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Optimizing 3D Printing Materials and Parameters for Robotics Applications

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Abstract **–** As a newly emerged additive manufacturing technology, 3D printing technology continues to gain popularity and play important roles as an enabling technology in producing various parts and components. With its salient merits of versatility, efficiency, and low-cost, 3D printing is extremely powerful in the design and fabrication of components in the research and development of novel devices and systems, for example, in the development of next-generation robotics technologies with enhanced functionalities and performance. In this study, investigation to evaluate the properties of different 3D printing materials for robotics applications is implemented. The focus of this study is to understand how changing specific parameters adopted in the fabrication affect qualities like the strength of the 3D printed objects. Through experimentation, important aspects, such as the influence of various parameters (printing material, layer thickness, and infill density) on the qualities such as the strength of 3D printed objects, have been revealed. Possible approaches to achieve optimal printing parameters for increased strength have been identified.

Keywords**:** 3D printing, additive manufacturing technology, materials, polymers, robotics

1. Introduction

3D printing, an additive manufacturing technology, is one of the revolutionary technologies that has been transforming manufacturing and industrial processes in the past decades [1-3]. 3D printing is a computer-controlled sequential layer by layer deposition of materials to create structures of three-dimensional shapes, which is an enabling technology for prototyping and manufacturing geometrically complex components. As one of the important integrated manufacturing technologies. additive manufacturing technology has been widely used for extensive customization and production of all types of open-source designs in biomedical, automotive, transportation, aerospace, construction, marine, and farming industries [4-7]. Though first emerged in the 1980s, 3D printing technology became relatively straightforward and affordable after year 2000. Nowadays, 3D printing technology has found a wide range of uses. The prominent advantages of 3D printing for industrial applications include flexible manufacturing systems, simple production, minimal human participation, minimized instrumentation footprint, little material waste, minimal postprocessing, and better energy efficiency. Despite significant advances achieved over the past decades on 3D printing technology, there are still challenges that need to be addressed to satisfy demands from increasing fields of applications with the 3D printing technology. Among different obstacles, the challenge on the selection of suitable 3D printing material and optimized fabrication parameters for specific applications requests significant endeavour to find solutions.

In this study, investigation will be implemented to identify how various parameters, such as the printing material, layer thickness, infill density, hardness and roughness, affect qualities such as the strength and durability of 3D printed objects to identify the optimal printing parameters for increased strength. A clear understanding on how changing specific parameters affect qualities is essential for the increasing popularity of the 3D printing technology as an important integrated manufacturing technology.

2. 3D Printing Materials and Selection

For the use of 3D printing technology to fabricate any parts and components for any applications, the key task is to identify optimal parameters to fabricate devices of enhanced performance to satisfy specific application. To achieve this goal, it is necessary to identify possible 3D printing materials, investigate the material properties of potential candidates, and evaluate their material properties to select suitable one with satisfactory quality, durability, and functionality [8-11]. To satisfy the needs for printing intricate models with high resolution, different methods of additive manufacturing have been developed, in which rapid prototyping has been one of the main methods. Additive manufacturing technologies are based on three main types, which include: (1) Sintering, where the temperature of the material is increased without being liquified to compose complex sharp resolution prototypes; (2) Melting, where electron beams are utilized to melt the powders; and (3) Stereolithography, in which an ultraviolet laser is used to expose a material with a suitable pattern. Some of the main methods in additive manufacturing are: (1) Stereolithography, also known as photopolymerization, in cross-sections of a photopolymer is cured by an ultraviolet laser and transformed from liquid to solid; (2) Fused deposition modelling (FDM), which uses melting thermoplastic filaments to be deposited layer-by-layer to form a 3D object; (3) Powder bed fusion (PBF), which uses a thin layer of powder to build a layer-by-layer 3D structure with a laser or an electron beam; (4) Selective laser sintering (SLS), which consolidates consecutive heated powdered material layers over one another; (5) Binder jetting (BJ), which uses an inkjet to bind the objects, instead of using lasers; (6) Direct energy deposition (DED), which uses a centred heat supply (electron beam or laser) to deposit a material layer-by-layer to repair or make new features on already existing products; (7) Laminated object manufacturing (LOM), which starts with a sheet joined to a substrate, followed by cutting and bonding of the forthcoming layers.

In this study, 3D printing with fused deposition modelling (FDM) is adopted as the fabrication technology to make parts and components for robotics applications. The materials to be adopted in FDM for robotics applications are expected to possess satisfying hardness, translucency, biocompatibility, and resistance to UV radiation, among other features to be considered. FDM 3D printing is a widely used additive manufacturing technology in recent years, which requires a continuous filament made of one or multiple thermoplastic materials as the source materials. In general, a wide range of materials can be adopted in 3D printing with FDM. Table 1 lists some frequently used FDM 3D printing materials and a general comparison of the benefits and limitations of these 3D printing materials.

Even though some common FDM 3D printing materials and their properties, such as those listed in Table 1, are searchable, the details of the material properties are still not well known. It is crucial to select a suitable 3D printing material for any specific application through quantitatively evaluation from careful experimentation. The selection of a suitable 3D material for a specific 3D printed parts and components largely relies on its intended application, which imposes restrictions on the physical, chemical, and mechanical properties of the material. The evaluation and screening of candidates of 3D printing materials allow users to make informed decisions on suitable material for the specific application, identify cost-effective choices for the budget, aware of the environmental impact of different materials to achieve sustainable and eco-friendly printing practice. For applications in healthcare and aerospace industries, compliance with strict regulations regarding materials is necessary to avoid legal and safety issues. For 3D printed parts and components in robotics applications, it is essential to investigate some fundamental properties of 3D printing materials, which include but not limited to melting temperature, temperature-dependent performance, hardness, impact strength, flexural strength, tensile strength, smoothness, and elongation. Detailed properties of these 3D printing materials on these aspects are mostly missing so far. It is the focus of this study to reveal some of the most important features of the smoothness, damage threshold, hardness, and their temperature dependences of these potential 3D printing materials for robotics applications.

3. Results and Discussion

3.1. 3D Printing Materials Investigated in This Study

Based on the information listed in Table 1, nine kinds of FDM 3D printing materials were selected in this study, which are PLA, PETG, ASA, ABS, PC, Nylon, Tough PC, CoPA Nylon, and TPU. For experiments on the measurements of smoothness, damage threshold, hardness, and temperature dependence, two types of samples have been prepared with the 3D printers: the disc samples for smoothness and hardness measurements and the sheet samples for load-bearing tests. Figure 1 shows the samples of circular discs with a diameter of 0.025 m and a thickness of 0.005 m. Figure 2 illustrates the PLA sheet samples of a width of 0.06 m, a length of 0.12 m, and a thickness of 0.16 cm. The source materials used in 3D printing were the filaments of 3D printing materials assembled in spools, as shown in Figures 3 and 4(b). The diameter of the filaments is 1.75 mm±0.03 mm.

Table 1: Comparison of benefits and limitations of different 3D printing materials.

Material	Chemical name	Advantages	Disadvantages
ABS	Acrylonitrile Butadiene Styrene	Outstanding durability. Resistance to elevated temperatures. Impressive strength-to-weight ratio. Robustness.	Tendency to warp unless printed within an enclosure. Emitting odorous volatile organic compounds.
ASA	Acrylic Styrene Acrylonitrile	A superior alternative to ABS. Enhanced thermal resistance. Improved mechanical properties. Enhanced resistance under UV exposure.	Significant warping. Releasing potentially harmful fumes during printing.
PP	Polypropylene	Exceptional chemical resistance. Exceptional resistance to fatigue	Tendency to warp easily during 3D printing. Weak adherence to the building plate.
PLA	Polylactic Acid	Low printing temperature. Minimal warping tendency. Degradable and eco-friendly. Odourless during printing.	Impossible to survive high temperature or heavy stress. Lower durability as compared to ABS or PETG.
Carbon Fiber	Carbon	Enhanced material's overall strength.	Likely lead to nozzle clogging. Increased wear on standard 3D printing nozzles.
Nylon	Polyamide	Exceptional toughness and resistance to both high temperatures and impacts. Commendable tensile and mechanical strength.	Not as easy to print like PLA and PETG. High-temperature nozzle up to 300°C may require. Severe moisture absorption leading to materials degradation.
PC	Polycarbonate	Exceptional high transition temperature ensuring high-temperature applications. Excellent natural flexibility.	Prone to moisture absorbance leading to warping or layer separation during printing. Caution when working with PC at high temperatures.
Nitinol	Nickel-titanium	Remarkable super-elasticity. Bendable without fracturing. Exceptional flexibility.	Mostly used in medical implants
PETG	Polyethylene terephthalate glycol-modified	Outstanding heat-resistance. Reduced brittleness. Easiness of printing with a smooth finish. Food-safe	High printing temperatures required. PETG is more hygroscopic than PLA.
TPU	Thermoplastic polyurethane	Flexible and stretchable. Shock-resistant and impact resistant. Excellent vibration dampening. Abrasion-resistant and chemical-resistant.	Must be printed at low speed. Susceptible to stringing and clogging. Difficult to post-process.

As shown in Fig. 4(a), two FDM 3D printers were used in this study: one 3D printer without enclosure was BIQU B1 SE Plus (BIQU) and the other one with enclosure X1-Carbon Combo from Bambu Lab.

Through the experiments in this study, it was found that TPU filament was too soft for the printing process, which easily caused clogging of the nozzle. It was also very difficult to achieve 3D printing with PC, Nylon, Tough PC, and CoPA Nylon due to the reason either the requirement of high-temperature nozzle or warping during the printing. Therefore, only the experimental results of PLA, PETG, ASA and ABS have been included in the following discussion.

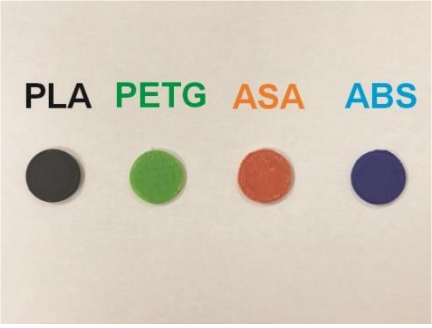

Fig. 1: 3D printed discs of PLA, PETG, ASA and ABS for hardness measurement.

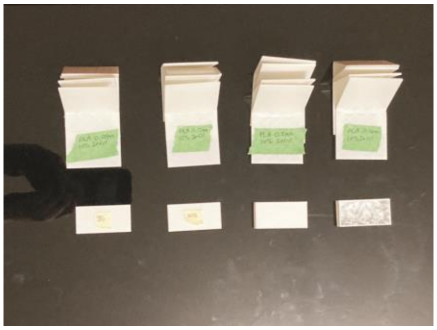

Fig. 2: 3D printed samples of PLA sheets with different structures For load-bearing test.

Fig. 3: Different 3D printing materials investigated in this study.

(a)

(b)

Fig. 4: 3D printing systems and spools of filaments used in this study: (a) X1-Carbon Combo from Bambu Lab (left) and BIQU B1 SE Plus (right); and (b) a spool of ASA filaments with a diameter of 1.75 mm±0.03 mm.

3.2. Durometer (Hardness) Measurement

Durometer is a standardized method to measure a material's hardness or resistance to localized deformation due to the indentation or abrasion. Hardness (durometer) is a dimensionless (unitless) physical parameter. Different durometer scales have been developed to quantify and compare the hardnesses of different materials. Hardness values range from 0 – 100. Materials with higher values are harder than materials with lower values. There are several different types of hardness (durometer) scales that quantify the hardness of different materials. The ASTM D2240 is the standard measurement system, which specifies 12 different hardness scales, including A, C, D, B, M, E, O, OO, DO, OOO, OOO-S, and R. It is important to know the hardness of 3D printing materials to ensure a successfully designed components. Figure 5 illustrates the experimental setup to measure the hardnesses of the discs made of PLA, PETG, ASA, and ABS. The testing results, shown in Figure 6, indicate that PETG possesses a hardness of D28 while the other three materials exhibit a hardness of about D20. The harness of all three materials shows a sharp decrease at higher temperature, which is shown in Figure 7. PLA sample shows that the hardness decreases at a relatively lower temperature while a higher temperature around 80°C is found for the ABS sample to start the decrease in the hardness.

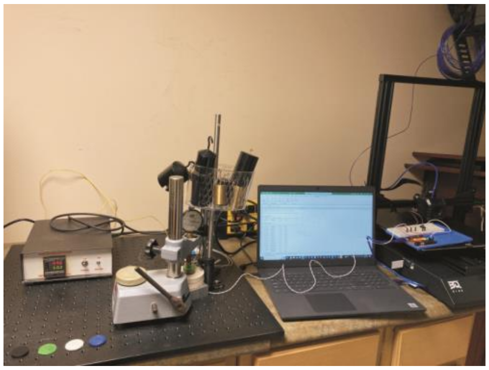

Fig. 5: Experimental setup for hardness measurement.

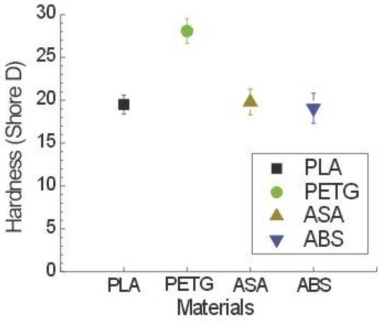

Fig. 6: Hardness of four materials at room temperature.

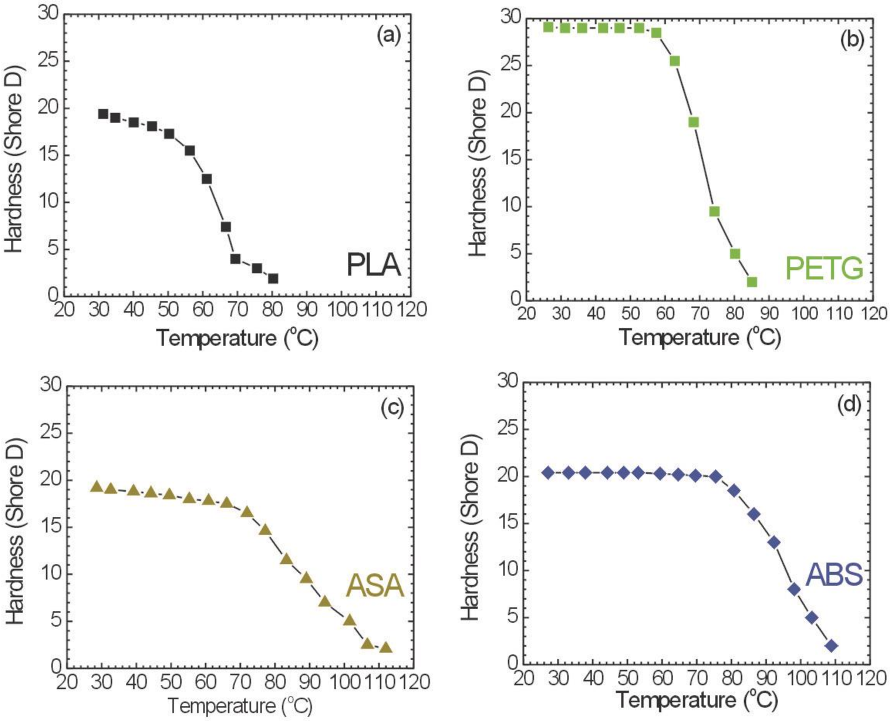

Fig. 7: Temperature dependences of the hardnesses of PLA, PETG, ASA and ABS materials.

3.3. Load-Bearing Test

The mechanical properties of 3D printing materials are crucial for the use of printed parts and components in applications [12-14]. Damage threshold is very important to reveal the maximal resistance of a part or component to external force, which is crucial to select suitable material and achieve optimized structural design to satisfy demands practical applications. Infill density is a parameter to indicate the “fullness” of the inside of a part or component, which usually defined as a percentage between 0 and 100, with 0% indicating a hollow part and 100% representing a complete solid. As the fuller the interior of a part or component, the heavier it is. The infill density closely correlates with the weight of a part or component. Besides weight, other characteristics of the 3D printing features, such as print time, material consumption, buoyancy, and strength, are impacted by infill density. With the experimental setup shown in Figure 8, the results from this study, as shown in Figure 9, indicate that, as the infill density increases, the damage threshold also increases. There is a large increase in the damage threshold when the infill density exceeds 10%. However, additional infill densities past 10% provide less of an increase. As the layer thickness is increased, while there is also an improvement in the damage threshold, the improvement is much less significant than the changes in infill density. Overall, 0.16 mm layer thickness is optimal for strength as it has very similar damage thresholds to 0.2 mm layer thickness.

Fig. 8: Setup for load-bearing test.

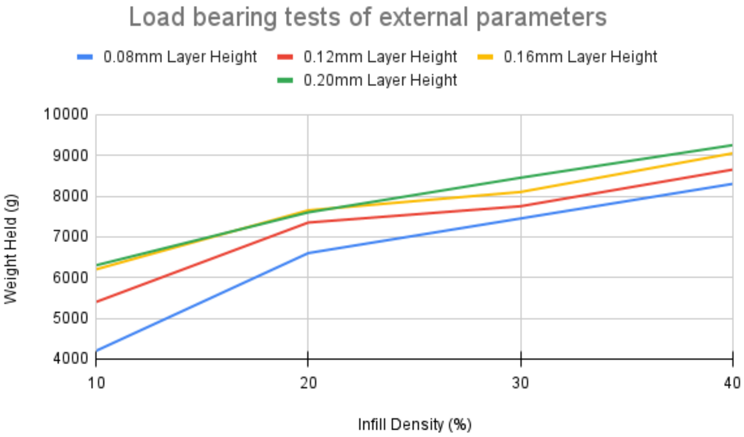

Fig. 9: Weight versus infill density of PLA samples from load-bearing test.

3.4. Surface Roughness Evaluation

Surface roughness is another important feature of the mechanical properties about the finished parts and components. It is an ongoing effort to identify effective methodology to characterize the surface properties of the 3D printed parts and components [15]. To compare the surface roughness of different samples, a standardized set of surface roughness has been adopted. Figure 10 shows a standard set (FLEXBAR Model No. 16008) used for the evaluation of the surface roughness of the discs made of PLA, PETG, ASA, and ABS. With the 30 specimens included in this standardized set calibrated in μ″ AA (Arithmetical Average), it is possible to estimate the surface roughness of the 3D printed samples fabricated in this study by making comparison with these surface roughness standards comparators. The surface morphology of these samples has also been observed using a Leica optical microscope to reveal the surface roughness at the micrometre scale, which is shown in Figure 11. The surface finishes of PLA and ASA samples are smooth than that of PETG and ABS samples.

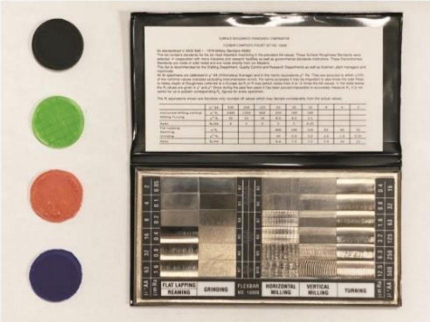

Fig. 10: Evaluation of the surface roughness of a sample with a standard set (FLEXBAR Model No. 16008).

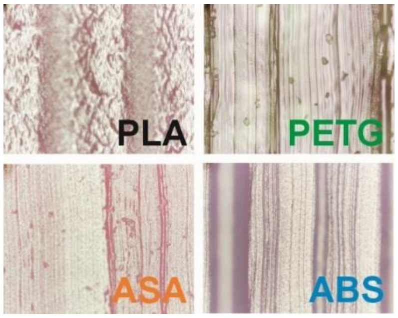

Fig. 11: Morphology of the surfaces of PLA, PETG, ASA and ABS samples observed by a Leica optical microscope.

3.5. 3D Printed Components for Robotics Applications

It has become evident that 3D printing technology is an enabling technology in the development and fabrication of parts and components for many applications, in particular, devices and systems. 3D printed parts and components can play an important role in robotics, in which they can serve as the building blocks to form indispensable parts of robots as well as scaffolds to be integrated with additional functionalities, for example, various kinds of sensors. It is necessary to select suitable 3D printing materials and printing parameters by evaluating demands on the physical, chemical, and mechanical properties of the materials, such as temperature range of the usage, damage threshold, and UV durability. In the occasions of uses in indoor environment, from the results derived from the experiments in this study, PLA should be a good candidate to achieve high strength and lightweight. PLA is widely accessible and performs only slightly worse than the more expensive alternative materials while possessing superior print quality. In case for outdoor applications, it may be better to select ASA for its excellent UV durability. Figure 12 shows the 3D printed parts and components with PLA in this study for robotics applications, including gears, clamps, junctions, holders, and other fixtures. Obviously, the versatility of 3D printing technology offers unlimited opportunities to fabricate 3D structures of arbitrary shapes and specifications for a wide range of applications and exhibits profound significance in all scenarios where conventional or unconventional parts and components are needed.

Fig. 12: Fixtures of different geometries and sizes fabricated with the 3D printing technology for robotics applications in this study.

4. Conclusion

In summary, evaluation on the properties of different 3D printing materials for robotics applications has been performed as well as an effort to understand how changing specific parameters affect qualities like the strength of the 3D printed objects. Through experimentation, important aspects, such as the influence of various parameters (printing material, layer thickness, and infill density) on the qualities such as the strength of 3D printed objects, have been revealed. In terms of external factors, infill density seems to have a significant impact on the strength of 3D printed components, while layer thickness seems to have a smaller effect. In terms of materials, PLA seems to be the material with the best balance of print quality and strength, while PETG offers the highest strength at the expense of print quality. The results derived from the experiments in this study can significantly impact how 3D printed parts and components can be utilized in different applications. For example, using the data obtained here on the optimal infill density and layer thickness, as well as the temperature ranges for various filament materials, we can create devices and systems to be integrated with these 3D printed parts and components, which are durable and resilient in robotics applications. This study has also investigated the use of 3D printed parts and components for robotics applications. With the aids from the 3D printed parts and components to achieve integration of embedded sensors, it is possible to enhance functionalities and performance of robots. Further improvement is currently undergoing, which relies on the further investigation on the material properties, optimized designs, enhanced strength, and integration in robotic systems to achieve enhanced functionalities.

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