Optimization of Process parameters of 3D Printer for Enhancing Mechanical Properties Using 3D Printed Specimen of PETG-CF Materials

A PROJECT REPORT

Submitted in partially fulfillment of the requirements for the degree of

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In

Mechanical Engineering

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DECLARATION

We, Ashish Kumar Jha, Fahad Ahmad, Kashif Khan and Nashit Tehami, student of B.Tech Mechanical Engineering hereby declare that the project titled **“Optimization of Process parameters of 3D Printer for Enhancing Mechanical Properties Using 3D Printed Specimen of PETG-CF Materials”** which is submitted by us to the Department of Mechanical Engineering, Galgotias College of Engineering and Technology, Greater Noida (Affiliated to Dr. A.P.J. Abdul Kalam Technical University, Lucknow) in partial fulfillment of the requirement for the award of the degree of Bachelor of Technology has not been previously formed the basis for the award of any Degree, Diploma other similar title or recognition.

Place: Greater Noida

Date: June ,2024

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CERTIFICATE

This is certify that the project entitled **"Optimization of Process parameters of 3D Printer for Enhancing Mechanical Properties Using 3D Printed Specimen of PETG-CF Materials"** is being submitted by **Ashish Kumar Jha (2000970400020), Fahad Ahmad (2000970400027), Kashif Khan (2100970409007)** and **Nashit Tehami (2100970409010)** in partial fulfillment for the degree of Bachelor Of Technology in Mechanical Engineering of the Galgotia's College of Engineering & Technology, Greater Noida is a record of their own work ,carried out under my supervision.

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ABSTRACT

The following experimental work focuses on optimizing the process parameters of the 3D-printer by making use of Response Surface Methodology (RSM) in order to produce the best mechanical properties for the 3D-printed specimen made of Polyethylene Terephthalate Polyethylene Glycol-Modified Carbon Fiber (PETG-CF). Additive manufacturing has been popular for their ability to produce complex parts while maintaining excellent mechanical properties. But to achieve best performance, control of process parameters is required. RSM, a mathematical model is used to investigate about the effect of various printing parameters such as Layer Thickness, Infill Density and Nozzle Temperature on various mechanical properties. This study combines the various experimental data and optimization algorithms to examine the best printing parameters that provide the best mechanical properties. The finding obtained from this work contributes to further advancement of additive manufacturing by providing clarity about the optimization of process parameters in order to get the best of mechanical properties of the PETG-CF material.

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NOMENCLATURE

AM	Additive Manufacturing
RP	Rapid Prototyping
STL	Stereolithography
RSM	Response Surface Methodology
CAD	Computer Aided Design
FDM	Fused Deposition Modelling
PETG	Polyethylene Terephthalate Glycol
ANOVA	Analysis of Variance
BBD	Box Behnken Design
CCD	Central Composite Design
NT	Nozzle Temperature
LT	Layer Thickness
MS	Mean Sum of Square
ID	Infill Density
WR	Wear Rate
TS	Tensile Strength
FS	Flexural Strength
DF	Degree of Freedom
SWR	Specific Wear Rate
SS	Sum of Square
PEEK	Polyether ether ketone
ABS	Acrylonitrile butadiene styrene
PLA	Polylactic Acid
TPU	Thermoplastic Polyurethane
CF	Carbon Fiber
SLS	Selective Laser Sintering

1. Introduction

1.1 Overview of Rapid Prototyping

Rapid prototyping involves direct creation of a physical model from Computer-Aided Design (CAD) data. Utilizing 3D printers, these technologies produce tangible 3D representations of digital models in significantly reduced time frames. These models serve not only research and development purposes but are also employed in scenarios where small quantities are required. Furthermore, rapid prototyping technologies have spurred a surge in customized products in the market. The application of rapid prototyping extends to the creation of complex parts, where traditional techniques such as casting would pose significant challenges. The unique advantages offered by rapid prototyping techniques over conventional methods have led to their widespread acceptance across various domains.

By using rapid prototyping, a prototype can be created in just a few hours or days, whereas traditional methods might require weeks or even months. This accelerated timeline allows for faster iterations and testing during the product development process, ultimately reducing time-to-market and development costs. Furthermore, rapid prototyping allows for the creation of prototypes with detailed geometries and intricate internal structures that are challenging or unattainable with conventional manufacturing techniques. As a result, designers and engineers can quickly and cost-effectively test and refine their designs, leading to higher quality products and improved overall performance. Rapid prototyping technologies continue to evolve, offering new materials, processes, and capabilities that further expand their applications across various industries and disciplines.

1.2 The Basic process

The process that are followed are further subdivided into 8 steps in additive manufacturing.
These steps are:

1. Conceptualization and CAD
2. Conversion to STL
3. Transfer to AM machine and STL file manipulation

4. Machine Setup
5. Build
6. Removal and Cleanup
7. Post Processing
8. Applications

1.3 8-Steps in Additive Manufacturing

There are 8 major steps in the rapid prototyping which by and large tells the major steps required to be followed in order to get the final product.

1. **Conceptualization and CAD**

   In this step of rapid manufacturing firstly the model is conceptualized and its basic ideation is lay out. This phase is called the conceptualization phase, where the researcher translates their creative vision into a well-defined concept. Sketching or mind-mapping techniques can be employed to solidify the initial ideas. In this step the main focus is to create a model which can fulfill the need. After the ideation and consideration of the thoughts of the final product a 3D CAD model is lay out using computer aided design. Computer-Aided Design (CAD) software facilitates the construction of a three-dimensional digital model. CAD software empowers researchers to not only design complex geometries but also conduct virtual simulations to evaluate the object's potential performance under real-world conditions.

2. **Conversion to STL**

   To prepare the digital model for the additive manufacturing process, a file format conversion is necessary. The Standard Triangle Language (STL) format efficiently translates the intricate 3D model into a collection of elementary triangular facets. Each facet represents a specific instruction for the 3D printer, dictating the precise location and volume of material deposition during the forthcoming printing process. While alternative 3D printing file formats exist, STL's widespread adoption stems from its inherent simplicity and broad compatibility with various printer types. This file format is read by a majority of 3D printers.

3. **Transfer to AM machine and STL file manipulation**

   Once the STL file has been converted, it is then transferred to the additive manufacturing machine, commonly known as a 3D printer. Different kind of software helps in transferring the file. Printer-specific software might offer additional functionalities to further refine the printing process. Researchers leverages these tools to calibrate parameters such as layer thickness, printing speed etc., to achieve the optimal outcome for their specific project. Furthermore, the software might incorporate support structures. These support structure provide the support particularly for objects with overhanging features or intricate geometries without which the 3D structure may fail out. Following successful printing, these support structures are removed in order to get the final object. Also, in this step the file manipulation is done. Here file manipulation refers to the changes made by the printer software in the minor section of the file which got corrupted in the process of file conversion or file transfer to the AM machine.

4. **Machine Setup**

   Just like any precise tool, the 3D printer requires calibration before each operation. This ensures consistent material flow and accurate movement for high-quality prints. The chosen printing material, typically filament (melted plastic wire), resin (liquid for vat polymerization), or powder (for sintering processes), is loaded. Calibration routines may involve adjusting the print head's temperature for optimal material flow, fine-tuning print speed, or adjusting the printing platform's level for a perfect starting base. Every parameter related to printing is calibrated in this step. Basically, in this step the machine is set up to mark at which it can build the required product uninterruptedly.

5. **Build**

   In this step the product is actually built physically. The printer precisely follows the instructions in the STL file, transforming the digital model into a physical object layer by layer. Depending on the technology used, material may be deposited through a heated nozzle (FDM), cured by a laser beam (SLA), or selectively fused with a heat source (SLS). Each layer bonds with the one below, gradually building up the object until the entire design is complete. The printing process duration can vary from a few minutes for small, simple objects to several days for complex or large designs. During the build process, the printer's software monitors and adjusts various parameters such as temperature, speed, and layer height to ensure the final object meets the desired specifications.

6. Removal and Cleanup

Once the printing cycle is completed, the printer needs to cool down before the object can be safely removed. The platform is lowered, and the printed part is carefully detached. Support structures, temporary features added during printing to support overhangs or complex geometries, are then removed using tools such as pliers or cutters. In this step the removal of the supports and unwanted area is removed and the product is cleaned accordingly. The cleanup process can vary based on the material and printing technology used. It may include removing excess resin or powder, along with post-processing steps like sanding, polishing, or applying surface treatments to achieve the desired finish.

7. Post Processing

In this step further the product is cleaned and is made ready for application. Not all 3D-printed objects are ready to use straight out of the machine. Some materials might require additional treatment to achieve the desired surface quality or functionality. This could involve sanding the surface smooth for a polished look, adding chemical treatments to enhance strength or heat resistance, or infiltrating porous materials with special solutions to improve their properties. Additionally, post-processing steps may include painting, coating, or assembly of multiple printed parts to create the final product. Quality control measures such as dimensional accuracy checks, surface finish inspection, and mechanical testing may also be conducted during the post-processing so as to ensure that the printed object meets the necessary standards.

8. Application

This is the final stage where the 3D-printed object finds its purpose and is the reason for which the product is actually made for. Depending on the design and chosen material, applications can vary widely. Prototypes for product development, functional parts for machines, custom medical implants, artistic creations, and even educational models are just a few examples of how 3D-printed objects are utilized in different fields. With the advancement of 3D printing technology, new applications are continuously being explored, from aerospace and automotive industries to fashion and architecture. As the technology becomes more accessible and affordable, the potential for innovation and creativity with 3D printing continues to expand.

1.4 Rapid Prototyping Techniques

1.4.1 Stereolithography

Stereolithography or SLA is one of the most commonly used additive manufacturing process and also one the earliest developed process having been introduced in 1986 [1]. The process begins with initiating a chain reaction in a resin layer using ultraviolet light or electron beams. The monomers, primarily epoxy-based or acrylic, are sensitive to UV light and, when activated, quickly form polymer chains. To stabilize the subsequent layers, the pattern within the resin layer is solidified. The unreacted resin is taken out after printing is complete for certain printed items, but some part of the liquid resin remains uncured therefore processes like heating and further curing of the uncured resin is required. To print composites of ceramic-polymer [2] or silicon oxy carbide [3], a dispersion of ceramic in monomer particles which could be utilized. High-gradability items can be printed by SLA with the resolution as minimal as 10 μm [4]. However, it's quite costly, requires a lot of time and is limited in the printing materials it can use. The dynamics of the reaction and the curing process are quite complex. The main factors affecting each layer are the energy from the light source's exposure [5]. SLA makes it simple to additively create complex nano-composites materials with excellent outcomes [6].

1.4.2 Powder Bed Fusion

Powder bed fusion is an additive manufacturing technique that uses fine powder particles which get deposited on the build platform by making the use of a roller and are then packed with each other during the process. The deposited fine particles are then fused together by making use of a laser or an electron beam. Vacuum is used to remove the leftover powder and further enhancement is done by the coating process on the obtained material. Several elements like packing of powder and the size distribution influences density of part obtained by powder bed fusion process [7].

When the liquid binder is made use of in place of a laser then the process is called 3DP. The size of the powder, the speed at which the powder gets deposited and the way the interaction between the powder and the binder takes place as well as the types of post processing methodologies used greatly affect the 3DP process [7].

When the parts are made using the binder method large openings are observed whereas using the laser method more dense parts can be produced [7]. The parameters that greatly affect the process are the intensity of the laser and the scanning speed. Very fine quality and difficult to produce part design without using the support structure can be easily made using this technique which is considered as a key benefit, there are also some demerits of this technique the major one being the high capital cost for the process.

1.4.3 Laminated Object Manufacturing

The laminated object manufacturing is one of the earliest available rapid prototyping processes. The laminated object manufacturing technique includes cutting of the sheets and laminating them by reducing the excess material before joining them. The leftover material after the cutting is used for the purpose of providing support and the desired object is obtained then the supports are removed and recycled for later use [8]. Several distinguished types of materials can be used for the Lom technique some of which are papers, polymers, composites and ceramics. A subset of LOM is called Ultrasonic AM which collaborates CNC machining with the lamination process [9]. Metal structures that have a great amount of strength can be built at low temperature by making use of the ultrasonic additive manufacturing [10,11]. The application of the Lom techniques can be found in a variety of industries which include paper manufacturing, electronics and smart buildings. Direct write technologies enable printing of electronic devices during the UAM lamination process [9]. For the manufacturing of large sized structures Lom process is widely used which results in low tooling cost and production cost.

1.4.4 Direct Energy Deposition

The direct energy deposition is an additive manufacturing process typically used to add extra material to the already built component or for the purpose of repairing. The classification of the direct energy deposition (DED) can be done on the basis of feedstock as wire feeding type and powder feeding type. The wire feeding type feedstock makes use of an electron beam as a source of heat energy whereas, on the other hand the powder feeding type makes use of the laser beam as a source of heat energy the process is carried out in the horizontal direction. The materials that can be made use of in this process are different types of metals, polymers and some ceramics. The laser energy net shaping and the laser deposition method are the typical examples of the direct energy deposition. Some of the key advantages that direct energy deposition offers over the other available additive manufacturing processes are that this technique is very cost efficient and provides a better control over the microstructure of the material that is to be deposited.

1.4.5 Fused Deposition Modelling

The fused deposition modeling is one of the most commonly used additive manufacturing techniques available. It is also cheap as compared to the other AM based processes. The FDM technique works on the technology of extrusion of thermoplastic material onto the build platform by making use of a nozzle. The filament is heated at the hot end of the nozzle to the extent until it gets converted into the semi-liquid state and is then extruded to the build platform layer by layer according to the 3D-CAD file. The process parameters like layer thickness, raster angle and print speed play an important role in determining the mechanical qualities of the material [5]. However, any mismatch between the layers of the printed filament can lead to the introduction of mechanical weakness in the part [12]. There are several advantages that the FDM process may have to offer some of them being faster printing speed, cheap cost, etc. However, shortcoming comes complimentary with advantages and some of the major shortcoming of the FDM techniques are the poor quality of the printed material and poor mechanical properties of the material it has to offer [13]. Several building guidelines have been introduced in order to gain the desired mechanical qualities such as building parts in such a way that the tensile load is carried on axially in the direction of material deposition. And making use of negative air gaps [14]. In order for the materials to be printed by this technique they must possess a low melting point and should be cheaply available, some of the materials that fulfill these criteria are ABS [15,16] AND PLA [17,18]. Another material which can be a good option for use in the FDM process is PEEK which is high in price but possesses good properties and a melting point of 615.15K. PEEK can be used to creates engine parts [19] and human organs [20-22] but this should be done by the process of injection molding if good strength is to be obtained the injection molding offers a tensile strength of 85-102 MPa[23-25] and on the other hand the PEEK printed with the AM process possesses a tensile strength of around 50-55MPa [26-29].

1.4.6 Binder Jetting

The binder jetting process conventionally makes use of a very fine layer of powder which is spread onto the building block by the help of a roller that evenly spreads the powdered material onto the build platform and then a liquid binder is made use of which is jetted[30] onto the evenly spread powder layer and then the electric heater is used for the purpose of curing the layer and then subsequently the next layer is deposited and the same process is repeated, the temperature throughout the entire process is maintained uniform. The most important factor in this whole process is the curing time. i.e., enough time should be given to the printed layer to completely dry out so that the powdered material and the binder gets fully binded together and no crack formation takes place in the printed part and that the printed part does not get stick to the surface of the roller which guides the next powder layer.

The binder jetting process is used in various industrial applications such as in electronic devices, biomedical applications and renewable materials.

1.5 Various materials used in additive manufacturing

Various materials that are used in the field of additive manufacturing. These materials are as follows.

1.5.1 Acrylonitrile butadiene styrene (ABS)

ABS is a polymer material commonly used in the form of wire filament. When heated, ABS emits moderate vapors, which are generally tolerable and not harmful, although they may affect sensitive individuals or some animals. Known for its flexibility, lightweight, and durability, ABS can be waxed, blended, or polished to achieve a glass-like finish by mixing it with acetone. Alongside PLA, ABS was among the first polymers introduced in wire filament form for use in 3D printers, especially in FDM processes. ABS has been present since the early stages of 3D printer industrialization and is popular due to its cost-effectiveness, productivity, and excellent material properties. Primarily used in the toy industry and other sectors requiring lightweight plastic materials, ABS is ideal for printing plastic toys, musical instruments, home appliances, and more.

Advantages:

- Flexibility and Durability: ABS is known for its resilience and robustness, making it suitable for a wide range of applications.
- Lightweight: ABS is a lightweight material, which makes it ideal for applications where weight is a concern.
- Cost-Effective: ABS is relatively inexpensive compared to other materials, making it a popular choice for many industries.

Disadvantages:

- Emission of Vapors: When heated, ABS emits vapors that, while generally tolerable, may affect sensitive individuals or animals.
- Limited Finish: While ABS can be polished to achieve a glass-like finish, it requires mixing with acetone, which may not always be feasible.
- Material Properties: The properties of ABS can differ significantly from those of other commonly used materials, which can limit its applicability in certain scenarios.

Applications:

- 3D Printing: ABS was one of the first polymers to be used in wire filament form for 3D printers, particularly in Fused Deposition Modeling (FDM) processes.
- Toy Industry: ABS is primarily used in the toy industry due to its lightweight and durable properties.
- Home Appliances: ABS is also used in the manufacturing of various home appliances due to its cost-effectiveness and excellent material properties.

1.5.2 Poly-ether-ether-ketone (PEEK)

PEEK, or Poly-ether-ether-ketone, is a material renowned for its exceptional tensile and wear strength, positioning it as one of the most valuable materials for mechanical performance compared to other plastics. Its versatility allows for various applications, from medical implants to aerospace components, as it can withstand high temperatures without deformation or structural compromise. Additionally, PEEK's lightweight nature makes it a preferred choice for applications where weight reduction is essential without sacrificing strength. This material offers several advantages over ABS, PLA, and TPE in terms of economical printing, primarily due to its enhanced durability and wide range of applications. PEEK's excellent thermal stability reduces the likelihood of failed prints and material wastage, while its durability ensures that printed parts are less likely to break or require frequent replacement, thus reducing overall material consumption and associated costs over time. Furthermore, PEEK's chemical resistance and biocompatibility make it suitable for a wide range of industries, including aerospace, automotive, and medical, where high-performance materials are essential.

Advantages:

- Exceptional Strength: PEEK is known for its remarkable tensile and wear strength, making it one of the most valuable materials for mechanical performance compared to other plastics.
- Thermal Stability: PEEK can withstand high temperatures without deformation or structural compromise, reducing the likelihood of failed prints and material wastage.
- Lightweight and Durable: Despite being lightweight, PEEK does not compromise on strength, making it a preferred choice for applications where weight reduction is essential.

Disadvantages:

- Cost: While PEEK offers several advantages over ABS, PLA, and TPE in terms of economical printing, it is generally more expensive than these materials.
- Printing Difficulty: Due to its high melting point and strength, PEEK can be challenging to print with, especially for those new to 3D printing.
- Limited Flexibility: While PEEK is incredibly strong and durable, it does not offer the same level of flexibility as some other materials, which can limit its use in certain applications.

Applications:

- Medical Industry: PEEK’s biocompatibility makes it suitable for medical applications, such as implants.
- Aerospace Components: Due to its ability to withstand high temperatures and its lightweight nature, PEEK is often used in the aerospace industry.

- Automotive Industry: PEEK’s exceptional strength and durability make it a popular choice for various automotive applications.

1.5.3 Polylactic Acid (PLA)

PLA, a biodegradable thermoplastic polymer, is sourced from renewable resources like cornstarch or sugarcane, distinguishing it as one of the most environmentally friendly plastics available. One of PLA's key advantages lies in its ease of printing. With a relatively low melting point compared to other thermoplastics, PLA is compatible with a wide range of 3D printers, including those with heated and non-heated beds. Additionally, PLA exhibits minimal warping and shrinkage during printing, helping to maintain the integrity of printed parts. Apart from its ease of use, PLA offers a wide range of color options. From an environmental perspective, PLA's biodegradability sets it apart. Under specific conditions such as exposure to moisture and high temperatures in industrial composting facilities, PLA can decompose into harmless byproducts like water and carbon dioxide within a few months to a few years, depending on the material thickness and environmental factors. However, it's worth noting that PLA does have limitations. It's unsuitable for applications requiring high temperature resistance or exceptional mechanical strength, as it tends to soften and deform at relatively low temperatures compared to other engineering plastics.

Polylactic acid (PLA) offers several advantages over other 3D printing materials. First and foremost, PLA is cost-effective, particularly when compared to high-performance materials like polyether ether ketone (PEEK), especially in applications where extreme temperature resistance or exceptional mechanical properties are not required. Additionally, PLA is known for its ease of printing due to its low melting point, reducing energy consumption during the printing process and eliminating the need for bed heating, thus lowering energy costs compared to materials like acrylonitrile butadiene styrene (ABS), which often require heated beds to prevent warping. Furthermore, PLA is less abrasive than materials like ABS and thermoplastic elastomers (TPE), resulting in reduced wear and tear on 3D printing equipment such as nozzles and extruders, leading to longer equipment lifespan and reduced maintenance costs over time. Moreover, PLA generally produces smoother prints compared to ABS and TPE, reducing the need for post-processing techniques. Finally, PLA is biodegradable and derived from renewable resources, making it environmentally friendly compared to petroleum-based materials like ABS and TPE. While PEEK is also derived from renewable resources, PLA's biodegradability offers additional environmental benefits, particularly in applications where disposable or short-term use items are prevalent.

Advantages:

- Ease of Printing: PLA is known for its ease of printing due to its low melting point, making it compatible with a wide range of 3D printers.
- Environmentally Friendly: PLA is biodegradable and derived from renewable resources like cornstarch or sugarcane, making it one of the most eco-friendly plastics available.
- Cost-Effective: PLA is cost-effective, particularly when compared to high-performance materials like PEEK, especially in applications where extreme temperature resistance or exceptional mechanical properties are not required.

Disadvantages:

- Temperature Sensitivity: PLA tends to soften and deform at relatively low temperatures compared to other engineering plastics, making it unsuitable for applications requiring high temperature resistance.
- Limited Mechanical Strength: PLA is not suitable for applications that require exceptional mechanical strength.
- Biodegradability: While PLA's biodegradability is an advantage from an environmental perspective, it can be a disadvantage in applications where long-term durability is required.

Applications:

- 3D Printing: PLA is widely used in 3D printing due to its ease of printing and wide range of color options.
- Disposable Items: PLA's biodegradability makes it ideal for applications where disposable or short-term use items are prevalent.
- Reduced Wear and Tear on Equipment: PLA is less abrasive than materials like ABS and TPE, resulting in reduced wear and tear on 3D printing equipment such as nozzles and extruders.

1.5.4 Thermoplastic Elastomer (TPE)

Thermoplastic Elastomers (TPEs) are highly adaptable materials, blending the elasticity of rubber with the processability of thermoplastics. They provide flexibility, resilience, and excellent impact resistance, making them ideal for a multitude of applications. TPEs can be effortlessly molded into various shapes using conventional plastic processing methods and are offered in a diverse range of hardness levels to fulfill specific requirements. They demonstrate favorable chemical resistance, weather resistance, and biocompatibility, rendering them suitable for utilization across industries, spanning from automotive to medical devices.

Thermoplastic elastomers (TPEs) offer several advantages over high-performance materials like PEEK, particularly in applications where extreme temperature resistance or exceptional mechanical properties are unnecessary, making them a cost-effective option. TPEs require lower processing temperatures compared to materials like PEEK and ABS, resulting in reduced energy consumption during the printing process, thus saving on electricity or heating costs. Additionally, TPEs often produce finished prints with smooth surfaces and excellent flexibility straight off the printer, minimizing the need for extensive post-processing. With their versatility in hardness levels and ability to be tailored to specific application requirements, TPEs provide greater design freedom and material efficiency, potentially reducing waste and optimizing print efficiency. Moreover, TPEs are known for their resilience and durability, making them suitable for applications where long-term performance is essential. Furthermore, many TPE formulations are recyclable, allowing for the reuse of excess material or failed prints, further reducing material costs and waste.

Advantages:

- Adaptability: TPEs are highly adaptable materials, blending the elasticity of rubber with the processability of thermoplastics, providing flexibility, resilience, and excellent impact resistance.
- Ease of Processing: TPEs can be effortlessly molded into various shapes using conventional plastic processing methods and are offered in a diverse range of hardness levels to fulfill specific requirements.
- Cost-Effective: TPEs offer several advantages over high-performance materials like PEEK, particularly in applications where extreme temperature resistance or exceptional mechanical properties are unnecessary, making them a cost-effective option.

Disadvantages:

- Limited Temperature Resistance: TPEs require lower processing temperatures compared to materials like PEEK and ABS, which can limit their use in applications requiring high temperature resistance.
- Material Properties: While TPEs are known for their resilience and durability, they may not offer the same level of mechanical properties as some other materials, limiting their use in certain applications.
- Recycling Challenges: While many TPE formulations are recyclable, the recycling process can be complex and time-consuming, which can be a disadvantage in certain scenarios.

Applications:

- Wide Range of Industries: TPEs demonstrate favorable chemical resistance, weather resistance, and biocompatibility, rendering them suitable for utilization across industries, spanning from automotive to medical devices.
- 3D Printing: TPEs often produce finished prints with smooth surfaces and excellent flexibility straight off the printer, minimizing the need for extensive post-processing.
- Design Freedom: With their versatility in hardness levels and ability to be tailored to specific application requirements, TPEs provide greater design freedom and material efficiency.

1.6 Economic printing of Additive manufacturing using FDM

Additive manufacturing, particularly Fused Deposition Modeling (FDM), offers numerous advantages over traditional manufacturing processes. One of the primary benefits is its cost-effectiveness. The manufacturing cost of materials using FDM is considerably lower compared to processes such as metal printing. This cost efficiency opens up avenues for exploration and encourages creative thinking due to the lower financial barriers associated with prototyping and production.

Moreover, the advancements in FDM technology have not only improved surface roughness and precision but also expanded the range of materials that can be used. In addition to PLA, FDM printers can now utilize a wide variety of materials, including ABS, PETG, TPU, and nylon, among others. This versatility allows for greater flexibility in material selection, enabling manufacturers to choose the most suitable material for their specific application requirements. As the range of compatible materials continues to expand, FDM-based 3D printers are becoming increasingly versatile and adaptable, further enhancing their appeal across various industries and applications.

Recent advancements in FDM technology have significantly improved surface roughness, addressing one of the major drawbacks of 3D printing. These advancements have also enhanced the precision of FDM-based printers, making them comparable to metal 3D printers in terms of accuracy.

Furthermore, some of the materials used in FDM 3D printing, such as polylactic acid (PLA), are biodegradable. This aligns with the sustainable development goals of many developing and developed economies. Further research and development in biodegradable materials will enhance the adaptability and environmental friendliness of FDM-based 3D printers.

1.7 Objective of Research Work

In recent times, the global market for manufactured goods has seen a significant increase in competition. It’s crucial for new products to penetrate the market swiftly, leading to a heightened focus on reducing product development cycle time in industries to gain a competitive edge. The primary objective of this research is to explore and evaluate the influence of various process parameters on the mechanical properties of PETG CF (Polyethylene Terephthalate Glycol - Carbon Fiber) material when used in Fused Deposition Modelling (FDM). This investigation aims to identify optimal conditions that enhance the mechanical performance of 3D printed PETG CF parts. Specifically, the research focuses on understanding the effect of different layer heights on the tensile and flexural strength of PETG CF printed parts and determining the optimal layer height. Additionally, it examines the role of material density, or infill percentage, on the structural integrity and mechanical properties of PETG CF, seeking the best infill density that provides strength while being material-efficient. The research also evaluates the impact of varying extrusion temperatures on tensile strength and flexural strength aiming to establish the ideal extrusion temperature for maximizing strength without compromising print quality.

Optimization of process parameters is systematically approached using Response Surface Methodology (RSM) to enhance tensile and flexural properties, analyzing the collective impact of infill density, layer thickness, and nozzle temperature with robust statistical methods.

The research aims to provide practical guidelines for manufacturers using FDM technology with PETG CF materials, enhancing the adaptability and environmental friendliness of FDM-based 3D printers by focusing on biodegradable and high-performance materials. Ultimately, this study seeks to contribute to the body of knowledge on additive manufacturing by optimizing FDM processes for PETG CF material to produce high-quality, mechanically robust components suitable for various applications.

2. Literature Review

K. Durgashyam concluded that by conducting the tensile and flexural test the effect of various process parameters on the mechanical properties of the PETG material can vary for excellent tensile properties of the PETG material the layer thickness should be minimum with high infill density. While for good flexural properties the infill density along with the layer thickness should be kept minimum as possible, the layer thickness has significant effect on the mechanical properties of the material.[30]

Osamah Fattah Taresh concluded that the filling pattern and infill percentage has an impact on the values of tensile strength and fractured strain. Also, the samples which had the excellent tensile strength were the one which followed the triangle infill pattern while the filled octet pattern has the minimum tensile strength. But excellent tensile strength was obtained with all the fill pattern when the infill density increases, the best tensile strength was obtained with 100% infill density. The specimen printed with the hexagonal filling pattern showed the lowest fracture strain while the octet pattern showed the highest fracture strain.[31]

Dinesh Yadav researched about influence of layer height, material density and extrusion temperature on the mechanical properties for PETG material on which he concluded tensile strength is more influenced by extrusion temperature, at max temperature, tensile strength was max and with min layer height. The optimal parameter was 225 degree C and 0.1mm layer height.

K Sathish Kumar in his paper concluded that the PETG and CFPETG material have mechanical properties (such as tensile, flexural, hardness) at 100% infill density as compared to lower density and CFPETG had higher mechanical properties at same parameters than PETG because of addition of carbon fiber in the material.[32]

T. Panneerselvam concluded about the various mechanical properties of the 3d printed PETG filament by the FDM process. In this study the various factors such as the layer height (0.2mm, 0.25mm, 0.3mm), infill percentage (20%, 50%, 80%) and the infill pattern (square, triangular and rectangular). In order to analyses the combined response of the tensile, flexural strength and hardness the Taguchi's grey relational analysis was used. The observation concluded was that the hexagonal infill patter has a significant effect on the tensile strength of the material. The hardness was concluded at the higher infill percentage, hexagonal infill pattern and higher layer thickness. It showed that 80% infill density, 0.3mm layer thickness and the hexagonal pattern show the highest mean values. The result showed that the tensile strength was significantly affected by the infill pattern. [33]

Ankita Jaisingh Sheoran reviewed about the various parameters and what effect they have on the various mechanical properties of the 3d printed material. They came to the conclusion that more research has been conducted on the composite other than thermoplastics. And the various parameters have various impact on the printed material. In context of the study the parameters such as infill patter, print speed and extrusion temperature has significant impact on the various mechanical properties such as tensile strength, surface roughness as well as dimensional accuracy while on the other hand the compressive strength was more impacted by the infill density, raster orientation and infill pattern. According to the study the printed parts have higher tensile and flexural strength when they are printed at 0 raster angle and high nozzle temperature. Similarly in the case of compressive strength the layer height is the deciding parameter when the layer thickness is high and infill density is less the print time taken will be less.[34]

Ming-Hsien Hsueh concluded that the different process parameters have different kind of effects on the mechanical and thermal properties of the PETG material and by taking the printing speed and temperature as variable parameters. The material selected was PLA and PETG and the comparison of both the materials. In order to reduce the complexity, the dimeter of the nozzle was taken as 0.4mm with the fixed parameters taken namely as infill density (20%), layer thickness (0.2mm), raster angle 450 and the bed temperature at 25oC. the study presented that the PLA filament showed more of an elastic behavior while the PETG filament presented itself brittle in nature. The melting point of the PETG filament was above 225oC. as the printing temperatures of both the materials increases there is an observed increase in viscosity which results in better fusion and decreased porosity. The study concluded that both the materials had asymmetry and that the tensile stress was less than the compressive stress. And as in the case of the PLA material the mechanical properties increase with the increase in the temperature. Whereas, for PETG material It was observed that the increase in the printing temperature as well as the print speed the properties were improved.[35]

Prajwal P. Agarwal conducted the empirical evaluation on the 3d printed PETG material for properties such as the ultimate tensile strength, dimensional accuracy and the printing time. The layer thickness, infill percentage and the orientation of the specimen were the varying parameters. To obtain the maximum strength the honeycomb structure was used. And in order to reduce the number of specimens to be used the Taguchi L9's array was used. According to the evaluations made, as an increase in the layer thickness is observed the percentage elongation increases as well, and also the material can sustain large amount of load which indicates towards a higher tensile strength.[36]

S. Swetha by varying the infill percentage (50% and 100%) and the layer thickness (0.1mm and 0.3mm) focused on designing, validating and 3d print the tensile specimen. And by taking one end of the specimen fixed a static structural analysis was carried out on Ansys 16.2. by carrying out the analysis it was observed that with increased layer thickness and decrease in the infill percentage the tensile strength decreases. A percentage error of 5 was observed between the experimented and stimulated results. The experimentally performed tensile and compressive test were validated by the static structural in Ansys.[37]

Sara Valvez et al concluded that in FDM printed PTEG composites along with the carbon and Kevlar fibers are the materials used for several uses in the Aircraft and Automotive industries, therefore it is important to study their mechanical behavior in terms of compression. In this regard we conduct static, stress relaxation and creep tests were carried out, in compressive modes, using either neat PTEG or PTEG composites reinforced with carbon or Kevlar fibers. As a result, it has been found out that the yield of compressive strength decreased in both composites compared to neat polymer and largest decrease is observed in PETG reinforced with Kevlar. When carbon and Kevlar were added it has been found that the values were around 9.9% and 68.7% lower were found, respectively. [38]

Imran Khan et al in his paper concluded that the triple-material based composites i.e. PLA, ABS and PETG were successfully printed. After the initial experiments printing speed (PS), infill density (ID), and layer thickness (LT) were chosen to be the parameters that have the most significant effect on the certain mechanical properties. The tensile strength (TS) and tensile strain (Ɛ) were selected as the output responses of this study. Increasing ID will show that the value of

Tensile Strength will be enhanced and the other two parameters namely, Layer Thickness and Print Speed will not have any effect on the Tensile Strength. However, keeping the Infill Density higher would not result in any significant defects formation [39]

Sara valvez concluded that the Taguchi method and ANOVA were used for determining the best printing parameters for in order to attain the maximum value of mechanical properties for PETG and PETG-CF material. The outcomes from the study for best bending properties for the PETG AND PETG-CF material was when the ranges of the parameters such as Extrusion Temperature, Printing Speed and Layer thickness were (265-C, 196-C, and 265-C), (20mm/s, 60mm/s, and 20mm/s) and (0.4mm, 0.53mm and 0.35mm) with the infill density kept constant at 100%. The effect of the printing parameters on the bending properties were examined using the Taguchi and ANOVA method. And it was determined that the process parameters like Nozzle Temperature, Print Speed and Layer Thickness have significant effect on the Bending stress and strain of the material and the Nozzle Temperature and infill factors have effect on the bending modulus. Similarly, for PETG-CF excluding the printing speed, all the process parameters have a significant impact on the bending property. The study also shows that the mean value of S/N ratio and mechanical properties were enormously affected by the infill density. The approval of the result was based on the comparison of the theoretical and the experimental results and the error obtained were less than 12% in majority of the cases.[40]

Moises Batista examined about the parameters such as nozzle temperature and layer thickness on the mechanical and tribological properties of the material. The obtained result indicated that the reinforcement of the carbon fiber with the PETG material has a positive as well as negative effect on the mechanical properties, the positive effects being increase in hardness and modulus of elasticity of the material whereas the negative effect being rise in irregularity. The examination also determines about the values of parameters at which the best mechanical properties were attained for PETG. They are Nozzle Temperature (265-C), Printing Speed (20mm/s), Layer Thickness (0.4mm) and the Infill Density kept constant at 100%. From the wear and friction analysis it was determined that as compared to PETG, the PETG-CF material possesses an elevated wear resistance and smaller wear track. [41]

SR Rubans printed the PETG-CF by the FDM process and examined the effects of the infill speed and the heat treatment on the mechanical properties. In the study it was concluded that having low infill speed produced more solid and heavier specimen which in turn provided better Tensile strength and heat treatment(annealing) of the printed specimen provided even better Mechanical properties of the PETG-CF part. The increase in mechanical properties after heat treatment (annealing) were observed to be as follows hardness (increase of 9.5%), Tensile Strength (increase of 11%) and impact resistance (increase of 16.6.%) as compared to the non- heat-treated specimens.[41]

Mohammad Taregh did a comparison of the mechanical properties of PETG and compared it with PLA (Polylactic Acid) and ABS (acrylonitrile butadiene styrene). From the experimental work it was found out that PETG possessed higher tensile strength and toughness than PLA and ABS, by using different raster angles the mechanical properties of the material could be varied. The PLA had the highest value for the tensile strength and elongation but showed deviation at 0 raster angle. Similarly, ABS showed poor adhesion and wave pattern due to its glass transition temperature. It was observed that by keeping the raster angle at 0 and 0/90 for PETG material the best mechanical properties were obtained and for PLA and ABS the raster angle was kept at 45 and 45/135 and 0 and 45/135. It was also observed from the experimental work that by increasing the nozzle temperature for the deposition of the PETG material the interlayer adhesion increases thereby providing better mechanical properties. [42]

2.1 Findings from literature

- Economic 3D printing is always a challenging work for the researchers. However, with the development of FDM based economic 3D printer this challenge is resolving day by day.
- The capability of economic FDM based 3D printers comes with a limitation of optimized printing for such materials. So, it becomes very crucial to assess the printing parameters and print quality of printed parts as the print quality will affect the mechanical properties of printed parts.
- There are wide variety of materials are available and the current study focuses on the mechanical properties of high strength PETG-CF.
- In the present era the need of 3D printed parts is raising day by day.

- From the literature survey various parameters are found which influences the mechanical properties of the 3D printed PETG-CF parts but among these parameters the most significant parameters are Nozzle Temperature (NT), Infill Density (ID) and Layer Thickness (LT) which have a great effect on the Tensile Strength (TS), Flexural Strength (FS) and Specific Wear Rate (SWR).

2.2 Research Gap

The current study focusing on a material called PETG+CF, which is a mix of PETG and Carbon Fiber (CF) (20% reinforced). This material is strong, clear, and can handle heat and chemicals well. It doesn't warp or shrink much, which is a problem with some other materials. Plus, it's tougher than many other materials, so it's a favorite choice for many people. However, there are several gaps in our understanding of this material. For example, we don't know how different 3D printing settings like nozzle temperature, layer height, printing speed, and infill density affect the final product. This is a significant gap because these settings can greatly influence the performance of the final product. Another gap is our understanding of how CF changes the way PETG behaves under repeated stress. This is important for applications that involve cyclic loading, such as automotive components and aerospace structures. We also need to learn more about how to treat PETG+CF samples after they're printed. Techniques like heating or using solvents could make the final product perform better, but there's not enough research on this topic. So, our research will address some of these gaps. We'll study the PETG+CF mix, how to print it best, and how to treat it afterward.

We have chosen to work with the PETG+CF material primarily due to the limited research conducted on it so far. Despite the scarcity of problems identified with this material, it has a wide range of applications. One of the major applications is in the aviation industry, where it is used in the manufacturing of seat brackets in aircraft. In recent times, gears made from this material have found use in the textile and food industry. The presence of carbon, which contains graphite, adds a self-lubricating property to the material. This unique characteristic can reduce wear and tear, thereby extending the lifespan of the gears. The potential of PETG+CF extends beyond these applications. Its high strength, thermal resistance, and chemical resistance make it a promising material for various other industries. However, the full potential of PETG+CF is yet to be realized due to the lack of comprehensive studies on its properties and optimization for specific applications. Our research aims to fill this gap. By studying the PETG+CF material, we hope to uncover new insights that could lead to its wider adoption in various industries. We believe that our work will contribute significantly to the existing body of knowledge and pave the way for the wider use of PETG+CF material.

3. Materials and Methodology

The proposed methodology is divided into different phases and the different phases are represented with the help of the flow chart.

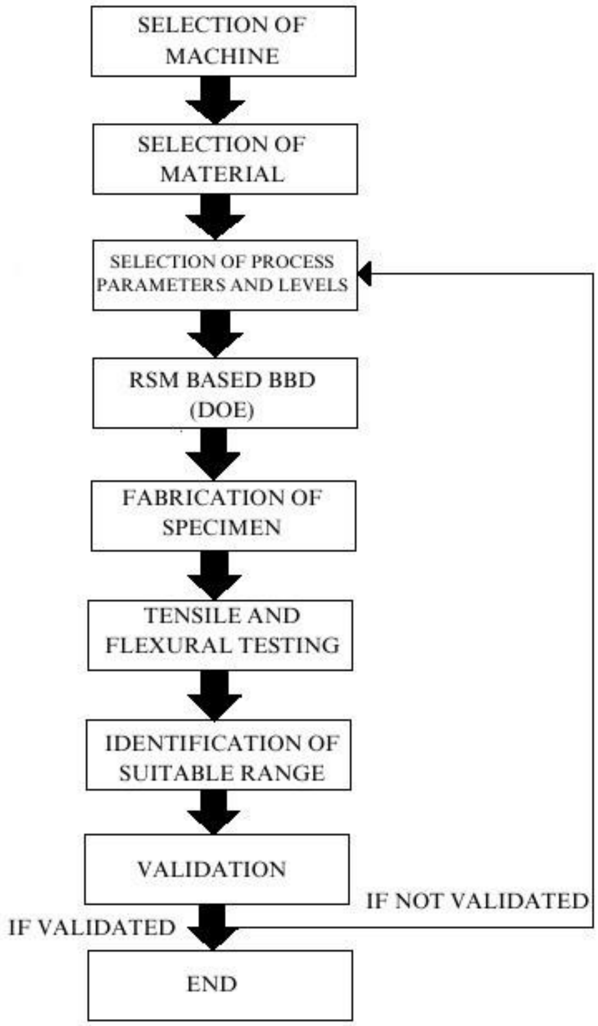


Figure 3.1: Research Methodology

3.1 Fused Deposition Modelling

The fused deposition modeling is one of the most commonly used additive manufacturing techniques available. It is also cheap as compared to the other AM based processes. The FDM technique works on the technology of extrusion of thermoplastic material onto the build platform by making use of a nozzle. The filament is heated at the hot end of the nozzle to the extent until it gets converted into the semi-liquid state and is then extruded to the build platform layer by layer according to the 3D-CAD file. The process parameters like layer thickness, raster angle and print speed play an important role in determining the mechanical qualities of the material [1]. However, any mismatch between the layers of the printed filament can lead to the introduction of mechanical weakness in the part [2]. There are several advantages that the FDM process may have to offer some of them being faster printing speed, cheap cost, etc. However, shortcoming comes complimentary with advantages and some of the major shortcoming of the FDM techniques are the poor quality of the printed material and poor mechanical properties of the material it has to offer [3]. Several building guidelines have been introduced in order to gain the desired mechanical qualities such as building parts in such a way that the tensile load is carried on axially in the direction of material deposition. And making use of negative air gaps [4]. In order for the materials to be printed by this technique they must possess a low melting point and should be cheaply available, some of the materials that fulfill these criteria are ABS [5,6] and PLA [7,8]. Another material which can be a good option for use in the FDM process is PEEK which is high in price but possesses good properties and a melting point of 615.15K. PEEK can be used to creates engine parts [9] and human organs [10-12] but this should be done by the process of injection molding if good strength is to be obtained the injection molding offers a tensile strength of 85-102 MPa[13-15] and on the other hand the PEEK printed with the AM process possesses a tensile strength of around 50-55MPa [16-19].

3.2 The Essentials of Printer

- Support 420°C Hot end
- High Precision
- Stability
- Fully Enclosed + Hot Chamber 70°C
- Outage Restored & Filament Detection
- Touch Screen

- Air Filter System
- Automatic Leveling Platform

Figure 3.2: CREATBOT F430

Figure: 3.3 Print Head of CREATBOT F430

3.3 Various process parameters used for the fabrication of part:

1. Orientation: Orientation or part builds orientation is basically defined as the inclination of the part with the bed or build platform with respect to the X, Y and Z axis. In this way the axis X and Y is parallel with the bed or build platform and the axis Z is perpendicular to the bed or build platform.

2. Contour width: The contour width in additive manufacturing refers to the width of each layer which is deposited with the nozzle.

3. Visible surface: The external surface of the 3-d printed object that improved surface exterior appearance.

4. Layer thickness: Layer thickness in additive manufacturing refers to the thickness of the layer that is deposited with the nozzle and it is basically depends upon the type of nozzle used.

5. Raster angle: In additive manufacturing raster angle is basically refers to the orientation with which the successive layer of material is deposited during printing process.

6. Part Fill Style: The part fill style in additive manufacturing defines the manner with which the nozzle fills the material in each layer during printing

7. Infill density: The infill density is the amount of material used to infill. The denser the infill the stronger the part. Infill density is measured in percentage.

8. Nozzle temperature: Nozzle temperature is one of the important factors that will affect the quality of the part. It defines how well the filament is melt then flow through it and then deposited with the previous layer.

3.4 Overview Of material

3.4.1 PETG (Polyethylene terephthalate glycol) material

Polyethylene terephthalate glycol (PETG) chemical formula ($C_{14}H_{20}O_5S$) is a copolymer and thermoplastic with a very good durability, moldability and chemical resistance. It is a kind of PET (Polyethylene terephthalate) which can be easily moldable, heat -bend and vacuum -formed into variety of shapes because of low molding temperature. Apart from these it also provides good bonding properties with solvents and adhesives. PETG is the improvement of the PET polymer. In order to produce the replacement, cyclohexane di-methanol and ethylene glycol in a molecular chain with a bigger monomer will mix, which is crucial for preventing PET crystallization. It is produced by the utilization of two-step melt- phase polycondensation process. It is a very simple process of combining the two monomers with the help of a small release of water. Two British Scientists, John Whinfield and James Dickson was the first who combine the PET and PETG in 1941. This can be done with the help of esterification process to heat the glycols with terephthalic acid. They together sophisticatedly created a long-chain molecule of PET that could turn into fibers with high dissolubility and melting point. By the 1946 PET became the mainstream material for the textile industry and by the 1952 it is also utilized in food packaging industry and by the 1976 PET is used for producing mineral water, carbonated drinks bottles. Despite its usefulness, there are various weakness like high crystallization temperatures, which in turn made it easy and opaque and start demanding for something that is more robust and reliable. Then PETG is came into existence. Polyethylene terephthalate glycol-modified, better known as PETG, was created by replacing ethylene glycol in the molecular chain with a larger monomer; cyclohexane di-methanol stopped the crystallization associated with PET.

3.4.2 PETG Carbon Fiber material

PETG Carbon Fiber is basically a composite material which combines the PETG (Polyethylene Terephthalate Glycol) thermoplastic with carbon fiber reinforcement. PETG is a durable, impact resistance and strong plastic that is most widely used in 3D printing and manufacturing because of its excellent mechanical properties and they can be easily processed. The formation of the PETG Carbon Fiber is done by simply embedding the carbon fibers with the PETG matrix the Carbon Fibers are arranged in a specific orientation in order to optimize the certain properties of the material like tensile and flexural strengths. On the other hand, Carbon Fiber is a material having high- strength, lightweight which is known for its stiffness and dimensional stability. The combination of PETG and carbon fiber produces a material with a very excellent mechanical properties as compared to the traditional PETG. When the carbon fiber reinforcement take place then it increases the material’s strength, stiffness and heat resistance while maintaining its lightweight nature. Because of its light weight and high strength and excellent mechanical properties it is used in automotive components, aerospace parts, and industrial machinery.

Additionally, PETG Carbon Fiber filaments often have a matte black finish, providing a visually appealing aesthetic to printed objects.

3.4.3 Properties of PETG

PETG (Polyethylene terephthalate glycol) is a type of thermoplastic polyester that offers a considerable amount of chemical resistance, durability for the purpose of manufacturing. It is basically a modification of PET (Polyethylene terephthalate) where the letter represents 'Glycol'. The Glycol is added at the molecular level in order to provide a good amount of chemical properties. The PETG offers a comparative advantage over the PLA/ABS in terms of strength and durability the PETG filament offers a greater strength it also offers greater durability as compared to PLA material whereas, on comparing with ABS superior mechanical properties are observed in PETG filament and also less shrinkage and warping is observed which provides good amount of dimensional stability during printing of complex designs. The PETG filament offers a great amount of flexibility which enables to prints parts much easily without bending of snapping which in turn contributes to achieving much greater toughness and resilience it also allows to print parts providing transparency and clarity which provides a good visual appearance for the printed parts. The material also offers a good chemical resistant property to a wide range of materials such as acid, bases and alcohol which allows it to be used with various other substances without compromising the structural integrity of the material. The printing of the PETG filament produces low odor and fumes which creates a pleasant environment for printing. The filament is recyclable which produces a less adverse effect on environment.

Table 1. PETG material data sheet

Properties	Specifications
Specific Density	1.27
Bonding	Excellent
Dissipation factor (at 1 MHZ)	0.02
Arc Resistance	125
Water Absorption Rate (%)	0.20
Hardness	R115
Machining	Good
Transparency	Translucent
Ultrasonic Welding	Excellent
Melting Point (°C)	180
Structure	Amorphous
Chemical Resistance	Good

Impact (Joules)	80
Compression Strength (MPa)	55
Max. Utilization Temperature (°C)	110
Tensile Strength (MPa)	53
Flexural Strength (MPa)	69
Coefficient of Expansion	0.00007
Dielectric Strength (KV/mm)	16
Flexural Modulus (MPa)	2040
Min. Utilization Temperature (°C)	70
UV Resistance	Good
Elongation (%)	31
Optical Transmittance (%)	90

Table 2. PETG CF material data sheet

Properties	**Specifications**
Specific Density	1.25
Bonding	Excellent
Dissipation factor (at 1 MHZ)	0.30
Arc Resistance	125
Water Absorption Rate (%)	0.20
Hardness	90 HRC
Machining	Good
Transparency	Translucent
Ultrasonic Welding	Excellent
Melting Point (°C)	225
Structure	Amorphous
Chemical Resistance	Good
Impact (Joules)	150
Compression Strength (MPa)	100
Max. Utilization Temperature (°C)	150
Tensile Strength (MPa)	59
Flexural Strength (MPa)	80.8
Coefficient of Expansion	0.00007
Dielectric Strength (KV/mm)	18
Flexural Modulus (MPa)	2987
Min. Utilization Temperature (°C)	70
UV Resistance	Good
Elongation (%)	10.4
Optical Transmittance (%)	90

4. Experimentation and Testing

4.1 Specimen preparation

Tensile specimen with a dimension 165mm x 19mm x 3mm. Flexural test specimen having the dimension 125mm x 12.7mm x 3.2mm and the wear test specimen having dimension 30mm x 8mm x 8mm. For Tensile Strength (ASTM 638), Wear (ASTM G99) and for the Flexural Strength (ASTM D790). The parts are modeled in the SolidWorks software and then the Cad file is converted into STL file. Then the STL file imported to the FDM Software (Ulti-maker Cura). The selection of the factors as per experimental plan. The fabrication is done with the use of PETG-CF. The modelling of parts and experiment is conducted as per ASTM standards. The parts are made by using the response surface design.

4.2 Selection of Process Parameters

After concluding the review of various research papers, we have come to the point of deciding about the parameters that will affect the mechanical properties as well as tribological properties of the PETG-CF printed parts. Therefore, from the review conducted three parameters have been chosen that will affects the mechanical and tribological properties, the parameters decided are Infill density, Nozzle temperature and the Layer thickness.

Table 3. Parameter of Experiment

				Level	
Factor	Symbol	Unit	Low (-1)	Medium (0)	High (1)
Infill Density	ID	(%)	50	75	100
Layer Thickness	LT	(mm)	.10	.15	.20
Nozzle Temperature	NT	(°C)	220	230	240

Figure 4.1: Diagram of tensile specimen

Figure 4.2: Diagram of flexural specimen

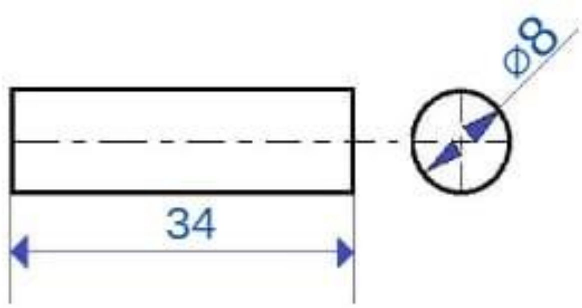


Figure 4.3: Diagram of wear specimen

After the CAD file of the specimen was prepared then RSM based (BBD) is used for the preparation of experimental runs on the FDM CreatBot F430 (3D printing) machine, then the test was conducted on the printed specimen. Tensile test and Flexural test were conducted on Servo Tensile Testing machine and the wear test was performed on the Pin on Disc Machine.

4.3 Specimens Testing

Tensile strength of the specimen is done as per ASTM which is used for determining the specimen's shape. Flexural strength of the specimen is determined at yield as per ASTM standards. For finding the flexural strength three- point bending test is conducted. The test is performed by placing the specimen on the span with the help of two supports and the load is applied on the middle of the specimen, until the specimen gets fracture. In a similar manner for determining the tensile strength one end of the specimen is attached to the fixed jaw and the other end of the specimen is held in the movable jaw and the load is applied on it until, the specimen get fractured. Tensile testing and three - point bending tests are performed on the Servo Tensile Testing machine with crosshead speeds of 3mm/s. Wear test is performed on the Pin on Disc Apparatus which is basically used to determine the specific wear rate as per ASTM. Before the start of the test, we have to calculate the mass of the specimen. Then keep the various parameters of the Pin on Disc Constant like track diameter, speed, load and time for which test is conducting. After conducting the test, we calculate the mass of the specimen. Then we calculate the difference between initial mass of specimen and final mass of specimen. Then we calculate the specific wear rate.

4.4 Machine parameter of Servo Control Tensile Test

Sample Standard	:	ASTM
Load carrying capacity of machine (KN)	:	50
Cross head speed (mm/min)	:	3mm/s
Room Humidity (%)	:	50
Room Temperature(°C)	:	25

(a) Figure Tensile Testing Machine

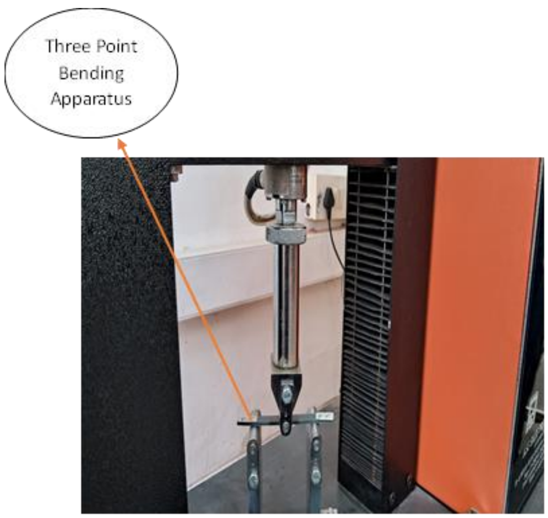
(b) Figure Tensile Test

(c) Figure: Fracture specimen after tensile test

Fig 4.4 Tensile Test Perform on Servo Control Machine

4.5 Machine parameter of Servo Control Flexural Test

Sample Standard	:	ASTM
Load carrying capacity of machine (KN)	:	50
Cross head speed (mm/min)	:	3mm/s
Room Humidity (%)	:	50
Room Temperature(°C)	:	25
Span length(mm)	:	100



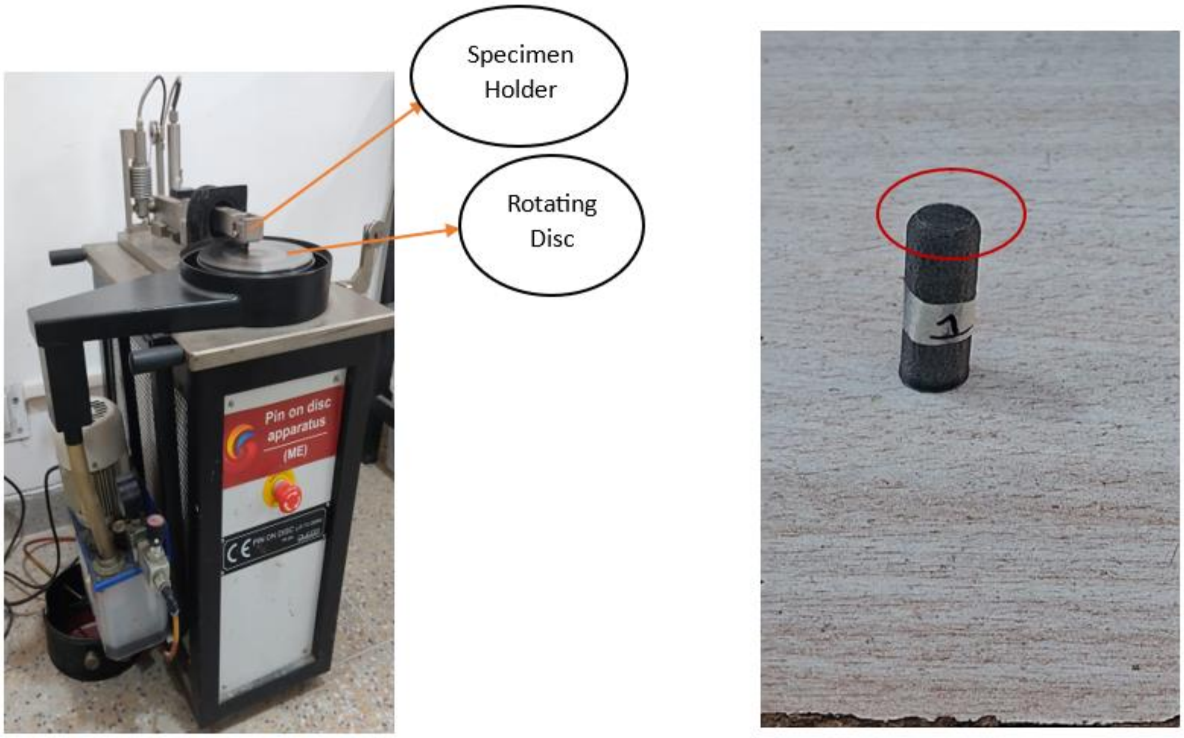
(d) Figure: Flexural test

(e) Figure: Specimen after flexural test

Figure 4.5 Flexural test of specimen

4.6 Machine parameter of Pin on Disc Test

Sample standard	:	ASTM
Speed(rpm)	:	150
Load carrying capacity of machine (KgF)	:	20
Room Humidity (%)	:	50
Room Temperature(°C)	:	25
Track Diameter(mm)	:	100



(f) Figure of Pin on Disc test

(g) Specimen after wear test

Figure 4.6 Pin on Disc test of specimen

The tests were conducted on RSM based Box Behnken Design (BBD) which is basically used for developing the mathematical model for specific wear rate, tensile strength and flexural strength. The BBD is used when the points are not dispersed and it is suitable for fitting a quadratic model. It is preferable if the curvature is assumed to be present in the system. Both BBD and CCD design can work but their structures are different, when the extreme points in the experimental region creates a problem then in that case, BBD have the advantage over the CCD. Maximum and minimum value of the factor is coded into +1 and -1 respectively using, so that all the input factors are represented in the same range.

Table 4 Experimental data obtained from the BBD runs

Run Order	Factors (Coded units) ID	NT	LT	Tensile Strength (MPa)	Flexural Strength (MPa)	Specific Wear Rate (mm^3/Nm)
1	0	-1	-1	14.44	2,7	6.12
2	-1	-1	0	15.88	3.0	2.39156
3	0	-1	1	15.2	2.9	1.7
4	0	0	0	16.236	3.2	2.9
5	1	0	-1	16.195	3.1	1.69578
6	1	1	0	16.172	3.4	5.17
7	0	0	0	15.302	3.0	2.29578
8	-1	1	0	16.331	3.1	2.2
9	1	-1	0	16.41	2.9	2.134
10	1	0	1	16.441	2.8	2.49156
11	0	1	1	14.52	2.4	2.28734
12	-1	0	-1	15.412	2.5	2.39367
13	0	0	0	15.875	3.1	3
14	0	1	-1	16.428	3.1	2.39156
15	-1	0	1	16.23	3.2	2.19578

5. Results and Discussion

RSM can be considered as one of the most useful tools that is used for prediction and optimization of various parameters. In our research work we have predicted the strength of PETG-CF material part which is printed by using fused deposition modelling machine and also the various process parameters that we considered have been optimized with the use of RSM. In this chapter we have discussed the overview of RSM. Response surface methodology is a statistical and mathematical technique which is basically used for developing and optimizing the processes. There are various applications of RSM and it is most widely used in those areas where the several inputs have substantially affected the performance measure or quality of process. The performance measure is known as response. And the input parameters that affects the process is known as independent variables. Response surface methodology also helps in the optimization of the various process parameters that will produces optimum response.[43]

The correlation between the response z and independent variables is given by: α1,α2,α3……………,αk is

$$Z= f(\alpha1,\alpha2,\alpha3\ldots\ldots\ldots\ldots\ldots,\alpha k)+€ \quad 1$$

where € include effects such as background noise the effect of the other variable and so on. Basically € is consider as statistical error and it is to be assumed that it has normal distribution with mean is zero and variance is σ^2. Then,

$$E(z) = \eta = E[f(\alpha1,\alpha2,\alpha3\ldots\ldots\ldots\ldots\ldots,\alpha k)] + E(€)= f(\alpha1,\alpha2,\alpha3\ldots\ldots\ldots\ldots\ldots,\alpha k) \quad 2$$

In the equation 2 the variables α1,α2,α3……………,αk are referred as natural variables, as these variables are expressed in terms of units of measurement like Newton, Newton Metre etc. The natural variables can be easily transformed into coded variables like y1,y2,y3…………,yk which are basically defined to be dimensionless with mean zero and the same standard deviation. The response surface can be expressed in coded form as,

$$\eta = f(y1,y2,y3\ldots\ldots\ldots\ldots,yk) \quad 3$$

Basically, first order model and second order model are used to develop the empirical relationship.

5.1 Response Surface Methodology and Robust Design

In Statistics RSM is most widely for developing the experimental design. It is an analytical technique which is used for the development of new process and also used for optimizing the performance of the process. With the use of RSM the objective of the quality improvement including reduction of the variability and improved product process and performance can be accomplished.

One of the professors whose name was Dr. Genichi Taguchi used the term robust parameter design (RPD) in order to explain his approach to this important problem. RRD approach, in its essence, favors minimizing process or product variation by the selection of controllable factor (or parameter) values that render the system resilient (or insensitive) to shifts in a collection of uncontrolled elements that make up the majority of the variability's origins. These outside influences were referred to as "noise factors" by Taguchi. RSM makes the assumption that while these noise effects can be controlled during process development for the sake of a planned experiment, they are uncontrolled in the field.

5.2 Sequential Nature of RSM

Phase 0: In this case firstly the ideas were generated that concern about the effect of variables or factors on the response surface study. This phase is basically known as the design of experiment. The purpose of the design of experiment is to reduce the number of experiments so that the successive experiments will be performed more efficiently and also reduces the number of runs. The main purpose of this phase is to find out the significant independent variables.

Phase 1: In this phase the experiment is done to find out whether the existing setting of the independent variables will produce the result having the value of response which is near the optimum. And if the set of independent variables are not significant with the optimum performance, then the adjustment must be done in the process variables that will push the value towards the optimum range. This stage of the RSM utilizes the use of first- order model and this optimization technique is known as steepest ascent/descent.

Phase 2: This phase signifies that the when the process is near the optimum value, then a model is developed which is used for the approximation of the true response surface within a small area which is near to the optimum. If there is a curvature appears in the true response surface near to the optimum range then in this case second order model is used. And when the correct model was developed, after that the model is analyzes in order to find the optimum range for the process.

5.3 Developing Heuristic Model

5.3.1 Linear regression model:

RSM is basically used for establishing a mathematical model on the basis of the true response surface. With the help of some unknown physical mechanism the true response surface is typically driven. The observed data from the process is used to develop the approximated model and the model which is develop is an empirical model. In order to build the empirical models in RSM multiple regression which is collection of statistical technique is used.

The first-order model with two independent variables is:

$$Y= Ao+A1x1+A2x2+€ \qquad (4)$$

The independent variables are called as regressors. We used the term “linear” because the equation (4) is a linear function of the parameters Ao, A1 and A2.

The response variable y is related to the k regressor variables. Then the model is given by:

$$Y= Ao+A1x1+A2x2+\ldots\ldots\ldots\ldots\ldots.Akxk+€ \qquad (4.11)$$

The model is known as the linear regression model having k regressor variables. The parameters Aj, j=0,1,………k is known as regression coefficients. The model which are difficult to analyzed in comparison with the equation (4.11), then these models are studied with the help of multiple regression methods.

The first order RSM based regression model with two variables including the interaction terms is represented as:

$Y = Ao + A1x1 + A2x2 + A12x1x2 + €$ (4.12)

Another example is that, two variables second order response surface model is represented as:

$Y = Ao + A1x1 + A2x2 + A11x^2 1 + A22x^2 2 + A12x1x2 + €$ (4.13)

5.3.2 Estimation of the parameters in linear regression models

In order to estimate the regression coefficients in a multiple regression model, the least square method is used. If it is considered that the n>k observations then the available response: y1,y2,y3……..yn. It is observed that the with each response yi there will a regressor value, xij denotes the i-th observation. The model can be written in matrix notation in terms of the observations as:

$Y = XA + €$ (4.14)

where,

Y denotes the observations nx1 vector.

The levels of the independent variables are denoted by n x p matrix, X,

The regression coefficients of p x 1 is denoted A and

The random errors of n x 1 vector is denoted by €.

5.4 Variable Selection and Model Building in Regression

According to the situation it is usual to fit the full model in the RSM. It means that in the steepest ascent, it is necessary to fit the full first order regression model and it requires to fit the full quadratic model for the analysis of the second order model. At the same time there are cases where the full model is not appropriate then, in those cases a model which is based on the subset of the regressors in the full model is important. Variable selection and model building techniques is basically used to find the best subset of regressors to include in the regression model. Now it is to assumed that the number of candidates regressors are K which is denoted by x1, x2, x3……….. xk while the response surface is single i.e. Y.

5.4.1 Procedure for variable selection

There are many techniques which are basically used for the selection of the right subset of variables for a regression model. This technique is also used for the optimization purpose in which it chooses the best model from the various available models and provide the explanation on the basis of which selection of best model is done.

5.4.2 All possible regression

This procedure requires that all the regression equations are fitted involving one-candidate regressors, two-candidate regressors, and so on. The evaluation of the equations are basically based on some criteria and the best regression model is selected from it. It is to be assumed that if the intercept is Ao is included in all the equations, then there will be the K candidate regressors and the total equation that is to be estimated and examined is 2^k. For example, if k = 5, then there are 2^5 = 32 possible equations, whereas if k = 12, then there are 2^{12} =4096. The number of equations increases exponentially when the number of candidates regressors increases. For full quadratic polynomial model, it is found that the candidate variables are limited and it is necessary for all the models to follow the principal of hierarchy. The higher order terms, such as the interactions and second-order-terms which is present in a hierarchical model necessitate the incorporation of every lower order term in the higher order. For example, if the two-factor interaction was present in the model then this required the inclusion of both the main effects.

5.4.3 Stepwise regression methods

Several methods have been proposed for the evaluation of small quantity of subset regression model adding or subtracting the regressor. These can be broadly classified into three categories:

1. Forward Selection
2. Backward Elimination
3. Stepwise Regression

5.5 Analysis of experiments

The experimental data obtained from the BBD design runs was analyzed on the MINITAB R21 software with the use of full quadratic response model which is given by

$$y = Ao + \sum_{i=1}^{k} Aixi + \sum_{i=1}^{k} Aiixixi + \sum_{i<j}^{k} Aijxixj$$

where y is response and xi is ith factor

In order to check the significance of F value given the ANOVA table is used. Due to the noise which is indicated by the p value, the probability of F value is greater than the calculated value of F. The significance of the corresponding term is established if the p value is less than 0.05. The p value must be greater than 0.05 for lack of fit.

Table 5: ANOVA (Analysis of experiment) of Flexural Test

Source	Adj SS	Adj MS	F-Value	P-Value
Model	0.97433	0.108259	12.99	0.006
Linear	0.8	0.266667	32	0.001
ID	0.72	0.72	86.4	0
NT	0.08	0.08	9.6	0.027
LT	0	0	0	1
Square	0.02683	0.008944	1.07	0.439
ID*ID	0.02314	0.023141	2.78	0.157
NT*NT	0.00314	0.003141	0.38	0.566
LT*LT	0.00314	0.003141	0.38	0.566
2-Way Interaction	0.1475	0.049167	5.9	0.043
ID*NT	0.0625	0.0625	7.5	0.041
ID*LT	0.0625	0.0625	7.5	0.041
NT*LT	0.0225	0.0225	2.7	0.161
Error	0.04167	0.008333		
Lack-of-Fit	0.015	0.005	0.38	0.784

Pure Error	0.02667	0.013333
Total	1.016	

S = 0.0912871 R-sq = 95.90% R-sq(adj) = 88.52%

In flexural test analysis the factors ID (Infill Density) and NT (Nozzle Temperature) are significant because their P value is less than 0.05 and the interactions ID*NT and ID*LT are significant because their P value is also less than 0.05.

But the factor LT is insignificant for a given set of parameters that we have chosen for our experiment because their P value is greater than 0.05.

And the interactions ID*ID, NT*NT, LT*LT, NT*LT are insignificant as their P value is greater than 0.05.

The coefficient of determination R-sq which basically shows the goodness of fit of a model has a value of R-sq= 95.90% which indicates the high significance of a model.

From the above experimentations we concluded the following regression equations:

FS = -31.5 + 0.1610 ID + .204 NT + 45.5 LT – 0.000127 ID*ID – 0.000292 NT*NT – 11.7 LT*LT – 0.000500 ID*NT -0.1000 ID*LT – 0.1500 NT*LT

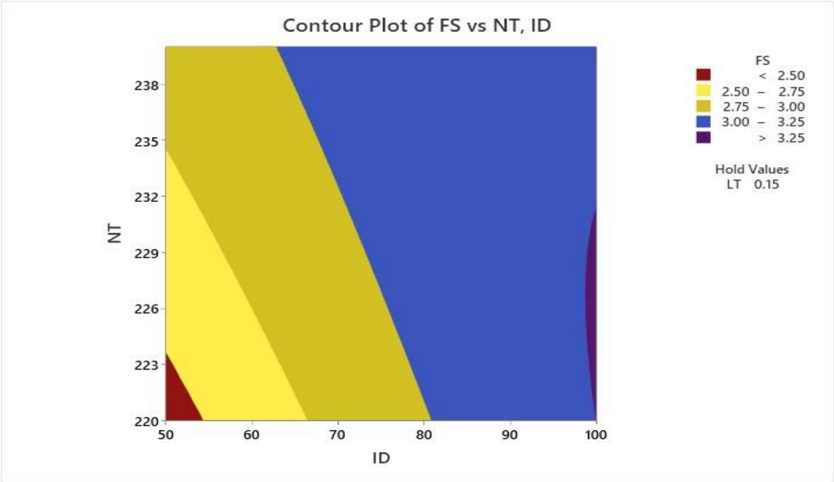


Figure 5.1 : Contour Plot between NT and ID and its effect on FS

It is a graph between NT (Nozzle Temperature) and ID (Infill Density) and its effect on FS (Flexural Strength) keeping the LT (layer thickness) at 0.15.

This graph shows that the good value of FS obtained at the Infill Density ranging from 75% to 90% and the best value is at 100% and the Nozzle Temperature at which the value of FS is good is ranging from 220 to 240 and the best value is obtained at 220°C to 230°C. This is because as the infill density increases the air gap between the molecules decreases and the structure become more dense due to which the force required to bend the structure got increases. And when the nozzle temperature is lower than the molten material gets proper time to solidify. Due to this reason every printed layer got the proper time to solidifies it increases the bonding between the layer and thus the structure between the layer get dense and thus the flexural strength increases.

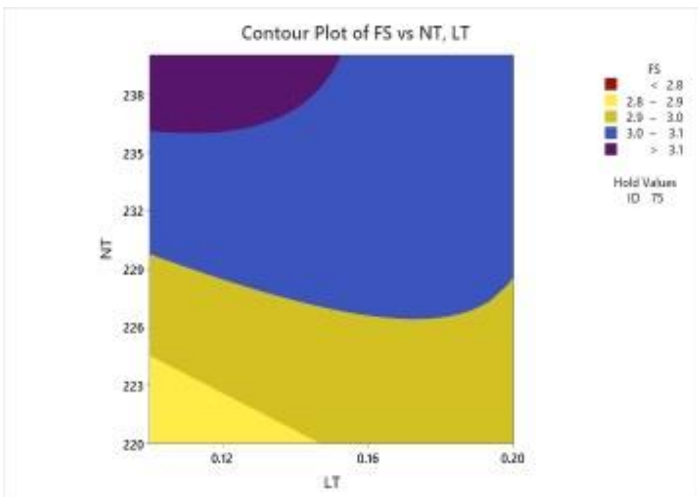


Figure 5.2 : Contour Plot between NT and LT and its effect on FS

It is a graph between NT (Nozzle Temperature) and LT (Layer thickness) and its effect on FS (Flexural Strength) keeping the ID (Infill Density) at 75%. This graph shows that the best value FS obtained at the Nozzle Temperature ranging from 236°C to 240°C and the layer thickness ranging from 0.12mm to 0.15mm. This is because as the layer thickness is low then the adhesion between the molecule is proper and they do not get separated upon the application of shear force but as the layer thickness increases from a certain range then it weakens the structure in z-direction which results in splitting between layers and thus reduces the overall flexural strength and as the nozzle temperature is high then it promotes better material flow and adhesion between layer during printing, resulting in a more homogeneous structure and improved flexural strength.

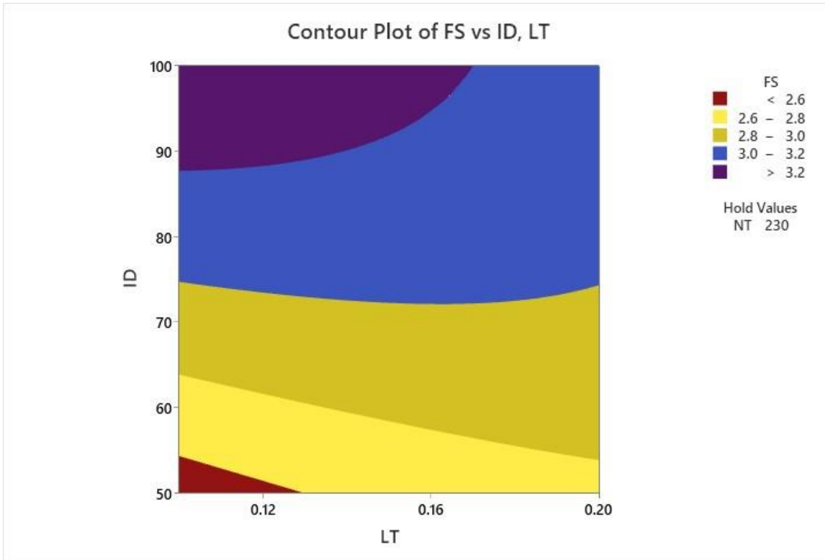


Figure 5.3 : Contour Plot between ID and LT and its effect on FS

It is a graph between ID (Infill Density) and LT (Layer thickness) and its effect on FS (Flexural Strength) keeping the NT (Nozzle Temperature) at 230°C.
This graph shows that the best value of FS obtained at the Infill Density ranging from 85% to 100% and the layer thickness ranging from 0.1mm to 0.18mm.

This is because as the infill density increases the air gap between the molecules decreases and the structure become more dense due to which the force required to bend the structure got increases thus flexural strength increases. As the layer thickness up to a certain range the flexural strength increases. The reason for this is because the thicker part shows more strength as compared to the thinner part as for determination of flexural strength load is applied transverse to the specimen length. So when the layer thickness is thicker then the each layer would provide the opposition against the failure as compared to thinner layer thickness.

Table 6: ANOVA (Analysis of experiment) of Tensile Test

Source	Adj SS	Adj MS	F-Value	P-Value

Model	6.28255	0.69806	33.43	0.001
Linear	4.1757	1.3919	66.66	0
ID	3.64095	3.64095	174.37	0
NT	0.0609	0.0609	2.92	0.148
LT	0.47385	0.47385	22.69	0.005
Square	1.34631	0.44877	21.49	0.003
ID*ID	1.08383	1.08383	51.91	0.001
NT*NT	0.24206	0.24206	11.59	0.019
LT*LT	0.16876	0.16876	8.08	0.036
2-Way Interaction	0.76054	0.25351	12.14	0.01
ID*NT	0.11357	0.11357	5.44	0.067
ID*LT	0.31979	0.31979	15.31	0.011
NT*LT	0.32718	0.32718	15.67	0.011
Error	0.10441	0.02088		
Lack-of-Fit	0.07079	0.0236	1.4	0.442
Pure Error	0.03361	0.01681		
Total	6.38696			

S=0.144503 R-sq = 98.37% R-sq(adj) = 95.42%

In tensile test analysis the factors LT (Layer Thickness) and ID (Infill Density) are significant because their P value is less than 0.05 and the interactions ID*ID, NT*NT, LT*LT, ID*LT and NT*LT are significant because their P value is also less than 0.05. But the factor NT is insignificant for a given set of parameters that we have chosen for our experiment because their P value is greater than 0.05. And the interaction ID*NT is insignificant as their P value is greater than 0.05.

The coefficient of determination R-sq which basically shows the goodness of fit of a model has a value of R-sq= 98.37% which indicates the high significance of a model.

From the above experimentations we concluded the following regression equations:

TS= -118.6 + 0.2781 ID + 1.151 NT -127.7 LT – 0.000867 ID*ID -0.002560NT*NT - 85.5LT*LT -0.000674 ID*NT +0.2262 ID*LT +0.572 NT*LT

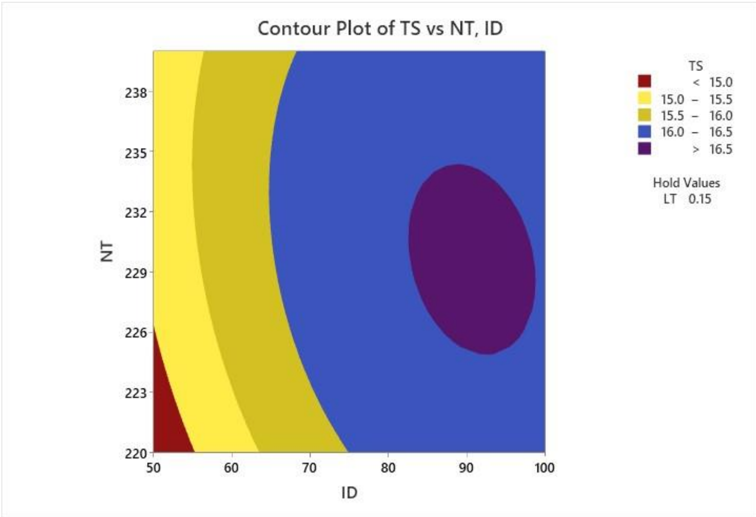


Figure 5.4 : Contour Plot between NT and ID and its effect on TS

It is a graph between ID (Infill Density) and NT (Nozzle Temperature) and its effect on TS (Tensile Strength) keeping the LT (Layer Thickness) at 0.15mm.

This graph shows that the best value of TS obtained at the Infill Density ranging from 90% to 100% and the Nozzle Temperature ranging from 225°C to 234°C.

This is because the extrusion behavior of the PETG-CF is directly impacted by the nozzle temperature.

As achieving higher temperature provides better flow and provides good adhesion between the layers. Which results in strong interlayer bonding at the molecular level. Which in turn results in obtaining greater tensile strength.

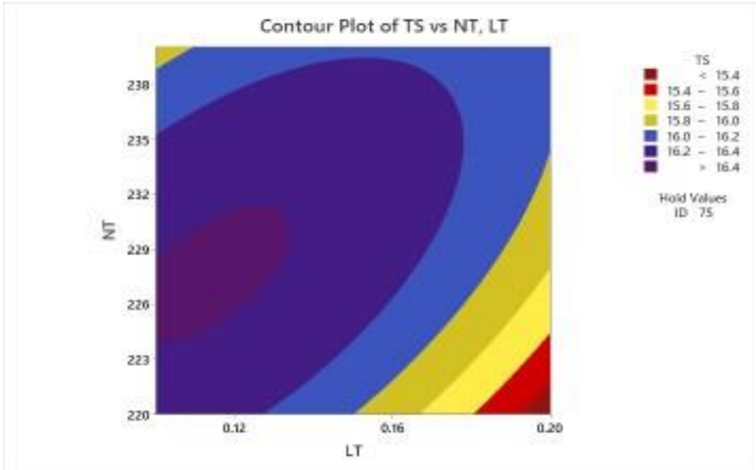


Figure 5.5 : Contour Plot between NT and LT and its effect on TS

It is a graph between NT (Nozzle Temperature) and LT (Layer Thickness) and its effect on TS (Tensile Strength) keeping the ID (Infill Density) at 75%.

This graph shows that the best value of TS obtained at the layer thickness at 0.1mm and the Nozzle Temperature ranging from 224°C to 228°C.

This is because the thinner layer may improve the tensile strength by reducing the likelihood of delamination between layers.

And lower temperature might be sufficient for thinner layers where interlayer adhesion is naturally stronger.

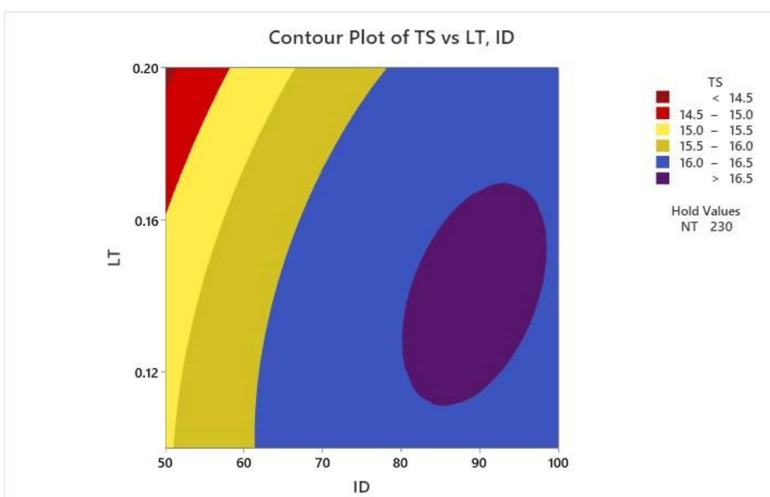


Figure 5.6 : Contour Plot between LT and ID and its effect on TS

It is a graph between LT (Layer Thickness) and ID (Infill Density) and its effect on TS (Tensile Strength) keeping the NT (Nozzle Temperature) at 230°C.

This graph shows that the best value of TS obtained at the layer thickness at 0.11mm to .16mm and the Nozzle Temperature ranging from 224°C to 228°C.

Thinner layers may require higher infill densities to maintain structural integrity and tensile strength.

Table 7 ANOVA (Analysis of experiment) of Wear Test

Source	Adj SS	Adj MS	F-Value	P-Value
Model	20.1559	2.2395	9.21	0.012
Linear	0.0654	0.0218	0.09	0.963
ID	0.0002	0.0002	0	0.981
NT	0.065	0.065	0.27	0.627
LT	0.0003	0.0003	0	0.974
Square	8.4206	2.8069	11.55	0.011
ID*ID	2.4321	2.4321	10	0.025
NT*NT	1.3947	1.3947	5.74	0.062
LT*LT	4.351	4.351	17.9	0.008
2-Way Interaction	11.6698	3.8899	16	0.005
ID*NT	0.417	0.417	1.72	0.247
ID*LT	11.2102	11.2102	46.11	0.001
NT*LT	0.0426	0.0426	0.18	0.693
Error	1.2156	0.2431		
Lack-of-Fit	0.9681	0.3227	2.61	0.289
Pure Error	0.2475	0.1237		
Total	21.3715			

S=0.493071 R-sq = 94.31% R-sq(adj) = 84.07%

In wear test analysis the interactions ID*ID, LT*LT, ID*LT are significant because their P value is also less than 0.05. But the factor NT, LT and ID are insignificant for a given set of parameters that we have chosen for our experiment because their P value is greater than 0.05.

And the interaction NT*NT, ID*NT and NT*LT are insignificant as their P value is greater than 0.05.

The coefficient of determination R-sq which basically shows the goodness of fit of a model has a value of R-sq= 94.31% which indicates the high significance of a model.

From the above experimentations we concluded the following regression equations:

$$\mathbf{WR = -308 - 0.291\,ID + 2.77\,NT + 18\,LT + 0.001299\,ID*ID - 0.00615\,NT*NT + 434\,LT*LT + 0.001292\,ID*NT - 1.339\,ID*LT - 0.206\,NT*LT}$$

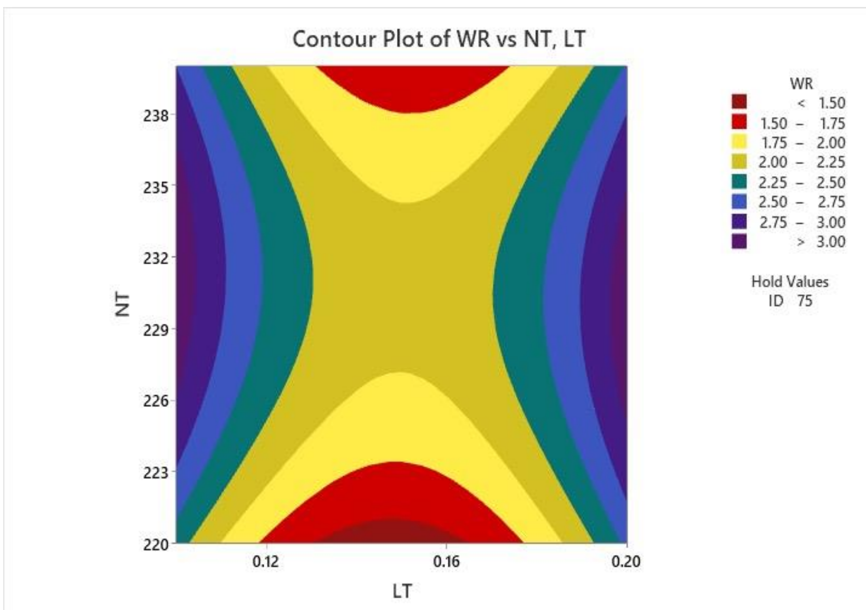


Figure 5.7 : Contour Plot between LT and ID and its effect on WR

It is a graph between LT (Layer Thickness) and NT (Nozzle Temperature) and its effect on wear rate keeping the ID (Infill Density) at 75%.

This graph shows that the best value of WR obtained at the layer thickness at 0.12mm to .18mm and the Nozzle Temperature ranging from 220°C to 240°C higher nozzle temperatures may be more effective at compensating for weaker interlayer bonding in thicker layers. Conversely, lower temperatures may be sufficient for thinner layers where interlayer adhesion is naturally stronger.

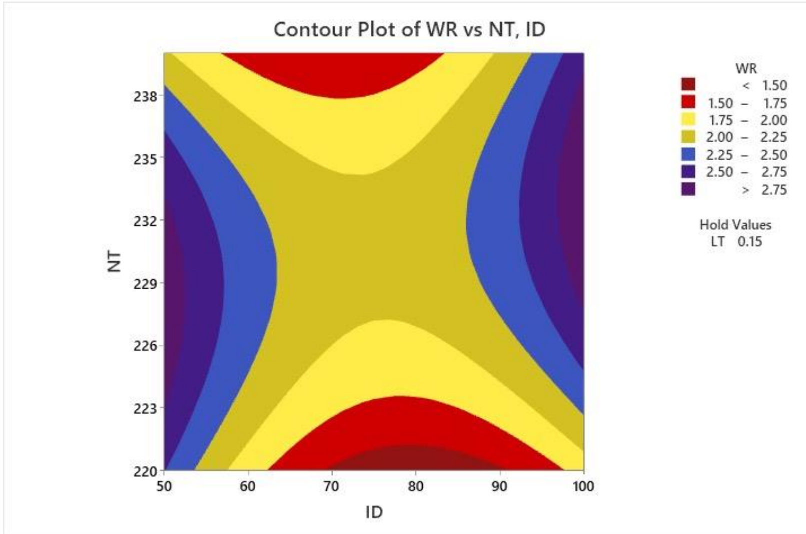


Figure 5.8 : Contour Plot between NT and ID and its effect on WR

It is a graph between ID (Infill Density) and NT (Nozzle Temperature) and its effect on wear rate keeping the LT (Layer Thickness) at 0.15mm This graph shows that the best value of WR obtained at the Infill Density at 62%-98% and the Nozzle Temperature ranging from 220°C to 240°C. It is generally observed having high nozzle temperature and high infill density often lead to high material bonding at the molecular level which in turn helps the material in withstanding wear which contributes in lower specific wear rates.

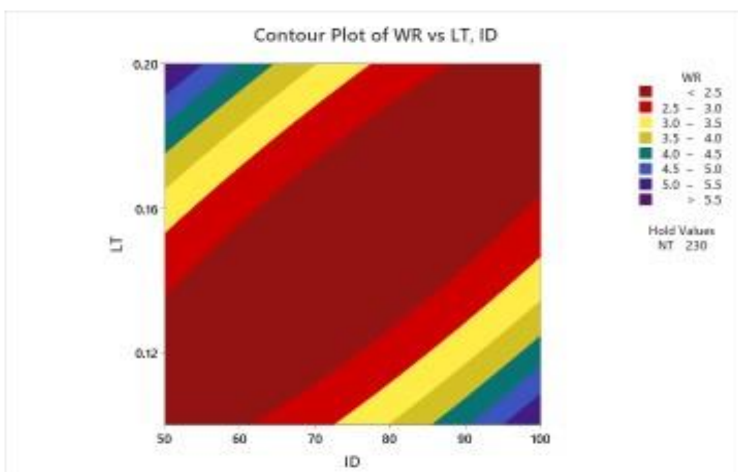


Figure 5.9 : Contour Plot between LT and ID and its effect on WR

It is a graph between ID (Infill Density) and LT (Layer Thickness) and its effect on wear rate keeping the NT (Nozzle Temperature) at 230°C.

This graph shows that the best value of WR obtained at the Infill Density at 50%-73% and the Layer Thickness ranging from 0.1mm to 0.15mm.

It can be observed that having higher infill density contribute to increased stiffness and high strength, while on the other side the layer thickness affects the surface finish of the printed parts.

Table 8 Result of Tensile Test from Contour Plot

N.T (°C)_	I.D (%)	L.T (mm)	T.S (MPa)
220-240	75-100%	-	>16
220-238	-	0.1-0.15	>16
-	79-100	0.1-0.2	>16

Table 9 After Intersection

N.T (°C)	I.D (%)	L.T (mm)	T.S (MPa)
220-238	79-100	0.1-0.15	>16

Table 10 Result of Flexural Test from Contour Plot

N.T (°C)_	I.D (%)	L.T (mm)	F.S (MPa)
220-230	98-100%	-	>3.2
236-240	-	0.1-0.16	>3.1
-	89-100	0.1-0.17	>3.2

Table 11 After Intersection

N.T (°C)	I.D (%)	L.T (mm)	F.S (MPa)
220-240	89-98	0.16-0.175	>3.2

Table 12 Result of Wear Test from Contour Plot

N.T (°C)	I.D (%)	L.T (mm)	SWR (mm^3/Nm)

220-240	-	0.12-0.16	1.5-1.75
220-240	60-90	-	1.5-1.75
-	50-60	0.1-0.12	<2.5

Table 13 After Intersection

N.T (°C)	I.D (%)	L.T (mm)	SWR (mm^3/Nm)
220-240	50-90	0.1-0.16	<2.5

Table 14 Intersection of Optimal Input Parameter

N.T (°C)	I.D (%)	L.T (mm)	T.S (MPa)	F.S (MPa)	SWR (mm^3/Nm)
220-238	79-98	0.15-0.175	>16	>3.2	<2.5

Discussion

When the nozzle temperature, infill density and layer thickness are in the range of (220-238°C), (79-100%) and (0.1-0.15mm) respectively, then the value of tensile strength would be above 16MPa. This is because the thinner layer may improve the tensile strength by reducing the likelihood of delamination between layers. As achieving higher temperature provides better flow and provides good adhesion between the layers. Which results in strong interlayer bonding at the molecular level. Which in turn results in obtaining greater tensile strength. On the basis of the range that obtained through contour plots the specimens were printed on the CreatBot F430 printer and then were tested on the Servo Control Tensile Testing Machine. After the testing the tensile strength obtained was 16 MPa and above.

Similarly, when the nozzle temperature, infill density and layer thickness are in the range of (220-240°C), (89-98%) and (0.16-0.175mm) respectively, then the value of flexural strength would be above 3.2MPa. This is because as the infill density increases the air gap between the molecules decreases and the structure become more dense due to which the force required to bend the structure got increases. And when the nozzle temperature is lower then the molten material get proper time to solidify. Due to this reason every printed layer got the proper time for solidification and thus increases the bonding between the layer and thus the structure between the layer get dense and thus the flexural strength increases. And when the layer thickness is low then the adhesion between the molecule is proper and they do not get separated upon the application of shear force but as the layer thickness increases from a certain range then it weakens the structure in z-direction which results in splitting between layers and thus reduces the overall flexural strength and as the nozzle temperature is high then it promotes better material flow and adhesion between layer during printing, resulting in a more homogeneous structure and improved flexural strength.

Similarly, when the nozzle temperature, infill density and layer thickness are in the range of (220-240°C), (50-90%) and (0.1-0.16mm) then the value of specific wear rate would be less than 2.5 mm^3/Nm. This is because higher the nozzle temperature and higher the infill density often lead to high material bonding at the molecular level which in turn helps the material in withstanding wear which contributes in lower specific wear rates. It is also observed that having higher infill density contribute to increased stiffness and high strength, while on the other side the layer thickness affects the surface finish of the printed parts.

Validation Experiment

N.T (°C)	I.D (%)	L.T (mm)	T.S (MPa)	F.S (MPa)	SWR (mm^3/Nm)
225	80	0.155	16.2479	3.3234	1.6248
230	90	0.16	16.4465	3.4185	1.9693
235	95	0.17	16.3813	3.5553	1.9866

After the suitable ranges have been obtained from the intersection then the validation experiment had been carried out. The specimens were printed on the suitable ranges obtained for the following parameters i.e. Nozzle Temperature (N.T), Layer Thickness (L.T) and Infill Density (I.D). after printing the specimen were tested for the various mechanical properties (T.S, F.S and SWR). The result obtained from testing the printed specimen showed that the values of T.S, F.S AND SWR were as follows (>16 MPa), (<3.2 MPa) and (>2.5 mm^3/Nm). This shows that the validation is justified.

6. CONCLUSION & FUTURE SCOPE

6.1 Conclusion

The current research work focuses on the effects of three process parameters like layer thickness, nozzle temperature and infill density on the responses like tensile strength, flexural strength and wear rate of the 3D printed test specimen. In order to perform the experiment basically RSM based Box Behnken Design (BBD) is used. Analysis of variance is used to established the empirical relationship between each response and various input parameters and their validity is proved. Then the mathematical models were generated on Response Surface Methodology (RSM) for each response based on results obtained from the testing. Then RSM is used for generating the contour plots between input parameters and response. In contour plot two input parameters were taken at a time and keeping the third one constant and predict its effect on individual response. So, from the contour plots range of Nozzle Temperature (NT), Layer Thickness (LT) and Infill Density (ID) obtained and their effect on the Tensile Strength (TS), Flexural Strength (FS) and Specific Wear Rate (SWR). Now after taking the intersection optimal range of input parameters were obtained. The optimality of the input parameters were validated by performing pilot experiments on the same machine (Creatbot F430) and testing were performed on the servo control tensile testing machine as per ASTM standard.

6.2 Future Scope

The future research and development could unlock the potential to make use of multi-scale modelling and simulation techniques to make a prediction on the mechanical behavior of PETG-CF specimen printed by the FDM technique under different loading conditions. By examining the microstructural behavior of the printed part deeper knowledge about the effects of various printing parameters on mechanical properties can be studied. This would further help in identifying the suitable printing parameters for mechanical performance targets. In future integrating more advanced optimization technique alongside RSM to improve the accuracy and efficiency of the process parameters for the optimization of 3d printed PETG-CF material can be done. Several methods such as generic algorithm could be employed to improve the complex parameter space and help in identifying the suitable printing that would provide the best mechanical properties at the same time reduce wastage and energy consumption. Also with further research multi-objective optimization could also be employed in order to optimize surface finish, strength and production cost.

In the near future there is also a chance of integrating various sensing and control technologies that could adjust the printing parameters in order to maintain optimal performance.

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