Cost, sustainability and surface roughness quality – A comprehensive analysis of products made with personal 3D printers

L Nagaraju
Asst Professor, Department of Mechanical Engineering , Princeton College of Engineering and Technology,TS,India

ABSTRACT

Additive manufacturing (AM), generally also referred to as 3D printing, has gone through vast development in the past 20 years which still continues. In particular, the market segment of personal 3D printers has achieved an average annually growth rate of approximately 170% from 2008 to 2013. The purpose of this research is to identify the best AM process applied in personal printers in terms of cost, sustainability, surface roughness, and human perception, as these aspects are essential for this new thriving market segment's future. In addition, the research investigates which objective roughness parameters are suitable for qualifying subjective perceptions. The primary AM processes, Fused Deposition Modeling, Stereolithography and Polyjet printing are in the focus of this research. Manufacturing costs as well as environmental impact are calculated, five independent roughness parameters (Ra, Rz, Rq, Rsk, and Rku) are measured and the subjective perception of samples is assessed through sensorial analysis. In conclusion, samples manufactured with Polyjet printing have the best subjective quality, but the highest costs and environmental impact. Biplots of roughness parameters versus sensorial ranking indicates a significant correlation between maximum peak-to-valley height Rz and tactile and visual perception, while the kurtosis of the topography height distribution Rku correlated best to the hedonic rank

Introduction

Background

Low-cost desktop 3D printers, or personal 3D printers, are those additive manufacturing (AM) machines with a unit price under $5.000 [1]. Though their history is much shorter compared to industrial 3D printers, this market segment has been booming in recent years, with an average annually growth rate of approximately 170% to date from 2008. The amount of personal 3D printers has surpassed industrial printers by several scales in terms of growth rate and quantity [1]. The rapid development of personal 3D printers is mostly based on the Stratasys' Fused Deposition Modeling (FDM1) technology [2], the first multi-material 3D printer ''Fab@Home'' [52] and the RepRap open source machine development project [3] since2007. As a result, a dominant quantity of personal 3D printers is based on Stratasys' patented technology FDM1 and Fused Filament Fabrication (FFF) technologies. The American Society for Testing and Materials (ASTM) classifies all of these AM principles as material extrusion technologies, in which material is selectively dispensed through a nozzle or orifice [4]. With the development of the personal 3D printing market segment, few fundamentally new processes have been developed and few existing AM processes have also been reapplied toward the personal 3D printer segment, including Vat Photopolymerization and Material Jetting. Vat Photopolymerization is an AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization [4] as Stereolithography Apparatus (SLA1). Polyjet1, as an AM process in which droplets of build material are selectively deposited and cured with UV light [4], is an example for Material Jetting

Research objective

A key advantage of AM is the ability to facilitate customized production and allow designs that were not possible with previous manufacturing techniques. With the significant development inprevious years, AM technology seems to open up new opportunities for the economy and society. Various challenges, however, can impede and slow the adoption of this technology, to which their cost effectiveness in comparison to traditional manufacturing methods and ability to fulfill the social demand on cleaner production and sustainability belongs. Therefore, the manufacturing cost and environmental impact of these AM processes have to be evaluated.

Besides that, the main application field of personal 3D printers is prototyping. According to statistics collected by 3D Hubs over 10,000 printers, their main applications are categorized as: Prototype, Hobby/DIY, Gadget, Art/Fashion, Scale model and Household [5]. Therefore, in comparison to mechanical or thermal properties, the tactile and visual perception along with esthetic coordination has more influence on how the consumers assess the quality of 3D printed parts

Today, the surface quality of plastics manufactured by FDM, SLA, and Polyjet printing and main influencing factors have been comprehensively researched. Previous studies have found that layer thickness and road width1 have significant influence on FDM parts [6]. Layer thickness, hatch and fill spacing affect the inclined and horizontal planes of SLA parts [7]. In Polyjet parts the layer thickness and built style (matte or glossy) are the most influencing factors [8]. In mutual comparison, FDM parts have the roughest surface [9]. Polyjet printing surpasses SLA in surface quality in all inclined surfaces but not for an inclination of 908, which is the vertical surface [9].

However, how the printed parts of these processes are perceived by consumers and which parameter will influence their perception has not been investigated yet. Therefore, this research will focus on the most relevant 3D printing processes for plastic parts, FDM, SLA, and Polyjet printing, and investigate which measured surface roughness parameters are suitable for qualifying subjective perceptions. In addition, costs and environmental impacts will be investigated

Sample preparation

Several samples were manufactured with different AM techniques to compare cost, environmental impact, roughness and sensory quality. The dimensions of the benchmark samples are 38.1 mm 38.1 mm 38.1 mm (1.500 1.500 1.500). Fig. 1 shows the sample details.

To achieve a performance evaluation and comprehensive perception by assessors toward 3D printing, the benchmark part includes key shapes and features, which are increasingly required or expected of AM processes and suitable for fabrication in a typical personal 3D printing machine. Similar geometric features are used in a study on AM process comparison including SLA and FDM by Mahesh et al. [10]. The geometric features shown in Fig. 2 are identified by two-letter names, such as SB, HC, etc. for referencing in the succeeding table and results. They are also summarized in Table 1 in alphabetical order

Manufacturing costs

According to Son [36], the manufacturing costs for 3D printing can be categorized in two different ways: (1) for ‘‘well-structured costs’’, e.g. labor, material, and machine costs and (2) for ‘‘illstructured costs’’ involving those associated with build failure, machine setup, and inventory. As the ‘‘ill-structured costs’’ relates more to possibilities for savings in a supply chain, the two major manufacturing costs models for 3D printing by Hopkinson and Dickens [37] and Ruffo et al. [38] are based on the ‘‘well-structured costs’’. The suitable equations for this research’s printing scenario and the main assumptions includes: (1) only one part is manufactured in each build, (2) the printer will completely depreciate after eight years and (3) the printer worked 100 h per week for 50 weeks per year (57% utilization).

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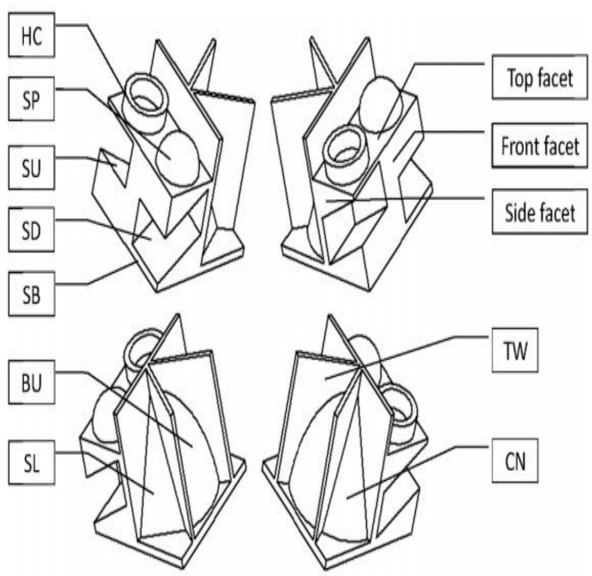

Fig. 1. The benchmark part.

where pmachine, machine cost; tdep, duration for machine depreciation (8 years) [37]; eu, annual utilization rate (57%); tman, manufacturing time for a sample; Slabor/tannual; average salary per hour in UC Davis for lab technician ($15/h) [39]; tassist; time for assistance for manufacturing's set-up and samples' cleaning (0.5 h); pmaterial, price for build material; mmaterial, weight for build material (including waste); psupport, price for supporting material; msupport, weight for supporting material; Pelec, machine power; pelectricity, average electricity price in Davis, CA ($0.1153/kWh) [40]. The costs for facility rent, maintenance, equipment and software (referred to as administrative overhead by Ruffo et al. with 1.4% in total cost) were ignored. All relevant data is listed in Table 3. For Polyjet parts secondary gel-like support material was used and its data is shown behind the build material in square brackets

As seen in Table 3, the Polyjet parts (IV and V) have the significantly highest costs among the three AM processes, whereas FDM parts (I and II) have the lowest. The price for the SLA part (III) is in the middle. Labor costs contribute greatly to manufacturing costs and the effect is more significant with relatively low-cost FDM printers. For cost per weight Csum/msmp, however, the SLA part (III) has the lowest value, followed by FDM parts and Polyjet parts. The cost per weight span only from 0.463 $/g (100%) to 1.223 $/g (about 260%), whereas the total cost span from $8.342 (100%) to $35.381 (about 420%). However, as the Polyjet printers have the ability to manufacture multiple parts within one build without a significant increase in time due to a scan width of 2.500 by UV lamp, the cost per part could be reduced correspondingly [28,41]. Because today the material costs of Polyjet printing are considerably higher than total costs for FDM and SLA products, it is not realistic for Polyjet to achieve the same price per unit as FDM or SLA. Multiple printings make Polyjet printing more competitive

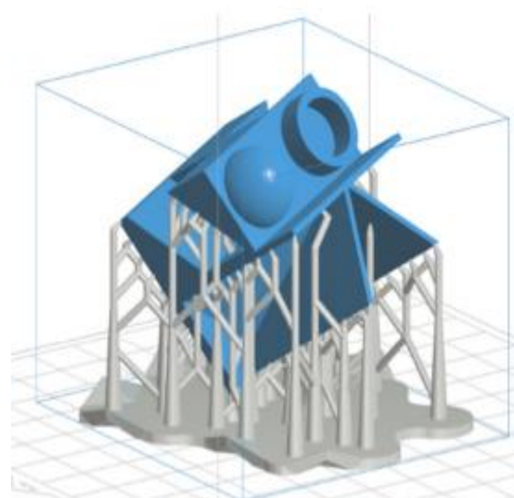

Fig. 2. Build direction of SLA sample in printer.

Environmental impact of the printed parts

With the maturing of 3D printing techniques, the public considers higher sustainability as a key advantage. It is expected that AM can reduce environmental impact and energy consumption significantly compared to traditional manufacturing practices, such as injection molding of plastics [32,48]. Many relevant studies were done on AM techniques, but without a specialized focus on personal 3D printers [31,42,43]. The following shows two approaches to analyze environmental impacts of the printed parts

Evaluation with life-cycle methodology

The first evaluation method to assess the environmental performance of AM processes is based on the work by Luo et al. [42]. As a life cycle methodology itincludes environmental impacts in all life cycle stages.

The hierarchical process model by Luo et al. applies EcoIndicator 95 [45] as Environmental and Resource Management Data (ERMD), which defines ways to quantify the consequences of impairment of the environment. Four AM products' life cycle phases are in focus: (1) raw material preparation, (2) build process, (3) product usage and (4) disposal. In the build process phase the environmental impact of AM per se and possible residues are considered, and in the use phase the material toxicity. Three different methods (recycling, landfill, and incineration) are available for the disposal phase. The entire methodology is shown in Fig. 3.

Table 1
Summary of the sample's features.

Abbreviation	Features	Nominal size
BU	Bullet	Base diameter 17.78 mm (0.7″)
CN	Cones	Base diameter 16.26 mm (0.64″)
HC	Hollow cylinders	Outer diameter 15.24 mm (0.6″) and inner diameter 11.43 mm (0.45″)
SB	Square base	38.1 mm × 38.1 mm × 1.27 mm (1.5″ × 1.5″ × 0.05″)
SD	Slot downwards	Inclination 30° beneath horizontal, slot height 12.7 mm (0.5″)
SL	Slope	Inclination 60° above horizontal
SP	Spheres	Diameter 15.24 mm (0.6″)
SU	Slot upwards	Inclination 30° above horizontal, slot height 12.7 mm (0.5″)
TW	Thin wall	Thickness 1.27 mm (0.05″)

The following equations calculate the environmental impact of the build processes, which is expressed in Energy in Process (E.P.) and represents the environmental impact of energy used to process one kilogram of print material.

The FDM samples have not only advantages in energy consumption during the build process, but also have low total life-cycle environmental impact in comparison to SLA and Polyjet printing. These advantages are mostly based on their high process overhead coefficient, recycling possibility and low material usage due to less than 25% infill. Especially the low infill density in FDM parts and the resultant reduction of the needed build material have contributed to the outstanding environmental performance: In view of total EPV per kilogram build material, the Polyjet samples IV and V are increased by factors of two and three compared with the FDM sample II. Ifthe weights of used materials are taken into consideration, the factors expand to about 11 and 17 respectively. Moreover, according to the LCA calculation by Kreiger and Pearce [32], the ABS and PLA parts manufactured by personal FDM printers have already an advantage in terms of energy consumption and CO2 emission in comparison to the conditional injection molded parts, if their infill is less than 79%, which is fulfilled in this research's samples. This whole discussion, however, does not take material strength and other mechanical properties into account

Conclusions

The research has focused on three important aspects of personal 3D printing processes, i.e. manufacturing cost, sustainability, and visuotactile perception of surface roughness. For manufacturing cost, two main approaches by Hopkinson and Dickens [37] and Ruffo et al. [38] exist, which are applied to personal 3D printers with appropriate assumptions to the print scenario. In calculation with the benchmark samples, the Polyjet parts have the highest cost while the FDM parts have the lowest. With personal 3D printing's scenario of one single part being manufactured in a build, labor cost contributes greatly to manufacturing cost. With more than one parts manufactured in one build, the cost of Polyjet printing could be reduced. In terms of environmental impact in life cycle, life cycle methodology and Eco-Indicator 95 are applied by Luo et al. [42]. FDM products have the lowest environmental impact while Polyjet products the highest, which could be attributed to FDM's relatively low process energy consumption and the possibility to be recycled when the products are disposed. An infill density less than 100% is also a crucial factor. Another approach by Bourhis et al. [43] focuses on the print process per se consumption with the more accurate Eco-Indicator 99. The electric, material and fluids consumption are in scope and analyzed separately during the print process. With this approach, FDM products have the lowest environmental impact while Polyjet parts have the highest. Fill ratio, density and part weight can be varied in FDM and change the impacts considerably.

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