TECHNICAL NOTE

Wood Furniture Waste–Based Recycled 3-D Printing Filament

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Abstract

The Michigan furniture industry produces >150 tons/day of wood-based waste that can be upcycled into a wood–polymer composite (WPC). This study investigated the viability of using furniture waste as a feedstock for 3-D printer filament to produce furniture components. The process involves grinding and milling board scraps made of both LDF-MDF-LDF (where LDF is light-density fill and MDF is medium-density fill) and melamine-particleboard-paper impregnated with phenolic resins, premixing wood-based powder with the biopolymer polylactic acid, extruding twice through open source recyclebots to fabricate homogeneous 3-D printable WPC filament, and printing with open source fused filament fabrication–based 3-D printers. The results indicate that there is a significant opportunity for waste-based composite WPCs to be used as 3-D printing filament.

The extraordinary number of uses for wood demonstrates its value and versatility, which also extends to its ability to be reused and recycled. In addition, wood is a renewable resource that sequesters and stores carbon, making wood increasingly viewed as the material of choice for a future not based on petrochemicals (Jakes et al. 2016). Extending the life of wood while increasing its value through upcycling presents opportunities for innovation that brings us closer to a sustainable future.

For example, the Michigan furniture industry produces more than 150 tons of wood-based waste per day (B. Gurn, Manager of Haworth production facility, Holland, Michigan, personal communication, March 2016), which is primarily landfilled and burned in a 38-MW wood waste–to–energy plant in Flint, Michigan (Michigan Biomass 2017). However, this waste has the potential to be upcycled into wood–plastic composites (WPCs) rather than burned, as there are well-documented challenges for waste-to-energy plants (Pavlas et al. 2010, Tabasová et al. 2012). WPCs are composites containing a wood component in particle form but within a polymer matrix that can provide greater performance, reduced price, and reduced environmental impact (Schwarzkopf and Burnard 2016). A wide range of modification techniques exist for wood involving either active modifications, such as thermal or chemical treatments, or passive modification, which changes the physical properties but not the biochemical structure (Ormondroyd et al. 2015). However, WPCs still have limitations owing to production methods, such as producing waste material or orientation-reliant fabrication, which may be alleviated with alternative manufacturing techniques, such as additive manufacturing.

Additive manufacturing (or 3-D printing) is different from subtractive manufacturing processes, which typically involve grinding, cutting, or milling, because 3-D printers function by building a part layer by layer, each as thin as 50 µm. This allows for a significant reduction in scrap and wasted material as well as a unique mentality when designing parts meant specifically for this manufacturing method (Steenhuis and Pretorius 2015). Although 3-D printing was developed several decades ago, significant growth has occurred in the past decade as 3-D printing has become more accessible to consumers (Wohlers and Caffrey 2014). The release of the open source RepRap (self-replicating rapid prototyper) 3-D printers has radically decreased the cost of 3-D printers (Sells et al. 2010, Jones et al. 2011, Bowyer 2014, Rundle 2014). RepRaps use fused filament fabrication (FFF), where a thin polymer extrusion

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from a heated print head is layered and then cools and connects to surrounding polymer (Steenhuis and Pretorius 2015). Many polymers are available on the market for FFF 3-D printing, including nylon, polycarbonate, high-density polyethylene, and high-impact polystyrene (Hunt et al. 2015). However, the most common FFF material is polylactic acid (PLA), which has an average tensile strength of 56.6 MPa (Tymrak et al. 2014), is relatively inexpensive, and has a glass transition temperature of 45°C to 60°C and a melting point of 150°C to 178°C (Farah et al. 2016), making it suitable for a wide range of applications, especially 3-D printing. PLA is a bio-based plastic made up a repeating chain of lactic acid and is recyclable using conventional methods. Specifically, PLA is a thermoplastic aliphatic polyester derived from corn and can even be composted like other organic matter. The low glass transition temperature and high melting temperature create a large temperature region, allowing for semisolid material flow. This is ideal for additive depositions, as it increases the printability of the material, printability being the ease with which a material works with and produces desired parts from a digital design. PLA is versatile, and PLA-based composites have been investigated in the literature, including composites with natural fibers (Oksman et al. 2003), kenaft fibers (Ochi 2008), microfibrillated cellulose (Suryanegara et al. 2009), man-made cellulose and abaca fibers (Bledzki et al. 2009), carbon nanotube (Kuan et al. 2008), and even metal composites (Fortunati et al. 2012, Laureto et al. 2017). There are already several PLA composite manufacturers in the market, including Laywood, Gizmo Dorks, and SainSmart (Gizmo Dorks 2009, SainSmart 2014, All3DP 2017), which create virgin wood–based 3-D printer filaments.

This study furthers these efforts by investigating the use of furniture waste as a feedstock for 3-D printer WPC filament to produce currently purchased furniture components. The process uses grinding and milling of two furniture waste materials: board scraps made of both LDF-MDF-LDF (where LDF is light-density fill and MDF is medium-density fill) and melamine-particleboard-paper impregnated with phenolic resins. A premixing process was used for the resultant wood-based powder with PLA pellets (NatureWorks, 4043D). This material was extruded twice through an open source recyclebot to fabricate homogeneous 3-D printable filament in volume fractions of wood:PLA from 10:100 to 40:100. The filament was tested in an open source FFF-based industrial 3-D printer. The results are presented and discussed to analyze the opportunity for waste-based composite filament production.

Methodology

In this work, four steps have been developed for the production of WPCs from furniture wood waste for 3-D printing filament. Wood-based waste material was received from several furniture manufacturing companies in both bulk (half-meter-size slabs) as well as sawdust (millimeter to submillimeter size). The first step in the method is size reduction from macro- to meso- to microscale. Once the furniture wood–based waste is fine enough in particle size (about 80 μm), the wood-based filler material with the consistency of baking flour is mixed with the matrix polymer. The third step is extruding the feed material into filament of homogeneous thickness and density to provide uniform properties. The last step is to load the WPC filament into a 3-D printer and print a part. To print a part, an object must be modeled in 3-D modeling software, imported into a slicing software, and then uploaded to a 3-D printer's firmware.

Furniture wood–based waste material particle size reduction

The material was received in a few different sizes and consisted of LDF-MDF-LDF and melamine-particleboard-paper impregnated with phenolic resins. These materials were used as obtained and not cleaned in order to more thoroughly test the recyclability of wood waste material. Whatever surface contaminates were on the as-received materials would likely be negligible due to the sheer amount of new surfaces generated when particles are reduced to micron size. Larger materials were broken up initially via band saw into 10 by 6-cm sections for feeding into a wood chipper (Fig. 1A). The material was cycled through the wood chipper three times, and the different sources of wood-based furniture waste were mixed together to form an even composition weight percent (wt%) of each supplier's materials. This combined furniture waste mix had a nominal particle size of 2 to 3 mm wide and 2 to 6 mm long. At this size, they were too large to be added to the PLA polymer for

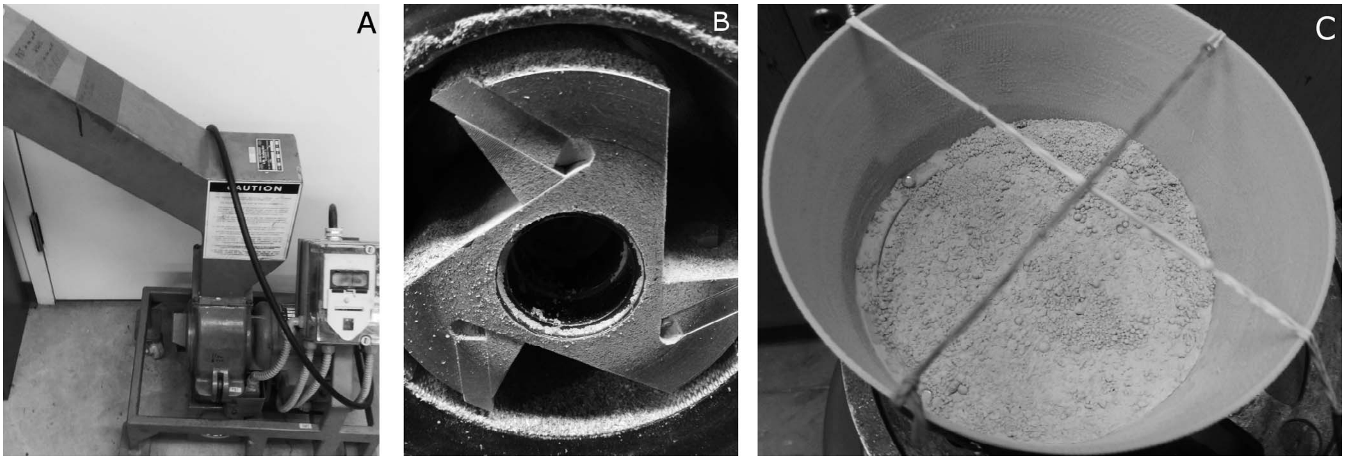


Figure 1.—(A) Wood chipper, (B) hammer mill, and (C) 80-m sifter assembly for wood-particle size reduction.

3-D printing through a standard nozzle (0.5 mm in diameter) but could be used on larger nozzles to achieve a particleboard-type print. As the goal of this work was to investigate fine structures, the material was hammer milled (Fig. 1B) with various mesh sizes ranging from 3.00 to 0.75 mm in batches of 200 g (50 g from each supplier) for 30 minutes at each mesh, resulting in a submillimeter average size of wood fiber mix. Initial trials of filament that were fabricated with wood fibers of this size met with reasonable success; however, the particle size was determined to be too large for a consistent FFF extrusion through a 0.5-mm nozzle on a standard delta-type RepRap 3-D printer (Irwin et al. 2014, Anzalone et al. 2015). Therefore, a fine particle sifter assembly (Pringle 2017a) was fabricated (Fig. 1C), and another assembly was printed out of PLA on a 3-D printer. The sifter assembly is made up of four sections: the bucket for particle collection, the replaceable stainless steel mesh (Kindustrial), the funnel for guiding particle flow, and the lid for sealing to prevent the loss of fine particles. One assembly incorporated a 210-μm stainless steel mesh and the other an 80-μm stainless steel mesh. The sifting was automated using a vibratory deairing device (model H-1756 from Humboldt) to produce sub-80-μm particles. Material was first loaded into the 210-μm mesh sifter and held onto the vibratory device with rubber bands to allow optimal shaking. The material initially vibrated for 1 hour before being transferred to the 80-μm mesh sifter and vibrated again for 1 hour. By the end of the process, the powder material had the consistency of grain flour and will be referred to here as wood-waste powder. Throughout this process, the moisture content was never directly measured. Through observation of the wood-waste powder material's lack of agglomeration and ease of free flow when handled, it was concluded that the heat generated during the size reduction process reduced moisture content to acceptable levels.

Filler matrix mixing

The temperature of PLA pellets (NatureWorks, 4043D) was raised to 210°C until the PLA became less viscous and could be stirred. The wood-waste powder was added gradually, and both materials were stirred and mechanically mixed (Fig. 2A). The mix was allowed to regain a temperature of 210°C to compensate for the temperature drop on material addition and to reduce viscosity. At batch sizes above 20 wt% wood waste or larger than 100 g, the wood-waste powder did not completely wet into the PLA matrix because of the thermal gradient created from the directional heat flow from the heating element. Therefore, longer stir times were conducted as batch sizes increased to

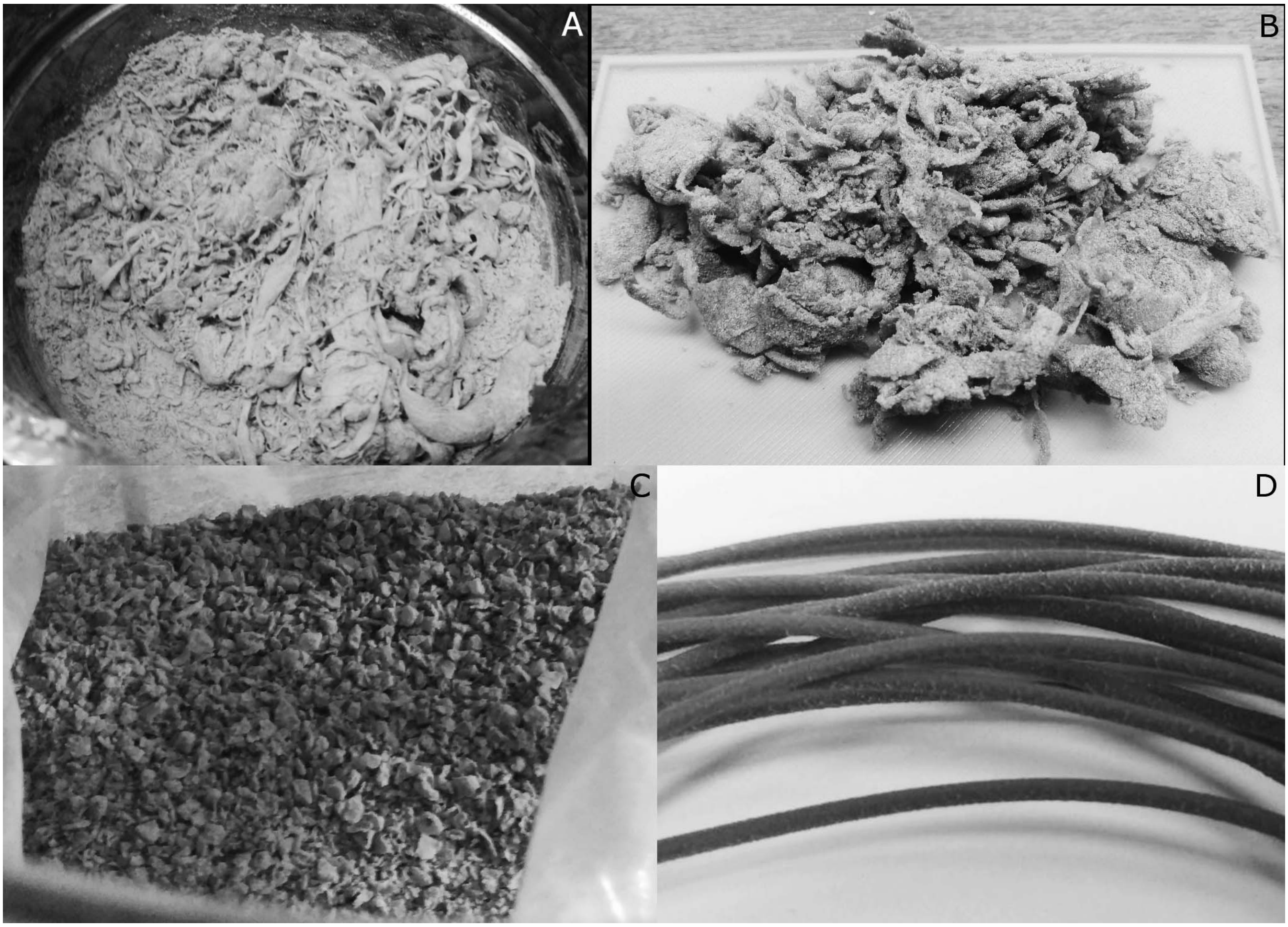


Figure 2.—(A) Polylactic acid (PLA) during moderate mechanical mixing with wood-waste powder, (B) PLA and wood-waste powder–based wood polymer composite (WPC) after mixing and cooling to room temperature, (C) chipped WPC, and (D) homogeneous WPC material after first pass through recyclebot.

improve wettability. Additionally, stir speed was increased to prevent the wood powder from charring at the mixing temperature. After a consistent mixed material was obtained, the batch was removed from the heating element and allowed to cool to room temperature, exposed to air, and placed on a metal surface to act as a heat sink (Fig. 2B) before it was fed into a wood chipper to obtain a particle size of roughly 3 to 4 mm in diameter with a nonuniform angular geometry (Fig. 2C).

Filament extrusion

The chipped WPC material (Fig. 2C) was then further homogenized by being added to an open source recyclebot (Baechler et al. 2013). The recyclebot is a waste plastic extruder that fabricates filament for FFF 3-D printers. The recyclebot used in this study was a vertical design (Fig. 3B), and a detailed procedure on its creation is described by Zhong et al. (2017; see also Zhong and Pearce 2018). The motor is capable of 15 rpm when set at maximum but should be done so only during the homogenization step, with the end nozzle off to prevent mechanical backlash to the motor. Wound nichrome wire 15 cm in length down the exterior of the barrel tube allows a uniform maximum temperature of 225°C. Owing to the nonuniform geometries of the angular WPC material as received from the wood chipper, feeding into the recyclebot was difficult; however, it was re-formed into a cylindrically shaped prefilament material (Fig. 2D). This prefilament was unsuitable for printing, as the diameter varied significantly, at an average of 1.45 mm (±0.3 mm), because of inconsistent feeding of material (volumetric flow) into the auger. The prefilament was then processed in the wood chipper again to obtain uniform cylindrical pellets. The now cylindrical WPC pellets allowed consistent volumetric flow into the recyclebot auger (due primarily to the rolling edge), allowing spooling of the material with more uniform diameter (±0.1 mm). Before filament fabrication, the auger of the recyclebot was purged of old material to prevent contamination by the addition of pure PLA pellets (Fig. 3A), which were run through the recyclebot until clear PLA filament was being extruded. Then the cylindrical WPC pellets were loaded into the designed and printed recyclebot hopper (Pringle 2017b) for a final run through the recyclebot to extrude WPC filament. During the extrusion process, the air-cooled WPC filament was then positioned through the photodiode at the bottom of the recyclebot, fed through several sensors (diameter and length), and attached to the autospooler. The correct thickness of filament is critical to having sufficient latent heat maintain a flexible core but allow a smooth and nonsticky exterior to the filament. The photodiode measures how far the filament produced dips and adjusts the spooling speed to maintain a constant gravitational pool of the filament exiting the extruder to maintain a consistent diameter (Fig. 3B). The degree of WPC filament thinning of the filament is adjustable by changing the distance between the extrusion hole and the photodiode sensor. Filaments of wood weight percentages of 10, 20, 30, and 40 wt% wood were produced. The observable rheology of the WPC filament changed in small but noticeable part due to increasing wood content. First, the higher the wood content, the more opaque and wood-like the filament appeared. There was a slight increase in the rigidity of the polymer as wood content increased and was determined through observations of handling the filament in spooled form and how easily each filament composition unspooled.

3-D printing WPC process

The final step in the methodology is 3-D printing, a desired part with the WPC filament created using a delta RepRap and an open source Re:3D Gigabot version GB2 (Re:3D 2013). An open source tool chain was used in all aspects of 3-D printing shown in Figures 4A through 4C. First, OpenSCAD version 2015.03-2 (OpenSCAD 2010), a script-based 3-D modeling program, was used for part design. After a part is modeled, it is exported as an STL (stereolithography) file and imported into a slicer program, Cura version 2.3.1 (Ultimaker 2012), to be exported as gcode. Cura allowed precise control of relevant printing

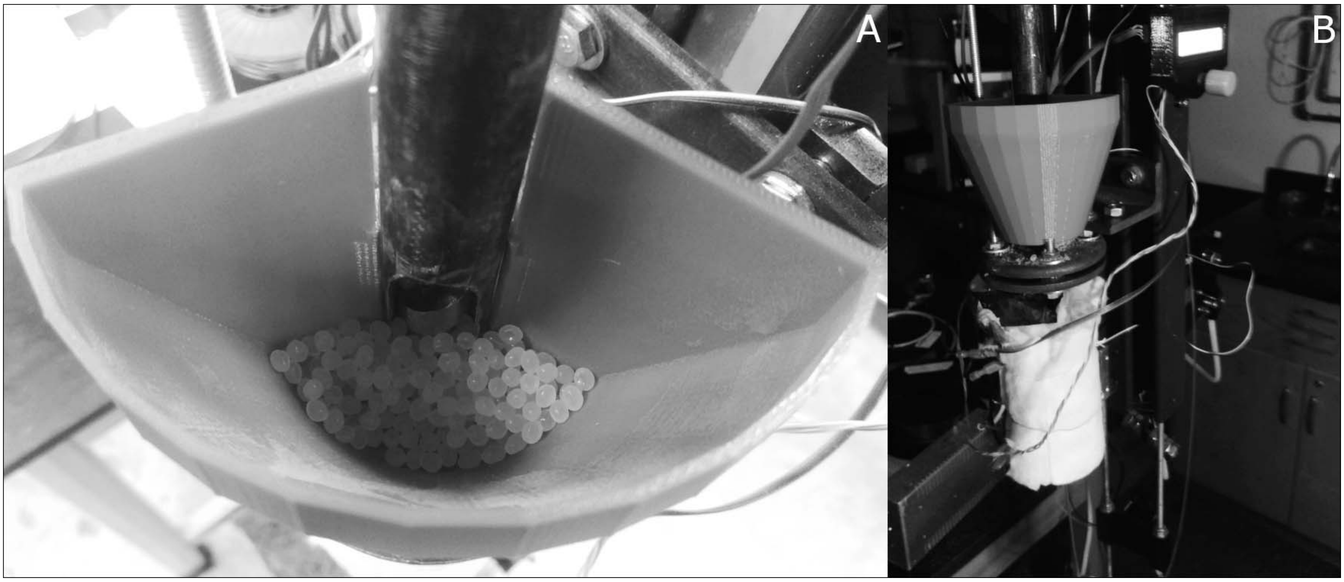
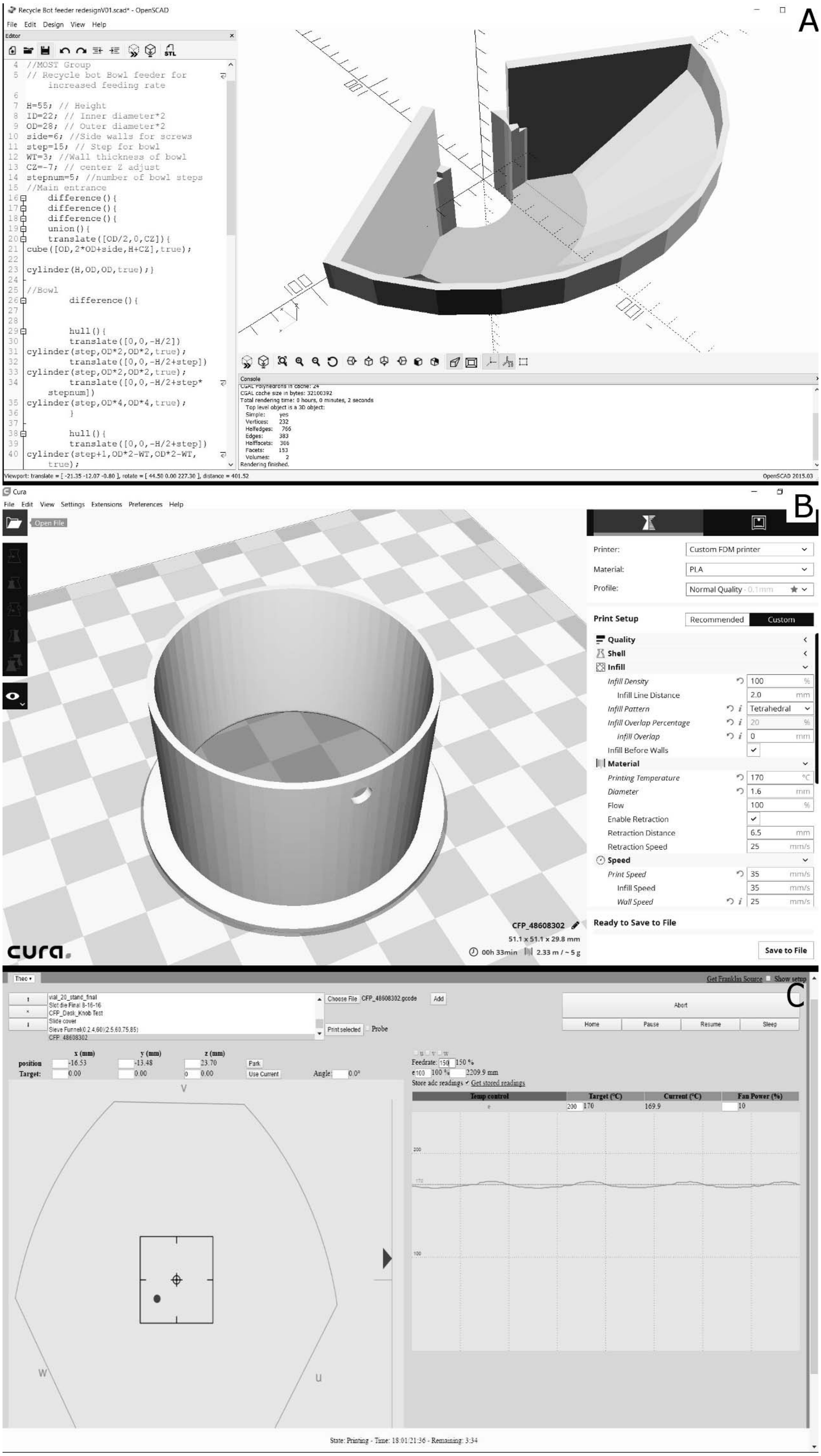


Figure 3.—(A) Vertical recyclebot hopper with pure polylactic acid (PLA) pellets and (B) vertical recyclebot showing hopper, heating zone, photodiodes (bottom), control, and spooler (upper right).



```
//MOST Group
// Recycle bot Bowl feeder for
    increased feeding rate

H=55; // Height
ID=22; // Inner diameter*2
OD=28; // Outer diameter*2
side=6; //Side walls for screws
step=15; // Step for bowl
WT=3; //Wall thickness of bowl
CZ=-7; // center Z adjust
stepnum=5; //number of bowl steps
//Main entrance
    difference(){
    difference(){
    difference(){
    union(){
    translate([OD/2,0,CZ]){
cube([OD,2*OD+side,H+CZ],true);

cylinder(H,OD,OD,true);}

//Bowl
        difference(){


        hull(){
        translate([0,0,-H/2])
cylinder(step,OD*2,OD*2,true);
        translate([0,0,-H/2+step])
cylinder(step,OD*2,OD*2,true);
        translate([0,0,-H/2+step*
    stepnum])
cylinder(step,OD*4,OD*4,true);
        }

        hull(){
        translate([0,0,-H/2+step])
cylinder(step+1,OD*2-WT,OD*2-WT,
    true);
```

```
Viewport: translate = [ -21.35 -12.07 -0.80 ], rotate = [ 44.50 0.00 227.30 ], distance = 401.52
```

```
CGAL Polyhedrons in cache: 24
CGAL cache size in bytes: 32100392
Total rendering time: 0 hours, 0 minutes, 2 seconds
  Top level object is a 3D object:
  Simple:      yes
  Vertices:    232
  Halfedges:    766
  Edges:       383
  Halffacets:   306
  Facets:      153
  Volumes:       2
Rendering finished.
```

Printer: Custom FDM printer
Material: PLA
Profile: Normal Quality - 0.1mm

Print Setup Recommended | Custom

Quality

Shell

Infill

Infill Density	100 %
Infill Line Distance	2.0 mm
Infill Pattern	Tetrahedral
Infill Overlap Percentage	20 %
Infill Overlap	0 mm
Infill Before Walls	✓

Material

Printing Temperature	170 °C
Diameter	1.6 mm
Flow	100 %
Enable Retraction	✓
Retraction Distance	6.5 mm
Retraction Speed	25 mm/s

Speed

Print Speed	35 mm/s
Infill Speed	35 mm/s
Wall Speed	25 mm/s

Ready to Save to File

Save to File

CFP_48608302
51.1 x 51.1 x 29.8 mm
00h 33min 2.33 m / ~ 5 g

vial_20_stand_final
Slot die Final 8-16-16
CFP_Desk_Knob Test
Slide cover
Sieve Funnel(0.2,4.60)(2.5,60,75,85)
CFP_48608302

Choose File CFP_48608302.gcode

	x (mm)	y (mm)	z (mm)
position	-16.53	-13.48	23.70
Target:	0.00	0.00	0 0.00

Angle: 0.0°

Feedrate: 150 150 %
e100 100 % 2209.9 mm
Store adc readings ✓

Temp control	Target (°C)	Current (°C)	Fan Power (%)
e	200 170	169.9	10

State: Printing - Time: 18:01:21:36 - Remaining: 3:34

Figure 4.—(A) OpenSCAD, (B) Cura, and (C) Franklin are used in the open source part creation process.

parameters, such as temperature, layer height, and printing speed (summarized in Table 1). The gcode was sent to Franklin (Wijnen et al. 2016), which is an open source firmware and control software. Franklin allows direct and real-time control of temperature, extrusion speed, cooling rate, and motor speed. Screenshots of OpenSCAD, Cura, and Franklin are displayed in Figure 4.

The spooled filament diameter was measured by a caliper to ensure that it was of sufficient consistency (±0.10 mm). In order to feed properly into a 0.5-mm hot end, a diameter of less than 2 mm is necessary to prevent binding of the filament. Several part files, including a desktop cable feedthrough and various desk and drawer knobs, as well as multiple blocks, were fabricated using the values in Table 1 and primarily 30 wt% filament. While pure PLA is printed normally at 210°C, a temperature of 185°C was used in order to reduce the amount of charring that the wood component of the filament would undergo through printing. As material is printed, the heat flow and buildup must be taken into account. Decreasing the print speed, increasing the print temperature, or decreasing the feed rate (mass flow rate) all increase the exposure of heat for a given section of filament. Likewise, if the print speed increases, the print temperature increases or the mass flow rate increases, and any given section of the print will be overall cooler as the total heat energy is dissipated over a larger volume.

Table 1.—3-D printing parameters used for recycled wood furniture waste–based filament.

Printing parameter	Value
Layer height	0.15 mm
Shell thickness	1 mm
Top/bottom thickness	1 mm
Fill density	33%
Printing temperature	185°C
Filament diameter	1.65 mm
Nozzle size	0.5 mm
Print speed	62.5 mm/s
Bottom layer speed	25 mm/s
Travel speed	100 mm/s

Results and Discussion

Recycled wood furniture waste–based WPC filament and repeatability

Uniform and homogeneous recycled wood furniture waste–based WPC filament was produced with the previously described methodology and is shown in Figure 5A. Filament was measured to have a diameter consistency of 1.65 ± 0.10 mm. This is not ideal, as most commercial filament is 1.75 ± 0.05 mm in tolerance. However, the extruder drive on the delta 3-D printer was adjusted through modifying the tightness of the idler against the filament to account for the difference in filament diameter. A 3-D printed desk cable feedthrough (shown in Fig. 5B) was used to test the viability of producing a purchased part for furniture manufacturing, to test filament printing parameters, and to demonstrate repeatability. The simple part has a flat base with a cylindrical wall and hollow center. Additionally, the part had a hole near the top, and it was important to maintain a circular shape. The weight percent that demonstrated the most success and ease of creation was 30 wt%, which was chosen based primarily on the wettability of wood-waste powder into PLA as well as the printability of the resulting filaments.

It is also important to note that during the filament extrusion and printing processes, no material flow disruptions were attributed to excess moisture content. These disruptions would be characterized by small ''pop'' sounds coming from the nozzle as polymeric material high in moisture is extruded as the water vapor is released. High moisture content would lead to porosity and inconsistent filament diameter. This effect can sometimes be witnessed in normal printing settings if filament is left in an environment with high humidity levels due to the hygroscopic nature of some 3-D printing filaments. Unfortunately, both wood and PLA are hygroscopic, and composite filament of these two materials should be kept in a controlled low-humidity environment.

The molecular weight of a polymer determines the physical properties. As polymers are exposed to elevated temperatures, they may degrade. Rheological studies of PLA from temperatures of 180°C to 200°C have been completed by Al-Itry et al. (2012), where the viscosity of PLA changed from 2,800 to 1,250 Pa/s when processed at 180°C and 200°C, respectively. Decrease in viscosity corresponds to a reduction in molecular weight. While exposed to these temperatures in the short term, increased chain mobility occurs, and extended influence leads to thermal degradation and thus a reduction in molecular weight as polymer chains break down. For recycled

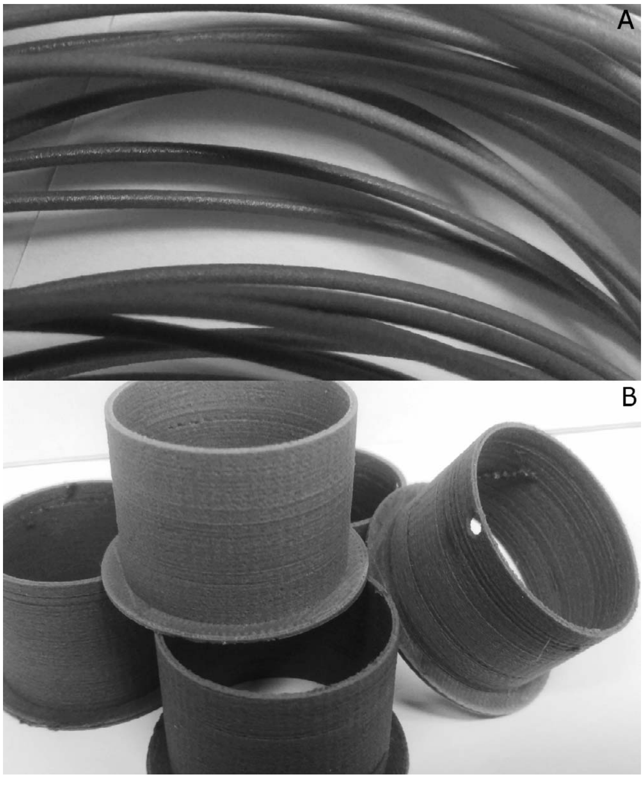


Figure 5.—(A) Spooled recycled wood furniture waste–based wood polymer composite (WPC) filament (removed from spool) with 30 wt% wood-based waste, and (B) five desk cable feedthrough parts 3-D printed consecutively, 30 wt% wood furniture–based waste.

materials, this means that there is a lifetime limit for the number of times a given batch of PLA may be recycled into filament and printed before mechanical properties degrade enough to prevent usage (Cruz et al. 2016).

Phenolic resins or melamine resins have a negligible impact on the extrusion of the filament produced with this methodology. These resins are thermosetting polymers and will decompose before transitioning to a liquid state, meaning that they may be treated as solid particulates. This research has found that resins, if they do not decompose in the filament fabrication process due to elevated temperatures, behave similarly to wood particles. Resin gets broken down in the reduction steps, as does wood. Therefore, in general, the particle size of the resins matches the wood particle sizes. While this means that resins may be treated as wood in terms of particle size, the material properties of the filament can change to reflect the properties of the resin. Filaments with higher concentrations of resin may show increased mechanical properties, water resistance, and heat resistance. In this work, resin, if not broken down to similar particle size, would have been sifted out early in the process.

3-D printing techniques for recycled wood furniture waste–based WPC filament

The recycled wood furniture waste–based WPC filament produced parts without many errors once an optimized printing profile was obtained. However, when compared with traditional filament, such as pure PLA, there were still a greater frequency of nozzle clogging and general filament blockages, most likely caused by particle size nonuniformity. When comparing the compositions, higher wood-waste percentages did demonstrate more clogging, but this is likely due to having more oversize particles for the selected nozzle size. Blockages occur when the nozzle of the hot end has restricted flow. Contamination on or within the filament or the ratio of the particle size versus the nozzle head diameter may restrict flow and cause a clog to occur. Contamination such as dust may settle on filament when left unattended in a printing environment. To prevent this contamination, a sponge was taped around the filament prior to entry into the printer to collect all surface contamination. Contamination within the filament would come from either the wood-waste material or the PLA pellets harboring unintended materials such as oils, but the concentrations necessary would need to be substantial and would likely prevent filament from even forming into shape. The smaller wood particles with a larger nozzle would reduce clogging potential; however, a smaller nozzle allows higher levels of precision in the 3-D printed part. A Gigabot by Re3D was also tested for capability with the wood filament produced, and no blockages were observed during the duration of the experiment. If nozzle size is appropriate for the particle size, the rate of clogging should be no different from that for pure PLA filaments. Figures 6A through 6C show several parts mid-print with both the Gigabot and delta RepRap.

Varying the print temperature, print speed, or extrusion rate changes the volumetric flow rate of material through the hot region of the hot end assembly on an FFF-based 3-D printer. As material passes through the hot region, the wood particles begin to char at a rate depending on how much time it takes a given volume of material to pass through and out of the nozzle. Longer duration will lead to darker colorations in the printed part. When blockages occur, if not all of the material is removed, then the remaining material will blacken and may lead to additional clogging issues. It is also important to note that with larger nozzle diameters, higher temperatures are necessary to uniformly heat the increased volumetric flow allowed for reliable inner-layer bonding. By varying one of the three parameters mentioned previously, the layers of a print may be colored to resemble the wood grain of traditional products (Kaipa 2012); this is shown in Figure 7B. By far, the easiest parameter to change is the print speed, as it may be done instantaneously in the Franklin firmware during printing. The print temperature is also simple to change; however, it is a delayed response, as the hot end must then warm or cool to the new temperature. Furthermore, if the print speed or print temperature or the extrusion rate is adjusted too much in one direction (more or less), then print quality may suffer if the filament material does not have sufficient time in the hot region to adequately transition toward the necessary material viscosity for printing.

Because 3-D printing allows for precise control of printing parameters, the internal geometry of printed parts is not constrained to traditional manufacturing requirements. Thus, an ideal internal geometry may be selected; many are available in open source slicing programs, such as Slic3r, for the intended application (Fedorov et al. 2012). Figure 7A shows a 20 percent in-fill triangular geometry for a drawer handle. Printing with lower in-fills has already been shown to be a key method to reduce the environmental impact of 3-D printing compared with conventional products (Kreiger and Pearce 2013a, 2013b) and to reduce the material used and the mass and the cost of the part. However, it is always important to note the layer deposition direction and, if possible, print a part to experience forces perpendicular to the layer direction so that the force acts on the layers in total of the affected region rather than on the inner-layer adhesion of the printed part (Vega et al. 2011).

Example application of recycled wood furniture waste–based WPC filament

WPCs have many varied applications, which are expanded with the use of 3-D printing. To demonstrate this, a high-resolution drawer knob was 3-D printed attached to a printed wood block using a wood screw threaded through a preprinted hole as shown in Figures 8A and 8B. The wood screw was easily twisted through both objects with a Phillips screwdriver, and the resulting connection withstood normal forces expected in everyday use. Additionally, because of the flexibility of 3-D printing orientations, unique or personalized surfaces may be printed onto objects, as shown in Figure 9. This is shown through the particular geometries or print directions that may be modified directly by altering gcode or, more conveniently, by changing parameters in slicer programs. This enables mass-scale personalization of not only furniture components with wood but also any 3D printed part using recycled waste–based plastic composites.

As the weight percentage of wood furniture waste filler increases in a given batch of material, the properties of the 3-D printed parts more closely resemble that of wood. With parts printed of at least 15 wt% wood furniture waste, the parts began to take on the smell and texture of wood with higher weights, exhibiting a stronger scent. In addition, 3-D printed parts could also be sanded, stained, and painted like normal wood products, further increasing the value of these WPC products. Furthermore, throughout this project, it

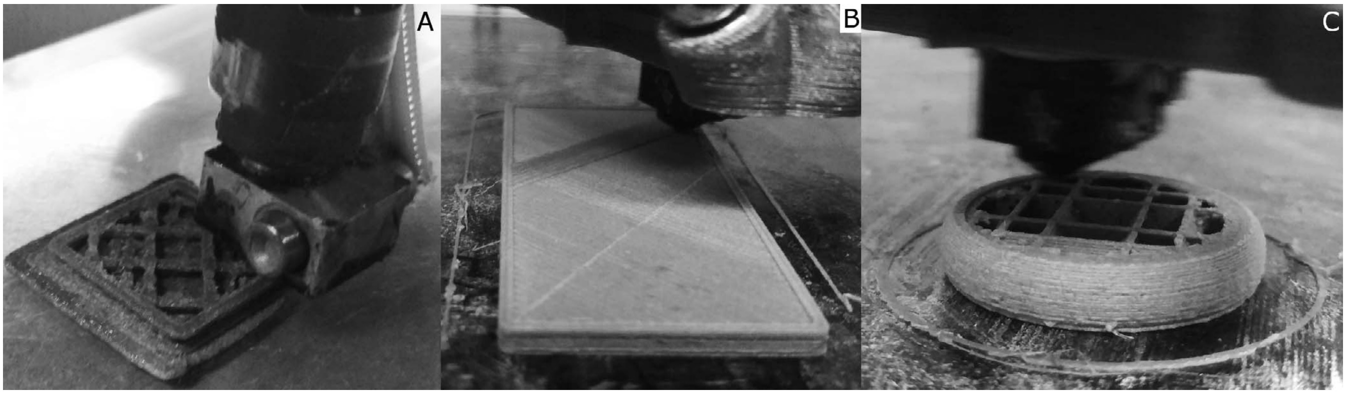


Figure 6.—(A) Test cube done on Gigabot with 20 percent in-fill, 25 wt% wood furniture waste; (B) test block done on delta with 100 percent in-fill, 30 wt% wood furniture waste; and (C) layer 34 of a drawer knob done on delta with tetrahedral-shaped internal geometry, 30 wt% wood furniture waste.

Figure 7.—(A) Internal view of a drawer handle with triangular geometry of in-fill, 30 wt% wood furniture waste, and (B) side view of same drawer handle; sidewalls have been textured during print to resemble an aesthetic wooden surface.

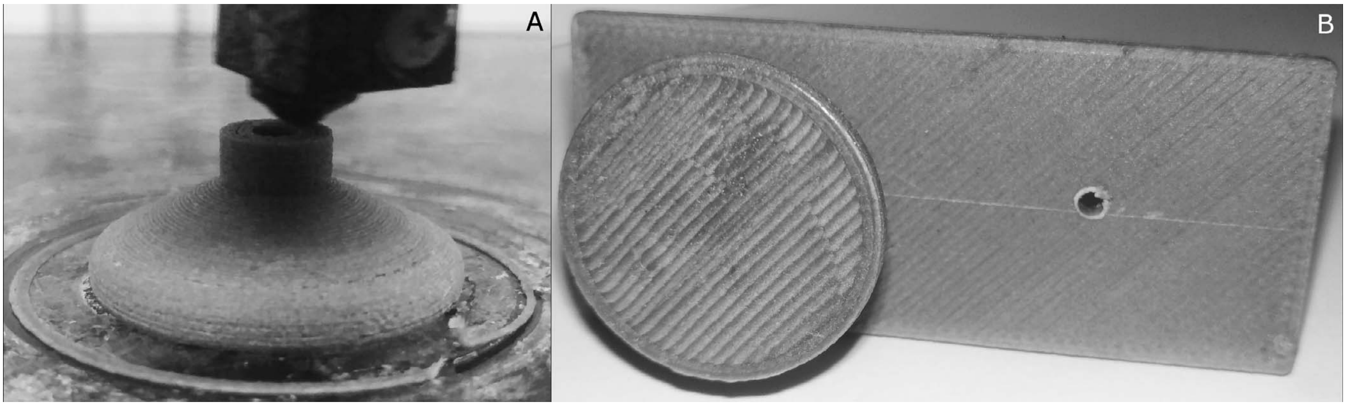


Figure 8.—(A) 0.15-mm layer height drawer knob being 3-D printed with a screw hole for attachment and (B) completed drawer knob fully attached on left of wood block with example preprinted hole on right of block, 30 wt% wood furniture waste.

became apparent that wasted wood parts or failed prints were also able to be recycled and that the material could be reused. This was done by feeding the discarded parts into a wood chipper and repeating the methodology to obtain filament once again. This recycling of printed parts did not seem overly detrimental as long as temperatures did not exceed 210°C for long durations, which would have led to degradation.

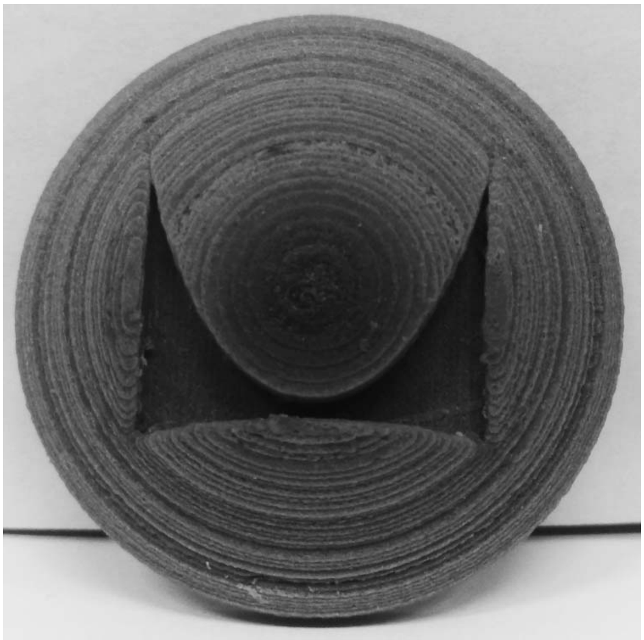


Figure 9.—Surface contours of a personalized drawer handle for with the Herman Miller emblem. A coloration change from the outsides to the center is shown due to induced temperature changes during printing to provide a tree ring.

Future Work

Future work is needed to quantify the mechanical properties of the furniture waste WPC after the first cycle and compare it with pure PLA, modified wood fiber powder WPCs (Zhang et al. 2016), and other wood fiber biocomposites (Le Duigou et al. 2016). As polymeric materials are recycled, they tend to degrade, and this is shown in the reduction in molecular weight. Work should be done on measuring the impact on the mechanical properties of polymeric materials with different molecular weights resulting from degradation during the recycling process. Improvement of the wettability of the wood-waste powder is essential to gain higher weight percentages in 3-D printing filaments. Other polymer materials should also be tested and compared to assess the ideal matrix for wood composite waste; the matrix likely has a large impact on wettability of the aggregate material. In addition, the impact of multiple cycles through the recyclebot should be tested (Cruz et al. 2016) and with the addition of colorants, which have been shown to have an effect (Wittbrodt and Pearce 2015). The scale-up of this process should also be evaluated with industrial equipment; larger and grouped or ganged 3-D print nozzles (multiple nozzles per print bed to make several parts at once) would improve output production. A continuous process of the four steps mentioned to streamline the filament production would be necessary for industry volume requirements. In addition, the environmental and economic performance of furniture waste WPCs should be evaluated. Finally, the market for the sale of furniture wood–based WPC should be evaluated in the context of an ethical filament market (Feeley et al. 2014).

Conclusions

This study has demonstrated a technically viable methodology of upcycling furniture wood waste into usable 3-D printable parts for the furniture industry. By mixing PLA pellets and recycled wood–waste material, filament was produced with a diameter size of 1.65 ± 0.10 mm and used to print a small variety of test parts. This method, while developed in the laboratory, may be scaled up to meet industry needs, as the process steps are uncomplicated. Small batches of 40 wt% wood were created but showed reduced repeatability, while batches of 30 wt% wood showed the most promise with ease of use.

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