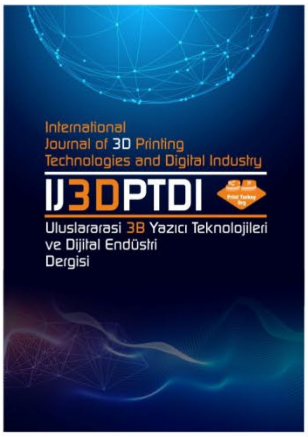

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SHAPE'S IMPACT ON DIMENSIONAL PRECISION IN 3D PRINTED COMPONENTS

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ABSTRACT

In this comprehensive exploration, the study explores the relationship between shape and the dimensional accuracy of components manufactured through additive manufacturing processes. The methodology involves the adept utilization of Autodesk Inventor Software, strategically embossing capital letters from A to O onto a rectangular plate. The resulting models are exported in STL format, laying the foundation for rapid prototyping. The investigation unfolds with the application of a Prusa İ3 desktop 3D printer, where specific settings, including layer height (ranging from 90 to 300 microns), 20% infill density, and a heated bed temperature of 60 ºC, are scrupulously chosen. Three different embossing methods are examined in this study to see how each affects dimensional correctness. These methods are join, cut half, and cut through. Through a meticulous comparative analysis, facilitated by high-resolution image acquisition and advanced processing techniques like binarizing and edge detection, the study discerns that embossing with join yields shapes characterized by higher dimensional accuracy, a conclusion substantiated by correlation coefficient analysis. This research stands as a significant contribution, offering valuable insights into optimizing additive manufacturing processes and elevating dimensional precision in 3D printed components.

Keywords: Additive Manufacturing, Shape Effects, Image Processing, Edge Detection, Dimensional Accuracy, STL Format.

1. INTRODUCTION

1.1. Advancements in Melt Extrusion

The details of the conventional melt extrusion additive manufacturing (AM) process, depicted in Figure 1, involve a systematic conveyance of filament feedstock to the system through an electric motor-controlled pinch roller mechanism. This complicated mechanism plays important role in facilitating the precise delivery of the filament, ensuring a controlled and uniform flow. Central to this process is the predominant use of amorphous thermoplastics, where materials such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) are ideal choices for feedstock filament. The selection of these materials is vital, as they exhibit properties conducive to the extrusion and layering process, ultimately contributing to the successful fabrication of sophisticated and precise three-dimensional structures. This initial phase sets the stage for the subsequent stages of melting, deposition, and layering, highlighting the significance of material choice in the additive manufacturing workflow.

At the base of the extrusion AM system resides the heated liquefier, a critical component where the filament undergoes the crucial phase of melting. The resulting molten material is then thoroughly propelled through a small print nozzle by the liquefier, forming what is commonly referred to as a road or bead as it exits the nozzle. The liquefier head assembly undergoes systematic maneuvers throughout the build environment, propelled by stepper motors. This orchestrated interplay of planar, x-y motion of the print head, synchronized with the z-motion of the build stage, lays the foundation for the layer-by-layer construction of intricate 3D structures [1-2]. This intricate dance of components in the extrusion process exemplifies the precision and complexity inherent in additive manufacturing methodologies.

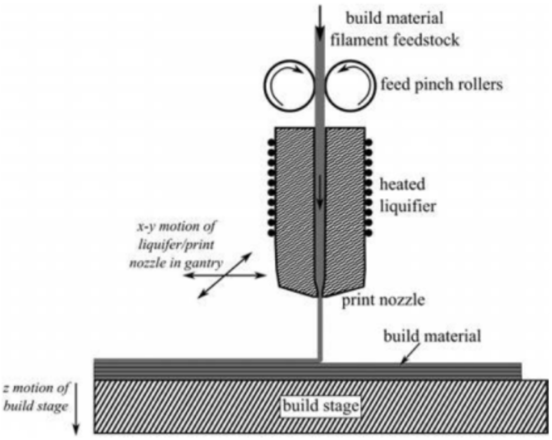


Figure 1. Typical extrusion based AM process [2].

The trajectory traced by the print head along the gantry is commonly known as the tool path, representing a critical design variable in the implementation of extrusion-based additive processes for part production. Achieving a consistent surface involves the typical printing of a contour or road along the part's perimeter. Internally, a lattice of roads is deposited, with each layer usually oriented at a fixed raster angle relative to the layer beneath it. The thickness of contours and roads assumes vital significance in shaping the dimensional accuracy and surface roughness of the final parts, as illustrated in Figure 2.

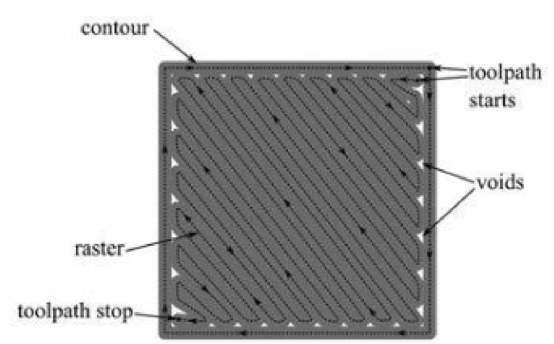


Figure 2. Typical toolpath with a single contour [2].

1.2. Optimizing Design and Product Characteristics in Melt Extrusion Additive Manufacturing

Dimensional accuracy, resolution and surface roughness are closely related to performance parameters and product design. The main factors affecting performance and production results are equipment track design, water and ambient temperature, and heating rate. Also, the control algorithms that control filament feed speed, path width, wafer thickness, and air gap are important considerations. The dimensions of the road, especially the width and thickness specified in the x-y plane of the build plate, play an important role in defining the basic limits of dimensional accuracy in the manufacturing process. These parameters directly affect the possible resolution of the printed object. In addition, the space between adjacent roads, known as the air gap, is an important factor affecting the correct size [3]. These important considerations highlight the importance of shaping the final product of the manufacturing process and providing a basis for understanding and optimizing the resolution and accuracy of printed parts. In additive manufacturing (AM) design software, a positive air gap means that two adjacent roads do not touch, while a negative air gap refers to a distance less than the distance between the centers of two adjacent roads (Figure 3).

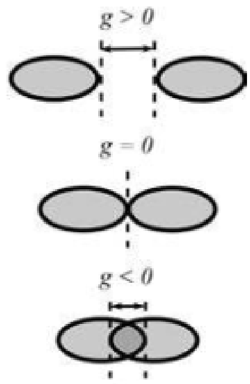


Figure 3. The positive, zero and negative air gap [4].

Implementing a minimum negative void is considered a strategy to reduce the void ratio between roads and increase the bounding area. However, this approach should be carefully considered as it can degrade the physical appearance of the part. Computer control of construction direction and raster model is important because it has a significant impact on construction time and mechanical properties. Critical process parameters such as liquefaction temperature, manufacturing environment temperature, and filament feed rate are critical determinants in ensuring the quality of manufactured components. Thermal stresses built up in a part during drying and cooling, influenced by the temperature of the manufacturing environment, can cause instability and distortion. In addition, other parameters that affect the dimensional accuracy are the materials selected, the nominal dimensions (small, medium, or large), the construction, the geometric characteristics of the laboratory and the topology (open or closed). The choice between thick-walled parts, such as frame or solid, and post-processing methods will have a significant impact on the final parts of the manufactured part.

Hannon et al. [5], studied the effects of printing parameters on the dimensional accuracy of the sample in the (Fused Deposition Modelling) FDM 3D printing. They produced cylindrical and dog bone tensile specimens with different process parameters such as orientation, mesh orientation angle, and layer thickness. They found that the layer thickness parameter had a significant impact on accuracy and that the grid orientation angle was not an important factor. Akbas et al. [6], researched the effects feed rate and die temperature for dimensional accuracy of FDM polymer parts. They printed 30 strips with the same width as the diameter of the nozzle for each sample. Using calipers to measure ribbon width at five locations, they created a linear regression model to find the relation between deviation and parameters. They found that polylactic acid (PLA) samples were more accurate than acrylonitrile butadiene styrene (ABS) samples. Bora and Negabola [7], aimed to use the Taguchi method to optimize the printing parameters (layer height, printing direction and exposure time) of a mask stereolithography (MSLA) tool. They performed analysis of variance (ANOVA) to determine the most effective factors and used regression equations to predict outcomes. They observed a significant effect of exposure time on production measures. Resende et. al [8], used the stereolithography (SLA) method to evaluate the accuracy of 3D printed castings. They produced samples using 3D layers with different thicknesses of 25, 50 and 100 micrometers. They found no significant difference in accuracy between layer thickness. Zarian et al. [9] studied the effect of printing parameters (orientation and position) on mechanical properties using polyetheretherketone (PEEK) biomaterials and the material extrusion (MEX) method. They classify the specimens based on their orientation and location. They observed no significant difference in mechanical strength between top and bottom printed samples and vertically and horizontally oriented samples.

Akıncıoğlu et al. [10] investigated the effect of infill density (25%, 50%, and 75%) on the wear properties of gyroid-patterned ABS samples. Their main objective was to determine the coefficient of friction values and to present the impact of infill density on wear and friction performance. They evaluated several performance indicators such as diameter deviation, hardness, surface roughness, test temperature, friction coefficient, weight loss, and wearing surface results. Their results indicated that infill density significantly affects the tribological and heating characteristics of ABS samples. Specifically, increasing infill density leads to higher friction and heat in the samples.

Norani et al. [11] studied the coefficient of friction and wear properties of ABS material by determining the optimal parameters for 3d printing process. They analyzed the dependent variables (friction coefficient and wear rate) as functions of the nozzle temperature, layer height and printing pattern. As a result of study, they found that layer height of 0.10 mm and nozzle temperature of 234 °C with triangle infill pattern is optimal to minimize the coefficient of friction and wear rate.

Chand et al. [12] studied the dimensional accuracy and surface roughness of 3D printed parts fabricated in different orientations. They explored four different part orientations to analyze the variations in dimensional deviation and SR. Additionally, fabricated parts were analyzed using scanning electron microscopy (SEM). The results showed that there was a variation in dimensional accuracy and SR with different part orientations.

Irene and Figueras [13], conducted a research for a comparison of the dimensional accuracy and form errors of Fused Filament Fabrication (FFF) 3D printed spur gears made from two different polymeric materials: PLA and Nylon-PA6. They designed and printed two types of gears with different module and teeth number printed. They used the sector span method to determine the base circular thickness and pitch of the gears. They measured the root and tip diameters to determine the roundness and concentricity errors. The results indicated that PLA generally provides better dimensional accuracy than Nylon.

Moradi et al. [14], investigated the additive manufacturing of ABS using statistical analysis and optimization methods. They considered the impact of layer thickness, infill percentage and contours number on the maximum failure load and elastic modulus of the final ABS product. They used both artificial neural network (ANN) and response surface method (RSM) to assess the impact of additive manufacturing parameters on build quality. They extracted main effect plots and 3D plots from the artificial neural network (ANN) and response surface methodology (RSM) models to analyze the process. They reported, although ANN is better, those two models are efficient for prediction of mechanical properties.

Zhao et al. [15] proposed a 3d machine vision method to detect the 3d printing defects. They reported from their experimental tests, method is accurate and robust for both potential defect region extraction and accurate defect detection.

Purpose of this study is to investigate the relationship between shape and the dimensional accuracy of components manufactured through additive manufacturing. The investigation focused on the influence of shape on the dimensional accuracy of components manufactured through additive manufacturing. Capital letters from A to O were embossed on a rectangular plate using extrusion through join, cut to half the plate thickness, and cut through options with Autodesk Inventor Software. Capital letters have been selected as each of them has their own geometric features such as straight-line end and curved edges. By this way the effects of the geometric features were also measured. High-resolution images of the specimens were captured using a 20.2 Megapixels CCD camera. These images underwent various image processing techniques, including binarizing, edge detection, edge enhancement, and image correlation. The dimensional errors in the manufactured components were identified through correlation of the images of the three replicated parts embossed with join, cut half, and cut through.

2. MATERIAL AND METHOD

2.1. Specimen Design and Manufacturing

Models were created to precise dimensional measurements using CAD (Autodesk Inventor) software using joining, cutting and semi-deep cutting techniques. A diagram with capital letters A to O mounted on a square plate 150 mm long, 100 mm high and 3 mm thick. The text size of 15 mm was chosen to improve the resolution and quality of the text. The carefully designed model is then exported to the STL file format, which lays the foundation for 3D printing. The work continued with the printing of prototypes for accurate measurement of dimensions using a Prusa İ3 desktop 3D machine (Figure 3) with a layer height of 90 to 300 microns and a diameter of 1.75 mm. Complex printing parameters were carefully configured using Simplified3D software (Figure 4).

Figure 3. Prusa İ3 desktop 3D machine.

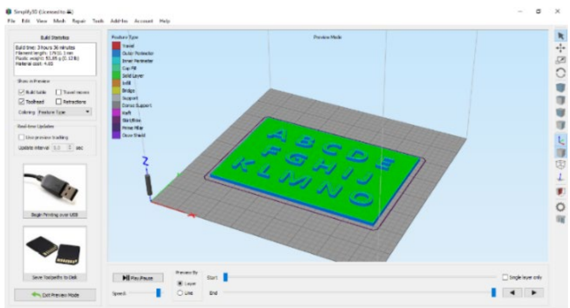


Figure 4. Printing settings of measurement samples [16].

The 3D printer's specifications include crucial parameters such as layer resolution, defining the thickness of each printed layer; build volume, determining the maximum print dimensions; XY positioning precision, ensuring accuracy in the horizontal plane; Z positioning precision, affecting vertical layer alignment; filament diameter, indicating the material thickness used for printing; extruder temperature, specifying the temperature range for material extrusion; and print material, denoting the type of material employed. These specifications collectively influence the printer's capabilities, precision, and suitability for diverse applications, emphasizing the importance of understanding and optimizing each parameter for achieving desired 3D printing outcomes. In the scope of material versatility, the Prusa İ3 3D printer showcases its capability by adeptly producing parts with both PLA and ABS materials. The printing process were meticulously managed, with a heated bed temperature of 60 ºC strategically chosen to elevate bonding and enhance surface quality, complemented by an extruder temperature set precisely at 195 ºC. The structural composition of the specimens was carefully designed, featuring a shell thickness of 0.8 mm, a layer height of 0.2 mm, and the incorporation of two shells to ensure robustness. The deliberate selection of a print speed at 80 mm/s further attests to the optimization of efficiency in the manufacturing process. Figure 6 visually encapsulates the tangible outcomes of three distinct manufacturing methods: (a) join, (b) cut, and (c) cut half. To explore the details of dimensional accuracy, the acquired images of replicated parts embossed with join, cut half, and cut through underwent a comprehensive analysis using various image processing techniques, such as binarizing and edge detection. This was followed by a correlation analysis aimed at identifying and understanding any potential dimensional errors within the manufactured components.

(a)

(b)

(c)

Figure 5. The produced samples (a) join (b) cut (c) cut half methods.

2.2. Dimensional Accuracy Assessment Through Image Processing Techniques

Edge detection, within the domain of digital image processing, serves as a cornerstone in image analysis by systematically identifying boundaries and transitions in image features. The underlying principle involves the recognition of intensity variations in image points, where distinct changes signify the presence of edges. The procedural steps in edge detection are integral to extracting valuable information from images, encompassing the acquisition of a color image, refinement to minimize noise while preserving authentic edges, intensification to enhance edge quality, thresholding to eliminate noisy edges based on magnitude, localization to estimate edge locations and pixel spacing, and the final retrieval of the processed image. In the context of digital image processing, an edge reflects alterations in light, color, and texture, providing essential cues for defining characteristics such as depth, size, orientation, and surface properties. This selectivity enables the selective identification of key edge points, making edge detection indispensable in applications like feature detection and extraction within the broader landscape of image processing [16 - 18]. Figure 6 serves as a schematic representation, delineating the sequential flow of the edge detection process. This academic discourse underscores the pivotal role of edge detection in extracting meaningful insights from digital images, contributing to advancements in fields ranging from computer vision to medical imaging.

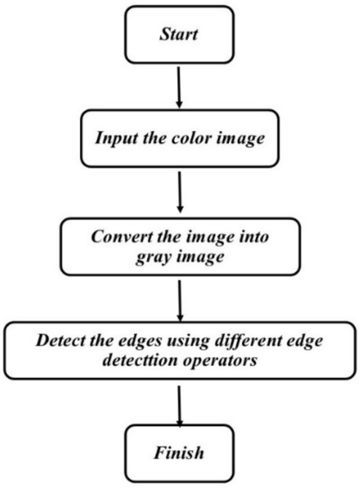
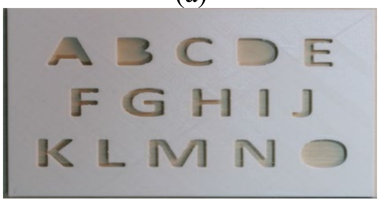


Figure 6. Flowchart of edge detection [16].

2.3. Image Correlation

For the image correlation, sample images were obtained from printed boards (printed through join, cut and cut to half depth of the plate thickness methods) and design environment of Autodesk Inventor (designed through join, cut and cut to half depth of the plate thickness with emboss) (Figure 7).

(a)



(b)

Figure 7. The images obtained from (a) design environment and (b) printer.

The images derived from edge-detected and enhanced images underwent a correlation process with the images acquired from the design environment and the physical parts produced through additive manufacturing. This correlation analysis serves as a crucial step in validating the fidelity and accuracy of the image processing techniques applied. By comparing the processed images with the original design and the tangible manufactured components, this correlation effort aims to assess the alignment and congruence between the digital representation and the physical realization. The correlation results provide insights into the effectiveness of the edge detection and enhancement procedures in faithfully representing the intended design and the subsequent additive manufacturing outcomes.

3. RESULTS AND DISCUSSION

The images obtained from the additive manufacturing process and the design environment for specimens embossed with join, cut, and cut half are displayed in Figure 8.

Figure 8. Images from design environment and additive manufacturing from top to bottom for embossed with join, cut and cut half, respectively.

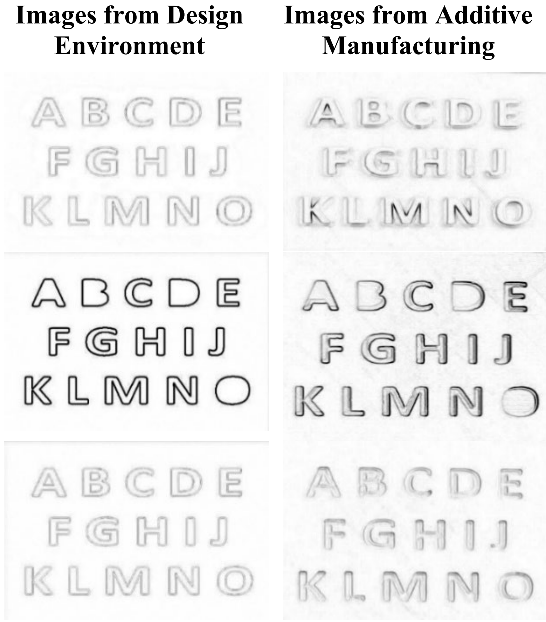


Figure 9. Images processed with edge detection from top to bottom for embossed with join, cut and cut-half, respectively.

The images processed using Sobel Edge filter from both the design environment and additive manufacturing for embossed with join, cut and cut-half, respectively are given in Figure 10. The correlation coefficients, computed using Matlab, were found to be 0.50, 0.28, and 0.37 for join, cut, and cut-half, respectively. The calculation of correlation coefficients was based on the entire plate, which included fifteen letters with different shapes. It is noteworthy that since each letter introduces a small amount of error, the accumulation of these errors contributes to a lower overall correlation coefficient.

4. CONLUSION

The study has contributed valuable insights into the intricate relationship between shape and dimensional accuracy in additive manufacturing. The computation of overall correlation coefficients, with values of 0.50, 0.28, and 0.37 for join, cut, and cut half, respectively, underscores the varying degrees of accuracy associated with different embossing techniques. Notably, the designed images exhibited near-perfect dimensions, highlighting the fidelity of the initial digital representation. In contrast, images derived from additive manufacturing showed more pronounced distortions, suggesting the presence of inherent challenges in achieving perfect replication through the manufacturing process.

Furthermore, the observed loss of information during resizing and transformation to gray level underscores the need for careful consideration in preprocessing steps to retain dimensional accuracy. The differential correlation coefficients between join, cut, and cut half emphasize the distinct impact of each embossing technique on the overall accuracy of the manufactured components.

As the research progresses, additional image processing and analyses are planned to explore deeper the specific influence of each letter in the images. This granular investigation aims to resolve the shape effects on dimensional accuracy, providing a comprehensive understanding that can inform optimization strategies for additive manufacturing processes. The outcomes of these forthcoming analyses are anticipated to contribute significantly to the refinement and enhancement of dimensional precision in 3D printed components.

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