

Evaluation of Advanced 3D Printing Parameters and Materials for 3D-Printed Belt Pulley Teeth*

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Abstract

The article describes testing and comparison of strength of 3D printed belt pulley teeth. Toothed belt pulleys are commonly used in wide range of applications, especially powering mechanical equipment in vehicles, or synchronizing rotating assemblies in machines. Often tooth and pulley designs are unique. Commonly used manufacturing method, especially during prototyping phase is 3D printing. Due to complex internal structure of FDM parts, strength of entire part is heavily dependent of 3D printing and slicing parameters. Slicing parameters and material properties vary between users, machines and environments. Their general inconsistency is compensated by calibrating equipment and proper material preparation. However, manufacturing parameters also vary between use cases. The person responsible for manufacturing a prototype must consider the design geometry and material type meeting use case requirements. This paper explores this topic by comparing two advanced slicing methods, three material combinations and verifying their results by testing strength of specific belt pulley tooth samples, meant to be used inside moving vehicle to transmit power.

Keywords: Belt pulleys, vehicle part, 3D printing

Introduction

Fused Deposition Modeling (referred later as FDM) 3D printing has become vastly common and available, and with it, there are growing demands for improving 3D-printed part's strength and quality. Two obvious areas that have significantly improved, are hardware and input material. 3D printers have become reliable, accurate, and capable of reaching higher speeds, higher temperatures and tighter part tolerances. They have also become more advanced in terms of built-in safety features and enhanced user experience. Second potent growth can be noted in FDM filament quality. New materials are more thermally stable and dimensionally consistent, which spares issues for inadvanced machine operators. Filaments have also improved in mechanical properties, both referring to manufacturers mastering existing formulas and creating new blends of thermoplastic polymers. These technological improvements have indeed led to 3D printed parts increase in strength, quality and better consistency. However, despite better machines and materials to manufacture, the key feature to strong parts is proper slicing method. As this document focuses on comparing 3D printing parameters, few issues need to be asserted. At first, it must be acknowledged, what makes a 3D print strong? Ideally, the strongest possible polymer part is cast or molded, with isotropic structure, having the strength of input material. That cannot be achieved in FDM technology, as all filament 3D prints are anisotropic, partially hollow, stacked two-dimensional structures consisting of imperfectly connected polymer splines. Therefore, the part's strength is limited by the volume of material it can accommodate. There are ways to improve durability of certain features of the print. Much research

prove, that decreasing the number and volume of air pockets inside a print, thus increasing the amount of material inside the print increases its strength as Tomasz Zachorski did in his research(2023), however it is not the most optimal method of filament usage. Infill usually increases strength in only singular, or two perpendicular directions of the part, which can, but rarely does correspond with required feature strength. It is especially important when considering 3D printed gears or toothed belt pulleys, that have stress features placed in circular pattern around their center. In such examples infill density does not provide sufficient reinforcement, but there are other areas that can be manipulated using slicer software, to increase 3D print's durability (Let's Print, 26.07.2025). Part's wall thickness is what provides required strength in wanted directions (CNC Kitchen, 25.02.2018). Increasing wall thickness beyond the area of expected stress does not contribute to more durability, therefore important stress area must be well utilized. Manipulating within wall thickness between number of perimeters and their thickness is as of now the biggest contributor to strength (CNC Kitchen, 19.10.2019). It is a known practice to decrease the outer perimeter thickness to provide better feature resolution. Usually, the minimum perimeter thickness is set to be the same as the nozzle diameter. There are still two methods to decrease air pockets between parallel segments of splines in the walls of 3D prints and further reinforcing them. These methods are Brick Layers (CNC Kitchen , 18.02.2024), which move adjacent perimeters half of layer thickness up or below another. This allows for slight overflow of extruded material when printing perimeters, filling air pockets better than traditional slicing method. When applying load to toothed belt pulleys or gears, almost all the forces are oriented on the rotation plane. Brick layers mostly benefit parts strength in vertical direction, henceforth during the experiment described in this article, this method will not be tested. Different method is to use special kind of infill, called Concentric Infill with Alternate Extra Wall (OrcaSlicer, 2024). Concentric Infill is extruded following perimeter direction. It effectively acts as additional perimeters. When its density is set to 100%, the part is printed as it was fully filled with perimeters. Alternate Extra Wall forces the slicer to add an additional perimeter to every other layer. When Concentric Infill's extrusion width is double the extrusion width of perimeters, every other layer, the infill lines are being extruded not on top of previous lines, but on top and between previous layer lines. This method is easier to implement than Brick Layers and for larger features it significantly increases 3D printed part's overall durability (Maker's Muse, 24.04.2026), because additional overlapping area covers significant portion.

In the scope of this article, standard slicing method with thickened perimeter extrusions (referred to as Standard Method) will be compared to the method utilizing Alternate Extra Wall and Concentric Infill, which in this article will be called Alternative Method. The comparison between these two methods will be tested on a sample of singular tooth of toothed belt pulley.

Test sample design

Tested samples, unlike normalized tension test samples, were designed to imitate the geometry of final part used in steering system: toothed belt pulley wheel. The wheel has 22 teeth and uses Gates® CDX tooth profile. A single tooth was isolated, and redesigned to fit the test bench, as shown in figure 1.

A single 3mm wide tooth was screwed in a rotating jig, and put between two stationary, steel, meshing "belt" teeth. A torque was applied at the shaft of the rotating jig, and its peak value was measured, before the sample failed. The test bench profile is shown in figure 2. This method of testing gear or pulley teeth strength has been proven effective in various articles (Lorenzo Pagliari, 04.11.2025).

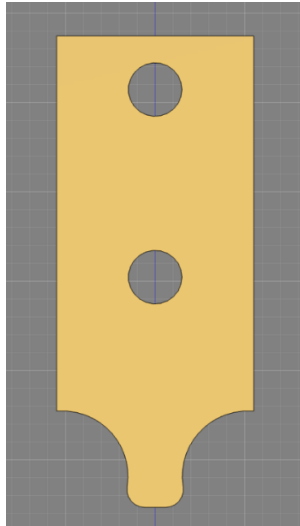


Figure 1- Test sample

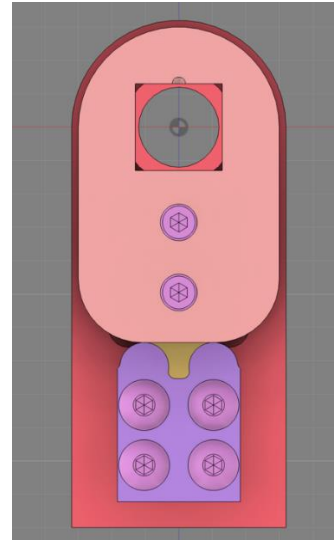


Figure 2 - Test jig profile with sample mounted

To construct the test jig, carbon fiber reinforced PA12 nylon 3D printing filament was used, as well, as steel belt teeth, to mesh with printed samples. Steel was used to eliminate any variables derived from the elasticity of the rubber belt, and to ensure proper jig stiffness. The torque applied to shear the sample tooth was measured with a digital torque wrench, as shown in figures 3 and 4.



Figure 3 - Test jig



Figure 4 - Torque wrench in a test jig

Each test sample was mounted in the jig and slowly using torque wrench. Maximum torque at the shaft was measured for single tooth, of a 22-tooth belt pulley. All tests were run in the same humidity and temperature. All polymer 3d-printed samples were similarly aged, for better result consistency.

Materials used for testing

The samples were printed with 2 materials, materials that are commonly used in real life applications when 3D printing functional elements, as well as injection molding: PA12 nylon, and its carbon fiber reinforced variant. In two mentioned manufacturing forms, these materials offer great mechanical properties. Pure PA12 lowers friction between elements and is impact, heat and chemically resistant (Mohammad Raquibul Hasan, 10.2024). PA12 with carbon fiber content offers higher tensile strength and stiffness, however due to exposed fibers, it is less wear resistant, and not as slippery as its pure variant. Preferably, pulley or gear teeth should be wear-resistant and mechanically efficient, but strong and stiff. During the testing in the scope of this document, an approach which offers a compromise of using both mentioned materials was tested. Teeth were printed with reinforced nylon, with thin outer layer of non-reinforced, slippery PA12. In theory, this approach should keep all benefits of using just

pure polymer alone, with partial increase of strength due to the use of carbon fiber content. To ensure the best adhesion between two different materials, both filaments used for printed samples came from the same manufacturer: Fiberlogy, with their PA12 and PA12CF15 nylon filaments.

Printing parameters

As stated before, two slicing methods were used to print tooth samples. 2 kinds of materials and their combination were tested with these methods, which sums up to 6 test batches. All samples were printed on the same 3D printer, in same ambient printing temperatures. All samples were printed with a 0.6mm nozzle, 0.24mm layer height, and 100% infill. Both Standard and Alternative slicing methods were used.

All layers in Standard Method were identical across all sample, in Alternative Method, there were two kinds of layers, one, identical on every even layer, other identical on every odd layer. Below are depicted layer profiles for all 6 test samples:

For single material samples, slicer line type is used to depict different printing features: red stands for infill, yellow for inner perimeter, and orange for outer perimeter. All printing speeds during this experiment were equalized along all sample batches, within material manufacturer's recommendations. Both infill and inner perimeter were printed 50% faster than outer perimeter.

- Standard Method, single material, both PA12 and PA12CF15 samples.



Figure 5 - Standard Method single material layer profile

In alternative method, every other layer there is no inner wall, which creates characteristic infill layer line offset. To compensate layer printing time differences, it was decided that infill and inner perimeter should be printed in equal speeds.

- Alternative Method, both PA12 and PA12CF15 samples.



Figure 6 - Alternative method, single material, even number layer profile



Figure 7 - Alternative method, single material, odd number layer profile

- Standard Method, PA12CF15 samples, with PA12 outer shell. Carbon fiber reinforced material is shown on green, pure material is shown in brown.

For following dual material batches, as in previous, all PA12CF15 infill and inner perimeters were printed with 50% greater speeds than outer perimeter consisting of pure PA12, as carbon fiber thermally and dimensionally stabilizes extruded polymer, allowing for increased speeds, without increasing the risk of shrinkage and warping.

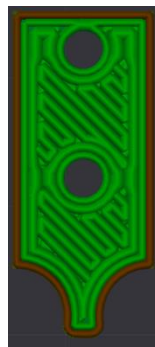


Figure 8 - Standard Method, mixed materials layer profile

- *Alternative Method*, PA12CF15 samples, with PA12 outer shell.

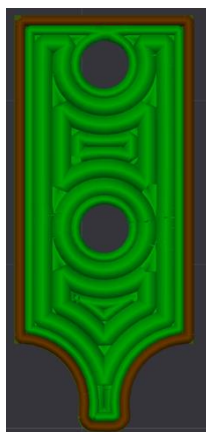


Figure 9 - Alternative method, mixed materials, even number layer profile

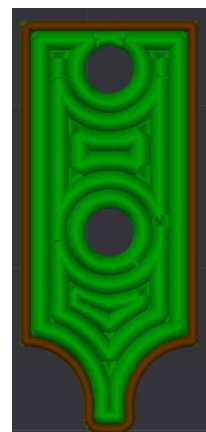


Figure 10 - Alternative method, mixed materials, odd number layer profile

5 Tests results

Each of 6 test batches consisted of 10 test samples.

Following are photos of test sample batches after testing:



Figure 11 – PA12, Standard Method. Average highest strain torque:13.19Nm



Figure 12 – PA12, Alternative Method. Average highest strain torque:14.04Nm



Figure 13 – PA12CF15, Standard Method. Average highest strain torque:18.96Nm



Figure 14 – PA12CF15, Alternative Method. Average highest strain torque:22.1Nm



Figure 15 - Mixed materials, Standard Method. Average highest strain torque:18.8Nm



Figure 16 - Mixed materials, Alternative Method. Average highest strain torque:18.28Nm

Conclusions

First and most visible characteristic of tested samples is material brittleness. Softer pure PA12 teeth had not sheared, but had stretched, while stiff reinforced nylon had broken cleanly. Some mixed material samples kept their broken tooth by the flexible PA12 outer shell. Comparing Standard to Alternative slicing methods, for single material, Alternative Method was stronger than Standard Method, by 6.43% for pure PA12, and by 16.58% for PA12CF15, however for mixed materials Alternative Method was weaker than Standard Method by 2.75%. For single material applications, for lesser equipped users with no access for dual extrusion 3D printers, Alternative slicing method is a measurable improvement over Standard one, when 3D printing polymer toothed pulleys or gears. However, Alternative method has not proven itself beneficial for dual material use, at least not in the scope of this experiment.

Dual material pulley teeth were expected to be weaker than their single material counterparts, but when slicing using Standard Parameters, part printed with reinforced nylon and pure nylon for the outer shell, was only 0.85% weaker, than the part printed entirely with the reinforced material.

Therefore, for strong and durable Gates® profile belt pulleys, that can be used in motor vehicle steering system or other mechanical accessory, mixing carbon fiber reinforced PA12 with pure frictionless PA12 is the most beneficial solution, as it is 33.87% stronger than regular PA12 part.

These results can be a foundation for further experimenting with different 3D printing parameters, to pursue even more strength optimized prototypes. However, it is important to remember, that these tests consider the strength of pulley teeth. Tested materials and parameters may be viable for geometrically similar elements, however, may fail to prove effective for completely different designs. This is why it is important to find the best slicing settings for every individual 3D print.

Acknowledgment

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