Development of open-source FDM printer to produce casting patterns and analysis of printed parts for dimensional accuracy*

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ABSTRACT

Most of the foundry industries in developed countries are shutting down or relocating in developing country, owing to stringent environmental regulations. India, as the fastest growing economy and high human resource, has the better opportunity to fix the leadership in the foundry industry, in the recent future. In 'SMART Foundry 2020' project, an IoT enabled, integrated smart manufacturing system is being developed. As a part of the project, FDM process is selected for printing the patterns of designs to cast. The FDM process must print dimensionally accurate patterns. This literature discusses the issues associated with the open-source design of the printer and a systematic solution for each problem. The improved design is calibrated for movement accuracy along each axis. The effect of modifications in FDM printer over accuracy and the precision of the printed part are analyzed.

1. Introduction

Owing to environmental regulations and profitability, most of the foundry industries in the USA and the UK are shutting down [1]. In this scenario, the Indian foundry market is leading at the second position and the growth rate was at 6% for 2016-17. The automobile sector is a major customer of the Indian foundry industry [2]. Indian artifacts and figurines, made with non-ferrous metals, are subject of fascination for tourists across the globe. Thus from highly automated industries to custom-made artifacts buyers, Indian foundry industry tries to serve and encompass all the needs in between. The method of casting the part, viz. sand casting, investment casting, etc., is decided considering profitability and design needs of the part to be cast. Irrespective of the method of production, one has to prepare a mould for casting purpose. A pattern is required for manufacturing each of these moulds.

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The pattern is a slightly oversized replica of the part to be cast, by adding dimensional (draft and shaking), shrinkage and machining allowances to the original shape and size of the part. In a conventional way, these patterns are fabricated using materials as natural wax, wood, clay, etc. The patterns are manufactured with conventional machines and manual labour. It is difficult to achieve dimensional accuracy and repeatability in multiple patterns for the same design of casting [3]. On the other hand, higher lead-time and scarcity of skilled labour makes the foundry operations even difficult, on economic aspects. The next generation of the traditional brass workers and artisans are not willing to enter the art and craft foundry business due to low marginal profit compared to efforts and dedication paid in.

While the automotive industry is setting the ground for 'Industry 4.0' and IoT enabled factories. The foundry industry should match up with the transformation pace of the other industries. 'SMART (Sustainable Metal casting by Advanced Research and Technology) Foundry 2020' is the multi-institutional project of Govt. of India to facilitate the foundry industry with interactive process chain enabled with IoT and smart manufacturing systems.

As a part of 'SMART Foundry 2020' project, College of Engineering Pune (COEP) is developing the rapid pattern printing and finishing process. The need for rapid pattern making underlines requirement of automation of pattern manufacturing from idea to reality. It leads to additive manufacturing as a better alternative solution against conventional manufacturing processes. Additive manufacturing encapsulates many methodologies to opt. However, for this project, FDM (Fused Deposition Modelling) fits as the best available solution due to its affordability and user suitability.

2. Development of 3D Printer

Unlike other machining processes, additive manufacturing adds the material layer upon layer to form 3D objects. It does not require any special tooling for each design specifications. Therefore, any simple geometry, as well as highly intricate designs, will be printed at the same operating cost. The part printing cost depends only on the type of material used in the part printing.

In FDM, the thermoplastic polymer is used in the form of a wire of standard diameter viz. 1.75mm or 2.85mm-3mm. The thermoplastic wire is heated in the hot nozzle of FDM printer, above its glass transition temperature (GTT). The thermoplastic material loses elasticity above GTT; the material is thereafter forced to pass through a nozzle. The extruded material through nozzle is deposited as per requirement of the design, in a single layer. Addition of layers one upon others will create the object in 3D.

Therefore, it is necessary to develop an FDM based 3D printer. RapFab 3D printer, an adaptation of LulzBot TAZ 5 (an open-source FDM printer), is developed at COEP, having built volume of 290×275×250mm^3. Initially, some problems are identified in the original design of the FDM printer. Also, the FDM process can be chosen for pattern printing only if the printed patterns are dimensionally accurate. Therefore, while manufacturing the new FDM printer, it is ensured that existing problems are eliminated.

2.1. Identified problems in previous design

Some problems are identified in the original design, which causes bad printing quality and frequent print failures due to problems like warping, uneven first layer, shrinkage in the printed parts. Also, the harmful material fumes caused due to high temperature causes respiratory problems and symptoms like headache, nausea, etc. These problems are eliminated in a systematic manner. The details are given in table 1.

Table 1
Existing problems affecting print quality and implemented solutions.

Sr. No.	Problems	Solution	Effect
1.	Warping at corners	Enclosed Chamber is designed and manufactured for FDM printer, ensuring controlled environment is maintained.	Affirmative
2.	Improper adhesion between layers		Affirmative
3.	Respiratory problems (Headache, Nausea, etc.)		Affirmative
4.	Shrinkage		Affirmative
5.	The first layer is printed badly	Heat Bed is leveled	Affirmative
6.	Uneven and low height of print than the design		Affirmative
7.	Nozzle digs through the layers later on	Replaced worn out dry bearings with new bearings	Affirmative
8.	Material deposition is not proper		Affirmative

2.1.1. Enclosed chamber

The FDM 3D printer requires a controlled room temperature environment for better quality of the print. The bed temperature and nozzle temperature are supposed to be maintained according to the model material being used. Both extreme low and high temperature of surrounding is not appropriate for good printing environment. The original 3D printer design was exposed to the surrounding environment. Lack of controlled environment for the 3D printer creates some problems like warping at corners of printed part, uneven adhesion and the most important are health problems like headache, respiratory issues and hence protection from hazardous fumes of model material is necessary.

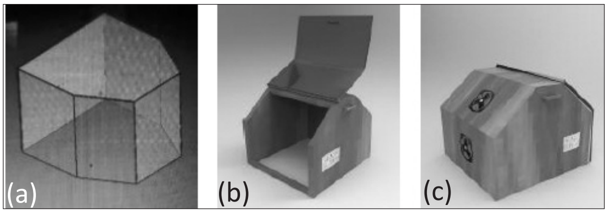

Fig. 1. (a) Primary Design for Closed Chamber; (b) & (c) Improved Design for Closed Chamber[4]

An enclosure is designed and manufactured for FDM printer. A temperature sensor is fixed to show ambient temperature inside the closed chamber.

2.1.2. Bed levelling

Consider an imaginary plane parallel to the nozzle movement plane. For the uniform height of the printed job, it is necessary to fix the heatbed exactly parallel to the imaginary plane nozzle movement. Misalignment of heat bed results into unevenly printed part.

In previous design of 3D printer, very small sized heat bed corners are provided, which are inadequate to hold the heat bed in a parallel position with respect to XY plane. Heat bed corners have spring loaded screw mechanism. Therefore, it is very difficult to fix all the four corner screws at the same height.

To avoid this problem, the size of the heat bed corner is increased. Spring-loaded screws are replaced with countersunk bolts in the fixture holding mechanism. The design is again improved for an aesthetic look. A snap-fit compact design is provided (Fig. 2).

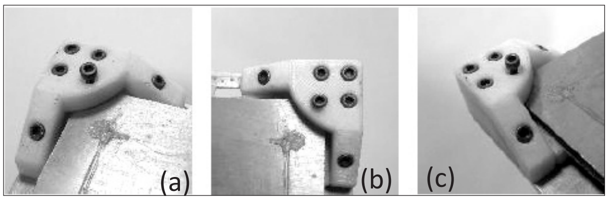

Fig. 2. Newly designed bed corners

A silicon gasket strip is provided at heat bed corner for better cushioning effect and relief from the accidental strike of the nozzle. If the bed is levelled properly, there is no need to adjust the bed level for a long time or until any breakdown happens.

2.1.3. Wear of linear bearing

The 3D printer has three axial movements given to nozzle with respect to the frame of the printer, viz. X, Y, and Z. In the adopted design, timing belt and pulley pair is used, for both X and Y axial movements. Lead screw and flange nut system is used, for Z-axis movement. Dry linear bearings over smooth rods of steel are used for additional support and smoother travelling.

Initially, these linear bearings were printed on FDM machine (instead of buying from outside), to cut down the cost. The expected life for the printed linear bearings is approximately 1500 working hours. However, these bearings are worn out within 300-350 hours of working only. The wear created a clearance between smooth rods and bearings. This leads to deflection of nozzle tip when subjected to jerk (a derivative of acceleration w.r.t. time) in any direction and axis. Nozzle deflection created a very bad quality of printed part (refer Fig. 3 (a,b)).

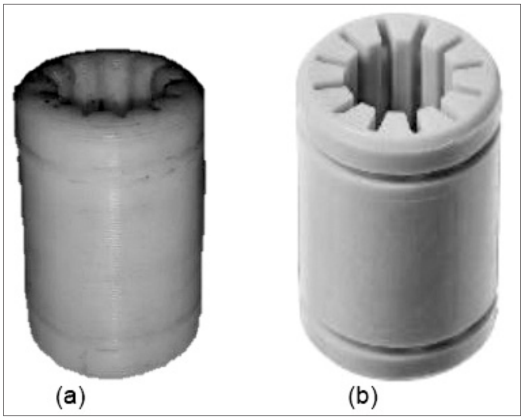

Fig. 3. (a) Worn out printed linear bearing; (b) Injection moulded linear bearing

Therefore, high-density injection moulded linear bearings are installed instead of printed linear bearings.

2.2. Modified FDM printer

The RapFab 3D printer is improved by eliminating the flaws. The implementation of the suggested hardware modifications has a positive effect on the issues. The modified RapFab 3D printer is shown in figure 4.

It is required to validate the hardware changes in the RapFab FDM printer while tackling the issues in the original design.

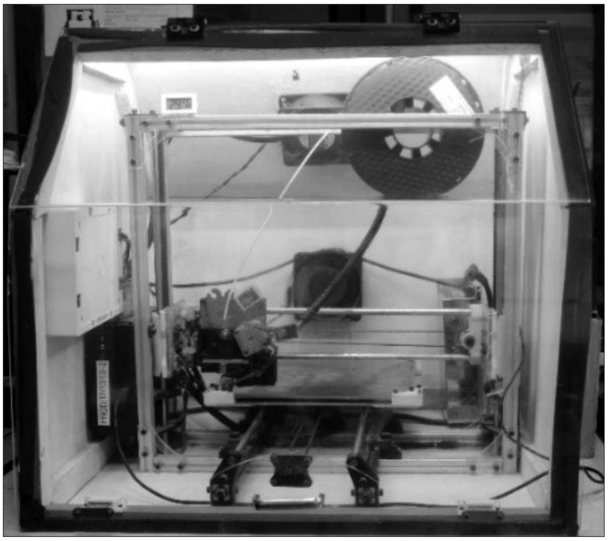

Fig. 4. Modified 3D printer for pattern printing

3. Validation of the design changes in the 3D printer

Printing process and print quality of parts are analysed for validation of the hardware changes.

3.1. Enclosed chamber

The problems, which are related to health and improper heating in the process of printing, are resolved with the introduction of an enclosed chamber. It is proven that the temperature is well maintained, due to the enclosed chamber, for a longer period irrespective of outside temperature. As an effect, the warpage of parts is reduced considerably.

3.2. Bed leveling

For validation of heat bed levelling, small blocks of size 20×20×5 mm^3 are printed in different locations of the bed. These printed parts are checked for dimensional accuracy using Rapid I (Vision Measurement System). The dimensional comparison of the printed parts is given in the table below. The dimensions in the Z direction (height of part) is shown in bold (Refer Table 2.)

Table 2
Dimensional comparison between design and printed part.

Part No.	Dimension to print	Dimensions after print	Error in Z direction
1		19.950×20.020×**5.00** mm3	**0.0 %**
2		19.945×20.000×**5.03** mm3	**0.6 %**
3		20.010×19.850×**4.98** mm3	**0.4 %**
4		20.040×19.960×**5.00** mm3	**0.0 %**
5	20×20×**5** mm3	20.000×19.930×**5.04** mm3	**0.8 %**
6		19.945×20.000×**5.00** mm3	**0.0 %**
7		20.050×19.950×**5.03** mm3	**0.6 %**
8		20.190×20.040×**4.97** mm3	**0.6 %**
9		20.000×19.980×**5.02** mm3	**0.4 %**

The maximum error in bed levelling is **40*µm*** and overall bed level is within tolerance as $\mathbf{0.0^{+0.04}_{-0.03}}$ **mm**. The output diameter of nozzle used in the current 3D printer is **0.5mm**. Whereas overall error is less than 14% or 7 times smaller than the nozzle diameter. In either direction, the error is less than 8% or 12.5 times smaller than the nozzle diameter. This signifies accuracy of bed level.

3.3. Wear of linear bearing and positional accuracy

The nozzle deflection is nullified after installation of new linear bearing and print quality is improved drastically. Comparison between the print quality of the printed parts before and after installation of the new bearing is shown in figure 5 (a, b).

From the data given in Table 2, it is evident that printed parts have inaccuracies in X and Y direction also. Therefore the overall dimensional accuracy of the printing process should be evaluated. It is

Fig. 5. (a) Quality of print when bearing had clearance; (b) Print quality after installing injection moulded bearings

equally important to carry out capability exercise for the 3D printer.

4. Capability Analysis and calibration

4.1. Capability analysis

A part with some key design feature is designed and printed to test the capability of the RapFab 3D printer[5]. The part consisted of following design features distributed along the top surface -

1. Cylinders of diameter varying from 1mm to 5mm and 10mm height.
2. Positive and negative steps at variation of 5mm.
3. Circular holes with diameter 1mm to 5mm.
4. A hollow wedge-shaped profile with a width of 10mm and wedge angle of 30°.

RapFab 3D printer was capable to print all of these features. Notably, the wedge-shaped part was printed without support. The cylinders of 1mm diameter were too weak to sustain while handling.

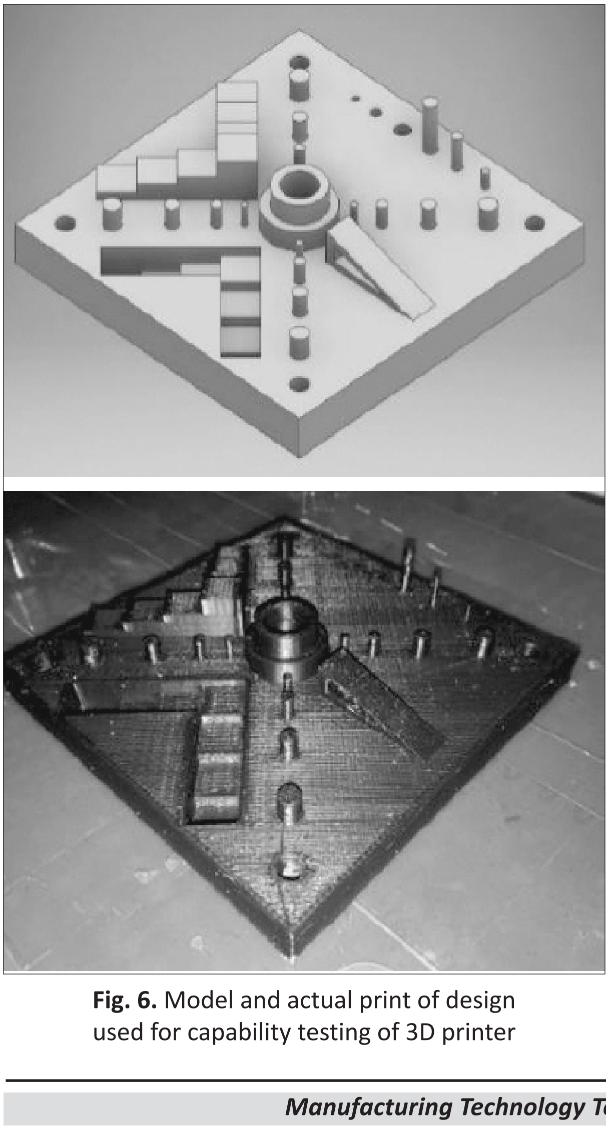

Fig. 6. Model and actual print of design used for capability testing of 3D printer

4.2. Calibration of movement

All of the movements in RapFab 3D printer are done by using stepper motors. The movement is carried out when microcontroller provides the step pulses to the stepper motor. For precise movement, a conversion factor, called as steps/mm, is defined in the firmware of the 3D printer. The 'step/mm' factor is separately defined for each of the stepper motors. This conversion factor may vary due to the changes in hardware used, such as pulley diameter, gear ratio, etc. The movement accuracy can be improvised through printer host software as 'Cura'; if the conversion factor is accurately calculated.

In order to calculate the conversion factor, a part having spread of 100mm×100mm×50mm is printed. The design of part has three segments perpendicular to each other. The part oriented such that it will have each of its legs along an axis. Refer the images 7 & 8 below.

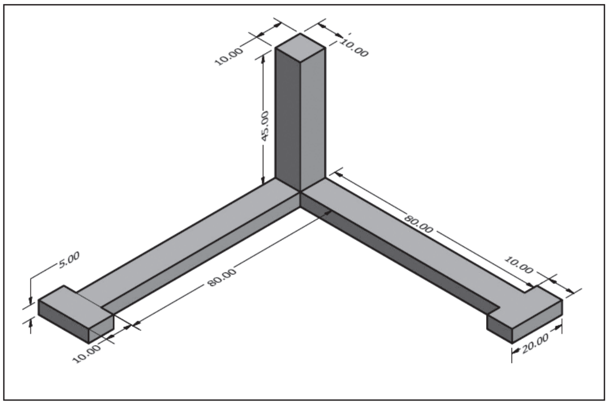

Fig. 7. Design of test part printed to check dimensional accuracy in x-y direction [6]

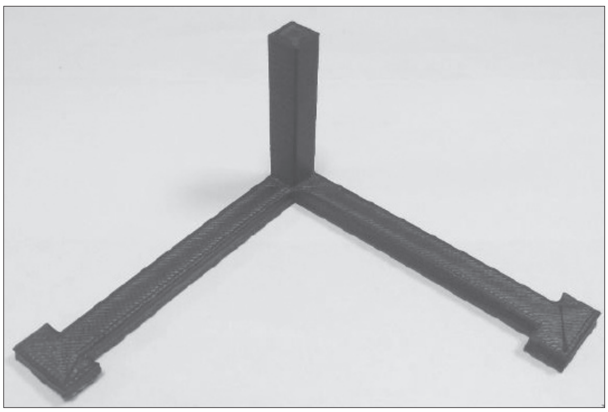

Fig. 8. Printed part for testing X-Y axial accuracy

The printed parts are checked for dimensional accuracy and error value along each axis is compensated by altering 'steps/mm' for the corresponding axis. This exercise is performed for two times until the printed part was dimensionally accurate with an error of <0.5mm. Such electronic calibration is done for X, Y, Z and Extruder motors.

The effects of hardware changes and calibration are tested by printing a pair of the brake shoe. The design of brake shoe is chosen because it is manufactured by the method of casting. These printed parts have no foreseen defect.

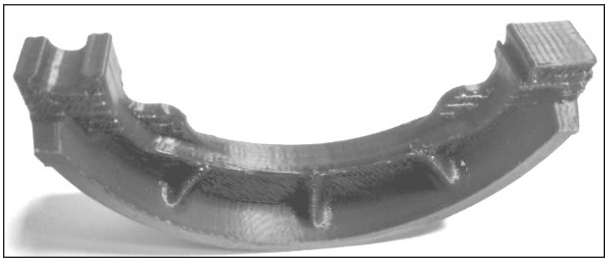

Fig. 9. Model of brake shoe used in drum brake is printed with much better quality of the print

Still, the overall accuracy and precision of output given by the 3D printer are not analyzed. Moreover, the reliability of the 3D printer needs to be assessed.

5. Reliability of RAPFAB FDM printer

There are two aspects of reliability for any processing machine. Firstly, the machine should be reliable that it would be in service for a defined period. Secondly, the output given by the machine should be within defined tolerance limits. This literature is not focusing on the prediction of life expectancy and reliability of individual components and/or the complete 3D printer. Instead, the accuracy of printed parts is analyzed by using a 3D scanner and reverse engineering software.

Table 3
Parts with key printing parameters.

Sr. No.	Part	Parameters		
		Printing speed (in mm/ sec)	Fill density	Support type
1	Human Cervical Vertebra	40	80%	Every where
2	Bevel Gear	40	50%	Every where
3	A.M. Plate	40	80%	None

5.1. Accuracy & precision of FDM printer

Accuracy and precision are tested using a method of 3D scanning and analysis of point-clouds.

Table 4
Results analysis through reverse engineering (RE) software

Sr. No.	Part Comparison	RE Registration RMS Error (in mm)	Remarks
1	HCV_1 with Original HCV	0.223 UL = 0.448 LL = -0.448	
2	HCV_2 with Original HCV	**0.296** UL = 0.45 LL = -0.45	Average RMS error is **0.232mm**
3	HCV_3 with Original HCV	**0.178** UL= 0.45 LL = - 0.448	
4	BG_1 with Original BG	**0.345** UL = 0.488 LL= -0.446	
5	BG_2 with Original BG	**0.333** UL=0.445 LL= -0.447	Average RMS error is **0.348mm**
6	BG_3 with Original BG	**0.367** UL=0.449 LL= -0.448	
7	AMP_1 with Original AMP	**0.1333** UL= 0.297 LL= -0.466	
8	AMP_2 with Original AMP	**0.1155** UL= 0.263 LL = -0.526	Average RMS error is **0.131mm**
9	AMP_3 with Original AMP	**0.1444** UL= 0.207 LL= -0.814	

HCV - Human Cervical Vertebra; BG - Bevel Gear; AMP – Additive Manufacturing Plate; UL- Upper limit; LL - Lower Limit; Part Name$_i$ – 'i'-denotes the part number.

The method gives output as a positional error between relative point clouds in terms of RMS error. This method can be applied to multiple parts of the same design; this will give a precision account in terms of accuracy.

5.1.1. Case Study: Accuracy and precision of printed parts

Therefore, to carry out this experiment, three parts are selected with different geometries and applications. The selected parts are as given below.

1. Human Cervical Vertebra (Biomedical)
2. Bevel Gear (Mechanical)
3. Additive Manufacturing Plate (Capability Analysis)

Each of these parts is printed thrice by using the same set of printing settings and material. This setting would create a common platform to analyze the geometrical accuracy and precision of the FDM printer. (Refer to Table 3 for print parameters settings)

Each printed part is scanned using Artec Spider 3D scanner available with COEP. The 3D scanner returns the scanned geometry in .stl (3D printable file format) and point-cloud format. Each output from 3D scanning is analyzed with the respective original design for accuracy mapping. The results of the analysis are given in Table 4.

6. Conclusion

This literature correlates the fact of upgradation requirement of foundry industry in India with the additive manufacturing technology. The patterns for casting can be fabricated using a 3D printer. The conclusion of the discussion is as follows.

- FDM can provide cost-effective solution for pattern printing while the traditional pattern manufacturing is getting unaffordable.
- The open-source FDM printers have some problems, which affects the output print quality, such as warpage of parts, health issues, misalignment of bed, uneven heights of the printed parts, etc.
- These problems are resolved with some hardware changes.
- The problem of uneven temperature profile and health-related issues have solved with the introduction of an enclosed chamber for FDM printer.
- A temperature sensor has installed inside the closed chamber. It has verified that the temperature inside the closed chamber is maintained, irrespective of surrounding temperature. As a result, the printed part, does not warp.
- Proper installation of redesigned corners of the heated bed has fixed the alignment problem of the bed. The bed is leveled in error magnitude of $\mathbf{0.0^{+0.04}_{-0.03}}$ **mm** .
- Use of injection moulded linear bearings has reduced the problem of bad print quality and deflection of the nozzle.
- The positional (movement) accuracy of the RapFab 3D printer is ensured by calibration of movement along each axis.
- Furthermore, the positional accuracy of the 3D printer cannot be maintained after prolonged use. It happens due to a decrease in belt tension, lack of lubrication. These problems created errors like backlash, vibrations and lack of precision. It suggests a need for maintenance over some use.
- The accuracy of the part is assessed using the RE method. Three different designs are printed in triples of each. Every part is compared with the respective original design.
- It is reported that the average RMS error in printed part is **0.232mm** for vertebra, **0.348mm** for bevel gear and **0.131mm** for AM plate.
- It can be concluded that the RapFab 3D printer is capable of printing the patterns with a minimum overall accuracy of 0.35mm.

7. Future Scope

Heat bed positioning error can be minimized by using highly accurate measurement system while aligning the heat bed during assembly.

Hardware upgradation and calibration of the FDM printer can surely increase the accuracy of the part. Even though, the part failure or print defects may occur due to various parameters. An in-process monitoring system is needed for FDM printers so that errors can be avoided and defect-free part printing will be possible.

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