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## EVALUATION OF DIMENSIONAL PRECISION IN FDM 3D-PRINTED PARTS VIA COMPUTED TOMOGRAPHY

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**Abstract:** This study investigates the dimensional and geometric tolerances of a 3D printed timing belt pulley for a Dacia Logan engine. Using FDM technology, six pulleys were printed—three with different materials and three with varying nozzle sizes (0.2 mm, 0.4 mm, 0.6 mm). Computed tomography (CT) was used for precise, non-destructive measurements. The printed parts were compared to the CAD model and the original metal component to assess deviations in accuracy and tolerances. The study focuses on how material properties influence shrinkage and warping, and how nozzle diameter affects surface quality and detail. Smaller nozzles offer higher precision but longer print times, while larger ones reduce time at the cost of accuracy. The goal is to evaluate the feasibility of FDM for producing functional automotive components and to identify optimal trade-offs between material choice and nozzle size for precision and efficiency..

**Key words:** Additive Manufacturing • 3D Print • FDM • Computed Tomography • Quality Inspect • Metrology • Form • Deviation • Tolerances • Evaluation.

### 1. INTRODUCTION

Additive Manufacturing (AM) also known as 3D Printing, is a transformative technology that fabricates three-dimensional objects by adding layers of material based on digital 3D models in an automated manner [1], [2]. This layer-by-layer build-up approach is the working principle of Additive Manufacturing. AM is revolutionary in its ability to fabricate complex 3D components with unmatched design variety that can surpass those achievable with conventional manufacturing techniques, often without the need for supplementary tools [1]. This manufacturing process offers shorter lead times and cost effective production, with the sacrifice of substantial challenges in quality assurance. Because of the layer-by-layer method of AM, internal defects and dimensional variations can be present in our workpieces [3]. X-ray Computed Tomography (CT) is an industrial tool that enables us to see not only external surfaces but also internal features of a workpiece without cutting or destroying the sample. GOM Inspect (now ZEISS Inspect) is a metrology software used for dimensional analysis and

evaluation of 3D measuring data from laser scanners, CT, coordinate measuring machines (CMM) and others. The extruder's nozzle diameter influences the layer height of the part and has great impact on surface quality and mechanical properties of the printed part [4].

This paper compares dimensional and geometric tolerances of eight 3D printed parts by Fused Deposition Modeling (FDM). 4 parts were printed with different materials, 3 parts were printed with the same material but different nozzle diameters, and the last part was printed with the same material and nozzle diameter as one of the previous 3, but with different print settings. All 8 parts were scanned by Computed Tomography, giving us a great virtual representation of the part. GOM Inspect 2018 was used in this study for comparing the CT scanned pieces' dimensions and geometrical tolerances to the original CAD model. The software offers the possibility of exporting a final report of the measurements in different formats, PDF in this case. This research allows us to see if these different printing parameters

affect the dimensional and geometrical tolerances of a 3D printed Belt Timing Pulley.

## 2. METHODOLOGY

### 2.1 Scanning by Computed Tomography

For measuring the tolerances on our parts, we wanted to be as precise as possible so in that case we used an X-ray computed tomography (CT) allows us to see objects in detail, both layer by layer and in 3D. This makes it especially useful for analyzing the results of an additive manufacturing (AM) process [1].

The fundamental configuration for an X-ray CT scan consists of acquiring multiple radiographic images, referred to as projection images or simply “projections”. These images are captured from numerous angular positions surrounding the specimen during a complete 360° rotation. Utilizing a reconstruction algorithm, it becomes feasible to create a three-dimensional representation of the object, highlighting all of its internal and external characteristics [5].

The Zeiss Metrotom 800 [6] represents a sophisticated industrial computed tomography (CT) system, specifically engineered for non-destructive three-dimensional analysis and dimensional assessment of intricate components. In this experimental study, the system was set up with the following scanning parameters: an acceleration voltage of 130 kV and a filament current of 61  $\mu$ A, which provided optimal resolution and contrast. A 0.25 mm copper physical filter was employed to mitigate beam hardening artifacts, while a Shepp-Logan mathematical filter improved the quality of image reconstruction. The detector recorded 2100 projections at a resolution of 1456 x 1840 pixels, with an exposure duration of 500 milliseconds for each projection. The resulting voxel size was 8.693  $\mu\text{m}^3$ , ensuring exceptional spatial resolution. Additional configurations included a digital gain of 2.5 and a binning mode of 1x1, facilitating detailed visualization and accurate dimensional analysis of the scanned specimens.

The preparation for a microCT investigation, as outlined in the sources, entails several essential steps. First, a suitable test component is designed, considering the characteristics to be

examined, such as density, geometrical features, and surface quality, along with the constraints of microCT scanning. These constraints include the limited penetration capability of X-rays, which diminishes with increasing material density and atomic mass, thereby necessitating a smaller sample size. After the design phase, the sample is produced using a method like Selective Laser Melting (SLM), exemplified using TiAl5V5Mo5Cr3 powder for the test specimen mentioned in the source. The final phase of preparation is the microCT investigation itself, which involves the critical task of selecting optimal scanning parameters. This selection is vital and must be customized to the shape and material of the sample, as well as the chosen scanning strategy, often requiring multiple scans and iterations to determine the best settings [7]. Furthermore, identifying an appropriate sample orientation is crucial to minimizing measurement uncertainties, ideally positioning the specimen to reduce the maximum penetration length and avoiding surfaces that are parallel to the X-ray beam or perpendicular to the rotation axis, as these can lead to scattering and noise that complicate the 3D reconstruction.

In order to ensure the accuracy and reproducibility of the results, a custom polystyrene fixture was designed to securely hold the plastic part in a stable, upright position on the rotary table. This step was crucial to minimize alignment deviations and potential motion artefacts during the scanning process. Prior to scanning, the CT system underwent a comprehensive calibration procedure, adhering to the VDI/VDE 2630-1.3 standard. This standard governs the accuracy of dimensional measurements in industrial CT applications. The calibration process, which lasted approximately 90 minutes, involved verifying the system's geometric and radiometric parameters. The purpose of this was to ensure measurement of traceability and compliance with metrological standards.

An aluminum filter (0.5 mm) was employed at the X-ray source to refine the energy spectrum of the emitted X-rays. This filter effectively attenuates low-energy photons, which are more likely to be absorbed superficially by the sample, leading to beam hardening artifacts and reduced image quality. By filtering out these lower-

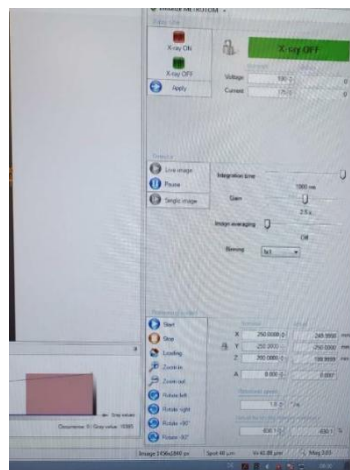
energy components, the beam is "hardened," resulting in a more uniform penetration through the sample and minimizing artifacts in the reconstructed images. The scanning process begins after the plastic component was mounted onto the rotary stage within the CT scanner. Subsequently, the scanning parameters were configured, encompassing the X-ray tube voltage and current, the integration time, and the detector gain. These parameters were meticulously tailored to the material properties and dimensions of the component under investigation. These settings were optimized to achieve a balance between image resolution, contrast, and scanning time, ensuring the capture of high-quality volumetric data. The resulting 3D dataset facilitated precise dimensional measurements, defect detection, and comparison with the original CAD model, providing valuable insights into the manufacturing quality and structural integrity of the plastic component. This methodology emphasizes the efficacy of industrial CT scanning in delivering accurate, non-destructive evaluations of complex parts, thereby enhancing quality control processes in manufacturing environments.



a)



b)



c)

**Fig. 1** a) Different aluminum filters; b) Support for the scanning piece; c) Parameters

## 2.2 Parts used and their 3D print parameter

In this study, eight parts were printed using Fused Deposition Modeling (FDM) technology, with the goal of analysing how different materials and printing parameters influence the precision of 3D printed components. All parts were scanned using X-ray Computed Tomography (CT), and the measurements were done in GOM Inspect software. Seven parts were printed with a Bambulab A1 Combo printer [8], and one part was produced with a Prusa MK4 printer [9].

The eight parts were divided into two groups, depending on what was tested. In the first group,

called Group A, the same material was used for all parts, but the printing parameters were changed, especially the nozzle diameter and the layer height. In the second group, called Group B, the same printing parameters were kept for all parts, but the material was different for each one.

For Group A, the material used was Bambulab PLA Matte [10]. The purpose of this group was to see how the nozzle diameter influences the quality and accuracy of the printed parts. Three different nozzles were used: 0.2 mm, 0.4 mm, and 0.6 mm. Each nozzle had a different layer height: 0.1 mm for the smallest, 0.2 mm for the medium, and 0.3 mm for the largest. Two identical parts were printed with the 0.6 mm nozzle to check if the results are consistent. The temperature of the nozzle was set at 220°C for all prints. The infill pattern used inside the part was Gyroid, with a density of 20%. For the top and bottom surfaces, the Grid pattern was used again. The slicing profile used the Arachne strategy for generating walls, and the walls were printed in the order inner first, then outer. These settings were chosen to observe how print speed and nozzle size affect the final shape of the parts.

In figure 2 we can observe the parts, the upper left one was printed using 0.2 mm nozzle, upper left 0.4 mm nozzle and the lower ones both were printed with 0.6 mm nozzle. The lower ones were printed using the same settings to test how consistent the printer can produce the same part. Using different nozzle diameters the print required varied, 5 hours for the part using the 0.2 mm nozzle, 2 hours 15 minutes for the 0.4 mm nozzle and 54 minutes for each part printed with 0.6 mm nozzle. In this time, it is also included the self-calibrations of the printer which it does before starting a new print which is around 6 minutes.



**Fig. 2** Parts from group A

In Group B, the printing parameters were the same for all parts, and only the material was different. The nozzle had a diameter of 0.4 mm, the layer height was 0.2 mm, and the nozzle temperature was also 220°C. The infill pattern inside was Gyroid, which offers good strength in all directions, and the surface layers were printed using the Concentric pattern. The same wall generation method was used, and support structures were activated only on the build plate.

Even though the printer settings were the same, each part from Group B was printed using a different type of PLA (polylactic acid) filament, coming from four different manufacturers. The materials used were Prusa PLA Galaxy Black [11] Bambulab PLA Matte Red, F3D PLA+ Black [12], and Creality Hyper PLA Blue [13]. All materials had a 1.75 mm filament diameter, with a declared tolerance between  $\pm 0.02$  mm and  $\pm 0.03$  mm.

In figure 3 there are the parts used for Group B, three of them were printed using Bambulab A1 combo (the upper right and the bottom ones) and the upper left one was printed using Prusa MK4. The parts made with the bambulab printer took 2 hours and 15 minutes, and the part made with Prusa MK4 took 2 hours and 30 minutes.



Table 1

## Measurements

| No. | Vendor + Material + Color               | Nozzle Diameter [mm] | Layer Height [mm] | Measurements (Deviation) |       |                   |                |       |                    |              |       |           |       |
|-----|-----------------------------------------|----------------------|-------------------|--------------------------|-------|-------------------|----------------|-------|--------------------|--------------|-------|-----------|-------|
|     |                                         |                      |                   | Bore Diameter            |       | Bore Cylindricity | Outer Diameter |       | Outer Cylindricity | Teeth Radius |       | Key Width |       |
| 0   | CAD PART                                | -                    | -                 | 26 ±0.2                  |       | Max 0.2           | 56.29 ±0.2     |       | -                  | 2.68±0.2     |       | 4 ±0.1    |       |
| 1   | Bambulab PLA (Red) - Different Settings | 0.4                  | 0.2               | 25.86                    | -0.14 | 0.17              | 55.96          | -0.33 | 0.24               | 2.67         | -0.01 | 3.99      | -0.01 |
| 2   | Prusament PLA Galaxy (Black)            | 0.4                  | 0.2               | 25.97                    | -0.03 | 0.1               | 56.02          | -0.27 | 0.23               | 2.68         | 0     | 4.06      | 0.06  |
| 3   | Creality Hyper Speed PLA (Blue)         | 0.4                  | 0.2               | 25.83                    | -0.17 | 0.19              | 55.95          | -0.34 | 0.28               | 2.66         | -0.02 | 4.04      | 0.04  |
| 4   | F3D Premium PLA (Black)                 | 0.4                  | 0.2               | 25.85                    | -0.15 | 0.12              | 56.14          | -0.15 | 0.24               | 2.67         | -0.01 | 4.22      | 0.22  |
| 5   | Bambulab PLA (Red) - A1                 | 0.6                  | 0.3               | 25.92                    | -0.08 | 0.32              | 55.87          | -0.42 | 0.27               | 2.66         | -0.02 | 3.89      | -0.11 |
| 6   | Bambulab PLA (Red) - A2                 | 0.6                  | 0.3               | 25.9                     | -0.1  | 0.28              | 55.95          | -0.34 | 0.18               | 2.56         | -0.12 | 3.9       | -0.1  |
| 7   | Bambulab PLA (Red) - A3                 | 0.4                  | 0.2               | 25.89                    | -0.11 | 0.26              | 55.94          | -0.35 | 0.19               | 2.64         | -0.04 | 4.01      | 0.01  |
| 8   | Bambulab PLA (Red) - A4                 | 0.2                  | 0.1               | 25.89                    | -0.11 | 0.11              | 56             | -0.29 | 0.23               | 2.66         | -0.02 | 4.02      | 0.02  |

#### 4. CONCLUSIO

This study demonstrated the influence of both material selection and printing parameters on the dimensional precision and geometric tolerances of 3D printed components produced via Fused Deposition Modeling (FDM). Using computed tomography (CT) as a non-destructive evaluation method, high-resolution scans provided detailed insights into the deviations from the CAD reference model. Although none of the analyzed parts achieved full conformity with the original tolerance specifications, the results highlighted critical trends that can inform optimization of FDM settings.

In Group A, where nozzle diameter and layer height were varied, smaller nozzles (e.g., 0.2 mm) produced more dimensionally accurate parts, especially in terms of bore diameter and key width, but required significantly longer print times. Larger nozzles (0.6 mm) led to increased deviations, particularly in outer diameter and cylindricity, underscoring the trade-off between speed and accuracy.

Group B, which compared different PLA materials under identical printing conditions, showed that material formulation impacts final part dimensions to a lesser extent than nozzle size. Nevertheless, the F3D Premium PLA exhibited the largest deviation in key width (+0.22mm), exceeding tolerance limits, whereas Prusament PLA Galaxy Black achieved the best

overall consistency across multiple measured dimensions.

In conclusion, this investigation confirms that both process parameters and material choice substantially affect the dimensional fidelity of FDM-printed parts. Fine-tuning nozzle size and selecting consistent materials can reduce deviations and improve the suitability of FDM components for applications where tight tolerances are required. CT-based inspection proves to be a highly effective tool for validating such manufacturing processes and enabling quality control in additive manufacturing environments.

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## EVALUAREA PRECIZIEI DIMENSIONALE A PIESELOR IMPRIMATE 3D PRIN FDM PRIN TOMOGRAFIE COMPUTERIZATĂ

**Rezumat:** Acest studiu investighează toleranțele dimensionale și geometrice ale unei roți de curea de distribuție imprimată 3D pentru un motor Dacia Logan. Folosind tehnologia FDM, au fost imprimate șase roți de curea – trei cu materiale diferite și trei cu dimensiuni variabile ale duzei (0,2 mm, 0,4 mm, 0,6 mm). Tomografia computerizată (CT) a fost utilizată pentru măsurători precise și nedistructive. Piese imprimate au fost comparate cu modelul CAD și cu componenta metalică originală pentru a evalua abaterile în ceea ce privește precizia și toleranțele. Studiul se concentrează asupra modului în care proprietățile materialului influențează contracția și deformarea și asupra modului în care diametrul duzei afectează calitatea și detaliile suprafeței. Duzele mai mici oferă o precizie mai mare, dar timpi de imprimare mai lungi, în timp ce cele mai mari reduc timpul, în detrimentul preciziei. Obiectivul este de a evalua fezabilitatea FDM pentru producerea de componente auto funcționale și de a identifica compromisurile optime între alegerea materialului și dimensiunea duzei pentru precizie și eficiență.

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