Additive manufacturing promises to revolutionize manufacturing industries. However, 3D printing of novel build materials is currently limited by constraints inherent to printer designs. In this work, a bench-top powder melt extrusion (PME) 3D printer head was designed and fabricated to print parts directly from powder-based materials rather than filament. The final design of the PME printer head evolved from the Rich Rap Universal Pellet Extruder (RRUPE) design and was realized through an iterative approach. The PME printer was made possible by modifications to the funnel shape, pressure applied to the extrudate by the auger, and hot end structure. Through comparison of parts printed with the PME printer with those from a commercially available fused filament fabrication (FFF) 3D printer using common thermoplastics poly(lactide) (PLA), high-impact poly(styrene) (HIPS), and acrylonitrile butadiene styrene (ABS) powders (<1 mm in diameter), evaluation of the printer performance was performed. For each build material, the PME printed objects show comparable viscoelastic properties by dynamic mechanical analysis (DMA) to those of the FFF objects. However, due to a significant difference in printer resolution between PME (X-Y resolution of 0.8 mm and a Z-layer height calibrated to 0.1 mm) and FFF (X-Y resolution of 0.4 mm and a Z-layer height of 0.18 mm), as well as, an inherently more inconsistent feed of build material for PME than FFF, the resulting print quality, determined by a dimensional analysis and surface roughness comparisons, of the PME printed objects was lower than that of the FFF printed parts based on the print layer uniformity and structure. Further, due to the poorer print resolution and inherent inconsistent build material feed of the PME, the bulk tensile strength and Young’s moduli of the objects printed by PME were lower and more inconsistent (49.2 ± 10.7 MPa and 1620 ± 375 MPa, respectively) than those of FFF printed objects (57.7 ± 2.31 MPa and 2160 ± 179 MPa, respectively). Nevertheless, PME print methods promise an opportunity to provide a platform on which it is possible to rapidly prototype a myriad of thermoplastic materials for 3D printing.

1. Introduction

Extrusion-based 3D printing is among the most widespread additive manufacturing techniques, with users spanning from hobbyists to industrial manufacturing companies [1–5]. The widespread adoption of extrusion-based 3D printing can be largely attributed to the low-cost and straightforward method of printing compared to other printing techniques (e.g. stereolithography, laser sintering, polymer jetting, etc.) [6–10]. Application of extrusion-based 3D printing techniques have enabled the rapid and customized production of 3D objects, ranging from example from art to coatings to force-sensing technologies [11–14]. A common extrusion-based additive manufacturing method is fused filament fabrication (FFF), in which a thermoplastic filament is heated and passed through a printer head to create a 3D printed object by layering the extrudate in specified shapes [15–18].
adoption of these novel 3D printable materials has been slow due to the high cost and the requirement for pre-processing the raw materials into filament or pellets. To date, the two foremost examples of extrusion-based 3D printing from a pellet feedstock rather than a filament feedstock, have been demonstrated by big area additive manufacturing (BAAM) techniques [28–30] and Titan Robotics’ Atlas printer series [31]. Titan’s Atlas printer series can be modified to print production scale projects from thermoplastic pellets, and contains a build volume of 30" x 30" x 45". However, the industrial scale of the BAAM techniques and the Atlas printers is not conducive to laboratory scale use. Thus, bench-top pellet extruders capable of printing less material have been fabricated such as, Direct3D [32] and the Rich Rap Universal Pellet Extruder (RRUPE) [33]. Although these two pellet extruders expand the variety of materials that can be printed [34] and are capable of printing smaller parts (on the order of 200 mm³ or less), they are not designed for 3D printing of material feedstock that is not pre-processed into the form of pellets. This limitation of pellet extruders further restricts which thermoplastic materials can be 3D printed and presents an obstacle to printing non-processed novel material feedstock. Rather than requiring new materials to be printed by the FFF or pellet extrusion techniques, the ability to print directly from powder granules makes the process of 3D printing novel materials more accessible by reducing the need for specialized equipment beyond a printer head.

Here, we report a bench-top PME printer that was fabricated through modification of the Rich Rap Universal Pellet Extruder (RRUPE) design [33] and tested with powders (particle size range of 0.038 mm–1 mm in diameter) of common 3D printing thermoplastics, including poly(lactide) (PLA), high impact poly(styrene) (HIPS), and acrylonitrile butadiene styrene (ABS) (Figure S8, S9, and S10). The sources of each of these thermoplastic powders were mechanically ground FFF printed parts. The parts being ground were often defective parts that would have been disposed of, normally. The resulting PME prints were compared to FFF prints based on print quality, print resolution, material viscoelasticity, and bulk material tensile properties to determine the initial viability of the PME 3D printing technique.

2. Printer head design and modifications

Development of a 3D printer that can directly use a thermoplastic powder build material requires an understanding of the fundamental relationships between the printer head design and printer performance. Therefore, the design of the printer head is the major focus of the current study as it is critical to the success of printing 3D objects directly from powder. Analysis of current printer heads (e.g. RRUPE) designed to print pellets (particle sizes ~3–5 mm in diameter) inspired us to iteratively design and optimize a bench-top PME printer head. The resulting PME printer (Fig. 1) can successfully print 3D objects, which establishes a 3D printing platform that reduces the time needed for pre-processing build materials and allows researchers the potential to rapidly prototype novel build materials.

Fig. 1. Photographs of the final PME printer head (A.) and the PME printer head assembled on the open-source MPCNC printer (B.).
2.2. RRUPE funnel modifications for PME

Extrusion with the RRUPE design was evaluated using a powdered poly(lactide) (PLA) build material (< 1 mm in diameter, see Materials and Methods section and Figure S8 in Supporting Information for additional details), however, no extrusion of the PLA build material was observed. An analysis of the RRUPE printer head (Fig. 3) after a PLA powder extrusion attempt revealed that the funnel was not delivering powder to the hot end. To address this limitation, the funnel geometry was redesigned in 3-steps (Fig. 3): (1) the angle of the funnel was increased from 139° in the RichRap funnel (Fig. 3E) to 146° in the PME funnel (Fig. 3F) to better match the helix angle of the auger (typically 24° – 32°) with the supplementary angle of the funnel which would facilitate powder delivery to the auger without over-filling and clogging the auger; (2) the sharp angles in the interior of the funnel were replaced with fillets (top-down view of the two funnels in Figs. 3G and 3H), which reduce the boundaries and points of friction that the powder experiences while traveling to the auger, and; (3) the two shelf cutouts (S₁, S₂) of RichRap’s design (Fig. 3E, 3G) were removed and replaced with a filleted, steep wall to reduce a non-productive build-up of powder build material within the funnel (Fig. 3F, 3H). These three key modifications allowed powder build material to be efficiently directed into contact with the auger, allowing improved powder feed into the hot end.

2.3. Motor and gearing system modifications for PME

Although the redesigned funnel delivered powder build material into the hot end, the extrusion was limited to a globule of material around the nozzle. To overcome this deficiency, the torque on the auger was increased. The NEMA 17 motor was replaced with a larger stepper motor capable of producing 0.88 N-m of torque and the gearing ratio was adjusted to generate a 4X torque ratio instead of the original 2X torque ratio (see the Gearing Ratio Calculations section in the Supporting Information for additional details). Combined with an increase in torque, increasing the diameter of the hot end nozzle to 0.8 mm from 0.4 mm allowed for consistent extrusion.

2.4. Addition and modification of an inlet

Despite constant extrusion, a buildup of powder material between the funnel and hot end was observed. This buildup of powder material exerted sufficient pressure to the top of the RPWHE and screws holding the hot end in place to split the funnel along the 3D printed layers adjacent to the screws. Although a funnel machined out of aluminum would help avoid this problem, the associated costs of machining this complex funnel part would create a large barrier to widespread adoption of powder melt extrusion. Therefore, to keep powder melt extrusion inexpensive and obtainable, the connection between the funnel and hot end was modified to consist of a short (5 mm) inlet from the funnel into the hot end (Fig. 3D) in order to reduce the observed pressure buildup.

The addition of the inlet extended successful extrusion to minutes from seconds, although the uniformity of the extruded material volume remained inconsistent. Therefore, it was hypothesized that the lack of consistency of the material feed into the hot end resulted in inconsistent extrusion. To facilitate a more consistent build material feed, the dimensions of the designed parts for the printer head and how they translated to the printed dimensions of the printer head parts were
Examined. This comparison was done to determine how the exact dimensions of the printer head affected the feed of the powder into the hot end. The dimensions of the printed parts were found to be 0.2–1.0% different than the design due to the extrudate contractions after printing [37]. Initially, it was assumed that these material contractions would not significantly affect the printer performance, especially as they would affect the funnel dimensions rather than the hot end.

However, the contractions of the material comprising the funnel inlet that allowed the auger to transport material into the hot end were especially damaging to the extrusion performance by reducing the space between the auger and the sidewalls increasing the potential for the auger to rub against the sidewalls, as well as, reducing the amount of powder build material able to reach the hot end at one time. By accounting for the material contractions, the auger hole diameter was...
printed to the appropriate size that promotes minimal contact between the auger and the sidewalls and allows for a more consistent build material feed into the hot end, which leads to improved extrusion uniformity.

With a redesigned funnel, greater torque limit, and more accurate design tolerances, the fabricated printer head obtained constant powder melt extrusion (Fig. 4); however, during extrusion, a build material obstruction was a product of heat creep. Heat creep is the process of heat diffusion and past the heat fins in the hot end, and as a result of the heat diffusion, the powder build material softens prematurely, and the increased viscosity of the coalescing powder granules clogs the hot end prohibiting any further extrusion or completion of 3D prints. Therefore, the most influential modification to the design of the printer head to enable PME printing was the design of the hot end to manage heat diffusion and minimize build material obstructions (Fig. 5).

2.5. Hot end investigation and optimization

To investigate the heat transfer within the hot end of the original RPWHE design, Solidworks Thermal Analysis software was used to simulate the thermal heat flow (Fig. 5A, heater cartridge reference temperature = 220 °C). This simulation revealed a large intermediate heat region (53 °C – 170 °C) attributed to heat creep through the hot end. To limit the intermediate heat region within the hot end, two more hot ends were designed (Figs. 5B and 5C). The first design, a long travel hot end (LTHE) (Fig. 5), was the same length as the RPWHE (L_A = L_B) but contained two annular heat fins to better confine heat flow and a longer metal insert into the hot end to bring higher temperatures farther into the hot end (Fig. 5, h_L < h_R). The LTHE design reduced the temperature of the medium heat region (50 °C – 170 °C) in comparison to the RPWHE. However, due to an increased amount of softened build material around the auger, using the LTHE resulted in increased lateral motion of the hot end during the print, reducing the straightness of the printed lines and the overall print quality. To overcome this challenge of a long moment arm, a short travel hot end (STHE) (Fig. 5C) was designed (see Figure S6 and the Moment Arm Calculations section in the Supporting Information). The STHE contains the same heat fins as the LTHE, creating a sharp transition between cold powder and melted plastic; however, the STHE is shorter than both the RPWHE and the LTHE (Fig. 5) to minimize lateral motion of the hot end during the print as a result of a smaller moment arm. The reduction of the distance between the nozzle and the funnel in the STHE likely reduced the lateral movement experienced during printing leading to increased print quality as evidenced by more uniform print lines with minimal side to side travel observed qualitatively from a printed line (Figure S7). Overall, minimizing heat creep allowed for improved extrusion while the STHE increased the uniformity of the printed layers resulting in the best overall performance.

With an improved funnel and the STHE incorporated into the printer, the material capabilities of the PME printer head were evaluated (Fig. 6). The print temperature of PLA powder, high impact polystyrene (HIPS) powder, and acrylonitrile butadiene styrene (ABS) powder build material was optimized by systematically tuning the temperature of the hot end and observing extrusion consistency as well as the connectivity of printed lines at defined 5 °C temperature intervals starting at 100 °C + glass transition temperature or the melting point

![Image](Images)

**Table 1**

<table>
<thead>
<tr>
<th>Build Material</th>
<th>Print Technique</th>
<th>Cube Length (cm) [% error]</th>
<th>Cube Width (cm) [% error]</th>
<th>Cube Height (cm) [% error]</th>
<th>Cube Volume (cm³) [% error]</th>
<th>Cube Mass (g) [% error]</th>
<th>Density of Printed Cube (g/cm³) [% error]</th>
<th>Density of Non-Printed Filament (g/cm³)</th>
</tr>
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<td>PLA</td>
<td>FFF</td>
<td>0.969</td>
<td>0.960</td>
<td>1.03</td>
<td>0.962</td>
<td>0.683</td>
<td>0.710</td>
<td>1.23</td>
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<td></td>
<td></td>
<td>[3.10]</td>
<td>[4.00]</td>
<td>[3.00]</td>
<td>[3.80]</td>
<td>[44.5]</td>
<td>[42.3]</td>
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<td>PME</td>
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<td>0.939</td>
<td>0.960</td>
<td>0.971</td>
<td>1.08</td>
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<td></td>
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<td>[21.1]</td>
<td>[12.2]</td>
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<tr>
<td>HIPS</td>
<td>FFF</td>
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<td>0.976</td>
<td>1.01</td>
<td>0.967</td>
<td>0.529</td>
<td>0.547</td>
<td>1.03</td>
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<td>[11.8]</td>
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<tr>
<td>ABS</td>
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<td>0.976</td>
<td>0.995</td>
<td>0.949</td>
<td>0.511</td>
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<td>1.13</td>
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<td>[2.20]</td>
<td>[2.40]</td>
<td>[0.50]</td>
<td>[5.10]</td>
<td>[54.8]</td>
<td>[52.4]</td>
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<tr>
<td></td>
<td>PME</td>
<td>0.846</td>
<td>0.993</td>
<td>0.960</td>
<td>0.806</td>
<td>0.652</td>
<td>0.809</td>
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<td>[0.70]</td>
<td>[4.00]</td>
<td>[19.4]</td>
<td>[42.3]</td>
<td>[28.4]</td>
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</tbody>
</table>
dimensions of the PME printed cubes are consistently shorter than the
Y resolution (0.4 mm) and Z-layer height (0.18 mm) [38].

In every material printed, the surface roughness values of the PME
printed cubes are more than those of the FFF printed cubes. This further

3. Print results and discussion

The print performance of the final PME design (Fig. 6) was first
compared by qualitatively observing the differences in print quality to
that of a commercially available bench-top FFF printer, the FlashForge
Creator Pro. The comparison in print quality between the two methods
of printing demonstrates the promise of the PME technique (Fig. 7 and
S31). A small cube (1 cm$^3$) was printed using both the PME (Fig. 7A, 7C,
and ABS (F.), as well as, for PME printed parts out of PLA (D.), HIPS (E.), and ABS (F.) Red is indicative of a peak (+) above the
designated 0 point (green) while blue is indicative of a valley (-) below
the designated 0 point. The range of the measurement is ± 500 microns
around the 0 point (For interpretation of the references to colour in this
figure legend, the reader is referred to the web version of this article).

Fig. 8. Three-Dimensional renderings of profilometer generated surface maps for FFF printed parts out of PLA (A.), HIPS (B.), and ABS (C.), as well as, for PME printed parts out of PLA (D.), HIPS (E.), and ABS (F.) Red is indicative of a peak (+) above the designated 0 point (green) while blue is indicative of a valley (-) below the designated 0 point. The range of the measurement is ± 500 microns around the 0 point (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

(see Table S3 for additional details). Operating at the optimized
printing temperatures for each powder build material, the final version
of the PME printer head was able to successfully complete 3D prints.

3.1. Print dimensions

Table 1 provides quantitative measurements of the dimensions of
each of the cubes printed in Fig. 7 and Figure S31. It is apparent that the
dimensions of the PME printed cubes are consistently shorter than the
target dimension of 1 cm. In the case of the PME printed ABS cube, the
cube length falls short of 1 cm by 1.5 mm. The dimensions of the FFF
printed cubes are also shorter than 1 cm, but not by more than 0.5 mm.
These quantitative measurements further validate the qualitatively
observed differences between the print qualities of the cubes discussed
in Section 3.

Although the dimensions of the PME cubes are consistently shorter
than those of the FFF cubes, the densities of the PME cubes are more
similar to that of a 100% infilled cube of the respective material than
those of the FFF cubes. The density of a 100% infilled cube was estimated
by calculating the density of the parent filament [39]. The FFF cubes are
consistently close to half of the desired density, which demonstrates
that although the print pattern follows the 100% infill pattern, there are
separations between the layers and not much layer overlap. In stark
contrast, the PME cubes are closer to the desired
100% density, which demonstrates that the PME layers overlap more
than that of the FFF layers to reduce the overall amount of void space
within the print. The overlap of the PME layers compared to that of the
FFF layers is another result of the inconsistent build material feed of
the PME printing process.

3.2. Print surface roughness

To help quantify the print quality and the inconsistent layers pro-
duced with PME versus those produced with FFF beyond the dimen-
sional analysis, surface roughness measurements ($S_a$) were taken using
a profilometer. The three dimensional surface maps of one side of each
cube are shown in Fig. 8. The PME cube surfaces are more hetero-
geneous compared to those of the FFF cube surfaces. Therefore, this
surface variability is reflected in the $S_a$-values for each cube, which are
0.032 mm for the FFF printed PLA cube (Figure 8A), 0.057 mm for the
PME printed PLA cube (Figure 8D), 0.016 mm for the FFF printed HIPS
cube (Figure 8B), 0.062 mm for the PME printed HIPS cube (Figure 8E),
0.013 mm for the FFF printed ABS cube (Fig. 8C), and 0.058 mm for the
PME printed ABS cube (Fig. 8F).

In every material printed, the surface roughness values of the PME
printed cubes are more than those of the FFF printed cubes. This further

verifies that the print quality of the PME printed parts is not as precise as the FFF printed parts due to printed layer inconsistencies produced by inconsistent build material extrusion in PME.

### 3.3. Print microstructures

To look closer at the difference in the layer consistency between the PME and FFF print methods, scanning electron microscopy (SEM) micrographs were taken of freeze-fractured tabs produced by each print method (Fig. 9). The PME printed layers were observed to either blend together or have gaps between adjacent layers due to uneven extrusion, whereas, the FFF printed layers are distinguishable from each other and contain minimal amounts of irregular gaps between adjacent layers. These visualized defects of the PME printed tabs provide insight into the internal structures of the 3D printed objects and suggest that microscopic defects due to less uniform extrusion give rise to poorer macroscopic print resolution compared with the FFF prints.

### 3.4. Bulk tensile properties of 3D printed objects

Before bulk tensile properties were analyzed, the integrity of the PME extrudate was verified to explore if degradation of the build material occurred during the powder preparation process. The powder preparation process involved taking FFF prints and mechanically grinding them into a powder form (see Materials and Methods in the Supporting Information for additional details). Comparison of the viscoelastic properties of the rectangular tabs printed by PME (average width = 10.9 mm, average thickness = 1.66 mm) and FFF (average width = 12.9 mm, average thickness = 1.00 mm) in each material (PLA, HIPS, and ABS) on a dynamic mechanical analyzer (DMA) revealed that printing using the PME process did not affect the material performance of parts relative to those printed by FFF (Figure S26). Specifically, the average storage moduli ($E'$) of tabs from each method directly are nearly identical under tension for each material. Further, as expected, the glass transition temperature marked by the alpha transition of the storage modulus trace is systematically greater than the temperature determined by DSC in every case (Figure S26 and Table S3).

To compare the mechanical properties of parts printed by the different methods, the bulk tensile properties of ASTM standard type 5 dog bones printed in PLA by both PME and FFF print methods were tested with the print layers oriented parallel to the direction of the tensile force (Fig. 10). The print temperatures of the ABS and HIPS materials were too high to complete full dog bone prints without destroying the inside of the PEK tube of the STHE, and therefore, these objects could not be printed with the current set up. Testing the dog bones with the print layers oriented parallel to the direction of the tensile force

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**Fig. 9.** SEM images of cross-sections of freeze-fractured 3D printed tabs from of PLA via the FFF printer (A.) and the PME printer (B.), of HIPS via the FFF printer (C.) and the PME printer (D.), of ABS via the FFF printer (E.) and the PME printer (F.). Scale bar = 1.0 mm.
reduced the amount of extraneous variables such as layer adhesion or number of layers present [39–41]. Although data beyond the initial failure is insignificant for the purpose of this study, the triangular shapes of the stress-strain traces can be explained by considering the print orientation of the dog bones. As tension is applied parallel to each printed strand, each strand breaks individually. Thus, when one strand in the print breaks, the bulk stress measured lessens, but the strain continues until every strand is broken.

Analysis of the stress-strain curves for dog bones prepared using each printing method revealed that the tensile properties of the tabs were affected depending on the print technique (Fig. 10). Less variation of the average tensile strength values between samples of the FFF printed tabs (57.7 ± 2.31 MPa) (Fig. 10A) than that of the PME printed tabs (49.2 ± 10.7 MPa) was observed (Fig. 10B). Furthermore, the average Young’s Modulus values exhibited by the FFF printed tabs (2160 ± 179 MPa) were more consistent (Fig. 10A) than those exhibited by the PME printed tabs (1620 ± 375 MPa) (Fig. 10B). The minimal variation of the FFF prints’ tensile properties is not surprising after observing the layer uniformity within the SEM micrographs (Fig. 9). Additionally, the inconsistency of the PME prints’ tensile properties is not surprising considering the lack of uniformity between layers within the PME prints as observed in the SEM micrographs (Fig. 9). Therefore, PME shows promise to be used as a viable 3D printing technique, however, to realize PME as an industrially viable printing option comparable to the FFF technique, further optimization and analysis of the PME print parameters and design will be needed.

4. Conclusions

A bench-top PME printer head was developed and tested. Each part of the RRUPE printer head was systematically investigated and modified to gain a fundamental understanding of the principles needed to fabricate a PME printer head. The final version of the PME printer head is able to successfully 3D print from a variety of thermoplastic powder build materials (PLA, HIPS, ABS). Printing by PME was also shown to minimally affect the viscoelastic properties of the material when compared to those of the FFF printed parts. However, the inconsistencies of the PME printed layers shown by dimensional analysis, surface roughness measurements, and SEM micrographs did present variable tensile properties in the printed parts when compared to the more consistent layers produced from the FFF print method. The layer inconsistencies of PME printed parts are likely a result of uneven powder melt extrusion which presents further challenges in achieving consistent material flow during extrusion, as well as being able to enhance PME print resolution. PME print methods have the potential to reduce the time needed for the processing of 3D printing build materials, presenting the opportunity to provide a platform on which it is possible to rapidly prototype a myriad of thermoplastic materials for 3D printing.

Declaration of Competing Interest

We confirm that there are no conflicts of interest related to this manuscript.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.addma.2019.100811.