Thermoplastics and Photopolymer Desktop 3D Printers

Subjects: Engineering, Manufacturing
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With the advancement of additive manufacturing technologies in their material processing methodologies and variety of material selection, 3D printers are widely used in both academics and industries for various applications. It is no longer rare to have a portable and small desktop 3D printer and manufacture your own designs in a few hours. Desktop 3D printers vary in their functions, prices, materials used, and applications. Among many desktop 3D printers with various features, it is often challenging to select the best one for target applications and usages. In this paper, commercially available and carefully selected thermoplastic and photopolymer desktop 3D printers are introduced, and some representative models' specifications and performances are compared with each other for user selection with respect to instructional applications.

Keywords: Three-dimensional printing ; additive manufacturing ; Desktop 3D Printers ; Specifications

1. Background

Three-dimensional printing, also referred to as additive manufacturing, is a new material processing technology that allows creating a physical 3D object from computer-aided modeling tools, such as CAD [1][2][3][4][5][6]. It started in the 1980s as a way to make prototype objects faster and cheaper [7]. In 1981, Hideo Kodama made a rapid-prototyping system using photopolymers. Three years later, Charles Hull invented stereolithography, a liquid photopolymer, that when hit with a UV laser, turns the liquid into a solid. This is called Stereolithographic apparatus (SLA). That same year, a startup company used a powder instead of a liquid, creating the selective laser sintering machine (SLS). At the dawn of the millennium, Wake Forest Institute for Regenerative Medicine printed synthetic scaffolds of a human bladder and then coated them with the cells for a human implant. Shortly after, different institutions fabricated a functional miniature kidney, prosthetic leg and bio-printed the first blood vessels [7].

Nowadays, 3D printers are used by professionals to make marketable objects [8][9]. Three-dimensional printers use software to slice a digital model and interpret the parameters into G-code, a language that the printer understands [10][11][12]. These printers are now commonly used in various fields to make custom models at a lower cost [3][13]. By virtue of the portability, easiness and low-cost maintenance and acquirement, instructional applications are highlighted by teachers and educators for their students in various subjects [11][12][14]. There are three classifications of 3D printers. They are desktop, professional, and industrial [1][3][13].

When it comes to desktop printers, the 3D printed objects produced are still not on par with industry standards for specific items that require a particular strength and durability [15]. It is interesting to know what desktop printers exit and how end-users select proper ones for their own applications.

1.1. Types of Standard AM (Additive Manufacturing) Processes

ASTM (American Society of Testing and Materials) generically defines seven classifications for additive manufacturing, namely [16][17] (1) Binder Jetting (BJ) [18][19][20][21], (2) Directed Energy Deposition (DED) [22][23][24][25], (3) Material Extrusion (ME) [26][27][28][29], (4) Material Jetting (MJ) [30][31][32][33], (5) Powder Bed Fusion (PBF) [34][35][36][37], (6) Sheet Lamination (SL) [38][39][40][41], and (7) Vat Photopolymerization (VP) [42][43][44][45]. Among these, the authors of this paper select ME types, called 3D printing, and researchers introduce nine different and popularly adapted methods in thermoplastics and photopolymer desktop 3D printing processes.

- **Fused Deposition Modeling (FDM or FFF)**: It is a material extrusion technique that prints plastic layer by layer at various thicknesses, speeds, and temperatures [46][47][48][49]. Some of notable works conducted [48][49] have shown the advantageous features of FFF technology with enhanced features by reducing printing time and waste through removing additional materials' needs for the supporting structure.

- **Stereolithography Apparatus (SLA)**: It is known its top accuracy and precision [50]. It converts liquid photopolymers into 3D objects, and the plastic is heated into a semi-liquid form, which hardens on contact with a UV laser. The object is then washed and cured to make it stronger and more stable. Some representative works are introduced in [3][46].

- **Digital Light Processing**: DLP is the oldest 3D printing method, and much like the SLA method, it uses a liquid plastic resin and an arc lamp (instead of a UV laser) to solidify the material to form the object. It is faster than SLA because it creates entire layers at once, whereas SLA has to draw out each layer [51][52]. An application for silk hydrogel printing is introduced in [53].

- **Selective Laser Sintering (SLS):** SLS technology uses a high-powered carbon dioxide laser to fuse metal (or nylon powder, ceramics, and glass) by partly melting the particles together. Since un-sintered material surrounds the print, this method does not require printed supports for stability. The un-sintered material is removed manually after the printing is carried out [54]. Due to its advanced and selective features for source selection, SLS is used for various applications in the medical field [55][56].

- **Selective Laser Melting (SLM)**: SLM also uses a high-powered laser that melts and welds metallic powders together by layer. The unused material is removed after the object is finished printing. SLM completely melts the powder, resulting in a more robust finished product over SLS [3]. SLM is heavily used in industrial applications for its complex geometry structure without space limitations [57][58]

- **Electron Beam Melting (EBM)**: EBM is similar to SLM, but instead of a laser, it uses a powerful electron beam in a vacuum to print metal objects. The product is solid and dense [3]. Some of its applications are introduced in detail in references [59][60]

- **Laminated Object Manufacturing (LOM)**: LOM is a method that fuses plastic or paper using heat and pressure with a laser and a roller. It is one of the fastest and most affordable methods for 3D printing [13]. With the advancement of rapid processing requirements and material selection, printing for materials such as composite and ceramic adapts LOM [61].

- **Binder Jetting (BJ)**: BJ was invented at MIT. It uses two types of materials (powder-based material and a bonding agent) to build objects. The materials can be ceramics, metals, sand, and plastics [3]. Binder Jetting is faster and more cost-effective than many 3D printing technologies. Binder Jetting machines can print quickly by using multiple heads to jet binding material simultaneously, turning out tens or even hundreds of parts in a single build. However, metal parts produced by Binder Jetting have inferior mechanical properties than DMLS/SLM parts. Additionally, the choice of materials used in Binder Jetting is limited [18][19][20][21][62][63]

- **Material Jetting Polyjet (MJ)**: The MJ method uses molten wax as the material to make molds and casts. A UV light helps the layers to cure, and a gel-like material is used for supports. The gel is removed afterward by hand or water jets [51]. MJ can produce smoother parts and surfaces than injection molding that guarantees very high dimensional accuracy. In addition, parts printed by MJ could have homogeneous mechanical and thermal properties. However, they are poor in mechanical properties so that parts cannot be used for functional prototypes [30][31][32][33].

1.2. Common Thermoplastic and Photopolymer Materials of Desktop 3D Printers

Below is the list of the commonly used thermoplastic and photopolymer materials in desktop 3D printers. Most of them are plastic polymers, and they mostly come in filament form. Excluded here are composite, carbon fiber, metal-based, wood, nylon, and silicone materials. Some of the materials used in specific printers use brand names, such as flex or Ninjaflex, and they fall one of the material lists below [46]:

- Acrylonitrile Butadiene Styrene (ABS);
- Polylactic Acid (PLA);
- Thermoplastic Polyurethane (TPU);
- Thermoplastic Elastomers (TPE);
- Polyethylene Terephthalate (PET);
- Polycarbonate Acrylonitrile Butadiene Styrene (PC-ABS);

- Chlorinated Polyethylene (CPE);
- Polyvinyl Alcohol (PVA);
- High Impact Polystyrene Sheet (HOPS);
- Acrylonitrile Styrene Acrylate (ASA).

2. Industry vs. Desktop 3D Printers

2.1. Printers for Industry

The main difference between industrial and desktop printers is print size, machine size, cost, and materials used. Industry printers have better accuracy, thicker layers, bigger build volumes, and a wider range of prices but are still more expensive than desktop printers [3]. Therefore, the major applications in industrial 3D printers are replacing conventional manufacturing processes such as parts with highly complicated geometry and requiring a certain level of mechanical properties. In addition, industrial printers always print with support to achieve better accuracy. Industrial printers also work with more expensive materials to produce better quality prints [13].

2.2. Desktop Printers

Desktop printers are not typically concerned with durability and strength. They are smaller and cheaper than industry printers. Mostly used for prototyping concept designs and replacing parts that don't require strength or durability. The accuracy of desktop 3D printers is often lower than industrial printers. This paper has selected five major commercially available 3D printer manufacturers and their iconic models to compare. These days, users' choice of printers is more individual based on their preference than satisfying certain requirements in desktop printers [51][52][3][5][13][7][48][56].

2.3. Challenges in Desktop Printers

Desktop 3D printers are quite different from industry ones in their size, accuracy, materials, and so on [51][52][3][5][13][7][48][56]. Some of the major challenges in desktop 3D printers are summarized below.

- **Lack of formal standards**: Due to the usage of desktop printers mainly for proof-of-concept models from CAD or similar purposes, standardization in material properties, extruder speed, the manufacturing process has not been recognized and established yet.
- **Limited repeatability**: Unlike molding in the conventional manufacturing process, various processing parameters, such as speed, temperature, material characteristics, and inherited characteristics of additive manufacturing, do not guarantee as repetitive results as conventional ones.
- **Software development and capabilities**: Development software is not often provided open-source, limiting the capabilities of tuning in system parameters for precise control in hardware and material processing.
- **Limited selection of materials**: Comparatively small and simple hardware in the printers also limits the number of materials to process. Typical desktop printers can process up to five different materials while industry ones are above 10 or more simultaneously or separately.
- **Low-resolution output**: Similarly extended to limited repeatability, desktop printers do not require mechanical properties of prints but while simple and rapid material processing.

3. Specifications of Desktop 3D Printers for Selection Criteria

Different from features and functions, important terms that determine printers are specifications. Below is the summary of them as well as tabulated in **Table 1**.

Table 1. Specifications of Desktop 3D Printers.

		Build Size	Layer Height	Printing Speed	File Format	Printing Software	Nozzle Temp. in C°	Bed Temp. in C°
Creality	Cr-10s	300 × 300 × 400 mm	0.1–0.4 mm	Normal: 80 mm/s, Max.: 200 mm/s Filament	STL, OBJ, G-Code,	CURA, simplify 3D, Repetier-Host	260 max	110 max
	Cr-10s pro	300 × 300 × 400 mm	0.1–0.4 mm	<180 mm/s, normal: 30–60 mm/s	STL, OBJ, G-Code	CURA, simplify 3D, Repetier-Host	<260	<110
	Ender 3	220 × 220 × 250 mm	0.1–0.4 mm	180 mm/s	STL, OBJ, G-Code	CURA, simplify 3D, Repetier-Host	255	110
	Cr-X	300 × 300 × 400 mm	0.1–0.4 mm	Normal: 80 mm/s, Max.: 100 mm/s	STL, OBJ, G-Code, JPG	CURA, simplify 3D, Repetier-Host	<260	<110
Prusa	I3 mk3	250 × 210 × 210 mm	0.05–0.35 mm	30–200 mm/s	STL, OBJ, G-Code, JPG	Simplify3D, Cura, Slic3r	300	120
Makerbot	Method	190 × 190 × 196 mm	20–400 microns	Up to 500 mm/s	makerbot, STL, OBJ, G-Code,	MakerBot Print, MakerBot Mobile	N/A	N/A
	Replicator+	295 × 195 × 165 mm	100 microns	175 mm/s max	Makerbot, STL, OBJ	MakerBot Print Software, MakerBot Mobile	N/A	N/A
	Z18	300 × 305 × 457 mm	100 microns	175 mm/s max	STL, OBJ	MakerBot Print Software, MakerBot Mobile	N/A	N/A
Ultimaker	3	215 × 215 × 200 mm	20–200 microns	<24 mm^3/s; 30 to 300 mm/s	STL, OBJ, X3D, 3MF, BMP, GIF, JPG, PNG	Ultimaker Cura Cura connect	180–280	20–100
	S5	330 × 240 × 300 mm	20–600 microns	<24 mm^3/s; 30–300 mm/s	STL, OBJ, X3D, 3MF, BMP, GIF, JPG, PNG	Ultimaker Cura Cura connect	180–280	140 max
Formlabs	Form 2	145 × 145 × 175 mm	25–100 mm	N/A	STL, OBJ	Formlabs	N/A	N/A

- Printing Speed: Speed that the printer moves while extruding;
- File Format: The file types that the printer recognizes;
- Printing Software: The splicing software that the printer is compatible with;
- Nozzle Temp: Maximum temperature that the nozzle will reach;
- Bed Temp: Maximum Temperature that the heat bead will reach;
- Power Supply: The amount of input and output voltage the printer requires to work;
- Filaments: The types of materials that are compatible with the printer;
- Features: The unique capabilities the printer has to offer;

- Price: The amount of money the printer costs.

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