Experimental Analysis of the Stringing Problem in FDM Printers

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Abstract. The 3D printing process known as additive manufacturing (AM) is used for fabricating 3D printed objects, layer-by-layer or even path-by-path. The aim of this paper is to study and minimize Stringing in Ender 3 printer by optimizing its printing process parameters. More specifically, this paper examines the effects of various printing and retracting speeds, nozzle temperatures, and distances on the creation of FDM 3D components. The procedure included statistical analysis, flat 0° horizontal build orientation 3D printing with PLA filament parallel to the bed of the Ender 3 printer, and FDM 3D solid modelling in relation to design. The experiment resulted in the smallest amount of stringing, and it was found that printing at 210°C nozzle temperature completely eliminates the stringing. Additionally, it is noted that printing at 200°C, 45mm/s retraction speed, and 5mm retraction distance can result in less warping effect.

Keywords: Stringing, FDM, Ender 3.

1 Introduction

Additive manufacturing (AM) is a developing technology that enables the production of complex objects across a wide range of industries. FDM (Fused Deposition Modelling) is the most widely used 3D printing technique, providing consumers with low-cost manufacturing facilities. FDM printers have three axes controlled by three stepper motors and offer less granularity than stereolithography. However, common issues such as stringing, or oozing can have an impact on product quality. The process can also be influenced by retraction settings, ambient temperature, and filamentquality. The objective of this study is to ensure better printing quality using FDM method by minimizing the amountof strings produced along with the product to support rapid prototyping by saving time. To validate the optimal parameters, a 3D model of a Differential Gear Assembly will be printed.

ICAMDMS 2024, February 23-24, Coimbatore, India

DOI 10.4108/eai.23-2-2024.2346991

2 Literature Survey

Fused Deposition Modelling (FDM), also known as Fused Filament Fabrication (FFF), stands as the pioneering and most widely adopted technology in the field of Additive Manufacturing. Numerous articles delve into the intricacies of FDM 3D printing, each offering slightly varied perspectives. Below, one of the most commonly used approaches is presented.

In the context of this technology, scientific consensus suggests that FDM 3D printed parts are constructed by heating and extruding long-fibre thermoplastic (LFT) polymer filament. This process occurs at a temperature close to the pointof fusion, facilitated by a heated circular nozzle. The semi-molten material is then meticulously deposited layer by layer to form the desired shape [1],[2],[3],[4].

In the realm of industrial applications, plastic component production lines have undergone a revolution. Additive Manufacturing (AM) has gradually replaced traditional subtractive methods, which often result in up to 95% raw material waste. Interestingly, as design complexity grows, the cost per unit rises significantly in subtractive manufacturing, while in AM, the reverse holds true [5].

Additive manufacturing (AM), also known as 3D printing, revolutionizes industrial production by enabling the creation of lighter, stronger parts and systems. Unlike traditional methods that remove material from larger blocks,

AM adds material to create an object. With advancements in AM, it's now possible to directly manufacture 3D physical objects of any shape using computer-aided design (CAD) models and vast numerical data. This once seemingly impossible feat significantly reduces manufacturing lead time by up to 50%, even for complex plastic components [5].

Fused Deposition Modelling (FDM), also known as Fused Filament Fabrication (FFF), is an additive manufacturing process where material is extruded through a temperature-controlled nozzle onto a heated table also known as print bed layer by layer to create the desired part. The process involves feeding thermoplastic filament (both the part material and support material) in the form of thin wire. The heated nozzle partially melts the wire, and as it moves along a predetermined path in X, Y, and Z directions, it deposits successive thermoplastic layers onto the bed. This layer-by- layer deposition results in the creation of an actual product, all achieved in a significantly shorter time compared to conventional manufacturing techniques, depending on the size and shape of the object [1],[2],[3],[4],[5].

Several parameters affect the quality of the manufactured part in FDM method. In general parameters like orientation, infill type and density, layer thickness, support placement and extrusion parameters were explored to improve the dimensional accuracy, surface finish, Production or printing time, and mechanical strength of the FDM-printed part [6],[7],[10],[12][13]. Proper feed rate ensures better print quality in FDM printing which was studied by Ferretti et al. on the relationship of volume flowrate to the defects.[9] The feed rate of the extruder is maintained by controlling a feeding motor extrusion by a controller. But there are issues like warping which was studied [8]. Print failures or misprints can lead to material waste, time loss, and financial repercussions. When configuring printer settings, one need to consider a multitude of variables, including layer thickness, support angle, extrusion temperature, platform temperature, print speed, extruder flow ratio, nozzle distance, infill type, infill density, surface layers, supports, seam type, and fan speed. Each of these significantly impacts the print quality and warrants careful consideration.

One crucial aspect is the effect of infill, which has been studied [13]. However, one of the most common yet often overlooked issues related to printer settings is the stringing problem. This occurs when small traces of polymer strings are left behind the nozzle during non-extrusion moments. The defect can persist, especially when creating features with narrow gaps. While strings caused by oozing can sometimes be mechanically removed or treated chemically for certain materials, addressing this challenge within internal features and joints remains complex. Overall, various factors influence print quality in FDM printing, and some of these insights can be gained through experience.

To the best of our knowledge, there is one publication available on minimising stringing by Haque et.al. which co related stringing with Nozzle temperature, Retraction distance, Retraction speed and printing temperature on the Ender 3 Pro machine [14]. It is observed that retraction speed had very minimal effect on stringing and concluded that parameter optimisation is machine specific. Our aim is to optimize these parameters for Ender 3 machine which is prevalently used by the beginners. In this study we propose to exclude retraction speed as it has little effect on stringing. Once the optimisation is done a complex differential gear assembly will be printed for confirmation.

3 Methodology

3.1 Material

The most prevalent thermoplastic filament, Polylactic Acid (PLA), has been employed to examine the generation of the stringing. Its diameter is of 1.75 mm. The PLA does have certain unique features. Due to its good layer Adhesion, rigidity and biodegradability, the PLA filament is chosen for this analysis.

3.2 Machine

The Ender 3 printer (Make: Creality Ender3, China), used to print the samples, is seen in Figure 1. Its dimensions are 440mm*410mm*465mm* and 220mm*220mm*250mm, respectively. Retraction distance, retraction speed, print speed, and extruder temperature were the four regulated parameters used in the printing process. These are among the most crucial factors affecting print quality. Retraction distance in this case refers to how far the extruder will pull the filament away from the nozzle. For instance, if the user specifies a minimum distance for the extruder to go before retracting, the extruder will retract 6 mm of filament into the bowden tube. The rate at which the extruder removes filament from the nozzle is known as retraction speed. The rate at which the extruder drops melted filament on the heated bed is referred to as printing speed. The temperature at which the filament melts before exiting the nozzle is known as the extruder temperature. Each filament has a different extrusion temperature. The PLA used in this FDM printer has a 1.75mm diameter.

Fig. 1. Ender 3 Printer used for experimentation

3 Experimental Setup

The Solid-Works program was used to design the specimen. The specimen was 32mm high, 15mm wide, and 40mm long. It was then stored in the.stl format. Later, it was converted into G-code files using the Ultimaker Cura 4.12.1 slicer program. Due to the fact that FDM printers can only read G-code files, it was done. Table 1 was followed for setting the parameters at the slicer program. The bed level was examined before the print began. The print bed was then heated to ensure that the extruded filament adhered to the bed properly. The samples were then produced using various values listed in table 1 with the assistance of the FDM printer seen in Figure 2. The bed level was checked before to the print starting. The extruded filament was then appropriately bonded to the print bed by heating the bed. With the use of the FDM printer shown in Figure 2, the samples were then created using various values mentioned in table 1. The filament is returned to the nozzle during the retract operation thanks to a gear movement. Therefore, the extruder might be damaged if the retraction speed is excessively high. Because slower printing speeds require more time and faster printing speeds damage print quality, the printing speed was fixed at 45mm/s. Due to the fact that these temperatures are ideal for printing PLA filament, the extruder temperature was maintained at 185° C, 200° C, and 210° C. The specimens were chilled once the print was finished before string counts were performed.

Fig. 2. Formation of Strings in fabricated specimens using Ender 3 Printer

4 Result and Observations

Table 1 gives the experimental measurements of Stringing Tests. From this table, sample number 16 and 17 was found out to have zero string formation.

Table 1. The experimental measurements of StringingTests

Sample No.	**Nozzle Temp (°C)**	**Retract Speed (mm/sec)**	**Retract Distance (mm)**	**No. of strings formed**	**String formation (%)**
1	185	35	5	300	100
2	185	45	3	265	88.33
3	185	45	5	205	68.33
4	185	45	7	141	47
5	185	55	3	220	73.33
6	185	55	5	105	35
7	185	55	7	67	22.33
8	200	35	3	63	21
9	200	35	5	52	17.33
10	200	35	7	27	9
11	200	45	3	226	75.33
12	200	45	5	22	7.33
13	200	45	7	98	32.67
14	200	55	5	7	2.33
15	210	35	5	3	1
16	**210**	**45**	**5**	**0**	**0**

According to the results of the ANOVA studyin table 2, table 3 and table 4, the F(42.066) is noticeably greater than the F critical(2.485). The ANOVA- Two Factor without replication also demonstrates that each Row group parameter has the same population distribution (F value is less than F critical). The distribution of the column group parameters is independent of each (the F value is much greater than the F Critical value). Therefore, row-wise groups must be used as the basis for parameter optimization. As a result, it is clear that each parameter group's settings must be associated with its specific parameter distribution.

Table 2.analysis of Stringing Test 1(S5 ingle Factor)

Groups	**Count**	**Sum**	**Avrage**	**Variance**
Column 1	17	3325	195.5882	96.50735
Column 2	17	765	45	62.5
Column 3	17	85	5	2
Column 4	17	1801	105.9412	10241.81
Column 5	17	600.31	35.31235	1137.948

Table 3. ANOVA for Two factor with replication

Source of Variance	**SS**	**df**	**MS**	**F**	**P-Value**	**F crit**
Between	388381	4	97095.26	42.06622	5.97E-19	2.4858
Within	184652.2	80	2308.153			
Total	573033.2	84				

Table 4. ANOVA for Two factor without replication

Source of Variance	**SS**	**df**	**MS**	**F**	**P-Value**	**F crit**
Row	51773.27	16	3235.829	1.558509	0.107222	1.804179
Col.	388381	4	97095.26	46.76509	2.51E-18	2.515318
Error	132878.9	64				
Total	573033.2	84				

Nozzle temperature plays a dominant role in stringing. Specimens 1,9,and 15 with 35mm/s and 5mm retraction distance shows a significant reduction in stringing at higher nozzle temperatures as shown in Figure-3. Similar trend can be seen from other specimens also in specimens 3,12,and 16 printed with 45mm/s retraction speed and 5mm retraction distance which is shown in Figure-4. A similar trend can be seen from other specimens also in specimens 6,14 and 17 printed with 55mm/s retraction speed and 5mm retraction distance which is shown in Figure-5

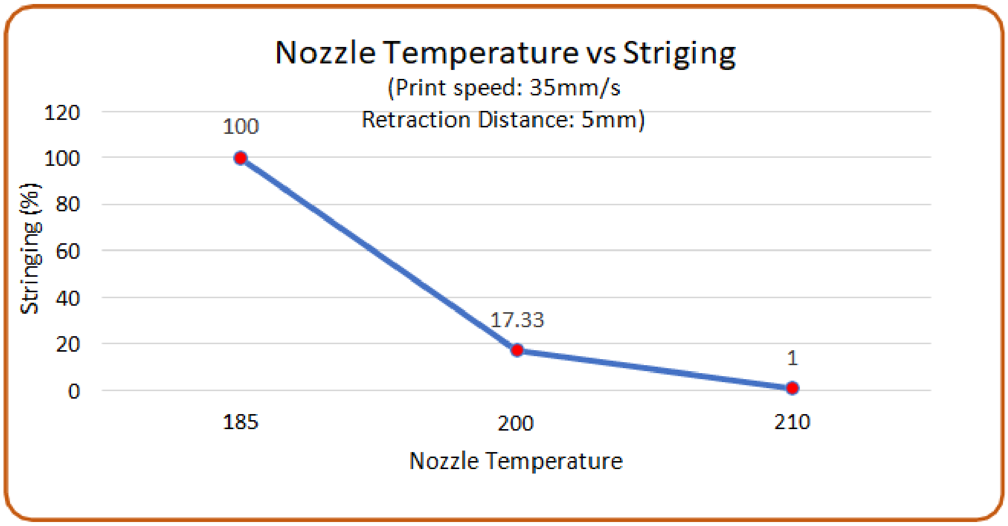

Fig. 3. Nozzle Temperature vs Stringing for specimens 1, 9 and15

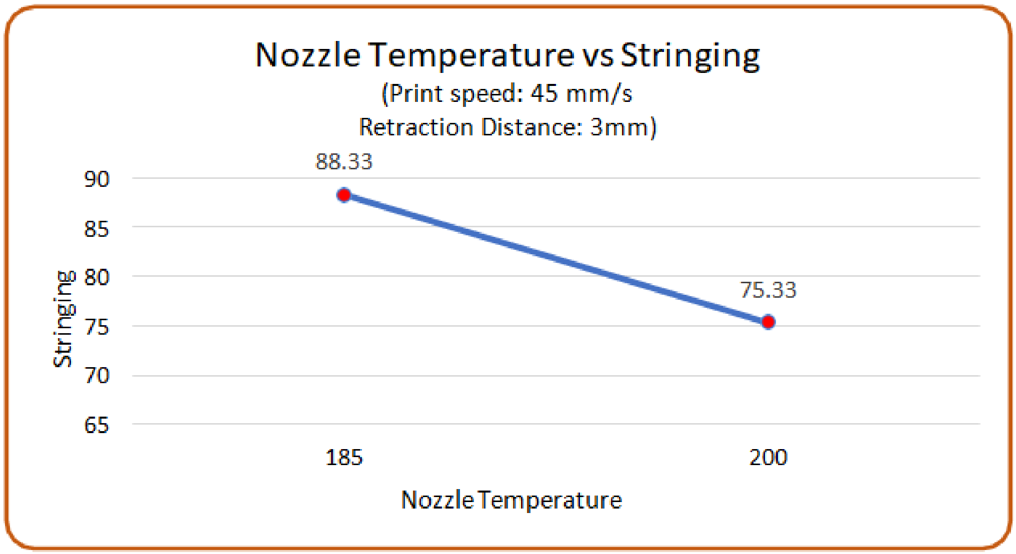

Fig.4. Nozzle Temperature vs Stringing for specimens 3, 12 and16

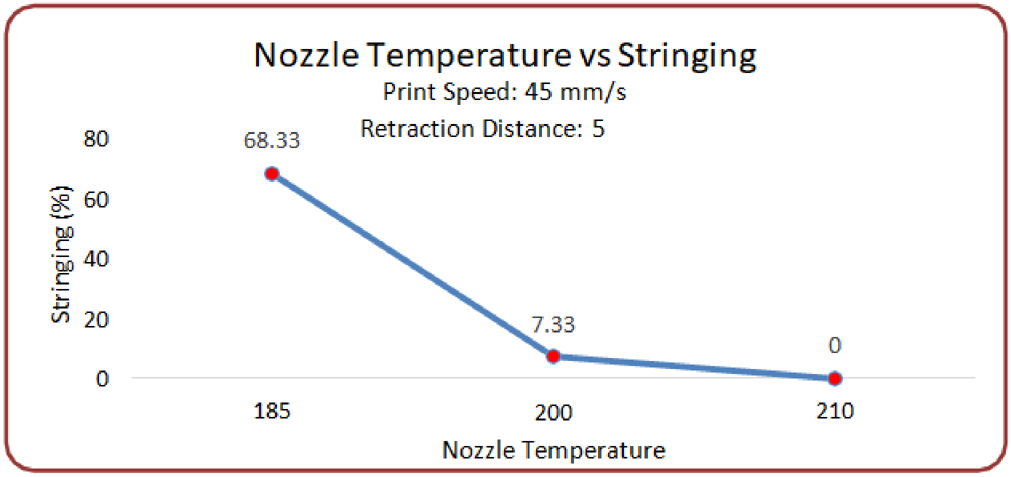

Fig. 5. Nozzle Temperature vs Stringing for specimens 6,14 and 17

Observing Figure-6 which was printed with Retraction speed of 45mm/s and retraction distance of 3mm in specimens 2 and 11 do not show much improvement in stringing. This trend is visible in Figure-7 also where the specimens 4 and 13 printed at 45mm/s retraction speed and 7mm retraction distance. In Figure-8, the effect of stringing with retraction distances of 3mm,5mm and7mm with retraction speed of 45mm at 200°C nozzle temperature on specimens 11, 12 and 13 can be observed.

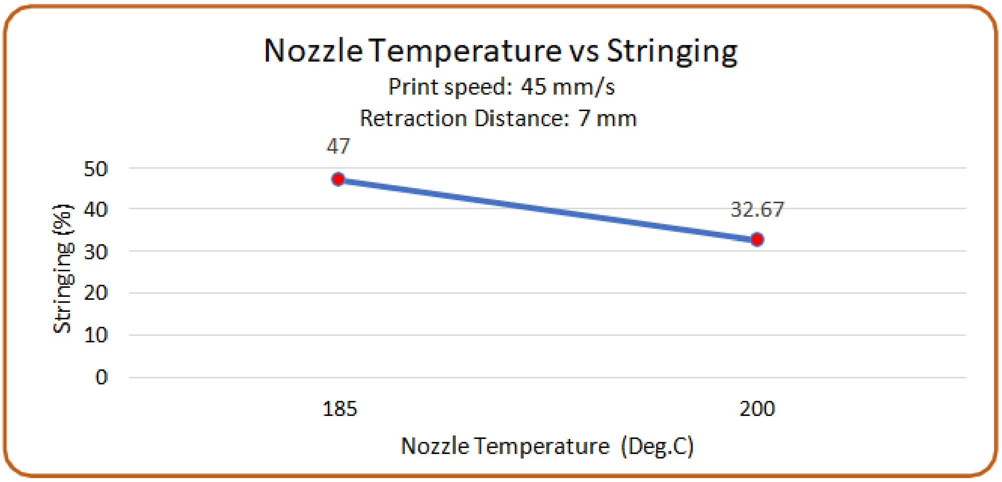

Fig. 6. Nozzle Temperature vs Stringing for specimens 2 and 11.

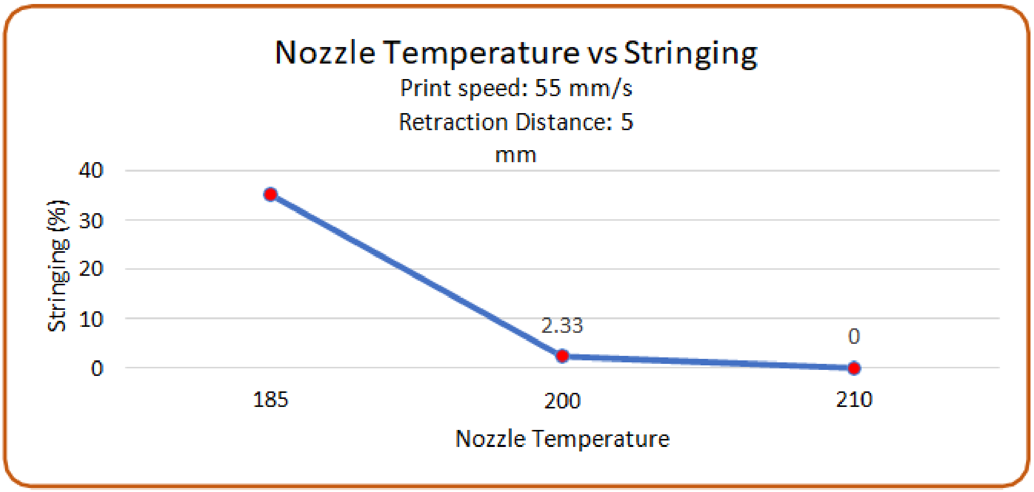

Fig. 7. Nozzle Temperature vs Stringing for specimens 4 and 13.

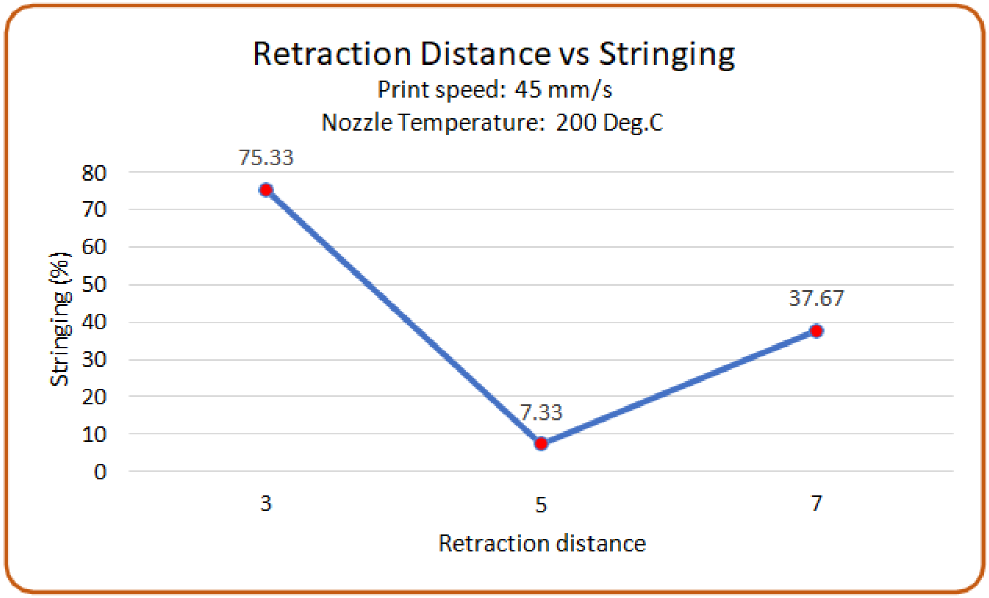

Fig. 8 Retraction Distance vs Stringing for specimens 11, 12 and 13.

The optimum parameters are, 200°C nozzle temperature and 45mm/s retraction speed, a retraction distance of 5mm. They show less string formation, which can be observed on specimen 12. With the optimal parameters a complex design was fabricated. The model chosen for fabricating is a differential gear model, which took 15 to 20 hours of printing time, which is seen in Figure-9.

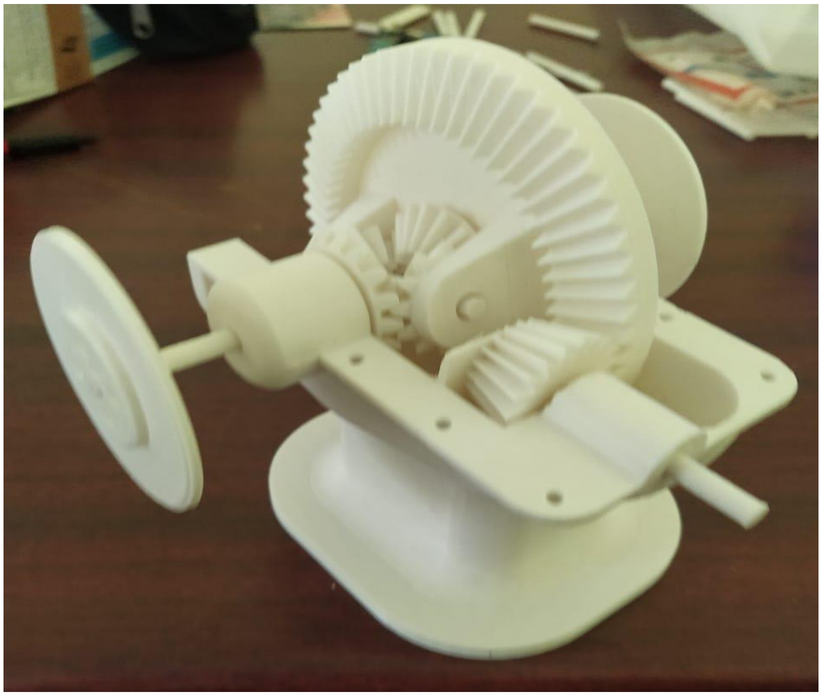

Fig. 9 Fabricated differential gear model.

5 Conclusion

The effects of stringing are cosmetic defects, material wastage and structural weakness. To overcome these effects this study was performed. Stringing at 210°C is reduced to almost zero at 45mm retraction speed and 5mm retraction distance, according to the above discussions. While other retraction speeds and distances show little improvement. At 200°C nozzle temperature and 45mm/s retraction speed, a retraction distance of 5mm results in a significant reduction in stringing (7.33%). In prototyping complex models with longer printing durations (15 to 20 hours for the Differential Gear model), a nozzle temperature of 200°C rather than 210°C is preferred to increase nozzle life, and a retraction speed of 45mm/s rather than 55mm/s to reduce stress on the filament, resulting in print failure. As a result, printing at 200° C Nozzle (Extruder) temperature with retraction speed of 45mm/s and retraction distance of 5mm is optimal for reduced stringing.

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