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EXPERIMENTAL INVESTIGATION ON MECHANICAL BEHAVIOUR OF 3D-PRINTED PART FOR BRAKE PEDAL APPLICATIONS

Industry 4.0, also known as digital manufacturing, is a new revolution in the manufacturing industry that employs tools such as reverse engineering, additive manufacturing, and design optimization techniques such as generative design. This most recent technological advancement can be used to enhance existing designs and products for performance and efficiency with the power of computation. Reverse engineering is a technique or approach in which one tries to understand, using deductive reasoning and little to no understanding of how something works, such as how a previously created device, process, system, or piece of software performs a function. It can be used to collect visual data to recreate models of desired objects using 3D scanning methods. This study used these various advances to optimise a 3D-printed brake pedal. It entailed reverse engineering the brake pedal using 3D scanning, followed by optimising the brake pedal design for mass and shape using generative design. The 3D printing process was optimised through a parametric study of the process parameters which include Type of Material, Layer Thickness, Infill Density, Infill Pattern, and Raster Angle. The result of experiment is revealed that material type (33.63%), Infill density (20.48%) and Layer Thickness (20.41%) significantly influencing the tensile strength of the 3D printed specimen. It also showed that Infill density (31.06%), material type (21.54%) and Layer Thickness (20.41%) are the most influencing process parameters of Impact strength. The findings were unified and used to create a Lightweight Polymer Brake Pedal optimised for High-Performance Applications in Electric Vehicles.

Keywords: Digital manufacturing; 3D printing; Reverse engineering; Generative Design; Brake pedal

1. Introduction

The introduction of advanced technologies in recent years has transformed many industries, including manufacturing. Digital manufacturing has transformed the traditional manufacturing landscape, providing unprecedented opportunities for efficiency, customization, and sustainability. To reshape the entire manufacturing process, this approach combines cutting-edge technologies such as additive manufacturing, robotics, artificial intelligence, and data analytics [1-2]. Additive manufacturing, also known as 3D printing, is at the heart of the digital manufacturing approach. This technology allows for the layering of complex objects using digital designs and a variety of materials. Additive manufacturing eliminates the need for traditional subtractive methods, resulting in less waste and the ability to produce highly customised products. By allowing the direct conversion of digital designs into physical objects, additive manufacturing simplifies the manufacturing process and allows for rapid prototyping, on-demand manufacturing, and decentralised production [3-5].

Algorithms for artificial intelligence (AI) and machine learning (ML) are critical in the digital manufacturing approach. AI can optimise operations, predict maintenance requirements, and identify potential bottlenecks by analysing massive amounts of data collected from sensors, machines, and production lines. Real-time detection of patterns and anomalies by ML algorithms enables proactive decision-making and continuous process improvement. AI-powered systems can also automate quality control processes, reducing defects and waste while ensuring product consistency [6-7]. Reverse engineering is used extensively in manufacturing and product development. Companies can learn a lot about a competitor's design and manufacturing techniques by reverse engineering them. This knowledge can help them improve their own products, identify cost-cutting opportunities, and investigate alternative production methods [8-9].

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Generative design algorithms can generate designs that balance various factors such as weight reduction, structural integrity, material usage, and manufacturing constraints by defining a set of performance criteria and constraints. This holistic optimisation approach allows for the development of designs that are not only efficient but also highly functional and innovative. It also encourages the use of unconventional and organic shapes that can be difficult to imagine using traditional design methods [10-12].

Traditionally, brake pedals have been predominantly manufactured using metal materials. However, recent advancements in material science have presented the opportunity to employ lightweight polymers even in high-performance settings. Recognizing this potential, the paper aims to delve into the realm of research that is needed to fully utilise these polymers within structural systems and, more specifically, brake pedals. By exploring the integration of high-performance polymers in the design and development of brake pedals, this work seeks to address the limitations of conventional manufacturing methods. Leveraging the advantages of digital production technology, such as 3D printing, will play a significant role in enhancing the overall design and manufacturing process. This amalgamation of high-performance polymers and digital manufacturing has the potential to revolutionise brake pedal production. However, despite the promising prospects, the research connecting the three distinct fields of high-performance polymers, digital manufacturing, and 3D printing process optimization remains scarce. Therefore, this paper aims to bridge this gap by conducting comprehensive research and development. The objective is to design and develop brake pedals that are not only lightweight but also maintain the required strength, toughness, and durability standards.

2. Literature survey

A few research articles published on topics of Digital Manufacturing and 3D printing process parameter optimisation are presented in this section.

Benamira et al. [13] investigate the primary and combined effects of layer thickness and printing orientation on mechanical and failure properties for two infill densities (100% and 40%). Tensile tests on 3D-printed PLA samples were used to achieve this. Based on the experimental results, an ANOVA analysis was performed to investigate these effects on the mechanical properties. Barberi et al. [14] discussed in their findings that both Topology Optimization (TO) and, in particular, Generative Design (GD) tools can be used effectively early in an Additive Manufacturing (AM) – focused design process to redesign components and make them stronger and lighter. Tuazon et al. [15] provide a brief overview of the various 3D printing techniques and materials currently employed in the automotive sector. For many applications, additive manufacturing has advanced significantly, particularly in the automotive sector. Its benefits and drawbacks for the sector, as well as new material developments for 3D printing applications in the automotive industry, are discussed. The outlook for the future is provided, and the issues that must be resolved are discussed. Muminovic et al. [16] conduct an experimental investigation into the effects of the most important manufacturing parameter (infill percentage) on the types of failure and service life of nylon gears produced using additive manufacturing. The experimental tests were conducted using a custom-made gear testing apparatus. The infill volume of the samples was tested at 20, 40, 60, 80, and 100%. All samples had the same infill types, shell thicknesses, and production rates. The testing of the gears' service life allowed for the characterization of various failure types.

Chen et al. [17] use topology optimization to create and 3D-print a lightweight aerospace bracket with fatigue performance. Before manufacturing, CAD software provided a rebuilt model that accounted for assembly requirements to improve the structure's fatigue performance. Raorane et al. [18] use reverse engineering to create a CAD model of an old, unused bicycle before applying specific conditions to the same model of bicycle to compare how they behaved under different conditions. The project's goal was to learn about reverse engineering, CAD modelling, and FEA before applying them to a bicycle in order to improve its efficiency. Ferretti et al. [19] studied the rapid advancement of technology and the extensive research focused on the effectiveness and processes of 3D printing. The singularities that occur throughout the majority of Fused Deposition Modeling (FDM) techniques have proven difficult to forecast in studies in the area; as a result, different individual descriptions of the parameters have been made, but their relationships have not yet been examined. The suggested study identifies the primary flaws brought on by a number of printing settings that could alter layer slicing and thus affect the defect rate. The chosen optimization method is then supplied with proof of its applicability, indicating that a quality improvement would be possible. The outcomes would contribute to the FDM process becoming a trustworthy method that might be applied to industrial manufacturing in addition to prototyping.

Sargini et al. [20] discussed how using the current additive manufacturing technique used, its applications, resulting in lighter car brake pedals. Patil et al. [21] aimed to use topology optimisation, along with theoretical, computational, experimental, and analytical approaches, to propose an ideal brake pedal design for the three-wheeler segment. The material used for an existing brake pedal remains unchanged because this study focuses on weight reduction without material substitution. A digital representation of an actual brake pedal was created using reverse engineering and computer-aided design (CAD) software. Altair Opti-Struct software will be used for finite element analysis and topology optimisation under the conditions of linear static stress analysis and modal analysis. Finally, without compromising performance requirements, a new, lighter version of the current brake pedal will be suggested. Nitin et al. [22] attempt to use reverse engineering to pinpoint the problem with the brake rod on the 150cc Bajaj Pulsar motorcycle. The 3D model of the brake rod was created using FEA techniques and the software programmes Unigraphics NX 11.0 and Hypermesh 14.0. The results of tests on both existing and modified brake rods were obtained under a variety of loads ranging from the lightest to the heaviest. This result considers a number of factors, including stress, displacement, and safety factor. The current brake rod has been adjusted in accordance with the findings.

The review of the literature reveals that there has been significant research in the various respective fields of Reverse Engineering, Material and Manufacturing optimization in brake pedal applications. However, there is a lack of research where the various fields are consolidated together for a single application. Furthermore, there are no modern result analysis tools or comparative studies of many parameters. This paper aims to address the lack of research in the integration of high-performance polymers, digital manufacturing, and 3D printing process optimization within the structural systems of vehicles, focusing on the design and development of brake pedals. Through extensive research and implementation, this work strives to unlock the full potential of these materials and techniques, ultimately leading to the creation of lightweight, high-performance brake pedals for a more efficient and sustainable automotive industry.

3. Experimentation

Understanding the design and functionality of existing components requires reverse engineering, and 3D scanning has emerged as a valuable tool for this process. When it comes to brake pedals, reverse engineering via 3D scanning provides numerous advantages, including accurate reproduction, analysis, and customization. The process starts with 3D scanning an existing brake pedal with specialised scanning equipment. The scanner records the geometry and intricate details of the pedal, resulting in an extremely accurate digital model. This digital representation provides a thorough understanding of the shape, contours, and dimensions of the pedal. The generative design algorithm identifies the most promising designs that meet the specified criteria by analysing and synthesising the results. Designers and engineers can then use these designs as inspiration and starting points for further refinement.The generative design of brake pedals takes into account not only structural and performance aspects, but also factors such as manufacturability and integration with other vehicle components. By optimising the geometry, material distribution, and overall structure of the pedal, generative design can improve functionality, response, and durability while potentially reducing weight and material usage.

The 3D printing process provides incredible manufacturing versatility, allowing for the creation of complex geometries and customised designs. To achieve optimal print quality and mechanical properties, however, various process parameters must be carefully considered. A parametric analysis of these parameters is critical for understanding their impact on print outcomes and optimising the 3D printing process. A parametric study entails systematically varying and analysing individual process parameters in order to determine their impact on final print quality, structural integrity, and overall performance. Layer height, print speed, nozzle temperature, infill density, and cooling settings are all commonly investigated parameters. A parametric study aids in the establishment of guidelines and recommendations for achieving the desired print outcomes by systematically exploring and analysing the effects of these and other process parameters. It delves into the interaction of parameters, their trade-offs, and the impact they have on the overall 3D printing process.

The Taguchi method, developed by Dr Genichi Taguchi, is a statistical method for improving 3D Printing process parameters in order to improve product performance and quality. The Taguchi method's three main components are parameter design, experimentation, and optimization. During the parameter design phase, engineers identify the controllable (process parameters) and uncontrollable (noise factors) factors that may affect the printing process. They then select the settings or levels for each factor to be examined. The following step is a series of experiments with a fractional factorial design, which allows engineers to explore a large parameter space with a small number of experiments. The design matrix distributes the various parameter settings and noise levels evenly. During the experimentation phase, engineers measure the response variables for each experiment, such as surface roughness, tensile strength, or dimensional accuracy. Statistical techniques such as analysis of variance (ANOVA) are then used to identify the significant factors and their ideal settings from the collected data.

The selected brake pedal is a Toyota Etios Brake pedal which will be used as a base for the generative design of the new brake pedal. This pedal will be reverse-engineered using a 3D scanner. The brake pedal is 3D scanned using the Formbuilder Blue laser scanner with an accuracy of 20 microns which creates a point data cloud of the brake pedal. The point cloud is used to make a CAD model of the brake pedal using inbuilt software (as shown in Fig. 1). The scanned CAD model is ready for further processing.

Fig. 1. 3D scanned model of the brake pedal

3.1. Process parameter selection:

The process parameters and their levels selected after referring to prior literature are shown in TABLE 1.

TABLE 1

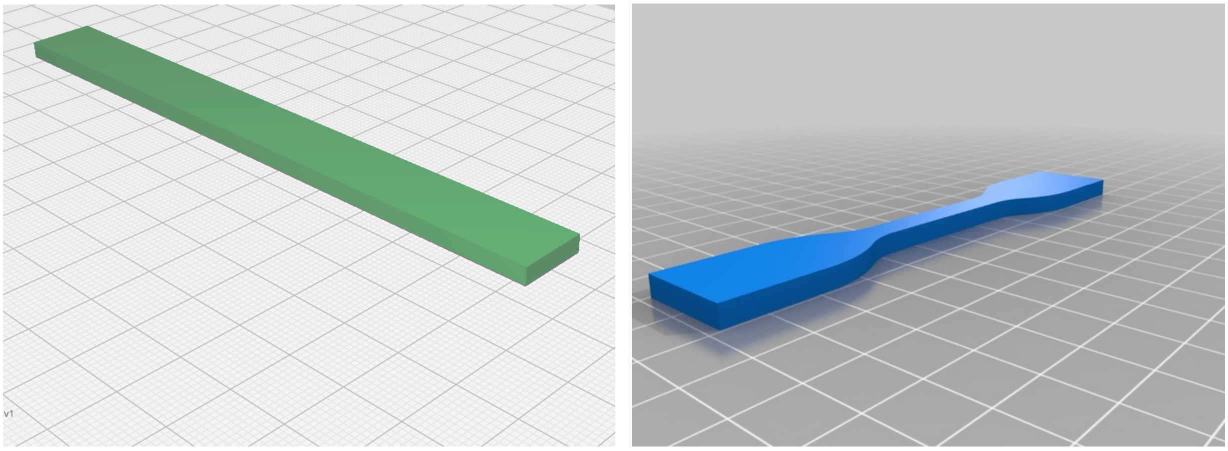
Process parameters with the 3 different levels

Levels	Material (a)	Layer Thickness, (mm) (b)	Raster Angle, (degrees) (c)	Infill Pattern (d)	Infill Density, (%) (e)
1	PETG	0.1	0	Cubic	60
2	Nylon	0.2	45	Gyroid	80
3	Polycarbonate	0.3	90	Octet	100

The 3D models of the test samples are prepared using Fusion 360 software according to the ASTM D638-14 and D256 standards for the testing for Tensile Strength, Impact Strength as shown in Fig. 2.

The CAD models are then uploaded to Ultimaker Cura software. This software will be used to put in the required parameters according to the Taguchi arrays (as shown in TABLE 2) and then slice the models (as shown in Fig. 3). After slicing is complete, the model can then be sent for 3D printing in the Voron 2.4 3D printer which is an FDM type 3D printer

Once the 3D printing process is complete, the part is left to cool for 15 minutes and then post-processed by removing the supports and clearing the surface. The 3D-printed test samples are ready for testing (as shown in Figs. 4-5).



a. Impact test sample model

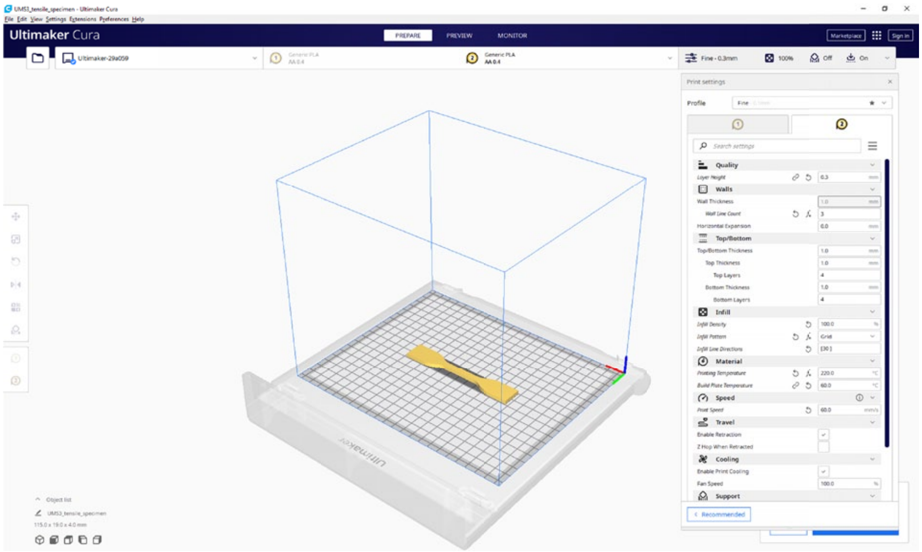
b. Tensile test sample model

Fig. 2. a. ASTM D256, b. ASTM D638-14

TABLE 2

Input parameters for the experimentation

Test No.	a	b	c	d	e	Material (a)	Layer Thickness, (mm) (b)	Raster Angle, (degrees) (c)	Infill Pattern (d)	Infill Density, (%) (e)
1	1	1	1	1	1	PETG	0.1	0	CUBIC	60
2	1	2	2	2	2	PETG	0.2	45	GYROID	80
3	1	3	3	3	3	PETG	0.3	90	OCTET	100
4	2	1	1	2	2	PC	0.1	0	GYROID	80
5	2	2	2	3	3	PC	0.2	45	OCTET	100
6	2	3	3	1	1	PC	0.3	90	CUBIC	60
7	3	1	2	1	3	Nylon	0.1	45	CUBIC	100
8	3	2	1	2	1	Nylon	0.2	0	GYROID	60
9	3	3	3	3	2	Nylon	0.3	90	OCTET	80
10	1	1	3	3	2	PETG	0.1	90	OCTET	80
11	1	2	1	1	3	PETG	0.2	0	CUBIC	100
12	1	3	2	2	1	PETG	0.3	45	GYROID	60
13	2	1	2	3	1	PC	0.1	45	OCTET	60
14	2	2	3	1	2	PC	0.2	90	CUBIC	80
15	2	3	1	2	3	PC	0.3	0	GYROID	100
16	3	1	3	2	3	Nylon	0.1	90	GYROID	100
17	3	2	1	3	1	Nylon	0.2	0	OCTET	60
18	3	3	2	1	2	Nylon	0.3	45	CUBIC	80



Fine - 0.3mm 100% Off On

Profile: Fine

Quality
Layer Height: 0.3 mm

Walls
Wall Thickness: 1.0 mm
Wall Line Count: 3
Horizontal Expansion: 0.0 mm

Top/Bottom
Top/Bottom Thickness: 1.0 mm
Top Thickness: 1.0 mm
Top Layers: 4
Bottom Thickness: 1.0 mm
Bottom Layers: 4

Infill
Infill Density: 100.0 %
Infill Pattern: Grid
Infill Line Directions: [30]

Material
Printing Temperature: 220.0 °C
Build Plate Temperature: 60.0 °C

Speed
Print Speed: 60.0 mm/s

Travel
Enable Retraction: ☑
Z Hop When Retracted: ☐

Cooling
Enable Print Cooling: ☑
Fan Speed: 100.0 %

Support

115.0 x 19.0 x 4.0 mm

Fig. 3. Model in Ultimaker Cura software

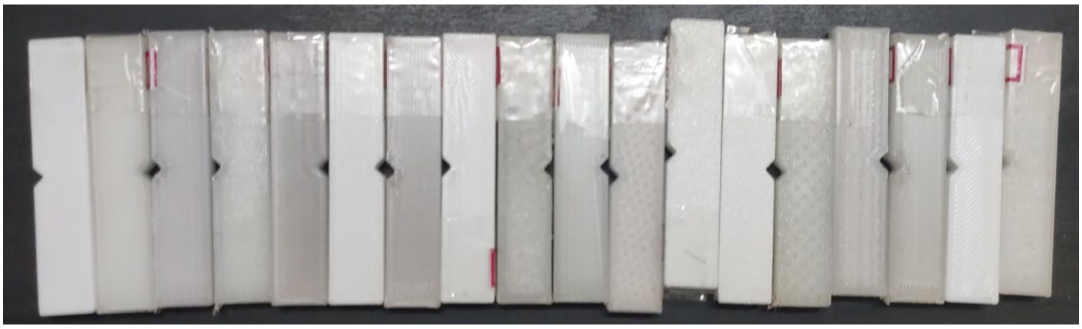


Fig. 4. (ASTM D256) 18 3D printed Izod Impact test 3D printed specimen

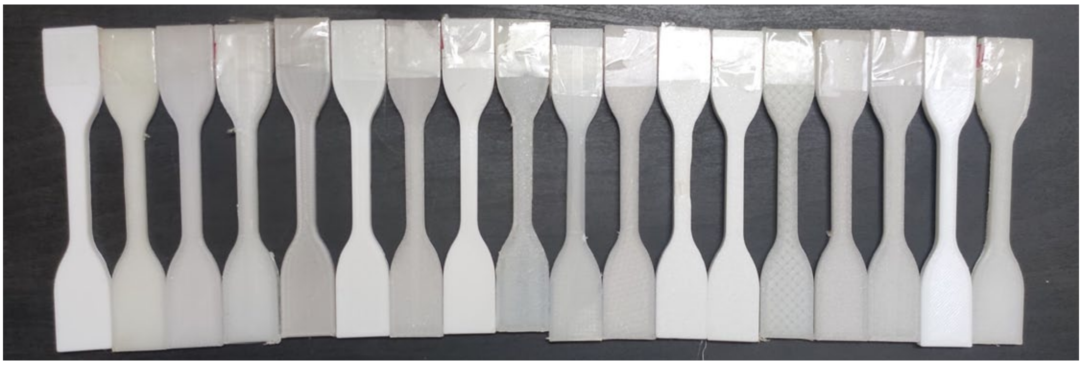


Fig. 5. (ASTM D638-14) 18 3D printed Tensile Strength test specimen

The tests are done according to the ASTM standards specified for each test. The Tensile testing is done in accordance with ASTM D638-14 standards and the test has been set up accordingly (as shown in Fig. 12). The purpose of this test is to determine the tensile strength of the samples and material in relation to their respective parameters. The tested samples are shown in Fig. 6.

The Tensile and Flexural tests are done on Bluestar UTES 40 HGFL with a capacity of 40 kN. The Impact testing is done in accordance with ASTM D256 standards, and the test has been set up accordingly

The purpose of this test is to determine the impact strength of the samples and material in relation to their respective parameters. The tested samples are shown in Fig. 7.

3.2. Generative Design of Brake Pedal

The CAD model of the brake pedal was uploaded to Fusion 360 software(as shown in Fig. 8 and Fig. 9), where it underwent further processing. The model was smoothened to provide a refined starting shape for the generative design process. Two types

Fig. 6. Post-test Tensile samples

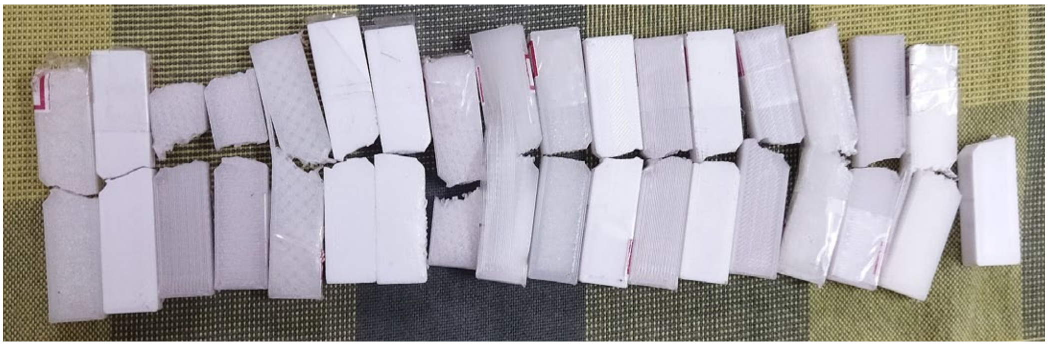


Fig. 7. Post-test Impact samples

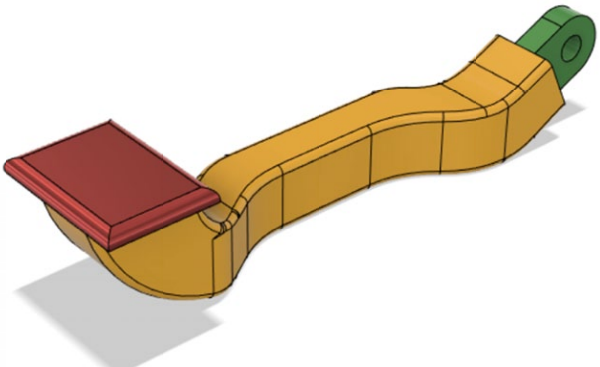


Fig. 8 Smoothened model of the 3D scanned brake pedal model

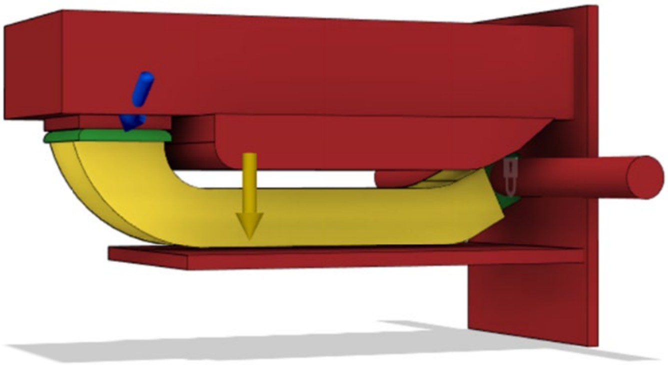


Fig. 9. CAD model with preserve geometry, obstacle geometry and starting shape

of geometries were created: preserve geometry, which represents the constant elements of the design, and obstacle geometry, which represents the empty spaces where no material is generated. These geometries, along with the starting shape, were applied in the generative design workspace.

Structural constraints and loads were then applied to define the design conditions. A load of 800 N was calculated, and the base plate and holder hole were selected as fixed constraints. The manufacturing method was specified as additive manufacturing, and the material chosen was Nylon. A pre-check of the model was performed, followed by using the previewer to evaluate the potential design outcomes.

The generative design process was initiated (as shown in Fig. 10), generating multiple design solutions that could be further analysed to identify the most optimal one. Through a thorough evaluation of the results, a brake pedal design was selected as the final optimised design. Post-processing was performed to refine and obtain the final optimised brake pedal design. Among the numerous possibilities, one solution was chosen based on the evaluation of different factors. This iterative approach, incorporates generative design within the Fusion 360 software, allowing for the exploration of various design alternatives and the identification of an optimised brake pedal design that fulfils the defined constraints and requirements.

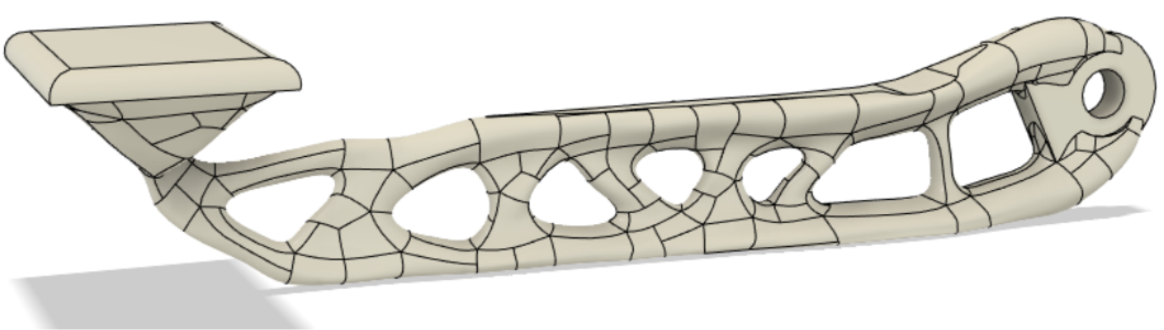


Fig. 10. CAD model of brake pedal made using Generative Design

4. Results and discussion

Using the DOE analysis tools like Minitab and Spreadsheets, the analysis of the results is done and can be observed from the following tables.

The aim of this work was to investigate the performance of a 3D printed brake pedal using a Digital manufacturing approach which includes Reverse Engineering, Generative Design, and 3D printing process optimisation. The investigation focused on evaluating the performance of a 3D printed brake pedal through comprehensive analysis of its mechanical characteristics, including tensile strength, flexural strength, and impact strength. A Design of Experiments (DOE) approach was employed, along with ASTM standard testing methods, to examine the effects of various specimen parameters on the brake pedal's mechanical properties. These parameters included infill pattern, raster angle, layer thickness, material, and infill density. The results were used to optimise the shape of the brake pedal using Generative design and Reverse Engineering.

The results obtained from the experimental tests (shown in TABLE 3) revealed significant insights into the influence of different factors on the mechanical performance of the 3D printed brake pedal. Among these factors, infill density consistently emerged as the highest contributing factor in all three tests, highlighting its crucial role in determining the overall strength and performance of the brake pedal. The filling of voids between layers, facilitated by the infill density, played a pivotal role in enhancing the mechanical properties.

Moreover, material selection demonstrated substantial influence on the brake pedal's mechanical characteristics, particularly in the tensile test where it had the highest contribution. The choice of high-performance polymers, such as Polycarbonate, exhibited notable effects on the tensile strength and overall performance. Additionally, the results indicated that both raster angle and layer thickness significantly influenced the tensile strength, suggesting that careful consideration of these parameters is necessary for optimising the mechanical properties of the brake pedal.

TABLE 3

Parametric study test results

Test No.	Factors					Responses	
	Material (a)	**Layer Thickness, (mm) (b)**	**Raster Angle, (degrees) (c)**	**Infill Pattern (d)**	**Infill Density, (%) (e)**	**Tensile (MPa)**	**Impact (kJ/m^2)**
1	PETG	0.1	0	CUBIC	60	22.5	4.2
2	PETG	0.2	45	GYROID	80	24.77	4.4
3	PETG	0.3	90	OCTET	100	31.49	5.3
4	PC	0.1	0	GYROID	80	25.33	4.1
5	PC	0.2	45	OCTET	100	47.69	10.2
6	PC	0.3	90	CUBIC	60	26.11	5.1
7	Nylon	0.1	45	CUBIC	100	40.97	9.8
8	Nylon	0.2	0	GYROID	60	37.5	7
9	Nylon	0.3	90	OCTET	80	34.9	5.5
10	PETG	0.1	90	OCTET	80	20.34	3.9
11	PETG	0.2	0	CUBIC	100	38	9.2
12	PETG	0.3	45	GYROID	60	20.26	3.6
13	PC	0.1	45	OCTET	60	33.57	5.5
14	PC	0.2	90	CUBIC	80	30.49	5.3
15	PC	0.3	0	GYROID	100	40.09	8
16	Nylon	0.1	90	GYROID	100	28.38	5.5
17	Nylon	0.2	0	OCTET	60	46.9	9.5
18	Nylon	0.3	45	CUBIC	80	37.99	8

4.1. Tensile strength

From the results obtained (as shown in the pie chart Fig. 11 and TABLE 4), it can be concluded that material has the highest contribution to the tensile test, followed by the Infill Density and Layer Thickness. The analysis revealed that the Material and Infill Density significantly influenced the tensile properties of the specimen. Additionally, the Raster Angle also exhibited a significantly higher level of contribution to the tensile strength, as observed through ANOVA analysis. The factors considered in the tensile test had an impact of 96.526%, while the remaining 3.474% was attributed to unknown factors.

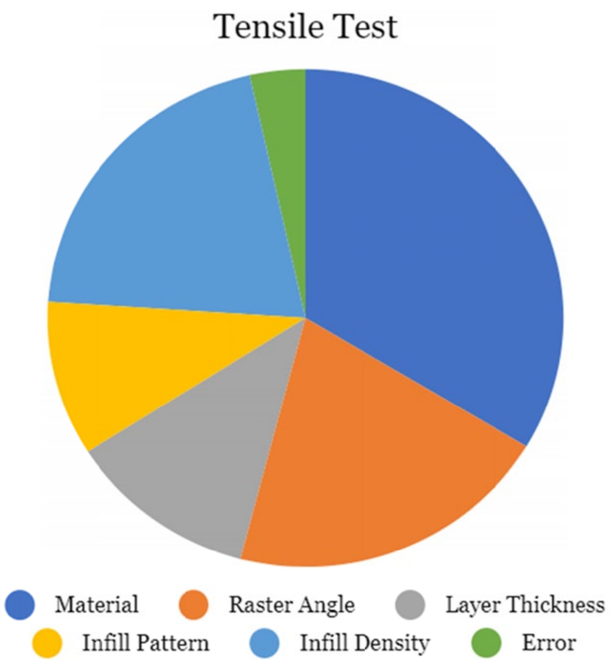


Fig. 11. Tensile Strength

4.2. Impact strength

In the impact test, material and infill density once again emerged as the highest contributing factor (as shown in the Fig. 12 and TABLE 5), indicating its primary influence on the mechanical properties of the specimen. The analysis showed that infill density contributed approximately 24.16% to the impact strength, while the material contributed 25.39%. The factors considered in the impact test had a total contribution of 92.6%, with an error percentage of about 7.3%. The material used was optimized to Nylon during the experimentation.

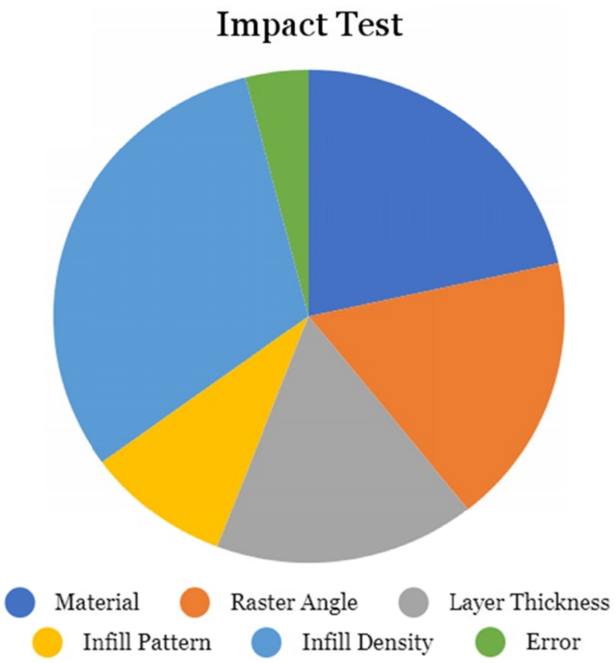


Fig. 12. Impact Strength

TABLE 4

ANOVA for Tensile Test

Source	**DF**	**Adj SS**	**Variance**	**F-Value**	**Contribution**
Material	2	414.11	207.05	19.365	*33.636*
Layer Thickness	2	251.39	125.69	11.756	*20.419*
Raster Angle	2	146.74	73.37	6.862	*11.919*
Infill Pattern	2	123.92	61.96	5.795	*10.066*
Infill Density	2	252.21	126.1	11.794	*20.486*
Error		3.48	21.38		*3.474*
Total	17	1188.37			96.526

TABLE 5

ANOVA for Impact Test

Source	**DF**	**Adj SS**	**Variance**	**F-Value**	**Contribution**
Material	2	18.014	9.0072	10.775	*21.543*
Layer Thickness	2	14.834	7.4172	8.873	*17.740*
Raster Angle	2	13.834	6.9172	8.274	*16.544*
Infill Pattern	2	7.621	3.8105	4.558	*9.114*
Infill Density	2	25.974	12.9872	15.535	*31.061*
Error		3.48	1.67194		*3.999*
Total	17	80.277			96.001

4.3. Influence of various parameters

The findings of this study emphasise the critical role of infill density, material selection, raster angle, and layer thickness in the mechanical performance of 3D printed brake pedals. These factors interact synergistically to determine the overall strength, stiffness, and impact resistance of the pedal. By optimising these parameters, it is possible to enhance the mechanical properties and safety of 3D printed brake pedals.

The results obtained in this study provide valuable insights into the influence of various parameters on the mechanical characteristics of 3D-printed brake pedals. The findings highlight (as shown in TABLE 6) the significant contributions of infill density, infill pattern, and material selection to the tensile, and impact strength of the brake pedal.

Material and Infill density showed consistent influence across all two tests, playing a critical role in determining the mechanical properties. By varying the infill density within the range of 60 to 100, it was possible to observe its impact on tensile, and impact strength. The ability of infill density to fill the voids between layers, along with its density characteristics, contributed significantly to the overall mechanical performance of the brake pedal.

Raster Angle also demonstrated a notable influence on the tensile strength, with different patterns leading to variations in the structural integrity of the printed brake pedal. The range of Raster Angles, including starting from 0°, 45°, 90° allows for a comprehensive analysis of their impact on mechanical properties.

Additionally, Infill Pattern had a significant influence on the impact strength, withcubic, gyroid and octet configurations. These results highlight the importance of selecting suitable materials with desired mechanical properties for 3D-printed brake pedals.

Minimum value of layer thickness is lead to better tensile strength. This is might be low value of layer thickness is lead to better bonding properties and axial loading capacity. Extrusion speed is used to spread the material with high and solidification. The result of experiment is indicated that higher tensile strength with low value of raster angle. High value of raster angle may lead to defect in the material deposition and voids which will affect the printed specimen strength and quality. Infill pattern is used to enhance the stability during impact resistance. The strength of the printed specimen depended on the infill pattern is selected. GYROID pattern is the most useful and provides and formal structure.

4.4. Generative design results

The generative design approach, coupled with reverse engineering, proved instrumental in optimising the brake pedal design. By scanning an existing brake pedal and importing the data into Fusion 360 software, a smoothened model was obtained for further analysis. The generative design process allowed for the exploration of various design solutions based on predetermined constraints and loads. Through iterative analysis and selection, an optimised brake pedal design was achieved, featuring a length of approximately 27.6 cm and a mass of 160 g. The design exhibited a maximum stress of approximately 41 MPa, with a minimum factor of safety of around 2, ensuring its reliability and durability in real-world braking scenarios.

The reverse-engineered brake pedal model was utilised as a starting shape in a smoothened form to optimise the mass and shape of the model. This was done using a Generative design approach which allowed for an Artificial intelligence-based algorithm to minimise the mass of the model with maximum stiffness.

The resultant was an optimised brake pedal of approximately 27.6 cm in length and 160 g in mass (as shown in TABLE 7). The maximum stress produced on the body was approximately 41 MPa (as shown in Figs. 13 and 14) with a minimum factor of safety of around 2.

TABLE 6

Response Table for Means

Level	Material	Layer Thickness	Raster Angle	Infill Pattern	Infill Density
1	27.88	27.78	27.80	24.59	28.29
2	27.06	24.35	26.21	27.80	16.69
3	22.52	25.33	23.45	25.07	32.48
Rank	**2**	**5**	**3**	**4**	**1**

TABLE 7

Specifications of optimised brake pedal

Description	Specifications
Dimensions	276*68*55.7 mm
Mass	160 g
Maximum von Mises stress	41.124 MPa
Minimum Factor of safety	2.012
Maximum Displacement	30.589 mm

Fig. 13. Von Mises stress acting on the body

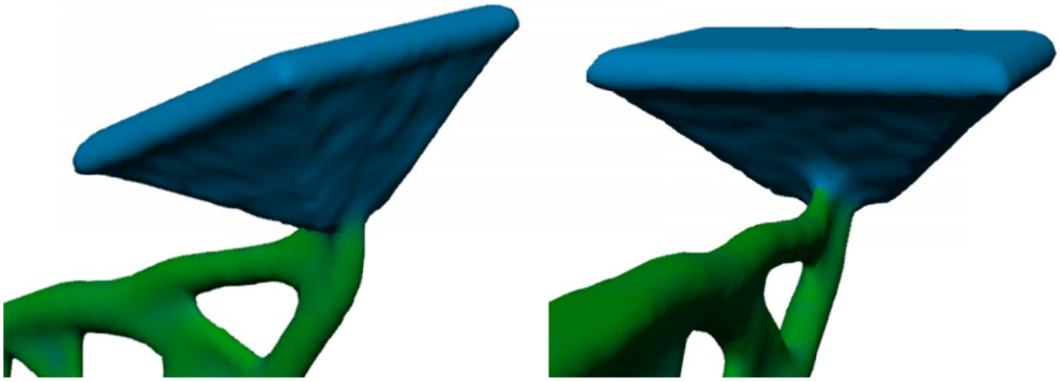


Fig. 14. Stress concentration at the Head-Lever Joint

5. Conclusion

This study delved into the investigation of a 3D-printed brake pedal to evaluate its mechanical performance in terms of tensile strength, and impact strength. Employing a comprehensive approach utilising Design of Experiments (DOE) and ASTM standard testing methods, the study examined the influence of various specimen parameters, including infill pattern, raster angle, layer thickness, material, and infill density. The results obtained shed light on the significant contributions of infill density, raster angle, and material selection to the mechanical properties of the brake pedal. Among these factors, infill density consistently emerged as the primary determinant across all two tests, underscoring its pivotal role in dictating the strength and performance of the brake pedal. Infill density and material selection were also found to exert notable influences on specific mechanical characteristics.To further augment the design process, the study incorporated reverse engineering techniques. A 3D scanner was employed to meticulously capture the shape and dimensions of a Toyota Etios brake pedal, producing an accurate digital representation. Leveraging this reverse-engineered model, the research team then embarked on a generative design approach.

By leveraging generative design, the study aimed to create an optimised brake pedal that surpassed conventional design limitations. The resultant optimised brake pedal showcased impressive characteristics, boasting a length of approximately 27.6 cm and a mass of 160 g. The pedal's structural integrity was exemplified by the maximum stress generated on its body, measuring around 41 MPa, with a minimum factor of safety of approximately 2. The careful selection of this design from a myriad of alternatives illustrates the efficacy of generative design in optimising complex mechanical components. The material determined by the ANOVA to be suitable for the application was Nylon.

The knowledge gained from this study can be leveraged to improve braking systems in various applications, including automotive, aerospace, and industrial sectors. Further research can focus on exploring additional parameters, such as raster angle and layer thickness, to refine the manufacturing process and further enhance the performance of 3D printed brake pedals. By continuously advancing the understanding of 3D printing techniques and material properties, we can unlock the full potential of additive manufacturing for producing high-performance brake pedals and contribute to the advancement of braking technology.

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