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Simulation of Warping in Fused Deposition Modeling

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Abstract

With the improving technology, manufacturing techniques are getting advanced every day. Additive Manufacturing, being a relatively recent technology, has some areas yet to be improved. Warping in Fused Deposition Modeling is one of them. This study examines the effect of different process parameters on warping. A thorough literature review is done with the aim of finding optimal parameters that minimizes warping. A model is developed with Response Surface Methodology with this data and a simulation that predicts warping for different process parameters is created. Warping is minimized with optimum process parameters as; bed temperature at 130 °C, extrusion temperature at 400 °C, print speed at 20 mm/s and layer height at 0.1 mm, which results in 0.6% warping for PEEK material in Fused Deposition Modeling. The simulation created plays a role as a guide when a process parameter is restricted and there is no option to apply its optimum, showing how to compromise it with other parameters to reduce warping. Or, more importantly, to simply predict the warping level with the chosen parameters before starting the process, which eliminates trial&error and results in efficiency in time and energy.

Keywords: additive manufacturing, fused deposition modeling, warping, response surface methodology

Abstract in lingua italiana

Con il progresso tecnologico, le tecniche di produzione si evolvono ogni giorno. La manifattura additiva, essendo una tecnologia relativamente recente, presenta ancora alcuni aspetti da migliorare. La deformazione (warping) nella Modellazione a Deposizione Fusa (FDM) è uno di questi.

Questo studio esamina l'effetto di diversi parametri di processo sulla deformazione. Viene svolta una revisione approfondita della letteratura con l'obiettivo di individuare i parametri ottimali che minimizzano la deformazione. Un modello è sviluppato utilizzando la Metodologia della Superficie di Risposta con questi dati, e viene creato una simulazione che predice la deformazione per diversi parametri di processo.

La deformazione viene minimizzata con parametri di processo ottimali quali: temperatura del letto a 130 °C, temperatura di estrusione a 400 °C, velocità di stampa a 20 mm/s e altezza dello strato a 0,1 mm, ottenendo una deformazione dello 0,6% per il materiale PEEK nella Modellazione a Deposizione Fusa.

La simulazione creata funge da guida nel caso in cui un parametro di processo sia limitato e non vi sia possibilità di applicarne il valore ottimale, mostrando come compensarlo con altri parametri per ridurre la deformazione. O, più significativamente, permette di prevedere il livello di deformazione con i parametri scelti prima di avviare il processo, eliminando prove e errori e portando a un'efficienza in termini di tempo ed energia.

Parole chiave: manifattura additiva, modellazione a deposizione fusa, deformazione (warping), metodologia della superficie di risposta

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Introduction

With swiftly advancing technology, every aspects of the industry are trying to improve and adapt to this rapid change. Newly developed manufacturing types and materials come with their own necessity for improvement, especially in cutting edge sectors like aerospace.

Additive manufacturing is one of the latest production techniques that is being enhanced and is still being refined. Since it is still a relatively new topic, there are many areas yet to be improved.

Fused deposition modeling, being one of the most used additive manufacturing techniques, is also subjected to this obscurity. There are several defects that emerges during and after fused deposition modeling process. Warping is one of the crucial, if not the most important, defect that arise in fused deposition modeling process. It represents the printed part to curl and lift, therefore end up being distorted.

There are not many analysis or simulation techniques to predict and prevent warping, compared to conventional manufacturing processes and their challenges. Because of this, usually trial and error is the instructive tool while choosing optimal fused deposition modeling process parameters to guess and minimize warping.

This study draws attention to this exact problem, and aims to provide a useful and comprehensive solution. The main objective is simulating and foreseeing the warping level that changes with various process parameters. The simulated prediction model allows to acknowledge and compromise the effects of different parameters on warping, while suggesting and allowing to choose optimum parameters to minimize warping in fused deposition modeling.

1 | Additive Manufacturing

Additive manufacturing made its debut in the industry in 1986, by Charles Hull, and it swiftly continues to gain popularity among the industry. It is first intended for rapid prototyping, however, nowadays it is also used for functional parts [21].

Differentiated than conventional manufacturing techniques, additive manufacturing does not produce the part by removing material, instead, it builds the product by adding material. Traditional manufacturing techniques uses subtractive machining, such as milling, turning, etc. Additive manufacturing on the other hand, forms physical objects by combining powder, sheet materials, or liquid layer by layer [16].

The definition of additive manufacturing according to American Society for Testing and Materials ASTM F42 committee is; “process of joining materials to make objects from three-dimensional model data, usually layer by layer, as opposed to subtractive manufacturing methodologies” [20, 22]. Therefore, final part consists discrete layers of material in additive manufacturing, whereas in traditional techniques the final part is created from extracting the material in bulk [5]. Traditional manufacturing, also known as subtractive manufacturing, is a process where parts are made, stamped, or molded from larger pieces of materials [22].

1.1. Advantages of Additive Manufacturing

Additive manufacturing, which has been in high demand in the industry recently, has valid reasons. It has many advantages due to its innovative and pioneer properties.

The first of the advantages is the design flexibility that additive manufacturing provides. It allows for creating complex geometries that might not be possible to create with conventional production techniques. It also provides customization without any extra cost, the product can be specialized according to the demand.

Secondly, additive manufacturing is significantly better than traditional methods in terms of material efficiency. Due to the creation of the product layer by layer, the material is only used where it is needed. It results much less material waste compared to subtractive

manufacturing, where the excess material is usually cut away and wasted.

Additive manufacturing also reduces assembly requirements. Even complex components can be produced as single or integrated parts, removing the need for assembly. This leads to the need of less joints and fasteners, which improves the mechanical properties of the end module, such as strength and durability.

Additive manufacturing has also has economic benefits compared to traditional manufacturing techniques. The cost of the tooling is reduced because there is no need for molds. Instead, support structures can be designed and used. The research [2] proved that additive manufacturing is more cost effective than traditional manufacturing techniques in the aerospace industry without sacrificing mechanical properties.

In addition to that, compared to the production of solid aerospace materials using additive manufacturing and conventional devices, results showed that additive manufacturing allows the fabrication of more complex parts with excellent accuracy and fewer errors [5].

Because of the material efficiency and less energy used due to simplified supply chain and decreased production time, additive manufacturing is a perfect example of sustainable manufacturing. It reduces the environmental impact caused by the production process [22].

Result of some of these benefits, such as rapid prototyping, integrated and consolidated manufacturing, elimination of tooling, on-demand manufacturing, shorter production runs and faster time to market leads to one really important advantage; time efficiency. It offers significant time efficiency benefits by streamlining design, prototyping, and production processes. It enables rapid prototyping, allowing for fast design iterations and shorter lead times, while eliminating the need for time-consuming tooling and molds. The ability to produce parts on-demand and locally reduces logistical delays, and the technology's flexibility in switching between different designs without retooling speeds up production runs. Additionally, additive manufacturing reduces assembly time by producing complex components as a single part, ultimately accelerating product development and shortening time-to-market.

1.2. Disadvantages of Additive Manufacturing

However, as always, there is the reverse of the medal. Although being efficient, innovative and beneficial in many subjects, additive manufacturing has its own disadvantages, complications and problems. Especially because it is a newly improving technology.

First, additive manufacturing has a material limitation that can be used, due to the specific material property requirements that is needed in the process. Even though new materials added to the usage everyday thanks to improving technology, the range of the material choice is still much smaller than traditional manufacturing techniques. Especially high strength metals and some specialized polymers are not suitable for additive manufacturing yet.

Some 3D-printed materials may not have the same mechanical properties, such as in terms of strength and durability, as those produced by traditional manufacturing methods.

Due to the limited chamber size and the build volume of the 3D printer, the product has a size limitation. This can cause restrictions for production of the larger components. Another issue with the larger parts is obtaining high precision and accuracy, which can lead to problems with part consistency. Also the surface finish can be rough with parts that are produced with additive manufacturing compared to the ones that are produced with conventional methods. As a result, they need additional post processing for the surface quality.

In some additive manufacturing processes, layer adhesion can be a weak point, potentially affecting the mechanical properties and durability of the final product.

Even though it is mentioned additive manufacturing has great time advantage due to many reasons, when it comes to mass production, additive manufacturing lacks production rate and it can be slower than conventional methods.

Also, many parts that are produced with additive manufacturing usually requires post processing due to poor surface quality or mechanical properties, which increases the overall production time.

Even though the waste of the material is reduced, the raw materials that are used in additive manufacturing can be more expensive than the ones used in traditional.

The initial investment in high-quality 3D printers and materials can be significant, increasing the equipment cost.

Last but not least, since additive manufacturing is quite new and less experienced technology, there is still bias towards traditional manufacturing techniques in the industry. This disadvantage will be overcome with more and more practice and improvements in additive manufacturing area.

1.3. Types of Additive Manufacturing

There are a lot of different additive manufacturing techniques developed throughout the years, which is divided by American Society for Testing and Material (ASTM) into seven areas [32]. Each of the seven main additive manufacturing categories has also several subcategories and variations. The categories with each of their subcategories can be seen in Figure 1.1. These subcategories refer to specific methods and technologies that fall under the broader processes but vary in terms of materials used, energy sources, or unique characteristics. Every subcategory optimizes specific aspects of the parent category, such as material compatibility, resolution, build speed, or application domain. Each of these technologies are specialized for different industries and applications, with trade-offs between cost, speed, accuracy, material availability, and post-processing needs.

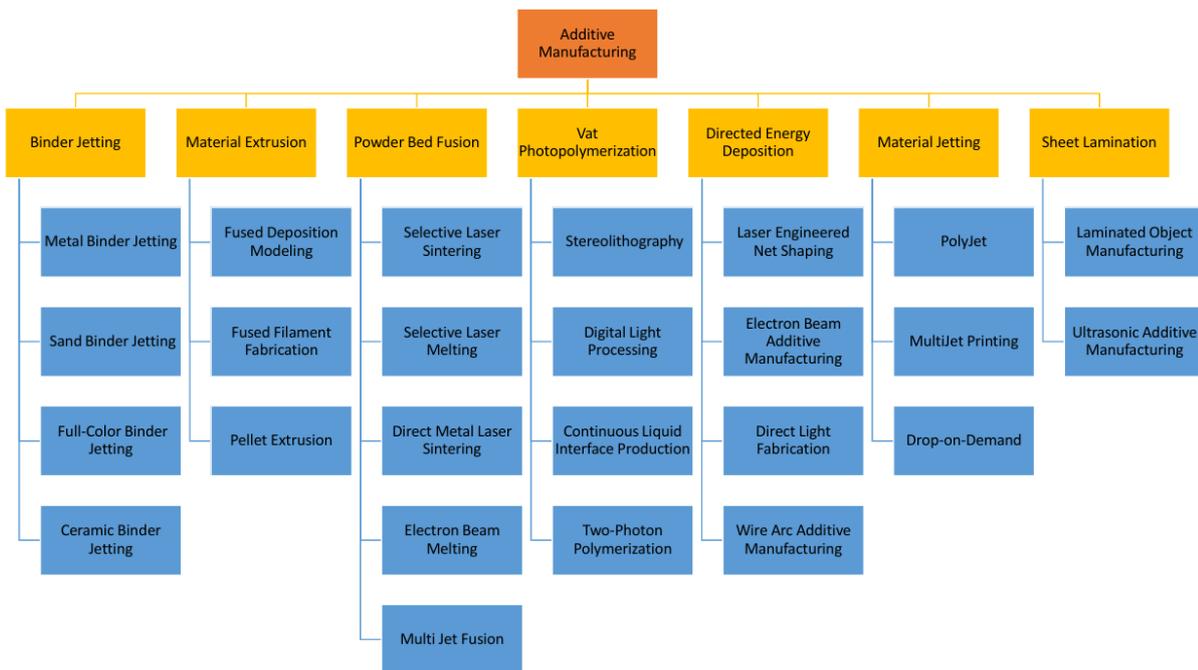


Figure 1.1: Additive manufacturing types and their subcategories.

1.3.1. Binder Jetting

Binder Jetting (BJT) is a process that includes a powder bed that can be metal or nonmetal, and a liquid binder that is applied from an inkjet print head or a binder spray head. In specific areas, binder solidifies the powder in order to create a solid part. When one layer is created, build platform moves below and a new layer of powder is deposited. Each layer is created following this procedure, resulting the end part. After the process

is done, usually a post-processing is needed, such as curing or sintering. In binder jetting process, there is material flexibility. Different type of powders can be used as mentioned, metals or nonmetals, such as ceramics or polymers. Also, complex and large parts can be produced in a short time period. Since there is no direct heat used in the process, the thermal distortion and the warping risk of the end part is eliminated. However, the product usually lacks strength in terms of mechanical properties, therefore it requires to go under post processing methods as mentioned, such as curing or sintering. Even after the post processing, the end part may still has less mechanical strength compared to other similar additive manufacturing techniques, such as powder bed fusion. The subcategories of Binder Jetting are; Metal Binder Jetting, Sand Binder Jetting, Full-Color Binder Jetting and Ceramic Binder Jetting. In metal binder jetting, metal powder is bound using a liquid binder, followed by post-processing steps such as sintering to strengthen the part. Sand binder jetting is typically used to create molds and cores for metal casting, where sand is bonded layer by layer using a binder. Full-color binder jetting is often used for producing full-color prototypes or models, typically with plaster or polymer powders. In ceramic binder jetting ceramic powders are bonded and then sintered to form dense, solid parts, often for technical applications [4].

1.3.2. Material Extrusion

In Material Extrusion (MEX) process, the material is heated and an extrusion nozzle deposits the material as a filament to the build platform. After each layer, platform moves down and a new layer is deposited on top. The part is created layer by layer as layers are fused together due to the melted material. After it cools down and solidifies, the desired end part is created. In material extrusion process, many different thermoplastics can be used as a material. It is considerably affordable and economic due to the low cost of the materials and the printers. Also, material extrusion technology is easy to use and operate, which makes it accessible by many. However, the end part usually has a low surface quality compared to other similar additive manufacturing technologies. Printing a large part can take long process time. Since the product is created layer by layer that are fused together, layer adhesion and weak bonds between the layers can be an issue. The subcategories of Material Extrusion are; Fused Deposition Modeling, Fused Filament Fabrication, Pellet Extrusion. Fused deposition modeling is the most common form of material extrusion, where thermoplastic filaments are melted and extruded layer by layer. Fused filament fabrication is similar to fused deposition modeling, but it is generally used in a broader, less trademarked context. In pellet extrusion, instead of filament, plastic pellets are used as the feedstock, which can reduce material costs and allow faster printing

[15].

1.3.3. Powder Bed Fusion

In Powder Bed Fusion (PBF) process, laser or electron beam is used in order to fuse the selected particles on the powder bed to create the desired part. Powder material can be metal, ceramic or polymer. After each layer, build platform moves down and a new powder layer is spreaded in the build platform. With powder bed fusion, complex geometries and internal structures can be created. It allows creation of lightweight components. Since metals and high-performance materials are applicable to the process, end part characteristics are usually good, strong and durable parts can be created with powder bed fusion. Also, there is no need of support part, unused powder in the build platform plays a support role during the process. Unfortunately, the materials and the equipment used in powder bed fusion are usually expensive. Because of the laser or electron beam usage, the process requires significant amount of intensive energy. The end part requires post processing due to the powder residual on the surface. Machining and heat treatment might be needed for finishing. The subcategories of Powder Bed Fusion are; Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM) and Multi Jet Fusion (MJF). Selective Laser Sintering uses a laser to sinter powdered polymers (typically nylon), fusing particles together without fully melting them. In selective laser melting, a laser fully melts metal powder to create solid metal parts with good mechanical properties. Direct Metal Laser Sintering is similar to selective laser melting, but often used to refer to processes where metals are sintered rather than fully melted. Electron Beam Melting Uses an electron beam rather than a laser to fully melt metal powders, typically in a vacuum environment. Multi Jet Fusion, a proprietary process developed by HP, which uses a fusing agent to selectively bind powder before heat fuses the powder [15].

1.3.4. Vat Photopolymerization

In Vat Photopolymerization (VPP), a curing device such as laser, UV light etc., selectively cures the liquid resin aka photopolymer that is contained in a vat to form solid layers. After each layer, the build platform goes down and the process repeats. Vat photopolymerization allows printing smooth surfaces and complex details. It is capable of producing complex geometries and fine features. However, it is limited in terms of material. Mostly resins are used in vat photopolymerization, which can be brittle or sensitive to UV light. After the vat photopolymerization process there is a requirement of additional curing and washing steps to remove the excess resin. The subcategories of Powder Bed Fusion are;

Stereolithography (SLA), Digital Light Processing (DLP), Continuous Liquid Interface Production (CLIP), and Two-Photon Polymerization (2PP). In Stereolithography, a laser is used to selectively cure a liquid resin to create detailed, high-resolution parts. Digital Light Processing is similar to SLA, but uses a digital projector to flash entire layers of light onto the resin at once, making it faster. Continuous Liquid Interface Production is a variation of DLP that continuously pulls parts from a vat of resin, enabling faster production without visible layer lines. Two-Photon Polymerization is a high-resolution technique using two lasers to polymerize very small volumes of material, allowing for extremely fine details [15].

1.3.5. Directed Energy Deposition

In the Directed Energy Deposition (DED) process, there is more than one nozzle head. One of them supplies the material, usually as wire or powder, while another one melts that material with laser beam, electron beam, or plasma arc as it is deposited on the build platform. The material used in directed energy deposition is usually metals. Almost any metal that is weldable can be manufactured with DED. Directed energy deposition can add material to the components to reinforce or repair them. It can create or repair large parts. It is capable of producing strong and durable parts with good mechanical properties. However, for directed energy deposition, expensive and complex machinery is needed. It may require post-processing due to lower precision. It is generally slower than other printing techniques. The subcategories of Directed Energy Deposition are; Laser Engineered Net Shaping (LENS), Electron Beam Additive Manufacturing (EBAM), Direct Light Fabrication (DLF), and Wire Arc Additive Manufacturing (WAAM). Laser Engineered Net Shaping uses a high-powered laser to melt metal powder or wire as it is deposited, building up parts layer by layer. Electron Beam Additive Manufacturing uses an electron beam to melt metal wire, typically used for large-scale metal parts in aerospace and defense. Direct Light Fabrication is a variation where metal powder is deposited and melted using a laser beam. Wire Arc Additive Manufacturing uses an electric arc to melt metal wire as it is deposited, allowing for large-scale parts to be produced, typically for heavy industries like shipbuilding [4].

1.3.6. Material Jetting

In material jetting, drops of photopolymer or wax material is deposited to the build platform, then it is cured with heat or UV light. It is possible to print with multiple materials in a single process with material jetting. Material jetting results in extremely accurate prints with smooth surface finishes. It is possible to print with multiple materials, in

different colors and complex parts in a single process with material jetting. However, material jetting has high upfront and operational costs. In addition to that, parts produced with material jetting tend to be brittle and less durable. The subcategories of Material Jetting are; PolyJet, MultiJet Printing (MJP), and Drop-on-Demand (DoD). PolyJet is a widely-used process where photopolymers are jetted and cured layer by layer to create high-detail parts, including multi-material and multi-color parts. MultiJet Printing is similar to PolyJet but refers to different proprietary technologies that also jet photopolymers or wax materials. In Drop-on-Demand materials are jetted only where needed, minimizing waste and allowing for very fine control over material deposition [4].

1.3.7. Sheet Lamination

In sheet lamination, thin sheets of material are stacked and bonded together using adhesives or ultrasonic welding. The sheets are then cut to the desired shape using a laser or blade. Sheet lamination uses inexpensive materials and it has quick build times. It minimizes the waste due to efficient use of materials. Also, it has no thermal distortion so it is suitable for large parts that require stability. However, the material choices are limited with mostly paper, plastic, or metal sheets. It has a lower resolution and less detail compared to other additive manufacturing technologies. In sheet lamination, also, the layers may not adhere as strongly, resulting in weaker bonding and reducing the overall strength of the part. The subcategories of Sheet Lamination are; Laminated Object Manufacturing (LOM), and Ultrasonic Additive Manufacturing (UAM). Laminated Object Manufacturing involves stacking and bonding sheets of paper or plastic that are then cut into the desired shape, often used for low-cost, large-scale parts. Ultrasonic Additive Manufacturing uses ultrasonic vibrations to bond thin layers of metal foil together, which can be cut into the desired shape. UAM can embed components like sensors or electronics during the build process [15].

2 | Fused Deposition Modeling

Fused Deposition Modeling is an additive manufacturing technology commonly used for producing 3D printed parts. It was developed by Scott Crump in the late 1980s and was commercialized by the company Stratasys. [27] Fused Deposition Modeling is one of the most accessible and widely-used 3D printing technologies, known for its simplicity and the wide range of materials it supports.

Fused Deposition Modeling is a cornerstone of the 3D printing industry, offering a balance between affordability, ease of use, and material versatility. Despite its limitations in terms of surface finish, mechanical properties, and print speed, it remains one of the most popular and widely-adopted additive manufacturing methods. By carefully selecting process parameters and materials, users can achieve functional prototypes and low-volume production parts suitable for a wide range of applications.

The material is deposited layer by layer to build the desired object. A spool of plastic filament is melted and deposited in a precise pattern using a heated nozzle onto a build platform, following a predetermined path designed by 3D modeling software. The extruder head moves horizontally in x-y direction, while the building platform moves vertically in z direction. When a layer is completed, platform moves down and the new sequence starts. As each layer is added, it cools and solidifies, creating a stable structure. The process continues layer by layer until the final 3D object is formed [26].

There are some key steps in fused deposition modeling. The process begins with designing a 3D CAD model using a software such as AutoCAD, SolidWorks, or any other 3D modeling software. The 3D model is then converted into a .STL file (Standard Triangle Language), which is sliced into multiple horizontal layers to provide a step-by-step guide for the printer [8].

The filament, typically a thermoplastic material, is loaded into the extruder, where it is heated to a molten state. Filaments are stored on spools and fed to the printer during the printing process.

The heated extruder head moves along the X and Y axes, depositing the material layer

by layer in the desired pattern. The molten filament is extruded onto the build platform, where it cools and solidifies. The platform moves down incrementally along the Z-axis as each new layer is deposited.

Once deposited, the material cools down and hardens quickly. A cooling fan is often used to speed up the solidification process, allowing subsequent layers to be deposited.

After printing, the part may require post-processing steps such as support removal, surface smoothing, or painting. Support structures are often printed alongside the object to support overhangs and complex geometries and must be manually removed after printing.

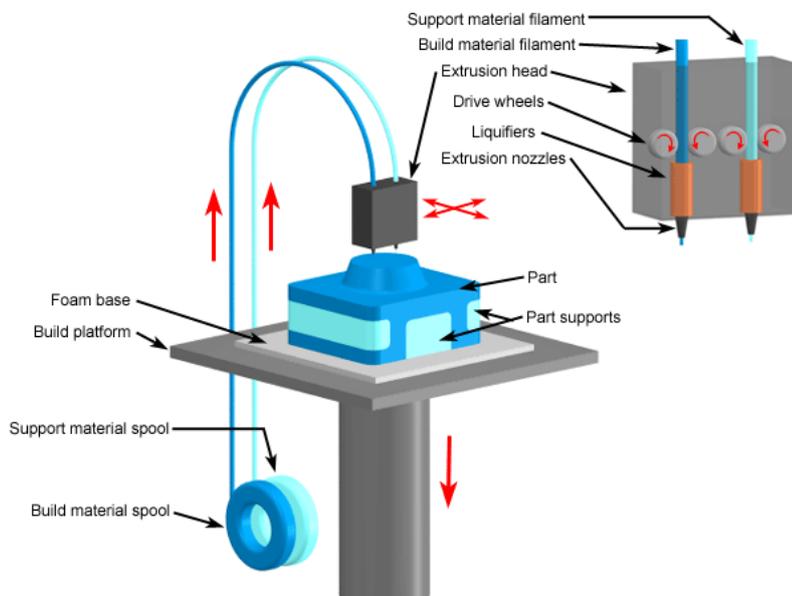


Figure 2.1: Fused Deposition Modeling Process [8].

2.1. Advantages of Fused Deposition Modeling

Fused deposition modeling offers a range of advantages that make it particularly appealing in diverse applications, from rapid prototyping to specialized industrial uses.

It is a versatile and cost-effective technology in additive manufacturing. It stands out for its flexibility, allowing users to adjust various parameters, making it particularly suitable for prototyping and small-scale production. This adaptability and relative affordability are key advantages that have contributed to its popularity in the field of 3D printing.

It offers several notable benefits beyond affordability and adaptability. It is known for its low material waste, as only the required material is extruded during the build process. This efficiency makes fused deposition modeling appealing for sustainable manufacturing

processes, particularly when using recyclable or biodegradable materials like polylactic acid (PLA). Furthermore, the relatively simple mechanism of fused deposition modeling printers makes maintenance easy, leading to reduced operational costs and increased accessibility in the industry [35].

Fused deposition modeling also offers a range of advantages that make it particularly appealing in diverse applications, from rapid prototyping to specialized medical and industrial uses. Its core strengths include cost-effectiveness and flexibility. FDM systems are less costly to acquire and operate than other additive manufacturing methods, which has helped popularize their use in educational settings, hobbyist communities, and even industry prototyping [1].

The simplicity of FDM printers, along with their minimal operational requirements, adds to this accessibility, allowing more users to engage in 3D printing without extensive technical expertise [29].

FDM is also valued for its adaptability in creating complex shapes and designs. By modifying parameters like raster angle and width, users can customize properties like flexural strength, which makes FDM advantageous in fields that demand specific mechanical traits, such as aerospace and automotive manufacturing [14].

The ability of FDM to support rapid iteration cycles is another significant advantage, especially in prototyping. Adaptive slicing and optimal deposition orientations help improve part quality and reduce print times, which benefits industries that require efficient production without sacrificing design accuracy [28, 30].

Thus, FDM's strengths lie in its economic viability, ease of use, material versatility, and capacity for customization. However, the method does face limitations in resolution and mechanical strength, which can affect the dimensional accuracy and durability of printed parts.

2.2. Disadvantages of Fused Deposition Modeling

Fused Deposition Modeling, while popular for its accessibility and ease of use, has several limitations that affect its suitability for high-precision, high-strength applications. One key drawback is the limited resolution of printed parts, where each layer of thermoplastic material is laid down in a visible, stepwise fashion, often resulting in noticeable layer lines on the final surface. This stepwise layering constrains the achievable surface smoothness, making parts unsuitable for applications requiring fine details or aesthetics without further post-processing such as sanding or chemical smoothing.

The mechanical properties of FDM parts are also impacted by weak inter-layer adhesion, as layers do not bond as seamlessly as in other methods like selective laser sintering (SLS) or stereolithography (SLA). This inherent layer-by-layer bonding introduces anisotropy, where parts are stronger in the horizontal plane and weaker along the build direction. Such a limitation makes FDM parts vulnerable to delamination under mechanical stress, limiting their performance in load-bearing or high-stress environments. Even with post-processing, these weaknesses mean that FDM-printed parts may not be suitable for structural applications.

Material selection is another constraint of FDM. While there are many thermoplastics available, such as ABS, PLA, and PETG, the process generally excludes high-strength, high-temperature-resistant materials like metals or ceramics unless heavily modified. For functional parts that demand durability, chemical resistance, or high thermal stability, FDM's limited material range reduces its usefulness. Although composite filaments (e.g., carbon-fiber-reinforced PLA) exist, their strength is still generally lower than parts produced via alternative additive manufacturing methods or traditional manufacturing techniques.

Thermal distortions and warping are additional issues in FDM. As thermoplastic layers are extruded at high temperatures, they contract upon cooling, which can cause parts to warp, especially on larger builds or materials like ABS that are more prone to shrinkage. Even with techniques like heated build platforms and enclosure use, these issues can be challenging to fully mitigate, leading to poor dimensional accuracy. Furthermore, FDM generally has slower production times compared to other methods, as each layer must be individually extruded and cooled before the next layer can be applied, which impacts production efficiency, particularly in professional settings where speed and consistency are critical [15].

Due to these disadvantages, process parameters of fused deposition modeling should be carefully selected and optimized to minimize defects.

2.3. Process Parameters

During the FDM process, there are many parameters that can vary. These process parameters affect the end part quality as well as the process efficiency.

In order to fully understand the effects of process parameters on the end-part, primarily each of them should be carefully analyzed.

One of the most important process parameters in FDM is the temperature. There are

several temperature parameters in the process that affects the end part in many ways.

2.3.1. Extrusion Temperature

While printing, the material filament is melted at a certain temperature. This temperature is called extrusion temperature, since the material is heated and extruded from the nozzle. Proper extrusion temperature is crucial for ensuring that each layer adheres well to the previous one, thereby producing more robust prints. When the extrusion or nozzle temperature is insufficient, it can result in under-extrusion, producing fragile prints. Conversely, if the temperature is excessively high, problems such as stringing or blobbing can occur. Extrusion temperature can vary depending on which material is being used, for thermoplastic, the extrusion temperature is typically in between 190°C to 260°C [26].

2.3.2. Bed Temperature

Another temperature parameter during the process is the bed temperature, which describes the temperature of the build platform. This parameter is important due to the fused first layer. When it contacts with the platform, there is the risk of warping due to temperature difference between the material filament and the platform. Therefore, build platform is heated to help adhering the first printing layer to the surface. This reduces the risk of curling and warping while maintaining the first layer adhesion to the bed throughout the whole process. When the bed is at an insufficient temperature, the part might not adhere to the platform, resulting in print failures such as edge lifting or curling. Usually bed temperature depends on the print material and ranges in between 60°C to 110°C.

2.3.3. Chamber Temperature

In addition to extrusion and bed temperature, chamber temperature also plays an important role during the process and for the end-part characteristics. It indicates the temperature within the enclosed build chamber, which encapsulates the entire printing environment. The purpose of the chamber temperature is to keep the part in an environment that is stable and warm enough while printing. It prevents temperature from fluctuating, resulting in a consistent thermal environment and more uniform cooling. The enclosed chamber and its temperature is especially important for materials that are more prone to warping or cracking during the cooling process. It provides gradual cooling instead of rapid cooling, which reduces internal stress and risk of warping. This results in more dimensional accuracy, specifically for large parts. Usually the chamber gets warm

unintentionally from the residual heat that is created by the bed and extrusion temperature. However, there are also advanced printers that have active chamber heating systems in order to control and maintain the chamber temperature. Depending on the requirements, the chamber temperature can range in between 40°C to 80°C.

2.3.4. Print Speed

Another key parameter in FDM is the speed. It determines many characteristics of the end-part.

The movement pace of the nozzle while it extrudes the material is controlled by the print speed. Higher print speed results in lower print time, however, end-part quality can be negatively affected in terms of surface finish and dimensional accuracy.

2.3.5. Velocity of Deposition

A more specific and accurate speed parameter is velocity of deposition. It combines the print speed that is related to the movement of the nozzle, with the flow rate of the material that is extruded from the nozzle. Therefore, the term velocity of deposition corresponds to the rate of material deposition to the build platform. It determines the speed of material build up on the platform, which affects the mechanical properties and dimensional accuracy of the end-part. If the print speed and flow rate are not compatible, such as one of them being too high or too low compared to the other one, it can cause under or over extrusion.

2.3.6. Cooling Fan Speed

In terms of speed parameters, there is also the cooling fan speed. It controls and determines how fast the extruded material filament cools down. Cooling fan speed plays an important part during the process with ensuring proper material solidification to prevent sagging or stringing problems.

2.3.7. Layer Height

Layer height also plays a crucial role in the printing process. It means the thickness of each layer that is printed. Using thinner layer heights enhances resolution though it extends the print time, whereas thicker layers produce quicker prints at the cost of resolution [20].

2.3.8. Infill Density

Infill density refers to the amount of material that is inside of the printed part. It is typically represented as a percentage, while 0% means hollow and 100% means completely solid. If it is at high density, the end-part becomes stronger yet heavier, while low density results in lighter parts but may reduce the strength [12].

2.3.9. Print Orientation

Print orientation describes the positioning of the model on the build plate during printing, such as horizontal, vertical, or at an angle. The orientation of the print can be modified and different orientation angles can be implemented. The orientation affects the print time, surface finish and strength of the end-part [20].

2.3.10. Raster Angle

A more extensive process parameter is the raster angle, also known as the infill angle. It refers to the orientation of the extruded filament for each printed layer. The raster indicates the path of the nozzle while the filament is extruded for each layer, while the raster angle indicates the angle between the deposition path and the reference axis, usually the x axis of the build platform. Mostly, alternating raster angles for different layers are chosen in order to increase the strength and mechanical properties. It allows the end part to be resistant to load and stress in specific directions, or even in all directions if desired, making the part isotropic. Alternating raster angle in between layers distributes the heat more even, resulting in less thermal shrinkage, therefore less warping and deformation. Since it also reduces the internal stress in each direction that is built up during printing, it prevents cracks and internal failure of the part [20].

2.4. Effects of Process Parameters

To optimize the process parameters to minimize warping as the aim of this study, first each of their effect on the end-part and their link to different defects should be examined, so that a deeper insight can be gained before focusing on the main topic.

The various process parameters in Fused Deposition Modelling have a significant impact on the mechanical properties, dimensional accuracy, surface finish, warping, and other characteristics of the printed part [26].

For instance, mechanical properties are highly dependent on layer bonding, which is influ-

enced by nozzle temperature, layer height, and print speed. Proper parameter selection ensures better strength, especially in the Z-axis, where FDM parts are typically weaker.

2.4.1. Nozzle Temperature

In terms of mechanical properties, optimal nozzle temperature leads to good layer bonding, which results in stronger parts. If the nozzle temperature is too low, adhesion between layers become weak, which results in brittle parts. Incorrect nozzle temperature can cause warping. If the filament is extruded too cold, it may not adhere properly to the build platform or to the previous layer, which results in warping and delamination. The accuracy of dimensions can also be affected by incorrect nozzle temperature. Too high temperatures cause stringing and oozing, while too low temperatures cause under-extrusion, which results in gaps and unfilled sections in the part. Surface finish is another property that is affected by the nozzle temperature. High temperature can cause rough surface finish, while low temperature causes under extrusion as mentioned, those gaps can occur in the surface too.

2.4.2. Bed Temperature

Optimal bed temperature decreases the risk of warping by ensuring the proper and secure adhesion of the first layers to the platform, and prevents them from shrinking too fast while cooling. If the bed temperature is too low, the adhesion of the layer to the platform can be poor, which results in lifting of the corners and inaccuracy of dimensions. Bed temperature is crucial in order to have a smooth and high-quality first layer, which affects the whole part.

2.4.3. Print Speed

If the print speed is too high, it can cause rougher surface finish due to imprecise deposition. An optimal print speed results in good surface quality and precision. Fast printing negatively affects the mechanical properties of the end part. Because the extruded layer may not fuse properly with the previous layer, it can lead to poor layer adhesion and weak components. Higher print speed can also lead to lifting or warping due to the incomplete adhesion issue between layers. Slower print speed reduces the risk of warping as the layers has enough time to properly adhere and bond together. Faster print speed reduces the overall print time at the cost of quality and strength of the component.

2.4.4. Cooling Fan Speed

Higher cooling fan speed solidifies the deposited material quickly, therefore it prevents sagging, stringing and especially overhangs. This results in better surface quality, however, excessive cooling can cause to poor adhesion between layers, which can weaken the component and affect its mechanical properties. Overcooling can also increase warping as rapid cooling can shrink the part and curl the edges. Using a low fan speed for the first layers helps with better fusion and bonding between layers. Of course, faster cooling fan speed results in less print time by increasing the solidification rate of the material.

2.4.5. Layer Height

Smaller layer heights leads to better layer adhesion and improves the strength of the part, specifically in z axis. It results in smoother surface finish and finer details. It also reduces warping due to better layer connection, specifically for large and flat surfaces. Whereas higher layer height causes less strength due to weaker bonding between layers. It results in rough surface finish and visible layer lines. Increasing layer height leads to less print time however at the cost of precision and detail of the part [20].

2.4.6. Infill Density

If the infill density percentage is high, it results in stronger and more durable components, while low infill density leads to weaker parts. However, high infill density consumes more material and increases the weight. It can increase warping because of internal stresses during cooling. Specifically if the part cools down unevenly due to the high print volume. It requires an optimal cooling to prevent this problem. Higher infill density increases the print time since there is more material to be deposited.

2.4.7. Print Orientation

In Fused Deposition Modelling, the strength of the part is anisotropic as it varies with the orientation of the part. Vertical z axis is weaker than horizontal x and y axes because of layer bonding. For the desired direction the mechanical strength can be improved by changing the print orientation. Print orientation affects the surface finish in terms of layer lines visibility. Vertical print orientation usually increases the visibility of layer lines, therefore decreases the surface quality. Whereas flat surfaces that are aligned with x and y axes usually have smooth surface finish. However, wide and flat surfaces that are aligned with build platform and oriented in x-y axes are more prone to warping. Angled

orientations or vertical placement can reduce the warping risk, but may require support structures. This can lead to an increase in print time [20].

2.4.8. Nozzle Diameter

Small nozzle diameters result in smoother surface finish and finer details, while a large nozzle can extrude more material quickly, however it reduces the precision of the part. Larger nozzle diameters produces thicker layers, causing a weaker strength in the z axis because of poor layer bonding between layers. It also worsens the warping risk due to the increased extrusion volume therefore an uneven cooling. A small nozzle diameter leads to longer print time, however it improves accuracy and details of the part.

By optimizing these parameters, mechanical strength, surface quality, and warping reduction can be balanced to create high-quality FDM prints tailored to specific needs.

3 | Warping

One of the main defects in FDM process is warping. It refers to the base of the part lifting or curling up from the build platform while printing, which causes dimensional inaccuracy of the end-part. This can lead to a distorted shape, or even complete print failures.

Warping usually happens stage by stage. As the process progresses, warping gradually increases. During the extrusion phase, the material filament is extruded as hot. When it begins to cool down, solidification starts and it slightly shrinks. As the process continues, each layer is deposited on top of previous ones. Since the top layers are more exposed, they cool down faster, resulting in uneven cooling. The bottom layers that are in contact with the heated building platform cool down and contract slower than the top layers. Therefore, during the process upper layers pull up the lower ones and result in a lifted or curled part. When the warping effect is extreme, it can end up causing the part to detach from the build platform and failing the printing process.

3.1. Reasons of Warping

There are a couple of reasons in the process that may cause warping. Warping is mainly caused by uneven thermal contraction while the part is cooling. It depends on the thermal behavior of the material that is used in the process. When heated thermoplastics expand, and when cooled, they contract. The material filament is heated and extruded from the nozzle while it is in a molten state. After extrusion, the layer cools down and thermal contraction causes it to shrink. If the cooling process does not occur evenly across the component, or if the cooling is too rapid, some parts contract and shrink more than the others, building up tension and creating internal stresses in the component. These internal stresses pull the edges of the component upward, leading to warping.

Uneven cooling worsens the warping issue. For example, if the corners of the component cool down faster than the center of it, this may lead corners to lift off.

If the bed adhesion is poor, the first extruded layer may not adhere properly to the build platform, causing the edges to lift up during the printing process. This issue is more

common for the materials that are more prone to shrinking, such as ABS.

Having a high build volume, such as a large part or a wide surface, is also a cause for warping, due to the greater thermal gradients existing in the component. Different temperatures in between the center and the edges create high internal stresses.

The printing temperature significantly affects the warping. If it is too high, it can result in excessive thermal expansion of the material, leading to more significant shrinkage while the material is cooling.

3.2. Most Influential Parameters on Warping

There are several process parameters in fused deposition modeling that contribute to warping as mentioned before. However, not all of them has the same effect on warping. Some of the process parameters has great effects on warping that even a slight change in them makes huge difference in the outcome. While the others may not change warping levels much even with great changes in them. Therefore, only important ones that has great effects on warping are selected to analyze.

They can be summarized as bed temperature, extrusion temperature, cooling fan temperature, layer height, print speed and cooling fan speed.

3.2.1. Bed Temperature

When the build platform is heated properly, a better first layer adhesion is ensured which is a crucial step to prevent warping. If the bed temperature is insufficient, it leads to poor adhesion therefore warping.

3.2.2. Extrusion Temperature

Not only the first extruded layer is important for warping. Proper adhesion between each and every layer is crucial to prevent warping. To ensure this, the extrusion temperature has to be chosen carefully. If the extrusion temperature is too high or too low, it may result in warping.

3.2.3. Print Speed

If the print speed is too high, the material does not have enough time to bond properly, resulting in weaker adhesion and increased warping.

3.2.4. Layer Height

Layer height plays a crucial role in warping prevention. Thinner layer heights lead to better contact between layers, which increases the strength of inter-layer adhesion that reduces warping.

3.2.5. Cooling Fan Speed

If the extruded filament cools down too rapidly, it increases warping. The cooling fan speed should be adjusted so that the cooling rate can be controlled to reduce warping.

3.3. Results of Warping

Warping is one of the most critical challenges in Fused Deposition Modeling. The results of warping can negatively impact the quality, functionality, and accuracy of the printed part. If it is not controlled, warping leads to many undesirable outcomes.

3.3.1. Dimensional Inaccuracy

Warping results in geometry deviations in the end-part, especially along its edges, which causes dimensional inaccuracies. This distortion arises due to inconsistent cooling and material shrinkage. In FDM, each layer is deposited at high temperatures, as it cools, the material contracts. When this contraction is uneven throughout the part, specific areas, such as corners and edges, may contract excessively, leading to curling or lifting. If the part has strict geometric tolerances to follow, such as most of aerospace components, warping may cause to inaccurate dimensions, causing the part to be dysfunctional and rejected. For instance, components that are designed to be assembled or fitted, such as gears or mechanical fittings, may no longer interlock to the other components, due to a slight distortion. Warping gets significantly more evident with larger parts, due to huge temperature gradients.

3.3.2. Layer Delamination

When the extruded layers cool down at different rates, internal stresses occur. These stresses weakens the inter-layer adhesion. Newly extruded upper layers rapidly cool down, while the lower layers have already cooled. Top layers exert tension on bottom layers, resulting in separation between the layers. This leads to layer delamination or cracking, during or even after the process, which reduces mechanical integrity. If layer delamina-

tion is significant, the end-part becomes more prone to fracture due to this mechanical weakness. Especially if the part will be carrying loads, or if its tensile and compressive strength is important during its mission, it will untimely fail because of poor inter-layer bonding.

3.3.3. Failure to Adhere to the Print Bed

One of the early indications of warping is the corners or edges of the printed part beginning to lift and curl away from the build platform. If there is a temperature difference between the extruded layer and the build platform, this phenomena occurs. When the temperature difference is significant, bottom layers that are in direct contact with build platform shrink much faster than the top layers, leading the part to lift from the platform. If the warping is severe and the part keeps lifting and curling up, it may lose contact with the platform and completely detach, resulting in print failure, therefore waste of material, time and energy. There are several applications in FDM to increase bed adhesion, such as usage of raft and brim. They will be explained in detail at the section solutions of warping. If the warping is severe, it can even cause the raft or brim to detach from the build platform. It becomes crucial specifically for large parts because even a slight warping may can cause adhesion problems.

3.3.4. Surface Quality Deterioration

Outer layers of the part, particularly edges and corners and the bottom surface, are deformed due to warping, resulting a bad surface finish. If the edges detach from the build platform, following layers are deposited to a non-uniform base, leading to a wrong surface alignment. Therefore, the end-part may have ridges, voids or rough patches, resulting in a need for post-processing. For significantly warped parts, some post-processing techniques such as polishing or sanding get more inconvenient. If the warping deformation is too severe to be fixed, the part may needed to be re-manufactured.

3.3.5. Loss of Structural Integrity

Due to warping, internal stresses occur within the part, which decreases the structural integrity, durability, and strength of the end-part. If the inter-layer bonds are weakened due to warping, mechanical failures can occur, the part may crack or break under stress. Mechanical components subjected to dynamic loads or prolonged stress, such as gears or joints, are more prone to fatigue due to weaknesses caused by warping. Over time, this can lead to the development of cracks or even complete failure when under load. Warping

can also generate areas within the component where stress concentrations are much bigger than others. These zones are prone to failing first, particularly in load-bearing components or those used in high-stress areas.

3.3.6. Functional Failures

Warping can cause components to become ineffective, particularly when it alters crucial elements such as holes, threads, or mechanical connections. Components intended for mechanical assemblies or moving parts might not function properly if warping changes critical features and causes misalignment. For example, mechanical gear printed with fused deposition modeling with warped teeth may not align correctly with other gears, causing functional failure in the overall mechanism.

3.3.7. Post-Processing Complications

Warping causes additional post-processing efforts to fix the surface finish or dimensional inaccuracies. Furthermore, altered geometry complicates the application of post-processing and dimensional adjustments. For instance, smoothing a warped component can be challenging since warped regions may demand excessive material removal, leading to further distortion. In extreme situations, it might be impossible to return the part to its original shape, causing material, time and labor waste. To flatten the base or smooth the surfaces of a warped piece, sanding, trimming, or applying heat might be necessary as a post-process application.

3.4. Solutions to Decrease Warping

Warping is a critical issue in FDM printing, as it compromises functional aspects of the printed object. Effective control of warping is essential for producing high-quality, dimensionally accurate, and functional parts. Understanding the thermal behavior of the chosen material and properly managing the layer adhesion and cooling process are key to minimizing warping and ensuring high-quality prints.

There are several strategies mentioned below that can be applied to reduce and prevent warping during the Fused Deposition Modeling process.

3.4.1. Bed Adhesion

It is now known that bed adhesion plays a crucial role in warping. In order to make the first filament layer adhere to the build platform more securely, adhesives such as glue sticks or kapton tape can be used. They enhance bed adhesion, ensuring that corners or edges do not lift during cooling. Specialized materials such as blue tape or BuildTak also provide extra grip for the initial layers, helping to mitigate warping by keeping the print firmly in place on the build platform.

3.4.2. Heated Build Platform

It is made clear that bed temperature is one of the most important parameters that affects warping.

A heated bed ensures that the initial layers do not cool too rapidly, reducing thermal stresses that lead to warping.

Some materials that are used in Fused Deposition Modeling, such as ABS, requires a heated build platform, typically ranging in between 90°C to 110°C to maintain adhesion and reduce shrinkage in the bottom layers. For PLA, typically 60°C is sufficient, while for PEEK it is typically around 120°C to 140°C [26].

There is an advance technology that is called multi-zone heated bed. It allows for different areas of the print bed to be heated to varying temperatures, based on the geometry of the printed part. By selectively increasing temperature in areas more prone to warping, such as the corners or edges, multi-zone heating minimizes the risk of corners lifting. This is particularly beneficial for large parts where the entire surface needs uniform heat distribution.

Some advanced printers also allow for gradually lowering the bed temperature as the print progresses. This gradual reduction avoids sharp cooling contrasts between the part and the bed and can be beneficial for high-warping materials.

Also, allowing the part to cool gradually while still on the heated bed reduces the sudden contraction that can lead to severe warping. After printing, the bed temperature can be slowly reduced in increments over time rather than turning it off immediately. This allows the part to reach ambient temperature gradually without introducing additional stress. Instead of removing the part immediately after the print, letting it remain in an enclosure where ambient temperature drops more slowly, prevents rapid cooling at the outer layers of the part. This is especially helpful for materials like ABS, which benefit from a slow

transition from the heated bed to room temperature.

3.4.3. Environmental Control

Environmental control also plays a key role in reducing warping. Enclosures can prevent drafts and temperature fluctuations from affecting the print, especially for temperature-sensitive materials like ABS. Maintaining a stable room temperature, ideally between 20°C and 30°C, minimizes uneven cooling. Humidity control is essential as well, since filaments like ABS and Nylon absorb moisture, leading to uneven extrusion and increased warping. Drying or storing filaments in low-humidity containers can prevent these issues.

Enclosed or heated chambers further reduce warping by maintaining a consistent temperature around the print, avoiding uneven cooling.

Fan control is also important in reducing warping. Lowering the fan speed during the first few layers prevents rapid cooling, allowing better adhesion. After the initial layers, fan speed can be increased to aid the solidification of the upper layers. Additionally, setting a slightly thicker first layer and lowering the print temperature can further reduce warping by minimizing thermal expansion and shrinkage stresses.

3.4.4. Raft or Brim Usage

Another technique is to apply a brim, which is an extra material layer around the base or a raft, which is a thicker material grid under the part to improve bed adhesion, which can help prevent the part from lifting. Brims are especially useful for smaller objects with limited base areas, while rafts provide more stability for larger models [12].

3.4.5. Material Choice

Different filament materials exhibit varied warping tendencies. Low-warp materials like PLA and PETG are more tolerant, while ABS and Nylon, with higher thermal expansion coefficients, require more precise temperature control. Hygroscopic materials, particularly Nylon and ABS, benefit from conditioning or drying to reduce extrusion inconsistencies, which can lead to warping. Filament dryers or dry storage are useful tools, especially in humid environments.

3.4.6. Bed Leveling

Precise bed leveling and first-layer height are critical for bed adhesion. An uneven bed can cause parts of the print to lift, resulting in shrinkage and warping. Regular calibration, either manually or with an automatic leveling system, ensures a uniform first layer distance, promoting consistent adhesion across the print surface.

3.4.7. Print Orientation and Layer Height

Print orientation and layer height are additional considerations in managing warping. Adjusting part orientation to reduce large horizontal surfaces and using smaller layer heights helps decrease shrinkage stress between layers.

3.4.8. Print Speed

Slower print speeds, particularly for the first layer, improve bed adhesion, allowing the material to bond securely to the platform before cooling. Higher print speeds on subsequent layers can maintain efficiency without significantly increasing warping.

3.4.9. Infill

Lastly, optimizing infill patterns and density can minimize warping by reducing internal stresses. Lower infill density, typically 10% to 20%, puts less stress on the model's outer shell, while patterns like grid or triangular structures distribute stress more evenly.

4 | Mathematical and Statistical Models

In order to gain insight and understand the warping phenomenon and its connection with the process thoroughly, mathematical models and functions that are related to warping are examined. This knowledge helped to create the specific model that is simulated in this project.

In mathematical models for warping in Fused Deposition Modeling, incorporating factors such as deposition layer count, part section length, chamber temperature, and material shrinkage rates take place. They provide quantitative analyses and suggests improvements to reduce warping deformation. These methods and models are fundamental in improving FDM processes by predicting and minimizing warping.

For warping in the Fused Deposition Modeling process, mathematical models focus on the interaction between various process parameters such as temperature gradients, material properties, and part geometry. Below are general formulations based on research models.

4.1. Thermal Shrinkage and Residual Stress Model

Warping occurs due to thermal shrinkage during cooling. A typical model expresses the relationship between the shrinkage, stress and the deformation [24]:

$$\sigma_{res} = E \cdot \alpha \cdot \Delta T \quad (4.1)$$

Where;

σ_{res} : residual stress

E : Young's Modulus of the material

α : coefficient of thermal expansion

ΔT : temperature difference (i.e. cooling rate)

4.2. Bending Moment and Warping

One of the most conventional analysis for calculating warping is with bending moment. A bending moment arises from uneven cooling, causing the edges of the part to curl. The bending moment in a beam-like structure which are common in additive manufacturing can be calculated as [11]:

$$M = \frac{E \cdot I \cdot \Delta T \cdot \alpha}{h} \quad (4.2)$$

Where;

M : Bending moment.

E : Young's modulus.

I : Second moment of area (depending on the cross-sectional geometry)

ΔT : Thermal gradient across the part.

α : Thermal expansion coefficient.

h : Thickness of the layer.

This bending moment is responsible for warping deformation.

4.3. Geometrical Shrinkage

Geometrical warping in FDM is influenced by the number of layers, section length, and material shrinkage rate. A simplified linear shrinkage model for an FDM printed layer can be expressed as [33]:

$$\epsilon_s = \frac{L_0 - L_f}{L_0} \quad (4.3)$$

Where:

ϵ_s : Shrinkage strain.

L_0 : initial length.

L_f : final length after cooling.

This shrinkage strain is directly related to warping, especially in large or thin structures where dimensional instability is more significant.

4.4. Warping Force and Deformation

For a thin plate-like part, the warping force can be estimated using the following equation [33]:

$$F_w = E \cdot \alpha \cdot (T_1 - T_2) \cdot A \quad (4.4)$$

Where:

F_w : Warping force.

E : Young's modulus of the material.

α : Thermal expansion coefficient.

T_1, T_2 : Temperatures at the top and bottom of the part during cooling.

A : Area of the printed layer.

4.5. Finite Element Modeling (FEM)

A more complex approach involves the Finite Element Method (FEM), where the warping is predicted by solving the coupled heat transfer and mechanical deformation equations over time. The FEM solves [6]:

$$\frac{\delta T}{\delta t} = k \nabla^2 T \quad (4.5)$$

$$\sigma = C : \epsilon - \sigma_t \quad (4.6)$$

Where:

T : Temperature field.

t : Time.

k : Thermal conductivity.

σ : Stress tensor.

C : Elasticity tensor of the material.

ϵ : Strain tensor.

σ_t : Thermal stress due to temperature changes.

By coupling thermal analysis with mechanical deformation, FEM can predict the warping behavior across complex geometries and materials.

These models can be modified based on specific FDM conditions and material properties, and they form the basis for warping analysis and mitigation in FDM printing.

A generalized function to connect warping in Fused Deposition Modeling with its process parameters can be developed by linking key parameters such as layer thickness, extrusion temperature, print speed, and environmental temperature to warping-induced deformation. Typically, the warping effect results from thermal gradients, cooling rates, and material properties. A simplified form of this relationship can be written as:

$$W = f(h, T_{ext}, T_{bed}, v, \alpha, k, E) \quad (4.7)$$

Where:

W : Warping deformation.

h : Layer thickness.

T_e Extrusion temperature.

T_b : Bed temperature.

v : Print speed.

α : Coefficient of thermal expansion (CTE) of the material.

k : Thermal conductivity.

E : Young's modulus (material stiffness).

4.6. Response Surface Methodology

Previous models serve as a starting point to minimize warping. Based on these insights, a more complex and accurate model is created with Response Surface Methodology to analyze and optimize warping in Fused Deposition Modeling.

Response Surface Methodology (RSM) is a system optimization method that uses statistical and mathematical techniques. It models processes that have several variables that affect a specific outcome. The aim is to analyze and optimize these variables to obtain a desirable outcome. It is frequently applied in experimental design and process optimization to create empirical models that depict the relationships between variables (inputs) and an outcome (output). It is especially advantageous in engineering sectors, where it helps determine optimal conditions, improve quality, or reduce costs [18].

4.6.1. Model Factors

There are two different types of factors that can be defined in response surface methodology [10].

Continuous Factors

Continuous factors refer to input variables capable of taking any value within a defined interval. For instance, temperature ranging from 0°C to 100°C and pressure from 5 psi to 25 psi are continuous factors. They can be finely tuned to any position within their specific ranges. In Response Surface Methodology, continuous factors are crucial, as they enable detailed modifications for optimizing the output. In terms of optimizing warping in FDM, continuous factors can be chosen as nozzle temperature, bed temperature, print speed etc.

Categorical Factors

On the other hand, categorical factors are qualitative variables that take discrete and specific levels or categories instead of values from a continuous range. For example, different type of process method can be categorical factors. In Response Surface Methodology, categorical factors can be used alongside continuous factors to investigate how various qualitative choices affect the response and interact with continuous factors. In terms of optimizing warping in fused deposition modeling, categorical factors can be chosen as different type of materials, such as PEEK, PLA, ABS etc.

In response surface methodology, experiments are often designed to study how both continuous and categorical factors affect the outcome, individually and in interaction.

In order to apply response surface methodology to a specific problem, such as in our case to optimize warping in fused deposition modeling process, first the application steps of response surface methodology should be clearly understood. Application of response

surface methodology can be divided into several key steps, typically focused on designing experiments, building models, and optimizing responses. [19]

4.6.2. Defining the Objective and Variables

Clearly identifying what is to be investigated and optimized is the starting point in response surface methodology. The objective can be such as minimizing the cost, maximizing mechanical strength or increasing part quality. Afterwards, continuous factors and, if there is any, categorical factors that have impact on the response should be chosen. Continuous factors can be such as temperature or pressure, while categorical factors can be material type or process technology. Lastly in this step, the outcome that will be modeled and optimized should be defined. It can be such as yield, strength, or efficiency.

4.6.3. Designing the Experiment

In response surface methodology, there are several specific experimental designs to efficiently collect the data that will be used while modeling.

Central Composite Design (CCD)

Central composite design is one of the most widely used experimental designs in the response surface methodology, specifically when quadratic models are needed to explain the correlation between the factors and the response. CCD includes factorial points, center points, and axial points. Factorial points are combinations of high and low levels, often coded as +1 and -1, for each factor. Center points are experiments performed at the midpoint of each factor level. They help estimate experimental error and verify model adequacy. Axial or star points extend beyond the high and low levels of the factorial points to help capture any curvature in the response. They are positioned at a distance (α) from the center, which is typically determined based on the number of factors and whether the design is rotatable. CCD is well-suited when exploring factors over a wide range, as it captures both linear and quadratic effects efficiently. It provides flexibility, as you can adjust the distance of the axial points (rotatability), and it is a powerful design for building accurate response surfaces in two or more dimensions. For example, if the effect of temperature and pressure on yield is being studied, CCD would include factorial points at both high and low temperatures and pressures, center points (at the average), and axial points to extend the range of each factor [7].

Box-Behnken Design (BBD)

Another response surface methodology experiment design is Box-Behnken Design. It needs less runs than central composite design, which can be beneficial while working with limited resources or avoiding extreme factor levels. It is an efficient design when factors do not need to be tested at extreme high and low values, making it safer and more practical in some applications, such as chemical reactions. BBD works well when the goal is to understand interactions without using a large number of experimental runs. It has center points and factorial combinations at midpoints. Center points are similar to the ones in CCD. BBD includes multiple center points for estimating experimental error and improving the robustness of the model. In terms of factorial combinations at midpoints, rather than including extreme combinations, BBD places points in the middle of the edges of the factor range. This reduces the number of runs while still capturing interactions [23, 25].

Key differences between CCD and BBD are number of runs since BBD generally requires fewer runs than CCD, making it more efficient when resources are limited. Also exploration of factor space, CCD includes extreme points (axial points) to capture more curvature, while BBD avoids extremes and tests factors at midpoints. Lastly, Application Suitability CCD is often preferred for a full quadratic model, whereas BBD is useful for moderate factor ranges where full exploration isn't necessary. CCD is chosen when a detailed, full quadratic model is needed and more experimental runs can be done, or when exploring the entire factor range is essential. BBD is chosen when more economical design with fewer runs is needed, or when extreme values may be unsafe or unnecessary. Both designs are valuable tools in Response Surface Methodology, offering different strengths depending on experimental goals and constraints. In the same experiment of temperature and pressure, BBD would include experiments at the midpoint of temperature, paired with high and low pressure (and vice versa), rather than exploring extreme values. This helps map the response surface without covering the outer corners of the experimental range [3].

There is also another type of experiment design used in response surface methodology, it is called Full or Fractional Factorial Designs. It is useful in the beginning phase of the application to identify important factors before building more complex models [13].

By choosing the appropriate design, a set of experiments that vary the levels of factors systematically can be generated, ensuring a thorough examination of the response surface.

4.6.4. Conducting the Experiments

The experiments will be performed for the chosen design, carefully recording the response at each combination of factor levels. Consistency is key to reduce experimental error, as this can impact model accuracy.

4.6.5. Developing the Response Surface Model

The fundamental of the response surface methodology is based on the measurement of the response of any physical system depending on the k number of independent variables x . This situation can be expressed functionally as follows [17]:

$$y = f(x_1, x_2, x_3, \dots, x_k) \quad (4.8)$$

In this equation y is the system response and x are independent variables. In any trial, the discrepancy between the observed \hat{y} value and the expected y value is interpreted as the error of the system and is denoted by ε . In this case, the equation to be used can be written in theoretical form as follows:

$$\hat{y} = f(x) + \varepsilon \quad (4.9)$$

Response surface models are usually in the form of a quadratic (2nd degree) or cubic (3rd degree) polynomial form involving variables and their interactions. Regression analysis will be used to fit a polynomial model which is often quadratic to the collected data. This model will help approximate the response surface. Such a polynomial equation is theoretically expressed as follows:

$$Y = \beta_0 + \sum_{i=1}^n \beta_i X_i + \sum_{i=1}^n \beta_i X_i^2 + \sum_{i=1}^n \sum_{j=1}^n \beta_{ij} X_i X_j + \varepsilon_0 \quad (4.10)$$

Where Y is the response of the system, X are the factors (variables), β_0 is the constant of the model, β are the coefficients of the variables determined by regression and ε_0 is the error.

Deciding what the independent variables will be is the most important decision that is made at the beginning of the experiment. Because a mistake made, such as including a less important variable for the system in the model, may cause an important variable to be left out of the model. In response surface methodology, the numerical values of the

independent variables to be studied are converted into coded values. Since the study will be conducted in a certain range, coding is performed according to the following formula:

$$X_i = \frac{\varepsilon_i - \varepsilon_{i0}}{S_i} \quad (4.11)$$

Where X_i is the variable code, ε_i is the variable value in the working range, ε_{i0} is the center value in the working range, and S_i is the step value.

The model can be also validated through statistical tests such as R-squared or lack-of-fit tests to ensure it adequately represents the response surface.

4.6.6. Analyze and Interpret the Results

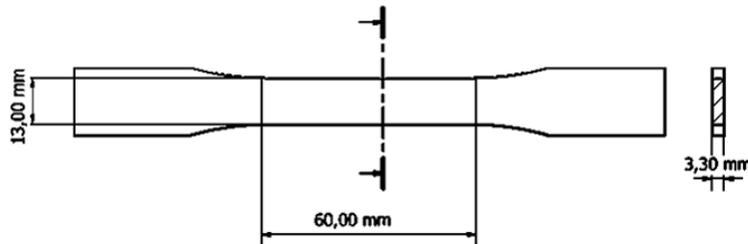
The relationship between factors and the response can be visualized using contour plots or 3D surface plots. These plots help identify patterns and regions of optimal response. Interactions between factors should be examined to see how they jointly affect the response.

4.6.7. Optimize the Response

The response surface model is used to determine the optimal settings for each factor that maximize or minimize the response. The model predictions of the model can be validated by conducting additional experiments at the predicted optimal conditions.

5 | Analysis

To simulate the warping levels, geometry of a sample part is necessary so that the baseline warping can be defined. This sample is taken from the previous master thesis of this subject. [31]



(a) Computer aided drawing with part dimensions.



(b) Printed part.

Figure 5.1: Dog bone sample. [31]

5.1. Application of Response Surface Methodology

After gaining deep insight about Response Surface Methodology, now it can be correctly applied to the desired problem, which is to optimize warping in Fused Deposition Modeling. To apply Response Surface Methodology to optimize warping in Fused Deposition Modeling with varying process parameters, these mentioned steps are followed and necessary Python functions is applied to accomplish each part.

In Fused Deposition Modeling, it is mentioned previously that warping can be influenced by various parameters. Since extrusion temperature, bed temperature, print speed, cooling fan speed, layer height and infill density are variables that can be defined and chosen

within a range, these parameters can be taken as continuous factors in the response surface model. Extrusion temperature, bed temperature, print speed and layer height are chosen as continuous factors in this analysis. In terms of categorical factors; material type, print orientation, build platform surface type, cooling method, infill pattern and extruder type can be defined. These variables do not have a range, instead, they take specific discrete values. As can be seen, other than print orientation, these are not direct process parameters. Therefore, no categorical factor is included in this analysis. However, the model can be improved with including categorical factors, which will require further literature review and data collection.

The objective and the factors of this response surface model are defined as in Table 5.1.

Objective	Minimize warping in the Fused Deposition Modeling process.
Continuous Factors	Bed Temperature ($^{\circ}\text{C}$), Extrusion Temperature ($^{\circ}\text{C}$), Print Speed (mm/s), Layer Height (mm)
Response	Warping Level

Table 5.1: Response Surface Methodology Model for Warping in Fused Deposition Modeling.

For this optimization, Central Composite Design (CCD) is used to set up a range of experiments for these continuous variables. CCD includes factorial, center, and axial points, which helps capture quadratic effects that can model curvature in the warping response.

5.2. Insights from the Program

Firstly, a CCD matrix is generated for the given set of factors. It includes factorial points, center points, and axial (star) points for these factors. Factor ranges are also defined in CCD as the resulting table includes columns for each factor, representing the range of process parameters. This design structure helps capturing both linear and quadratic effects.

Quadratic response equation is implemented with the necessary reference and coefficient values. To increase accuracy and simulate the experimental environment and its expected errors better, a noise variable is included.

Afterwards, the second-order model is fitted with regression analysis. Scikit-learn library is used in this part, to leave room to further improvement with machine learning.

From SciPy library, optimize and minimize functions are used to define objective function to minimize based on the model. Then, initial guess for each factor's midpoint and bounds for each factor are created. Afterwards, the response is minimized.

Finally, response surfaces are plotted for pairs of factors in order to visualize and analyze the interaction better.

5.3. Quadratic Response Equation

Quadratic response equation is implemented with the experimental data collected from several experiments in the literature. In order to increase the accuracy, various papers that focus on different process parameters are chosen. Each of them is carefully examined and analyzed to obtain necessary values.

The equation is created for PEEK (Polyether Ether Ketone) material. However, it can be adapted to any material that is used in fused deposition modeling which has experimental data on warping.

PEEK is a high-performance thermoplastic that has unique properties and requirements in fused deposition modeling compared to more common materials like PLA or ABS. Processing of PEEK demands higher temperatures and careful environmental control, particularly because of its high melting point, thermal stability, and tendency to warp due to significant thermal contraction during cooling.

5.3.1. Reference Values

To modify the response equation for warping with PEEK, first reference values such as target or optimal settings are adjusted.

Extrusion Temperature

PEEK has a high melting point which is typically around 343°C, and extrusion temperatures between 380°C and 410°C are recommended for proper layer adhesion and material flow. Insufficient extrusion temperature can lead to weak interlayer bonding, while higher temperatures risk degradation. Empirical data shows that 400°C is often an optimal balance, ensuring strong layer adhesion without risking excessive decomposition of the polymer.[9]

Bed Temperature

PEEK typically requires a high bed temperature, usually around 120–140°C, to maintain adhesion and minimize warping. A bed temperature below 120°C would likely lead to poor adhesion and increased warping, while temperatures above 140°C could lead to other print quality issues. According to studies, a heated bed around 130°C helps to reduce the thermal gradient between the print layers and the base, which minimizes warping by preventing rapid cooling. [12]

Print Speed

Printing PEEK usually requires slower print speeds (10–30 mm/s) compared to PLA or ABS. The reduced speed allows the high-viscosity material to bond properly and maintain temperature, which is critical for such a demanding thermoplastic. A print speed of 20 mm/s is generally optimal for achieving good layer adhesion without increasing thermal stress or risking defects [12].

Layer Height

Layer heights are similar to other materials but are generally kept between 0.1–0.2 mm to avoid excessive internal stress in each layer [9, 34].

Given these relationships gathered from experimental studies, here is the quadratic equation for warping in fused deposition modeling:

$$W = \beta_0 + \beta_1(T_{bed} - 130)^2 + \beta_2(T_{nozzle} - 400)^2 + \beta_3(S - 20)^2 + \beta_4H + \beta_5(T_{bed} - 130)(T_{nozzle} - 400) + \epsilon \quad (5.1)$$

Where;

W : Warping.

β_0 : Baseline warping level.

β_i : Factor coefficients, derived from insights from the literature.

ϵ : Random noise term to simulate variability in experiments.

The purpose of these reference values is that; in response surface models, centering around these reference values helps simplify the interpretation of the model. By subtracting these optimal or reference values from each factor, we can interpret the coefficients as representing how much deviation from these values contributes to an increase in warping.

For example, when T_{bed} is exactly 80°C , $(T_{bed}-80) = 0$, meaning the bed temperature term does not contribute to warping. As T_{bed} deviates from 80°C , the quadratic term $(T_{bed}-80)^2$ increases, modeling the increased warping due to suboptimal temperatures.

5.3.2. Coefficient Values

Each coefficient in the quadratic response equation is chosen with empirical data from the literature on PEEK printing behavior and demonstrate how specific characteristics of PEEK relates with the chosen parameters.

Baseline Warping Level β_0

This baseline reflects typical warping under otherwise optimal conditions. Literature indicates that PEEK high crystallization rate and thermal contraction of PEEK can lead to warping even with optimized print settings. As mentioned before, the reference part is a 60 mm x 13 mm x 3.3 mm dog bone sample. With aiming $<0.5\%$ warping, baseline warping level is selected as 0.3 mm, representing a minor amount of warping that might persist despite optimized conditions, a phenomenon noted in high-performance polymers where perfect thermal stability is challenging to achieve. [31]

Bed Temperature Coefficient β_1

The bed temperature deviation term $\beta_1(T_{bed} - 130)^2$ models how deviation from 130°C affects warping. Higher or lower bed temperatures relative to this reference point will increase warping. Research shows that maintaining a high bed temperature close to the glass transition temperature of PEEK ($\tilde{143}^\circ\text{C}$) reduces rapid cooling and associated warping. When PEEK is printed below 120°C , warping is significant due to poor adhesion; conversely, excessively high temperatures can soften the base too much and reduce stability [12]. The coefficient 0.05 reflects the sensitivity of PEEK to bed temperature changes. Empirical studies suggest that bed temperature strongly influences warping for high-performance polymers, so a larger coefficient than those used for PLA or ABS is appropriate.

Nozzle Temperature Coefficient β_2

The term $\beta_2(T_{bed} - 400)^2$ captures the effect of nozzle temperature deviations from an optimal 400°C . PEEK requires a narrow nozzle temperature range for consistent extrusion and layer bonding. Research indicates that PEEK's optimal nozzle temperature lies between 380°C and 410°C , where adequate viscosity and layer bonding are achieved

without degradation. Lower nozzle temperatures cause poor layer adhesion, while higher temperatures risk polymer degradation. The coefficient 0.04 is higher than typical for PLA or ABS because of PEEK's sensitivity to even slight deviations in extrusion temperature. An optimized nozzle temperature significantly reduces internal stress between layers, thus reducing warping, but deviations from 400°C increase stress more noticeably than in lower-melting thermoplastics.[9, 34]

Print Speed Coefficient β_3

The print speed deviation term $\beta_3(S - 20)^2$ reflects how moving away from an optimal 20 mm/s impacts warping. For PEEK, a slower print speed ($\tilde{20}$ mm/s) is typically used to allow sufficient cooling time for layer bonding. Higher speeds can cause inadequate bonding and increased internal stress, leading to warping, whereas much slower speeds may lead to material overheating. The choice of 0.02 indicates moderate sensitivity to speed. Literature shows that PEEK requires precise speed control, but the impact on warping is less than that of temperature changes. This coefficient is smaller than for temperature terms but significant enough to capture the effect of speed [12].

Layer Height Coefficient β_4

The coefficient reflects a strong effect of layer height on warping. Studies indicate that layer height significantly impacts internal stress buildup in high-performance materials like PEEK. Thicker layers retain more heat, which increases thermal gradients within the printed structure and exacerbates warping. PEEK typically benefits from thinner layers (e.g., 0.1–0.2 mm) to reduce stress. The value of 0.3 is chosen to represent a relatively strong effect. Literature suggests that thicker layers create more internal stress in PEEK than in lower-melting-point materials. This high coefficient reflects the increased warping tendency with larger layer heights in FDM of PEEK [20, 34].

Interaction Term for Bed and Extrusion Temperature β_5

This interaction term $\beta_5(T_{bed} - 130)(T_{nozzle} - 400)$ models the combined effect of bed and extrusion temperature on warping. For high-performance materials like PEEK, both bed and extrusion temperatures must be precisely controlled to ensure that each layer bonds correctly without causing contraction. Studies indicate that improper balancing of these temperatures leads to increased thermal gradients, which drive warping. The 0.002 value captures this interaction effect. Although not as influential as individual temperature terms, the interaction reflects the need to carefully balance bed and nozzle temperatures

in PEEK printing. [9, 34]

The quadratic response equation becomes:

$$W = 0.3 + 0.05(T_{bed} - 130)^2 + 0.04(T_{nozzle} - 400)^2 + 0.02(S - 20)^2 + 0.3H + 0.002(T_{bed} - 130)(T_{nozzle} - 400) + \epsilon \quad (5.2)$$

This equation models warping for PEEK material as a function of deviations from optimal values, with terms reflecting quadratic and interaction effects. Afterwards, a second-order polynomial model is used to fit the response surface. The model captures linear, quadratic, and interaction effects for each factor on warping. Using the fitted model, the response surface can be visualized and optimal process parameters can be identified to minimize warping. A function is created to calculate the predicted warping for given factor levels, it minimizes and optimizes these levels to achieve the lowest warping value. For continuous factors, the range is chosen to include the optimal value and hold it approximately at the middle. Therefore the chosen ranges are chosen as shown in Table 5.2.

	Starting Range	Ending Range
Print Bed Temperature (°C)	60	200
Nozzle Temperature (°C)	350	450
Print Speed (mm/s)	5	50
Layer Height (mm)	0.1	0.4

Table 5.2: Continuous Factors Ranges.

6 | Results

Contour plots are generated to visualize the response surface for pairs of factors, with the other factors held at optimal values.

The plots for warping prediction in Fused Deposition Modeling for PEEK material are as follows.

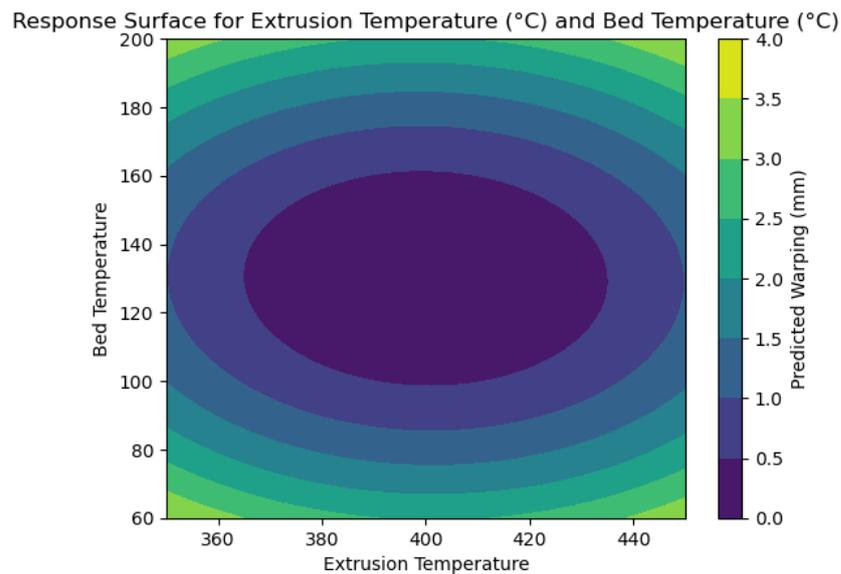


Figure 6.1: Bed Temperature and Extrusion Temperature effects on Warping for PEEK.

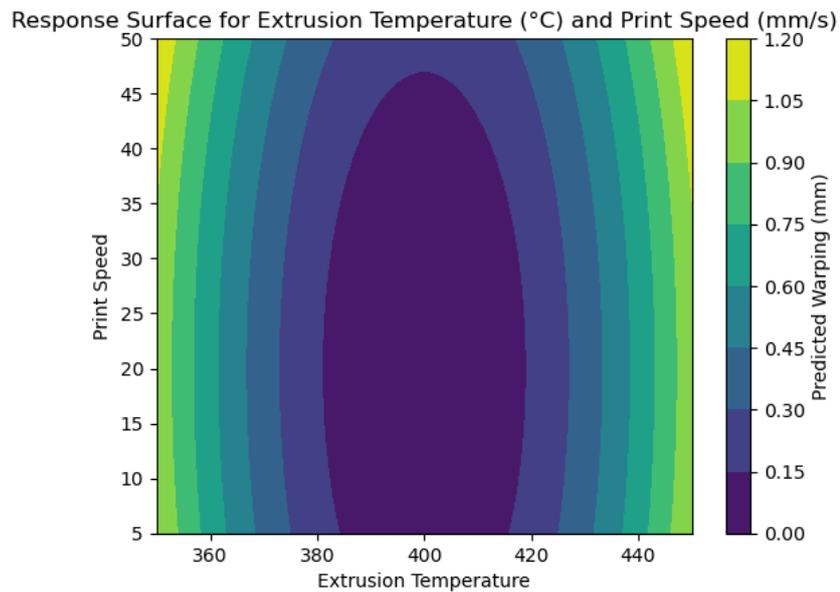


Figure 6.2: Print Speed and Extrusion Temperature effects on Warping for PEEK.

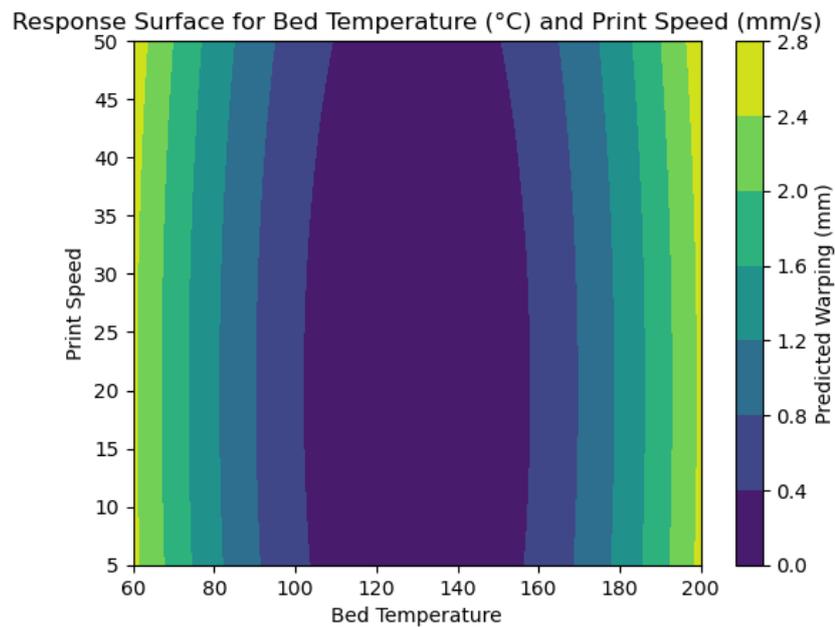


Figure 6.3: Print Speed and Bed Temperature effects on Warping for PEEK.

Since layer height has a narrow gap and contributes proportionally linear to the warping, the plots for predicting warping with different layer heights are done separately in order to visualize the change better.

The plot showing the predicted warping as a function of layer height can be seen in Figure 6.4.

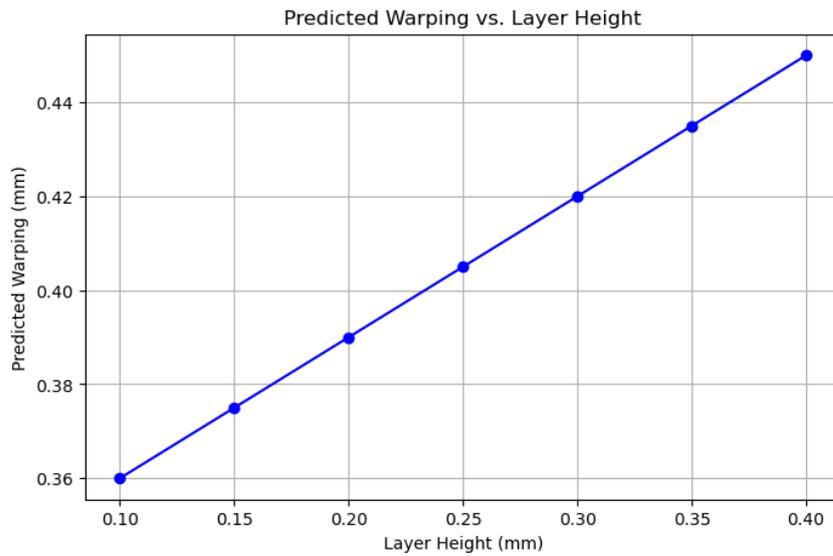


Figure 6.4: Different Layer Height effects on Warping for PEEK.

As layer height increases from 0.1 mm to 0.4 mm, the predicted warping also increases, reflecting the influence of layer height on warping in FDM according to the hypothetical model. The linear increase in warping with changing layer heights can be seen in Table 6.1

Layer Height (mm)	Predicted Warping (mm)
0.1	0.3637
0.15	0.3842
0.2	0.4093
0.25	0.4227
0.3	0.4367
0.35	0.4514
0.4	0.4667

Table 6.1: Warping Level with different Layer Height values.

With all of the parameters being at optimal, 0.3637 mm warping is achieved, including baseline warping of 0.3 mm. This means that 0.6% warping is achieved for 60 mm dogbone sample. Only 0.0637 mm of warping is measured on top of baseline level with optimal process parameters. For 60 mm dogbone sample, it is only 0.1% of the geometry. If the process parameters are held at optimal and compromised, very low warping levels are possible.

7 | Conclusions and future developments

The main objective of this study was to simulate warping levels with changing process parameters in Fused Deposition Modeling.

Literature data and experiments were carefully examined to obtain optimal process parameters to decrease warping.

Afterwards, a response surface model is created to simulate and predict the warping levels for different process parameters.

It is seen that a minimum warping level is achieved with optimal process parameters as: bed temperature at 130 °C, extrusion temperature at 400 °C, print speed at 20 mm/s and layer height at 0.1 mm. This values gave 0.3637 mm warping, which includes also predicted baseline warping of 0.3 mm that assumed to happen even with most optimal conditions. This results in 0.6% warping for 60 mm dog-bone sample. When the baseline warping is not considered, only 0.0637 mm of warping is measured, which is only 0.1% of the geometry. This results led to understanding how much warping can be minimized with optimal parameters.

With the help of the model created, warping can be predicted for any process parameter value. The researcher can add their own experimental data to simulate the response, or to simply predict the warping that they may encounter in the process.

This model plays a crucial role as a guide for warping levels in fused deposition modeling. It eliminates the need for trial experiments and gives an insight for what to expect.

Therefore, this study results in huge efficiency in time and effort, which is crucial in terms of sustainability. With the model developed, warping levels can be simply predicted before starting the process and the parameters can be aligned according to that. If they cannot be changed, other parameters can be compromised with the help of the model offers by showing coupled responses of process parameters.

As always, there is room for future developments. The model can be improved to analyze the data better and make more accurate predictions.

In the program developed, machine learning algorithm is implemented, so that the model can be trained by literature data to make its own predictions. In order to achieve this, the data gathered from the literature can be extended and used to taught to the algorithm with using machine learning. Most importantly, users can implement their own desired data, such as their own experiments, to predict more specialized and specific results.

This model can be extended with more process parameters, and for different material types. Warping is not the only defect that is encountered in fused deposition modeling. The same approach can be used to optimize also other problems.

With this approach, finally in the big picture, Fused Deposition Modeling technology can be perfectionized and its application can be extended to wider areas.

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List of Symbols

Variable	Description	SI unit
σ	stress	N/m ²
σ_{res}	residual stress	N/m ²
E	Young modulus	N/m ²
α	thermal expansion coefficient	-
h	layer thickness	mm
ϵ	strain	-
T_e	extrusion temperature	°C
T_b	bed temperature	°C
v	print speed	mm/s
W	warping	mm
k	thermal conductivity	W/(mK)
F_w	warping force	N
C	elasticity tensor	N/m ²

