Experimental Dimensional Accuracy Analysis of Reformer Prototype Model Produced by FDM and SLA 3D Printing Technology

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Abstract. The subject of this paper is the evaluation of the dimensional accuracy of FDM and SLA 3D printing technologies in comparison with developed reformer polymer electrolyte membrane (PEM) fuel cell CAD model. 3D printing technologies allow a bottom-up approach to manufacturing, by depositing material in layers to final shape. Dimensional inaccuracy is still a problem in 3D printing technologies due to material shrinking and residual stress. Materials used in this research are PLA (Polylactic Acid) for FDM technology and the standard white resin material for SLA technology. Both materials are commonly used for 3D printing. PLA material is printed in three different height resolutions: 0.3 mm, 0.2 mm and 0.1 mm. White resin is printed in 0.1 mm height resolution. The aim of this paper is to show how layer height affects the dimensional accuracy of FDM models and to compare the dimensional accuracy of FDM and SLA printed reformer models with the same height resolution.

Keywords: Reformer · 3D printing · FDM · SLA · CAD model

1 Introduction

3D printing technology allows fabrication of objects through a sequential layering of material based on digital CAD model, [1, 2]. A variety of 3D printing processes are now commercially available, differing from each other in the way they build a model. In the process of 3D printing, the material is softened, melted or irradiated in order to deposit material layer by layer, [3]. As a technology which can achieve production of complex geometry parts, first 3D printing was developed for the purpose of rapid prototyping. Nowadays, there are examples of 3D printing technologies used for specialized customer products, structural models in architecture, aerospace and medical industry with the tendency to wider use in industrial applications, [2, 3].

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Geometrical inaccuracy from shrinkage and residual stress induced deformations are key sources of defects in 3D printing, [4]. Material shrinkage has been a major cause of part inaccuracy. Most common and commercially available 3D printing technologies are FDM (fused deposition modeling) and SLA (stereolithography), [2]. In this paper, FDM and SLA technology would be compared in terms of dimensional accuracy of finished parts based on digital CAD models of PEM fuel cell reformer, [5]. 3D printing is still in early stages of commercialization and thus presents a high potential for research and development, [6].

FDM is a material extrusion 3D printing technology in which softened thermoplastic material is extruded through a nozzle or orifice onto a platform (Fig. 1). FDM machine is equipped with computationally controlled extruder mechanism. The platform can be equipped with resistant heaters in order to keep extruded material at certain temperature holding material on the platform. Printing material in form of a filament is guided by two pulleys into the extruder. At the extruder end heater block heats and keeps material at a temperature above melting point allowing a steady flow of material filament through the nozzle. Nozzle extrudes softened material on a pre-defined path, creating the first layer. Thereafter, the platform moves downwards allowing the nozzle to generate next layer. Printing continues, layer-by-layer, until a model is finished, [1, 2, 7]. Dimensional accuracy of a printed model is determined by layer height and nozzle diameter more than extrusion temperature, printing speed and infill percentage and pattern, [8].

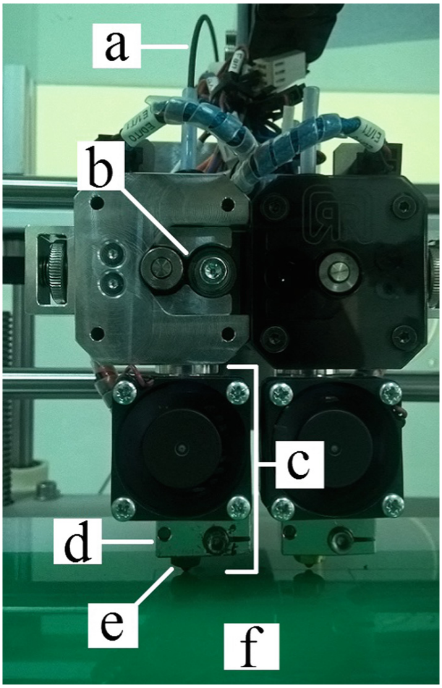

Fig. 1. FDM printing technology: (a) material filament; (b) two pulleys; (c) extruder; (d) heater block; (e) nozzle; (f) platform/heated bed.

FDM uses a vast variety of thermoplastic materials with different mechanical properties, which makes this particular technology favorable for industrial use. Most common materials in FDM technology are ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) polymer. PLA is environmental friendly biodegradable plastic in comparison with petroleum-based ABS, [9]. The melting point of PLA is at 175 °C, [10].

During printing, heated material cools at a lower temperature of platform/heated bed causing changes in material volume, i.e. shrinking, which leads to dimensional inaccuracies as opposed to the digital CAD model, [11, 12]. Model accuracy depends on the physical properties of the material during heating and cooling, [3]. PLA has proven to be more dimensionally stable after print compared to ABS material, which is why this material is a subject of this study, [9, 10].

SLA (Stereolithography) is vat photopolymerization 3D printing technology in which liquid photopolymer is selectively irradiated by a laser beam causing light-activated polymerization of liquid material (Fig. 2), [1, 3]. Main components of SLA machines are a light source, build platform and resin tank. Liquid photopolymer-resin is stored in resin tank with a transparent bottom. UV laser is used as a light source to initiate the polymerization of liquid material. Print starts by lowering of the build platform into the resin tank, leaving space between bottom of the tank and build platform equal to layer height. UV laser directs the light through the bottom of the resin tank selectively curing a layer of material. When laser finishes irradiating the first layer, the platform moves up to allow wiper to pass across the tank to circulate resin. The process continues layer-by-layer until the model is printed, [1–3]. The whole process is enclosed to prevent other light sources from curing the resin material.

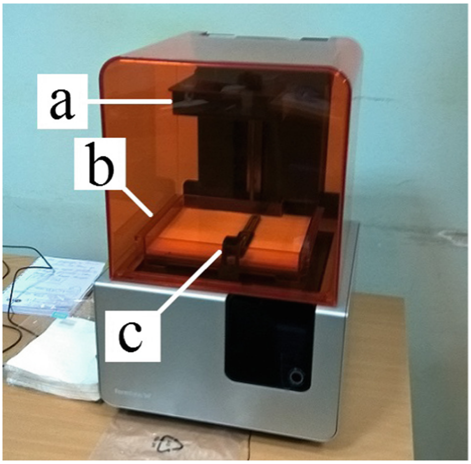

Fig. 2. SLA printing technology: (a) build platform; (b) resin tank; (c) wiper.

The resin material used in this research is white standard resin developed by Formlabs Inc. (Somerville, MA). The resin material is thermoset plastic which remains in solid state after polymerization, [13]. SLA prints have a smooth finish, with no visible layer lines, [2]. SLA prints have dimensional inaccuracies due to heating and cooling of the cured resin during the printing process, [3, 14].

2 Materials and Methods

In this research, PEM fuel cell reformer model is used as a geometric benchmark for comparing the dimensional accuracy of FDM and SLA 3D printing technologies. Reformer model can benchmark flat surfaces, circular features (holes and cylinders) and surface finish.

Benchmarking is used to compare different similar systems to establish a standard of performance. There are three types of benchmarking in 3D printing: geometric, mechanical and process benchmarking. Geometric benchmarking is used to compare dimensional accuracy, surface finish, flatness and straightness of printed models, [6]. Geometric benchmarking in 3D printing has a wide application in present research. Recent research of Sljivic et al. [4] compared the dimensional accuracy of consumer grade and professional FDM 3D printer with complex three-dimensional model of one particular cathedral located in Bosnia and Hercegovina, [4]. Queral et al. examined dimensional accuracy of several 3D printing technologies (i.e. FDM, SLA, SLS-Selective Laser Sintering, PolyJet) for fabrication of modular coil frames on stellarator device, [15]. Ogden et al. analyzed the influence of process parameters on dimensional accuracy of 3D printed human vertebra which can improve 3D printing for medical and tissue engineering applications, [16]. One of the aims of benchmarking is to find best possible technology and solution for fabrication of non-conventional parts that are not practical to be produced by standard machining methods. One of such models is the subject of this paper, i.e. polymer electrolyte membrane (PEM) fuel cell reformer.

Reformer is the first main reactor of a PEM fuel cell. Reformer consists of three plates-upper and lower cover plate and middle plate. Reaction volume of the reformer is placed in the middle plate, with inlet and outlet channel-both with a diameter of 3 mm. Reaction volume dimensions are $34 \times 37.4 \times 4$ mm. The thickness of lower, middle and upper plates are 3.8 mm, 4 mm and 1 mm, respectively. Lower plate contains the hole, 6 mm diameter, for filling the catalyst. Plates have two channels, 5 mm diameter, for cartridges that connect all three plates. External dimensions of all plates are 60×60 mm, [17]. Digital CAD models of all components of PEM fuel cell reformer are developed in SolidWorks software (shown on Figs. 3, 4, 5 and 6).

FDM printer German RepRap X400 (Feldkirchen, Germany) and SLA printer Formlabs Form2 (Somerville, MA) were used for this research in order to make PEM fuel cell reformer prototypes. Digital CAD models of reformer were converted to STL format, which uses triangular facets to approximate the shape of an object, in order to prepare models for adequate slicing software. For FDM printer Simplify3D® slicer software (Cincinnati, OH) is used for generation of G-code. SLA printer uses PreForm (Formlabs, Somerville, MA) software for preparation of printing process.

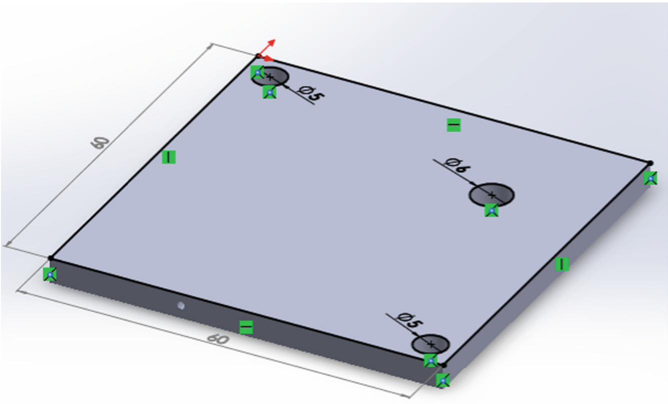

Fig. 3. Digital CAD model of reformer PEM fuel cell lower plate.

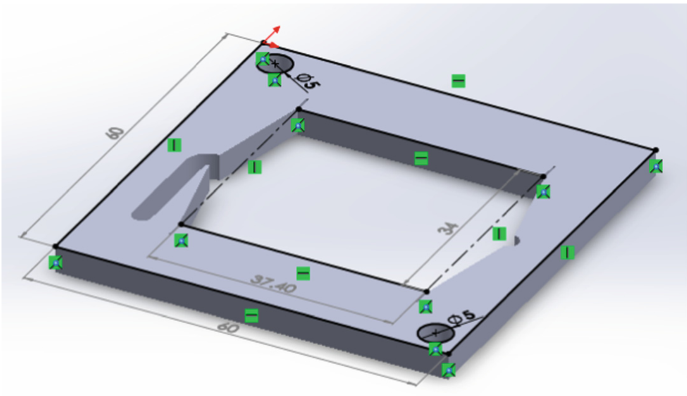

Fig. 4. Digital CAD model of reformer PEM fuel cell middle plate.

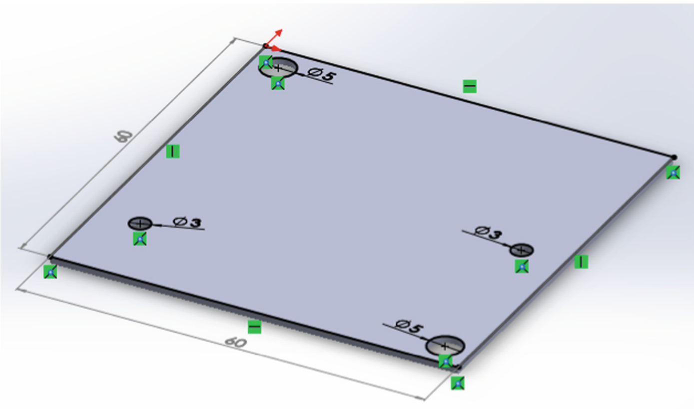

Fig. 5. Digital CAD model of reformer PEM fuel cell upper plate.

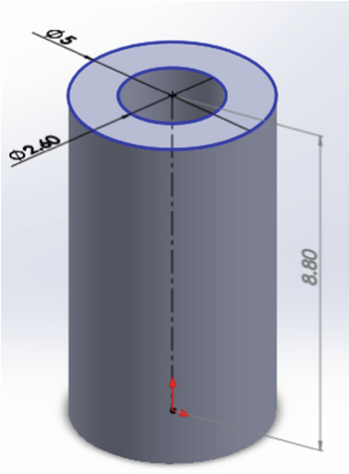

Fig. 6. Digital CAD model of reformer PEM fuel cell cartridge.

Three prototypes of PEM fuel cell reformer were made with a different height resolution of print: 0.3 mm, 0.2 mm and 0.1 mm. 0.3 mm and 0.1 mm height resolutions represent lowest and highest resolution for selected FDM 3D printer. Other printing parameters are the same for all three printing processes. FDM printer is equipped with 0.4 mm brass nozzle, nozzle temperature is set at 200 °C. Platform temperature is set at 60 °C, keeping extruded material on the platform. Hexagonal infill pattern with 50% infill is for all three prototypes. Printing speed is 40 mm/s. Print with the height resolution of 0.3 mm is shown on Fig. 7.

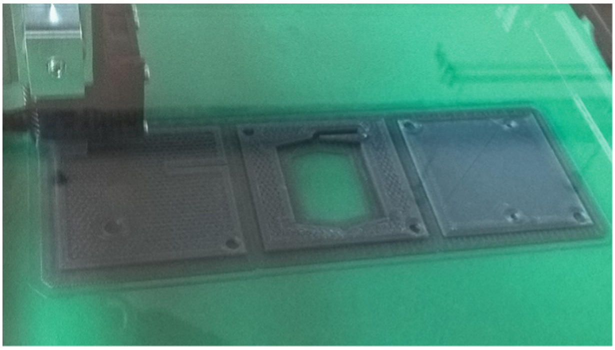

Fig. 7. FDM printing of PEM fuel cell reformer.

As a general rule for FDM printing, parts should be printed with their shortest dimensions in the vertical direction (FDM), [10]. Before the printing of models, first few layers are printed as a stand (raft) for better grip of a prototype to the platform.

SLA printing was performed with lowest height resolution possible for selected SLA printer, which is 0.1 mm (Fig. 8). This particular print combined with FDM print of the same height resolution allows comparison of dimensional accuracy of these 3D printing technologies.

Fig. 8. SLA print of PEM fuel cell reformer.

Larger support structure for SLA printing is needed in order to successfully finish print. Otherwise, print might fall off the platform, resulting in failed process. Every model is printed with a stand for better grip to build platform. All printed prototypes for this research are shown in Fig. 9.

Fig. 9. All printed prototypes of PEM fuel cell reformer: (left to right) FDM 0.3 mm, FDM 0.2 mm, FDM 0.1 mm, SLA 0.1 mm.

SLA print has the smoothest surface, with no layer lines noticeable. FDM print with lowest height resolution has the roughest surface of the three printed by FDM printing technology. The smoothest surface is on the prototype with 0.1 mm resolution, but still not comparable to SLA print.

3 Results and Discussion

Dimensions of interest of all FDM and SLA printed PEM fuel cell reformer components are listed in Tables 1, 2, 3 and 4. Relative deviations of printed models from the digital CAD model are calculated by the equation, [3]:

$$\varepsilon = \frac{l - l_0}{l_0} \tag{1}$$

where l is a measured dimension of printed model and l_0 is the appropriate dimension of digital CAD model. Multiplying equation by 100 gives a percentage value (%) of relative deviation. In Tables 1, 2, 3 and 4, relative deviations are listed in brackets.

Measurements are performed with the digital calliper "ORION 31170210". Dimensional range is 0–150 mm with 0.01 mm resolution. Digital calliper was last time calibrated on 22.03.2018 according to DIN 862:2005 standard in accredited metrology laboratory "21. MAJ DOO" (Belgrade, Serbia), under certificate number 789/2018.

Table 1. 3D printed upper plate

Features	Original CAD model	FDM 0.1 mm res.	FDM 0.2 mm res.	FDM 0.3 mm res.	SLA 0.1 mm res.
External dimension	60 × 60 mm	59.89 × 59.95 mm (−0.002 × −0.001)	59.76 × 59.84 mm (−0.004 × −0.003)	59.70 × 59.82 mm (−0.005 × −0.003)	59.97 × 60.32 mm (−0.0005 × 0.0005)
Two channel holes	5 mm	4.93 mm (−0.014)	4.76 mm (−0.048)	4.69 mm (−0.062)	4.98 mm (−0.004)
	5 mm	4.85 mm (−0.03)	4.72 mm (−0.056)	4.65 mm (−0.07)	5 mm (0)
Inlet and outlet holes	3 mm	2.56 mm (−0.14)	2.51 mm (−0.16)	2.43 mm (−0.19)	2.99 mm (−0.003)
	3 mm	2.78 mm (−0.07)	2.55 mm (−0.15)	2.51 mm (−0.16)	3 mm (0)
Thickness	1 mm	1.18–1.28 mm (0.18–0.28)	1.30–1.44 mm (0.3–0.44)	1.23–1.38 mm (0.23–0.38)	0.93–1 mm (−0.07–0)

For FDM prints, negative values of relative deviation in Tables 1, 2 and 3 suggest material shrinking after a finished print process. Plates printed with 0.3 mm height resolution have maximal external dimension relative deviation of −0.005, i.e. 0.5% shrinkage from original CAD model. Change to 0.2 mm height resolution results in slight improvement in dimensional accuracy of external dimension on all three plates, except in one external dimension in the case of the lower plate, where maximal relative deviation is −0.005 (−0.5%). Best results were measured on plates with 0.1 mm height resolution. Maximal relative deviation was measured on the lower plate with the value of −0.003 (−0.3%), and on middle and upper plate smallest relative deviation is just −0.001 (−0.1%).

Table 2. 3D printed middle plate

Features	Original CAD model	FDM 0.1 mm res.	FDM 0.2 mm res.	FDM 0.3 mm res.	SLA 0.1 mm res.
External dimension	60 × 60 mm	59.87 × 59.91 mm (−0.002 × −0.001)	59.79 × 59.87 mm (−0.003 × −0.002)	59.79 × 59.87 mm (−0.003 × −0.002)	60.00 × 60.00 mm (0 × 0)
Two channel holes	5 mm	4.43 mm (−0.114)	4.14 mm (−0.172)	4.03 mm (−0.194)	5 mm (0)
	5 mm	4.31 mm (−0.138)	4.19 mm (−0.162)	4.14 mm (−0.172)	5 mm (0)
Reaction volume	34 × 37.4 mm	33.90 × 37.46 mm (−0.003 × 0.002)	33.85 × 37.52 mm (−0.004 × 0.003)	33.73 × 37.51 mm (−0.007 × 0.003)	34.02 × 37.4 mm (0.0005 × 0)
Thickness	4 mm	4.64–4.72 mm (0.16–0.18)	4.56–4.80 mm (0.14–0.2)	4.71–4.95 mm (0.18–0.24)	3.91–4 mm (0.02–0)

Table 3. 3D printed lower plate

Features	Original CAD model	FDM 0.1 mm res.	FDM 0.2 mm res.	FDM 0.3 mm res.	SLA 0.1 mm res.
External dimension	60 × 60 mm	59.80 × 59.87 mm (−0.003 × −0.002)	59.72 × 59.73 mm (−0.005 × −0.004)	59.73 × 59.73 mm (−0.005 × −0.005)	60.00 × 60.33 mm (0 × 0.005)
Two channel holes	5 mm	4.69 mm (−0.062)	4.45 × mm (−0.11)	4.44 mm (−0.112)	5 mm (0)
	5 mm	4.65 mm (−0.07)	4.53 mm (−0.094)	4.43 mm (−0.114)	5 mm (0)
Catalyst hole	6 mm	5.83 mm (−0.028)	5.75 mm (−0.042)	5.70 mm (−0.05)	6 mm (0)
Thickness	3.8 mm	4.18–4.27 mm (0.1–0.12)	4.15–4.31 mm (0.09–0.13)	4.34–4.54 mm (0.14–0.19)	3.79–3.8 mm (–0.002–0)

Holes have a greater relative deviation from the original CAD model, than the external dimension of plates. Holes with 5 mm diameter have relative deviation in range from −0.03 (−3%), measured on the upper plate with 0.1 mm height resolution, to −0.194 (−19.4%), measured on the middle plate with 0.3 mm height resolution. Inlet and outlet holes on the upper plate, with 3 mm diameter, have relative deviation from −0.07 (−7%) to −0.19 (−19%), but with more measured dimensions closer to the maximal relative deviation. This suggests that model accuracy depends on the size of the printed features. Smaller features tend to have greater relative deviations.

The same goes for the plate thickness. Largest relative deviation was measured on the upper plate, which has the smallest thickness of the three. The maximal relative deviation value is 0.38 (38%). Middle and lower plates have smaller maximal relative deviation of thickness, i.e. 0.24 (24%) and 0.19 (19%), respectively. All mentioned maximal relative deviations in thickness were measured on plates printed with 0.3 mm height resolution. Overall, largest variation in plate thickness is located at plates printed with 0.3 mm layer height. Larger variation in thickness suggests low flatness of particular plate. Values of thickness in Tables 1, 2 and 3 show that height resolution greatly influences on flatness and straightness of a printed model. On the upper plate thickness varies from 0.18 (18%) to 0.28 (28%), i.e. variation of which is 10%, in the case of the plate printed with 0.1 mm height resolution. For 0.2 mm plate that variation is set at 14% and for 0.3 mm plate at 15%. Best improvement of plate flatness and straightness is present at prints with 0.1 mm height resolution. The same follows for the other two plates.

In Table 4 are listed dimensions for two cartridges for each print. Because of the difficulty of printing circular features layer-by-layer, cartridges had to be printed with the longest dimension in a vertical direction.

Table 4. 3D printed cartridge

Features	Original CAD model	FDM 0.1 mm res.	FDM 0.2 mm res.	FDM 0.3 mm res.	SLA 0.1 mm res.
Height	8.8 mm	9.00 mm (0.023)	9.03 mm (0.026)	9.06 mm (0.029)	8.87 mm (0.008)
	8.8 mm	9.02 mm (0.025)	9.06 mm (0.029)	9.07 mm (0.030)	8.76 mm (−0.004)
Ex. diameter	5 mm	4.92 mm (−0.016)	4.87 mm (−0.026)	5.12 mm (0.024)	4.96 mm (−0.008)
	5 mm	4.94 mm (−0.012)	4.83 mm (−0.034)	5.13 mm (0.65)	4.97 mm (−0.006)
In. diameter	2.6 mm	2.40 mm (−0.077)	2.24 mm (−0.138)	1.90 mm (−0.269)	2.6 mm (0)
	2.6 mm	2.39 mm (−0.081)	2.29 mm (−0.119)	2.14 mm (−0.177)	2.6 mm (0)

Tables 1, 2, 3 and 4 show undoubtedly that shrinkage of FDM printed models are present in a horizontal plane, and that in height FDM material expands. SLA print with the layer resolution of 0.1 mm (Tables 1, 2, 3 and 4) has noticeably higher dimensional accuracy than FDM print of the same height resolution. Some dimensions are equal to corresponding dimensions of digital CAD model, e.g. a diameter of holes and the external dimension of plates printed closer to build platform. Deviations from digital CAD model are present in height of cartridges and the external dimension of plates positioned vertically to build platform during the printing process. This suggests that dimensional inaccuracy of SLA prints originates from an accumulation of errors during the print process. Highest deviations from original model are present in last layers of print, i.e. highest accuracy is present in dimensions closer to build platform.

For the purpose of better understanding the behaviour of polymeric materials used in 3D printing technologies and to obtain higher accuracy results, future research will include Digital Image Correlation (DIC) method of receiving relative movement, i.e. deformation, of the observed structure, [11–14, 18–21].

4 Conclusion

3D printing represents an emerging manufacturing technology, with plenty of space for research and development. One of the biggest challenges in 3D printing is to minimize dimensional inaccuracies compared to digital CAD model, caused by 3D printing process and material properties. For research geometrical benchmarking is used to measure and compare the accuracy of different printing technologies and printing parameters within the same 3D printing technology.

FDM and SLA nowadays present two most common 3D printing technologies. In this research, a PEM fuel cell reformer is used for geometric benchmarking to compare dimensional accuracy, surface finish, flatness and straightness of printed models of two different printing technologies. The aim of benchmarking is to compare strengths and weaknesses of printing parameters and different printing technologies in order to make improvements.

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