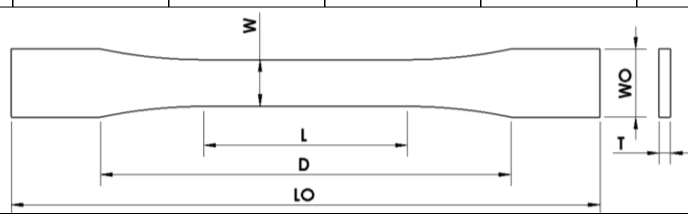
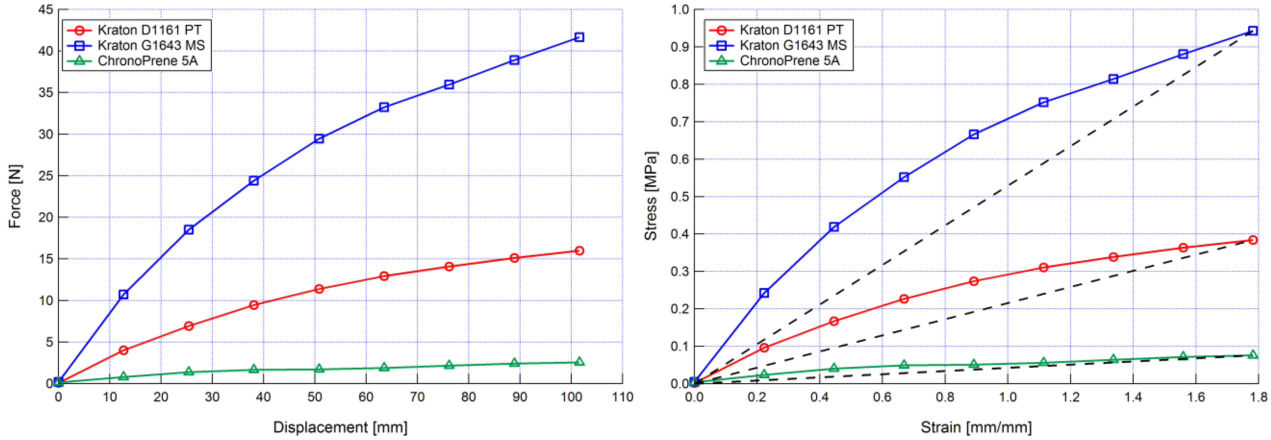


Table 3. Prescribed and actual dimensions for the ASTM D575-91 specimens

Dimension, mm	Diameter	Thickness
Standard	28.6	12.5
Tolerance	± 0.1	± 0.5
D1161 PT	28.56	12.40
G1643 MS	28.66	12.47
ChronoPrene 5A	28.8	12.55

<u>Experimental Testing</u>

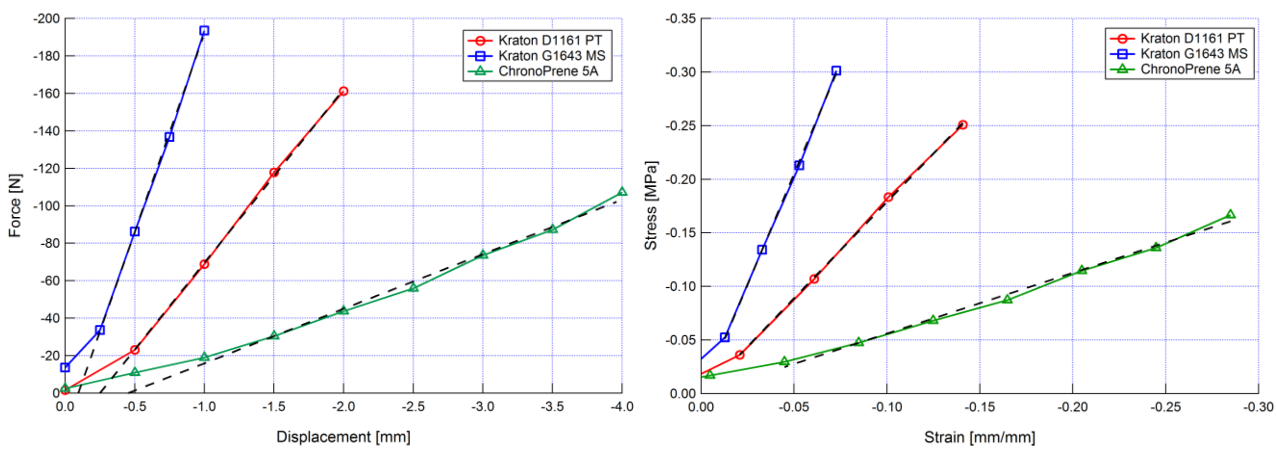
Before testing all specimens were conditioned for 48 hours at 23±2 °C and 50±5 % relative humidity, in accordance with ASTM Procedure A of Practice D 618. The tests were conducted at 23±2 °C and 50±5 % relative humidity. For tensile testing the specimens were placed in the grips of a custom testing machine, taking care to align the long axis of the specimen and the grips with an imaginary line joining the points of attachment of the grips to the machine. The distance between the ends of the gripping surfaces, *D*, is indicated in Table 2. The speed of testing was ~125 mm/min and the testing was stopped when the extension reached 101.6 mm. The load and the extension values were recorded at constant displacement intervals. As seen in Fig. 4a none of the specimens showed a significant linear region and no pronounced toe region was observed. In accordance to ASTM D 638-02a, the stress was calculated by dividing the load-extension curve by the original average cross-sectional area of the specimens (Fig. 4b). Since no linear region was present, the secant modulus was calculated by dividing the maximum nominal stress by the corresponding strain. The results are shown in Table 4.



(a) (b)

Figure 4. Experimental force-displacement curves for tension testing of Type I specimens (a); Engineering stress-strain curves for tension testing of TPE specimens (secant moduli shown with dashed lines) (b).

For the compression testing the specimens were placed between the platens of the testing machine and conditioned by applying 10% of the total load in five successive cycles. For the final cycle the machine was stopped at constant intervals of deflection for recording purposes (ASTM D575-91). Figure 5a shows the force-deflection curves for the three materials under testing. Pronounced toe regions followed by regions of linear behavior can be observed for all specimens.



(a) (b)

Figure 5. Experimental force-displacement curves for compression testing of cylindrical specimens (zero-strain point compensations shown in dashed lines) (a); Engineering stress-strain curves for compression of TPE specimens with (least square fits of elastic moduli are shown with dashed lines) (b).

Following ASTM 638-02a recommendations, the linear region of the curves has been extended through the zero-force axis, and the intersection points have been selected as zero-deflection points, from which all deformations have been measured. Using the original cross-sectional areas, the stress-strain curves shown in Fig. 5b have been obtained, and the elastic moduli were calculated by linear regression from the experimental data in the linear regions. The results for the three TPEs used in this work are presented in Table 4. Due to their internal structure, with elastic segments linking harder domains, TPEs deform much easier in tension than compression, as demonstrated by the much larger compression modulus compared to the tension secant modulus for each tested material.

Table 4. Experimental tension secant moduli and compression moduli for 3D printed TPE test specimens.

Material	Tension Secant Modulus MPa	Compression Modulus MPa
Kraton G1643 M	0.529	4.13
Kraton D1161 P	0.216	1.80
ChronoPrene 5A	0.047	0.567

Fabrication of Composite Parts from Thermoplastic Elastomers

Novel 3D printing techniques, such as FEAM, can already combine rigid thermoplastic materials with metallic and other type of fibers, enabling fabrication of fiber reinforced composites and even electromagnetic active components, such as speakers, sensors, and solenoids [6, 8, 11]. By integrating TPE mini-extruder developed in this project in the FEAM system we gained the ability to seamlessly combine elastomers with rigid materials opens a new, and largely unexplored, range of applications for additive manufacturing technologies. Several proof of concept parts have been designed and manufactured using Kraton G1643 M TPE and BendLay, a clear rigid thermoplastic material popular in 3D printing. Figure 5a shows a multi-material annular part in which a 2.54 mm (10 fabrication layers) core of elastomer has been sandwiched between two BendLay outer plates of similar thickness. This part demonstrates the ability to deposit the two types of thermoplastics in rapid succession. The adhesion at the interface between Kraton G1643 M and BendLay was found to be very good, making these materials mutually compatible for composite part printing.

(a) (b) (c)

Figure 5. Annular composite part with an thermoplastic elastomer core sandwiched between rigid thermoplastic plates (a); Capacitive force sensor with elastomer intermediate layer and outer shells that incorporate metallic wire fabricated monolithically by FEAM (b); proof of concept vibration absorber with elastomer annular region (c).

Using the same material combination a fully functional capacitive force sensor with elastomer intermediate layer, which improves sensitivity, and outer rigid shells that incorporate metallic wire electrodes was fabricated monolithically by the newly expanded FEAM system (see Fig. 5b). Finally, to test the ability to seamlessly switch between the two types of printing materials in the same deposition layer, a proof of concept vibration absorber was designed and fabricated. This part includes a compliant and dampening annular region of TPE bordered internally by a shaft housing and externally by a rigid mounting flange, both made from BendLay, as shown in Fig. 5c. As in the previous cases the inter and intra layer adhesion between the two materials was excellent, resulting in a flawless monolithically fabricated composite part.

Conclusions

We have designed, analyzed, constructed, and tested a mini-extruder capable of extruding various TPE formulations in a wide range of Shore A hardness directly from commercially available pellets. The compact size of the device and ease of control allows it to be incorporated on a typical 3-D printer system, adding the ability to fabricate elastomer or composite parts containing both rigid and elastic, rubber like, thermoplastics. Three TPEs, spanning the range of 5 – 52 Shore A hardness have been selected to test the mini-extruder, and standard test specimens for tension and compression have been fabricated. The experimental results show that the printed material has good mechanical properties for both tension and compression. During the tension tests we reached strain exceeding 180% without rupture and without remnant plastic deformation of the parts. The elastic moduli of the 3D printed material were comparable to the values published by the manufacturers of the TPEs under consideration, indicating good fusion intra and inter layer fusion. To our knowledge, the parts fabricated from ChronoPrene 5A have the lowest durometer ever 3-D printed.

Additionally by integrating the TPE mini-extruder in the newly developed FEAM additive manufacturing system we were able to produce good quality composite parts seamlessly combining the deposition of thermoplastic and rigid elastomers both in successive layers and inside the same fabrication layer.

The newly developed additive manufacturing capabilities open a wide range of applications for free form fabrication, such as soft robotics, testable prototypes of injection-molded rubber products, catheters and other minimally invasive medical instrumentation, soft consumer products, etc.

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Author Disclosure Statement

The authors have no financial conflicts.

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