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Research Article

Design and Analysis of the Housing of Ball Screw's Nut with Generative Design Method

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Abstract:

Product design is highly developed with different CAD software and design tools. It is convenient to generate innovative design models with the development of design tools. One of the creative design tools is generative design, which has become an interesting solution for many industries recently. In this study, it is aimed to generate the optimum design of the housing of a ball screw's nut, which is a part of the z axis of a woodworking cnc router by the Generative Design (GD) tool in terms of strength, weight, manufacturing process, manufacturing cost, and manufacturing duration with the Fused Deposition Modeling (FDM) process on Autodesk Fusion 360 software. The generated model's mechanical properties have been compared to the one produced by a traditional method.

1. Introduction

An AI tool is a software application that uses artificial intelligence algorithms to perform specific tasks, analyze data and solve problems. AI tools can be used in a variety of industries such as finance, education, manufacturing, etc. One of the artificial intelligence tools is generative design (GD), which is one of the upcoming design tools allowing the users set up design goals into the GD tool including parameters such as preserved and obstacle geometries, load and safety requirements, materials, manufacturing methods, cost constraints. The software generate and evaluate tens or hundreds of potential designs according to a set of criteria. Generated models can be manufactured by 2, 2.5, 3 and 5 axes milling process, die casting, additive manufacturing (AM) process or an unrestricted manufacturing process according to the manufacturing method selected. AM is gaining popularity and gradually used in almost every industry. GD solutions are mostly adapted to additive manufacturing method.

GD process was first introduced by Frazer in the 1970s, given that it has been quoted from Krish[1]. In 1989, GD was further studied with the release of parametric CAD tools [2]. In 1997, Bentley and Wakefield [3] have had contribution for development and optimization of the first generation of GD systems based on genetic algorithms. Then, some representative GD methods like cellular automata, L-systems, and swarm systems were developed [4]. GD has gained superior reputation and has been widely studied and used in various fields [5], since the rapid development and popularization of a new period of intelligent automation technology and optimization algorithms.

Adriano Nicola P. et all [6] obtained around AlSi10Mg of 67 g, which is a front tire housing of a trailer to be manufactured by selective laser sintering (SLS) process, since the starting weight of the studied part was around 148 g, it is reached a noticeable mass reduction of 54% with GD method.

Currently, 3D printing integrated with GD has been tested in the fields, such as the redesign of a seatbelt bracket by General Motors and the design of cabin partitions by the European Aeronautics, and Astronautics Corporation for Airbus [7]. From these works, it can be seen that GD can make full use of the design space provided by 3D printing technology, and 3D printing can ensure the manufacturability of generative results.

Bright et al. [8] performed GD of a helicopter frame and gained a derivative frame model with better fracture and deformation resistance. Wu et al. [9] has done optimization of the roller seat of a wind turbine blade turnover machine by GD process. The generative roller seat ensured strength, stiffness and also reduced the mass to 44.4% of the initial model. From the studies and applications of GD, it can be seen that it can automatically generate a large number of design models in a short period, which is convenient for designers as it allows them to choose the most appropriate model. Moreover, models generated by GD have a good mechanical property and light mass. Accordingly, in this article, it is aimed to generate the optimum design of the housing of a ball screw's nut, which is a part of the z axis of a woodworking cnc router by the GD tool, in terms of strength, weight, manufacturing process, manufacturing cost, and manufacturing duration with the Fused Deposition Modeling (FDM) process on Autodesk Fusion 360 software. The mechanical properties and manufacturing cost of the generated model have been compared to the one manufactured by a traditional method.

2. Material and Methods

In this study, structural optimization of the housing of a ball screw's nut, which is a part of z axis of woodworking cnc router was performed using the GD tool. Autodesk Fusion 360 software has been used as a GD design tool. The system components are given in Figure 1.

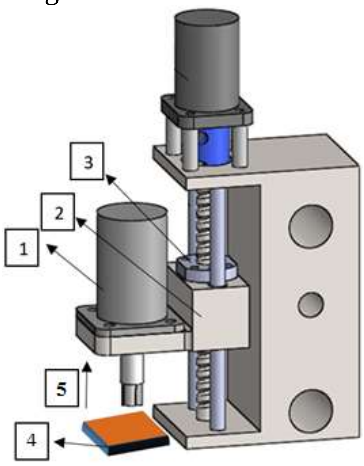


Figure 1*: Components of the system*

Definition of the system components in Figure 1:

1. Motor of the cutting head (Weight of 11 kg)

2. Housing of the ball screw's nut (Weight of 0,541 kg)

3. Ball screw's nut (Weight of 0.5 kg)

4. Workpiece

5. Cutting force of 500 N applied to the workpiece by cutting head (This force is reacted to the housing of the ball screw's nut.)

According to the GD parameters set up, the CAD model, on which GD to be performed is Fusion 360. Its dimensions are given in Figure 2. After designing CAD model of the housing, preserved and obstacle geometries are designed and set on the GD tool (Figure 3). In this study, GD process has been carried out with and without defining starting shape to observe the difference about the generation of GD model and their mechanical properties. Starting shape illustration is given in Figure 4.

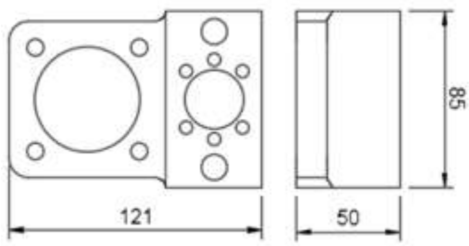


Figure 2: *Dimensions of body of ball screw's nut*

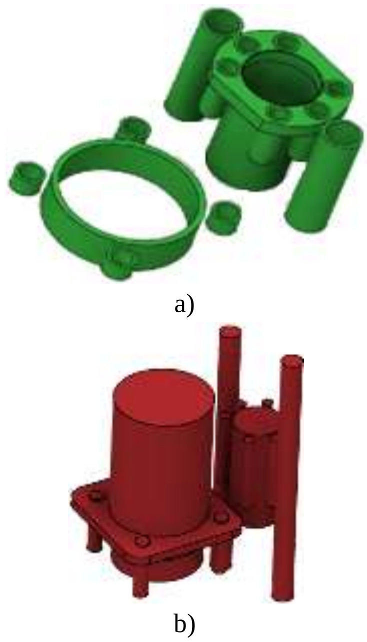


Figure 3: *a) Preserved geometry b) Obstacle Geometry*

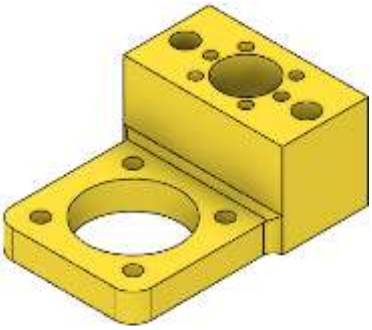
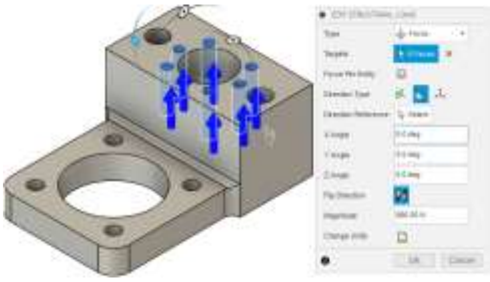
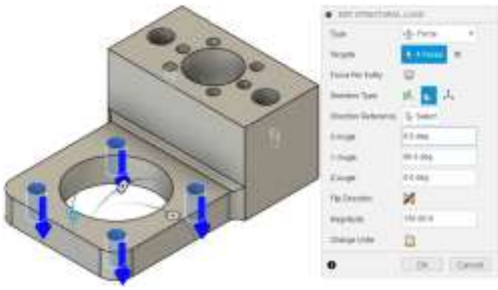


Figure 4: *Defining the starting shape*

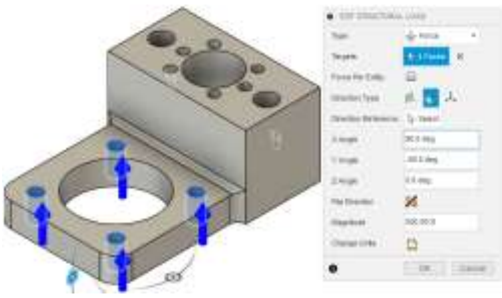
a)



b)



c)



d)

Figure 5: *a) Structural constraint, b) Load applied, c) Load applied, d) Load applied*

In the objective and limits section, 2 of minimum safety factor (SF), lower mass than the original one and 1 mm of maximum displacement in global shape are set up for target GD model.
Load cases and structural constraints are defined with respect to the working configuration of the housing as shown in Figure 5.

The model has been fixed in Figure 5a, 980 N and 150 N of loads, which are applied to the housing during its movement upward have been set up as structural loads in Figure 5b and Figure 5c respectively. 500 N of load in Figure 5d, which is the cutting force acts to the workpiece during cutting process and reacts to the housing has been set up.

After setting up the load and constraint cases, manufacturing process and material were set up. Manufacturing process considered for the realization of the component is fused deposition modelling (FDM). Therefore, additive manufacturing has been set up as a manufacturing process and unrestricted manufacturing method also has been set up to see the other possible design models.

The housing material selected for FDM process is PA 603-CF. Its mechanical properties is given in Table 1.

Table 1: *Mechanical properties of PA 603-CF.*

Mechanical Properties	**Value**
Density	1.1 g/cm^3
Yield Strength	63 MPa
Tensile Strength	75 MPa
Young Modulus	4.7 GPa
Poisson Ratio	0.40

PA 603-CF has 1.1 g/cm^3 of density, 63 MPa of yield strength, 75 MPa of tensile strength, 4.7 GPa of young modulus, 0.4 of possion ratio.

3. Results and Discussions

After all parameters have been set up, GD models have been generated for starting shape and without starting shape definition with manufacturing processes of AM and unrestricted. Totally 4 different design models were generated by the GD tool.

GD design solutions and the mechanical properties of them obtained by the Fusion 360 GD Tool are given in Table 2. As it is seen from design models in Table 2, there is not much design difference among starting shape and without starting shape solutions. Solution 3 designed for the additive manufacturing process with starting shape has been selected as the best design solution where its max von-Mises stress is the lowest, minimum safety factor is the highest compared to the other solutions. Its mass and maximum displacement are also satisfying. Mechanical properties of the part designed for solution 3 has been checked on Ansys software performing static analysis. Structural constraints with applied loads are given in Figure 6a. Maximum displacement and maximum von-Misses stress are given in Figure 6b and Figure 6c respectively.

According to the static analysis results on Ansys maximum displacement is 0.459 mm and maximum von-Misses stress is 17.374 MPa. Minimum safety factor is 3.63.

Maximum displacement analysis result given by the Fusion 360 GD Tool is 48% lower than the one given by Ansys. Maximum von-Misses stress analysis result given by the Fusion 360 GD Tool is 16% higher than the one given by Ansys. Minimum safety factor given by the Fusion 360 GD Tool is 15% lower than the one given by Ansys

Table 2: *Mechanical properties of the models generated by the GD tool.*

Mechanical Properties	Without Starting Shape		With Starting Shape	
	Additive Manufacturing	Unrestricted	Additive Manufacturing	Unrestricted
	Solution 1	Solution 2	Solution 3	Solution 4
				
Max von-Mises Stress	22.222 MPa	20.591 MPa	20.192 MPa	21.109 MPa
Min Factor of Safety Limit	2.835	3.060	3.120	2.984
Max Displacement	0.277 mm	0.226 mm	0.238 mm	0.233 mm
Mass	92 g	80 g	96 g	78 g

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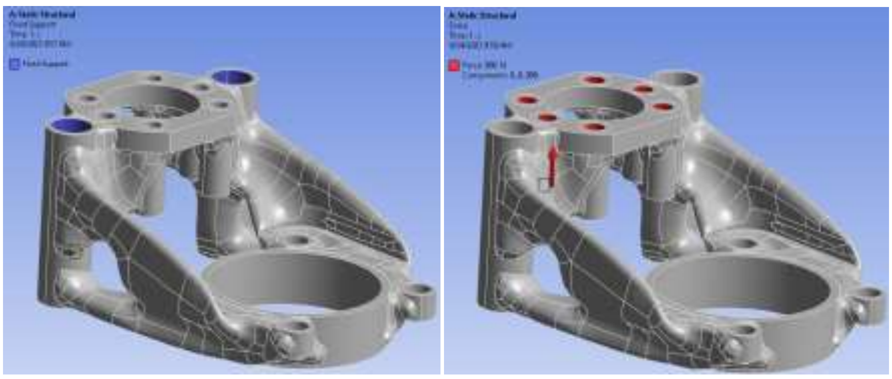
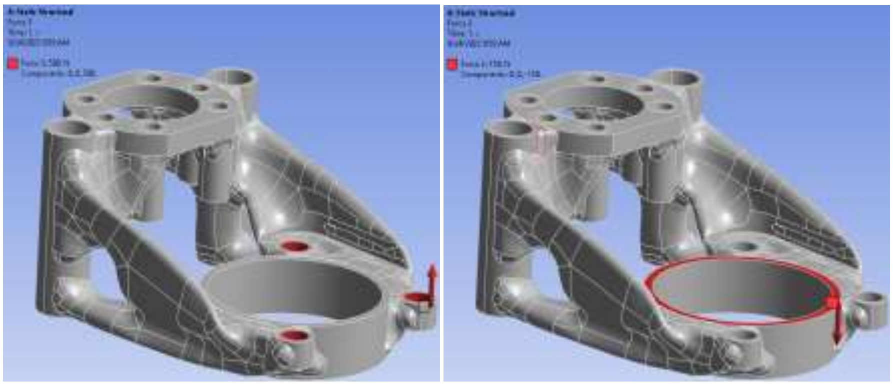
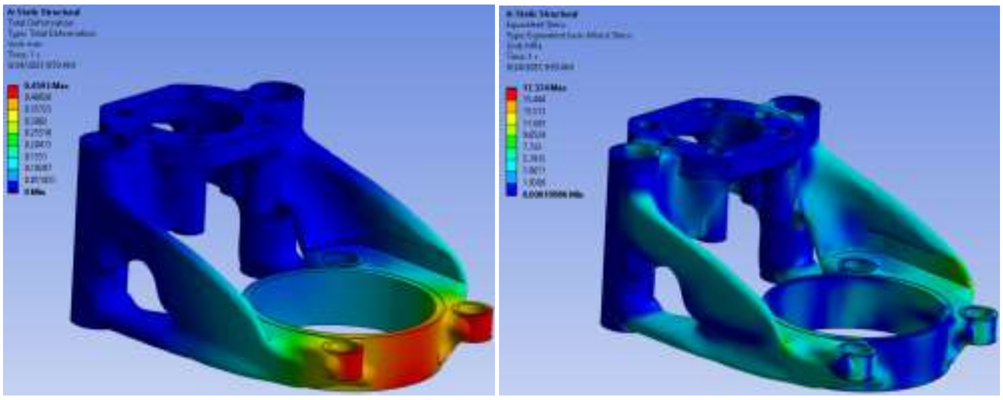




a)



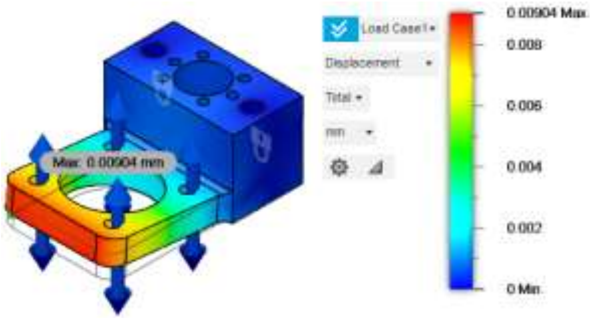
b) c)

Figure 6*: a) Structural constraints b) Max displacement c) Max von Misses Stress analysis*

Figure 7: *Local defect occurred on a part generated by the GD tool.*

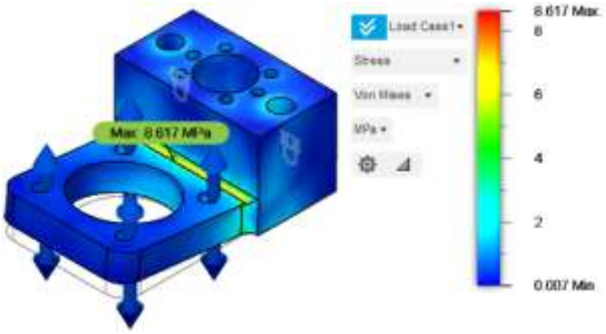
In solution 1, local design defect occurred on the model, which can be edited manually. It is shown in Figure 7.

Structural analysis of the housing was performed to be able to compare the GD model analysis results with the one of the housing model without optimization. Analysis results are illustrated in Figure 8. The material used as a housing without optimization is 3003-H16. Its mechanical properties are given in Table 3.



a)

b)



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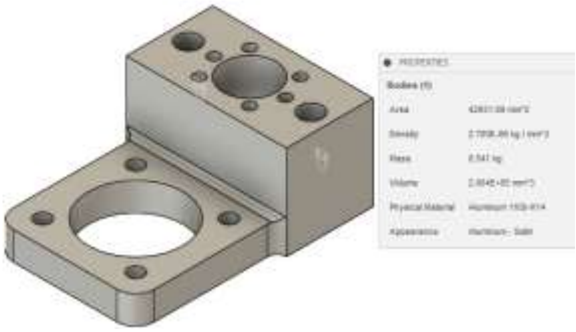


d)

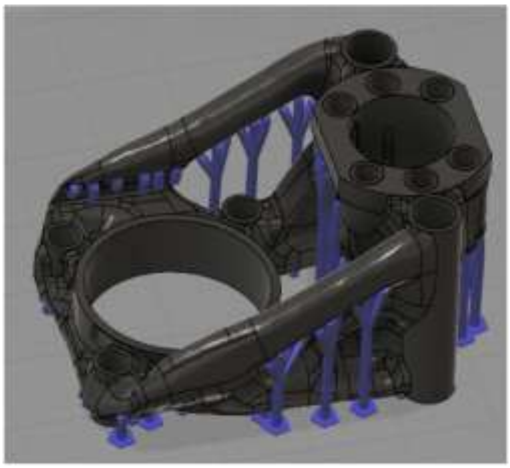
Figure 8: *a) Max displacement b) Minimum safety factor c) Max von-Misses Stress analysis results and d) 3003-H16 Material properties.*

Table 3: *Mechanical properties of 3003-H16.*

Mechanical Properties	**Value**
Density	2.7 g/cm^3
Yield Strength	96.53 MPa
Tensile Strength	110.3 MPa
Young Modulus	69.64 GPa
Poisson Ratio	0.33

Additive manufacturing simulation has been created on the Fusion 360 software so that the design obtained with the GD tool for the solution 3 can be printed on a 3D printer. According to the simulation output, the printing time (6 hours, 4 minutes, 18 seconds), the amount of filament used (16.7 m), the number of printing layers (333), time and material consumption rates are given in print statistics in Figure 9a with FDM simulation model in Figure 9b. Analysis results and manufacturing cost of the housing of ball screw's nut designed by the GD tool is compared to the one without optimization given in Table 4. The housing with 3003-H16 material produced by cnc milling process has 8.6 MPa of maximum stress, 11.2 of minimum safety factor, 0.00904 mm of maximum displacement, weight of 541 g, 5 hours 40 minutes of manufacturing duration.

a)



b)

F***igure 9: a)*** *FDM simulation statistics,* ***b)*** *FDM simulation model.*

Manufacturing quotation for the housing was asked to three companies by sending 3D CAD file. The approximate manufacturing cost is 86 €. The housing with PA 603- CF material designed by the GD tool and to be manufactured by FDM process has 20.2 MPa, 3.12 of minimum safety factor, 0.238 mm of maximum displacement, weight of 96 g, 6 hours 4 minutes of manufacturing duration. Manufacturing quotation for the housing was asked to three companies by sending 3D CAD file. The approximate manufacturing cost is 13.50 €.

4. Conclusions

According to results, maximum displacement analysis result given by the Fusion 360 GD Tool is 48% lower than the one given by Ansys. Maximum von-Misses stress analysis result given by the Fusion 360 GD Tool is 16% higher than the one given by Ansys.

Table 4: *Comparison of cnc milling of 3003-H16 material with FDM process of PA603-CF material designed by GD.*

Material	3003-H16	PA 603-CF
Manufacturing Method	Cnc Milling	FDM
Maximum Stress (von-Misses)	8.6 MPa	20.2 MPa
Minimum Safety Factor	11.2	3.12
Maximum Displacement	0.00904 mm	0.238 mm
Weight	541 g	96 g
Manufacturing Duration	5 hours, 40 min	6 hours, 4 min
Manufacturing Cost	86 €	13.50 €

Minimum safety factor given by the Fusion 360 GD Tool is 15% lower than the one given by Ansys. Although there are differences in static analysis results in between the Fusion 360 GD Tool and Ansys, mechanical properties of PA 603-CF material designed with the GD tool is

satisfactory compared to that of 3003-H16 material designed without optimization.

PA 603-CF material weight is 82.3% less than 3003-H16 material weight. Manufacturing time is close to each other in both manufacturing methods. PA 603-CF material manufacturing cost with 3D printer is 84.3% less than the manufacturing cost of 3003-H16 material with cnc milling.

Lighter design with the GD tool and ease of 3D printing of complex shapes are of great importance in reducing costs. Models generated by the GD tool is easy to manufacture and aesthetically pleasing.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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