

INVESTIGATION OF ADVANCED METHODS AND STRATEGIES FOR
HYBRID MANUFACTURING PROCESS PLANNING

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HYBRID MANUFACTURING PROCESS PLANNING**

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ABSTRACT

INVESTIGATION OF ADVANCED METHODS AND STRATEGIES FOR HYBRID MANUFACTURING PROCESS PLANNING

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Additive manufacturing (AM) often leads to parts with suboptimal surface quality and poor dimensional accuracy due to the nature of the layer-wise production technique. This issue is especially pronounced in material extrusion based additive manufacturing technology, where challenges such as surface staircase effects and the quality of internal features are prevalent. Hybrid additive manufacturing, which combines additive and subtractive manufacturing processes, presents a promising solution. It aims to enhance surface quality and dimensional accuracy by integrating material extrusion with precision subtractive milling in a single, streamlined process. This dissertation focuses on developing novel process planning methods for additive/subtractive hybrid manufacturing, specifically targeting the integration of fused filament fabrication (FFF) and milling. The study first aims to understand the fundamentals of the steps involved in hybrid additive manufacturing and explore the capabilities of the developed hybrid manufacturing platform. With the developed foundation, the researcher suggested an optimal way to apply milling to FFF parts and quantified the impact of the secondary processing on the part's surface quality. The main target of the study is

to create advanced tool path and process-planning strategies for hybrid AM and evaluate them through virtual test cases and experiments carried out on the established platform.

Keywords: additive, subtractive, hybrid, manufacturing, fused filament fabrication, milling



ÖZ

HİBRİT ÜRETİM SÜREÇ PLANLAMASINA YÖNELİK İLERİ YÖNTEM VE STRATEJİLERİN İNCELENMESİ

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Katmanlı üretim tekniğinin doğası gereği, eklemeli imalat ile gerçekleştirilen üretim sonucunda genellikle yüzey kalitesi bozuk ve boyutsal doğruluk açısından optimal olmayan parçalar üretilir. Bu sorunlar, özellikle yüzey merdiven etkisinin ve iç dolgu özelliklerinin parça kalitesini bir hayli etkilediği malzeme ekstrüzyonuna dayalı eklemeli imalat teknolojisinde daha da belirgindir. Eklemeli imalat ile frezeleme süreçlerini birleştiren hibrit eklemeli imalat yöntemi, daha kaliteli parçalar elde etme konusunda umut veren ve uygulanabilirliği son yıllarda sıklıkla tartışılan bir çözümdür. Bu yöntem, malzeme ekstrüzyonu metodunu hassas frezeleme ile tek bir çatı altında bütünleştirerek üretilen parçaların yüzey kalitesini ve boyutsal doğruluğunu artırmayı amaçlar. Bu tez, özellikle ergiyik filaman ile imalat (FFF) ve frezelemenin bütünleştirilmesini hedefleyerek, eklemeli/çıkarmalı hibrit imalatı için yenilikçi süreç planlama yöntemleri geliştirmeye odaklanmaktadır. Çalışma ilk olarak, hibrit eklemeli imalat kapsamında yer alan adımların temellerini anlamayı ve bu amaçlarla geliştirilen hibrit imalat platformunun yeteneklerini keşfetmeyi amaçlar. Bu çalışmada,

geliştirilen bu temel yetenekler kullanılarak, FFF parçalarına frezeleme uygulamasının en uygun metodu önerilmiş ve bu tarz bir ikincil işlemenin parçanın yüzey kalitesi üzerindeki etkisini niceliksel olarak değerlendirmiştir. Çalışmanın ana hedefi, hibrit eklemeli imalat için gelişmiş takım yolu ve süreç planlama stratejileri oluşturmak ve bunları sanal test ortamında ya da geliştirilen üretim platformunda gerçekleştirilen deneyler aracılığıyla değerlendirmektir.

Anahtar Kelimeler: eklemeli, hibrit, üretim, ergiyik filaman ile imalat, frezeleme





To my family

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*"En azından üç dil bileceksin. En azından üç dilde, ana avrat dümdüz gideceksin.
En azından üç dil... Çünkü sen, ne tarih ne coğrafya... Ne şu, ne busun. Oğlum Mernuş!
Sen, otobüsü kaçırmış bir milletin çocuğusun." Bedri Rahmi Eyüboğlu*

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
BJT	Binder Jetting
BRep	Boundary Representation
CAD	Computer Aided Design
CNC	Computer Numerical Control
CSG	Constructive Solid Geometry
DED	Directed Energy Deposition
DoF	Degree of Freedom
FDM	Fused Filament Fabrication
FFF	Fused Deposition Modeling
MEAM	Material Extrusion Additive Manufacturing
MEX	Material Extrusion
MJT	Material Jetting
PBF	Powder Bed Fusion
PLA	Poly Lactic Acid
RPM	Revolutions per minutes
SHL	Sheet Lamination
SM	Subtractive Manufacturing
STL	Standard Tessellation Language
VPP	Vat Photopolymerization
WCS	Workpiece Coordinate System

LIST OF SYMBOLS

f_z	Feed per tooth
R_a	Average Surface Roughness
R_t	Total Surface Roughness
R_z	Peak-to-valley Surface Roughness
T_g	Glass Transition Temperature
T_m	Melting Temperature
v_c	Cutting speed



CHAPTER 1

INTRODUCTION

Traditional manufacturing techniques have long been the backbone of industrial production, with typical methods like machining, milling, and molding being used to transform raw materials into mechanical components for mass production. To meet the demands of industry, conventional manufacturing techniques have historically specialized in producing parts quickly and inexpensively. Although it has proven its usefulness for economic and technological reasons, they typically involve substantial material waste, restricted design options, and sometimes lengthy lead times depending on the application.

These conventional manufacturing methods are being challenged by Additive Manufacturing (AM), a paradigm shift in modern manufacturing. It revolutionized today's production industry with its unique way of producing goods, building them layer by layer immediately from digital designs. A classical technique, for instance, subtractive manufacturing, starts with a block of material and progressively removes material to achieve the desired shape, as AM builds up parts just by adding material wherever necessary, which is completely unlikely. With the recent introduction of AM, manufacturers now have remarkable flexibility in product design and development and the ability to rapidly test their innovative ideas. It enables the creation of complex geometries that were once thought impractical or impossible to produce through conventional means.

Although metals have been the primary material considered in mechanical design due to their structural reliability, strength, and mechanical performance, the emergence of AM has brought production to homes while extending the serviceable materials beyond the metals. It has attracted the attention of many users through its profound

impact on customized production and prototyping. While metals continue to predominate in real-world designs, the adaptability of other materials like thermoplastics has found use cases where they function as structural elements supporting light loads. In these specialized scenarios, conventional manufacturing, tailored for mass output rather than single-part production, often necessitates significant overhead and economic inefficiency. It is within this space that 3D printers and Material Extrusion Additive Manufacturing (MEX) have gained remarkable popularity among hobbyists and industry professionals.

Among the standard AM technologies classified in ISO 52900-2021 [1], MEX stands out for its use in polymer applications through thermal reaction bonding. According to the standard, MEX is defined as “an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.” This method involves the heating of thermoplastic (typically in the form of filament feedstock) within an extrusion nozzle up to its melting temperature, enabling it to be extruded onto a build platform. The sequential buildup of layers, guided by the thin slices of the digital model obtained by slicing software, leads to the formation of the object.

MEX technology is expected to grow in popularity with the rising need for low-cost customized products. As technology has progressed, users now have practically limitless scope for their designs. The simple workflow has made 3D printers accessible to both individuals and industry for rapid prototyping. Fused Deposition Modeling (FDM) and Fused Filament Fabrication (FFF) are two other names for this technique, and all those terms will be interchangeably used throughout the dissertation.

The objects produced through FFF, however, often exhibit quality problems like visible stair-steps, surface defects, and deviations in size and shape. These problems arise from the layer-wise nature of the process and part resolution due to smallest build element as well as other factors such as the inaccuracy of the used machinery and thermal dynamics causing shrinkage and distortion.

One potential solution to address these challenges is secondary processing. Hybrid manufacturing is a relatively undiscovered zone that could help us enhance productivity, quality, and design options in production by combining FFF and subtractive techniques in a way that helps them operate better together. Milling is a viable alter-

native since it treats FFF items as near-net-shaped products and finishes the surfaces to make them flat and reach the desired dimensions.

This dissertation attempts to establish a novel method with the goal of uniting material extrusion additive manufacturing and precision subtractive milling into a single, streamlined process. By combining additive and subtractive processes in a robust way, this research hopes to overcome FFF's current limits and show a viable method to increase the quality of the output. This study aims to improve fused filament fabrication and redefine process boundaries by solving the inherent problems with this hybrid paradigm.

1.1 Significance of hybrid additive manufacturing

Fused filament fabrication is known for fabricating complex geometries with a simple processing pipeline using inexpensive base materials. But this technology must address inherent problems such as poor surface quality, shrinkage, part distortion, and the inability to reach close tolerances.

Milling, on the other hand, despite its superior precision and surface finish, might be restricted by its inability to easily produce complex structures and unreachable internal features.

The strategic combination of additive and subtractive methods, referred to as hybrid additive manufacturing, provides a game-changing perspective by utilizing each method's strengths to overcome the existing limits. The goal of hybrid AM is to find the optimal balance between these processes. In this way, the design freedom of additive methods can be combined with the surface finish and dimensional accuracy typical of subtractive ones. With the advancement of fully integrated hybrid AM technology, light weighted structures, intricate designs, and assembly parts can be created with superior quality and dimensional accuracy.

There are several reasons why hybrid AM is important to the economy, production industry, and innovation ecosystem. The following are a few of the most crucial factors that help to highlight its significance.

- Increased productivity:

One of the most remarkable aspects of hybrid AM is its potential to increase productivity. FFF entails a well-known trade-off between surface quality and production speed. Fabrication times can be reduced if layers are made thicker; however, the surface quality may suffer as a result of the intensified staircase effect. Hybrid AM provides a straightforward solution to this issue: saving time by building in bigger layers and then smoothing out the surfaces with milling afterward. This acceleration in process speed has profound implications for its users, contributing to improved efficiency but at the expense of the complexity of process planning and integration.

- Enhanced product quality:

Surface roughness and dimensional accuracy are typically used to characterize FFF product quality. Depending on the layer height and deposition angle, FFF objects can have a surface roughness ranging from a few microns to many tenths. With low-priced equipment and other material-induced challenges, dimensional inaccuracies on the order of millimeters are sometimes inevitable. A hole on an FFF-made product, for instance, may shrink by as much as a tenth of a millimeter, depending on the object's dimensions and the properties of the feedstock material. The main benefit of secondary processing through milling lies in its ability to provide a high-quality surface finish and precise tolerances, which in turn can lead to the fabrication of repeatable, easy-to-assemble, and fully functional FFF parts.

- Customized production with high design freedom:

AM gives designers more freedom and flexibility than ever before, while the quality improvement achieved by secondary processing extends its use to real-world applications. This extended design space creates the opportunity for the realization of previously impossible innovations due to constraints in manufacturing. Thus, hybrid AM may simplify the process of creating individualized goods that fit the needs of the users. This customized approach may be especially helpful in fields where the parts are tailored to an individual's needs, like medical implants.

- Reduced waste and sustainability:

There is a rising emphasis on sustainability in various industries, so Hybrid AM may contribute to the objective of sustainable production by reducing material wastage. Due to the precision of subtractive methods, secondary milling can remove as little material as necessary to achieve the desired level of surface finish. FFF's ability to incorporate recycled materials and the potential for reincarnation of existing objects encourage a sustainable form of production.

Overall, FFF is great for intricate geometries but has problems with surface quality, while milling is precise but limits design freedom. Thus, synergizing these methods may offer an optimal balance with further developments in the future, which may transform modern manufacturing by triggering innovation.

1.2 Research objectives and scope

This dissertation is based on the development of hybrid AM through the combined use of FFF and milling. The scope of this study is delimited to the combination of FFF and milling, thereby excluding consideration of other hybrid AM methods. The theoretical work on hybrid process planning is to be realized with comprehensive experiments on a unique multi-axis hybrid manufacturing platform. This work is driven by the following primary objectives.

- Foundational understanding of the topic:

The preliminary goal of this research is to learn the fundamentals of hybrid AM and the benefits of merging those technologies. This involves becoming familiar with the terminology and concepts within this scope by conducting a review of the state-of-the-art and identifying gaps and challenges in this domain.

- Exploration of the capabilities of the hybrid manufacturing platform:

An important objective has been the investigation of the capabilities and limitations of the employed multi-axis hybrid manufacturing platform. This includes looking into secondary opportunities such as multi-axis fused filament fabrication.

- Introducing machining into FFF production:

The study aims to find the optimal way to apply milling to an FFF part and quantify the impact of secondary processing on the part's surface quality. Process parameter optimization must also be based on the underlying mechanisms to share insights with users who are interested in testing out milling on FFF parts on their own systems.

- Innovative tool path- and process planning for hybrid AM:

The main objective of the study is to design and implement novel approaches to synchronize FFF and milling within a process planning framework. This involves the initial development of the necessary foundation, such as the tools for slicing, machine simulation, and command generation. The analysis of the objects to be manufactured, the process planning methods applied in certain scenarios, and the decision-making procedures for determining process sequencing are all integral parts of the overall framework.

- Validation through experimentation:

This study also aims to realize the proposed process planning framework via a series of experiments on the hybrid manufacturing platform. The experiments are initially devised and executed for parameter optimization for both individual additive and subtractive stages of the production. These preliminary subgoals are necessary for getting the hybrid manufacturing platform ready for optimum fabrication before the fully integrated system can be realized. Following the development of the suggested process planning framework, sample components are to be manufactured.

Collectively, these objectives form a clear roadmap for the dissertation, guiding the exploration of hybrid AM and establishing the foundation for meaningful contributions to the field. The last target is to wrap up the implications of the research findings, the benefits and problems that were discovered during the investigations, and the insights that were gained with a clear conclusion.

1.3 Research methodology

This section describes the methodology followed throughout the research in order to accomplish the given objectives. The current part covers the statement of any experimental setups, measurement tools, data analysis techniques, and utilized software in detail.

The hybrid manufacturing platform, or Hybro, is the primary experimental setup used throughout the study, which is adaptable to a wide variety of manufacturing scenarios with the flexibility introduced. Hybro is a multi-axis, custom-built workstation that could streamline the processes of both fused filament production and precision milling on a single setup. The configuration of the system and its separate axes are shown in Figure 1.1. The following is a short description of Hybro's main features and functions.

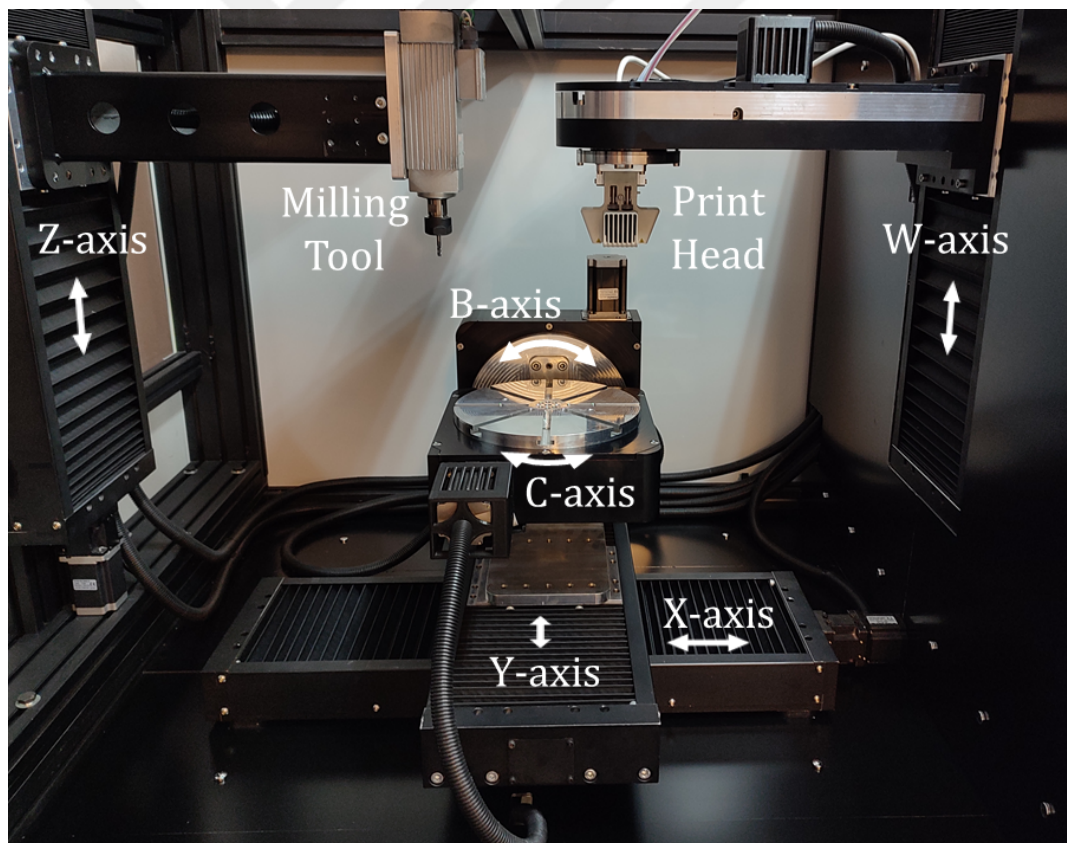


Figure 1.1: The hybrid manufacturing platform, Hybro

- Positioning/orientation in five Degree of Freedom (DoF):

The production platform, armed with 5-axis positioning functionality, provides the user with greater freedom of movement. Specifically, the platform is of the table-tilting type, with linear axes on the X, Y, Z, and W tables and rotational axes on the B and C tables. Depending on the kind of item being manufactured, positioning and orienting the Workpiece Coordinate System (WCS) with respect to the additive or subtractive tool is possible via an X-Y-W-B-C or X-Y-Z-B-C kinematic chain, respectively.

- Print head for fused filament fabrication:

For FFF, the primary extrusion unit is a dual-extrusion Ultimaker print head that has been adapted for use. The main extrusion unit contains two separate connection interfaces for Ultimaker print cores, one of which can accommodate a standard nozzle and the other of which can rotate around its own axis. Therefore, specialty nozzles with asymmetrical orifice can be housed in the latter print core for this purpose [2],[3]. The interface seamlessly connects the print cores and temperature control unit of the print head, where separate filament feeding mechanisms are built for each print core. With the help of a stepper motor and a gear set, the Bowden tube extruder can push the 2.85 mm diameter filament through the nozzle in this configuration. This equipment can be used to fabricate polylactic acid (PLA) and other common thermoplastics.

- Spindle (i.e., milling head) for subtractive manufacturing:

The milling function of the hybrid manufacturing platform is provided by a Hertz HMA95 spindle mounted on a linear Z-axis. It serves as an inexpensive milling unit to which various cutting tools can be attached by collets in the range of $\phi 3$ mm – $\phi 13$ mm. A Siemens Sinamics V20 inverter provides precise control over the spindle speed, which can be adjusted between 1000 rpm and 24000 rpm.

- Rotational DoF for the print head:

An extra axis of rotation (known as Q-axis) allows for continuous adjustment of the print head with respect to the build table. This function will not be utilized within the scope of this work.

In total, there are 9 axes involved in the hybrid manufacturing system:

- 4 for translation (X, Y, Z, W),
- 3 for rotation (B, C, Q),
- 2 for the feedstock itself (F1 and F2).

The motion axes are driven by stepper motors under the control of the drivers' custom-built firmware. These drivers, tailored for precise positioning, are equipped to execute frequent, high-frequency positioning commands for individual axes. Additionally, the firmware incorporates a multitude of functionalities that facilitate motion execution and system state inquiries. A detailed explanation of these firmware functions is provided in subsequent sections.

For data transmission to each axis, an RS-485 interface connection is employed, operating at a baud rate of 115200. The drivers can communicate with the computer with the help of simple software running on the real-time control unit, an Arduino Mega 2560.

Within the scope of this study, the utilization of specific software tools is vital for fulfilling the objectives comprising: (i) the design of solid models, (ii) their conversion into mesh representation, (iii) the slicing of those models, (iv) the generation of the tool paths, and (v) sending motion commands to the axes.

The design of solid models is executed through the Siemens NX modeling software. Notably, the Rhinoceros 3D and Grasshopper 3D environments offer an alternative to applying special modeling techniques, particularly for the realization of parametric designs. In this study, the designs are usually represented through mesh models, referred to as Standard Tessellation Language (STL) models. Such models can be exported from the design software mentioned.

Slicing of the STL models, which is a common practice in FFF before generating tool paths, is carried out by the dedicated software developed in MATLAB®. The same platform is used to build the simulator to further visualize the expected outcome and simulate the motion.

Within the scope of this thesis, the experimentation is carried out by attaching several nozzles and milling equipment to the hybrid production platform. Nozzles and print cores from the standard Ultimaker series are utilized, with sizes ranging from 0.4 mm to 0.8 mm. A wide variety of endmills, chamfering tools, T-slot cutters, and drilling tools were utilized for milling.

A subset of the experimental studies also make use of specialized tools that are attached to Hybro's specific interface. Notably, in this context, the idea of temporarily integrating hot ironing tool onto the Z-axis is realized.

In addition to the hybrid production platform and its associated software, a multitude of measurement tools have been employed to evaluate certain properties of the parts manufactured. Some of the performance criteria are regarding the overall appearance, surface characteristics, and dimensional accuracy of the fabricated artifacts. Rarely, unique measurements like the temperature distribution in the working environment are also managed.

For any detailed magnification requirements, the Topcon universal measuring microscope, featuring a 10x magnification objective lens, is utilized. The micrographs presented in this dissertation is taken with this device.

A MarSurf PS10 surface profiler with a 2 μm stylus tip is used to quantify surface roughness parameters, a key performance metric for the manufactured components. The roughness calculation algorithm described by ISO 21920-2 [4] is used, with a cutoff frequency of 0.8 mm. The surface profiles are taken in line with the standard, ISO 21920-3 [5].

In instances requiring temperature distribution analysis of the manufacturing environment, the Optris PI 640i thermal camera is engaged. This device captures radiometric images and real-time videos within the workspace, offering an optical resolution of 640×480 pixels and the ability to measure temperatures ranging from $-20\text{ }^{\circ}\text{C}$ to $900\text{ }^{\circ}\text{C}$.

Moreover, a multitude of calipers, micrometers, and other measuring instruments are utilized to quantify the dimensional accuracy of the final products.

1.4 Organization of the dissertation

The current part provides an overview of each individual chapter in the dissertation. The significance of hybrid additive manufacturing is outlined, and the introduction provides the basis by describing the study's goals, scope, methodology, and a detailed plan for the subsequent exploration of the topic. Here, the organization of the dissertation is presented to assist readers in progressing through the following chapters.

Chapter 2 provides a review of the literature on hybrid AM and the process planning involved. This chapter examines the advantages and drawbacks of several approaches in order to identify gaps and opportunities that advance the present research.

In order to systematically address the aforementioned research objectives, a step-by-step investigation is pursued in this study. Accordingly, the exploration of individual constituent processes is carried out with careful experimentation on Hybro to establish the groundwork. First, Hybro is used to experiment with the FFF methodology, determining the best extrusion parameters, verifying the resulting tool paths, and investigating other benefits that arise from the system's multi-axis functionality. Subsequently, the focus shifted to the implementation of precision milling on 3D-printed workpieces. Therefore, the feasibility of each method is thoroughly evaluated before they are coupled. All prerequisites have been fulfilled, and optimal settings have been determined for these two methods. Independent research into the FFF and milling are the topics of Chapters 3 and 4, respectively. The complete integration of the hybrid methodology is to be addressed afterward.

The specific focus of Chapter 3 is the multi-axis FFF. The development of necessary tools such as slicing and simulation software is described clearly. This section covers the role of skeletonization and multi-axis slicing in the manufacturing of FFF objects in a support-free manner. Sample parts are manufactured, and the findings of the experiments are provided in detail.

The consequence of the milling operation on the 3D-printed products is next studied in Chapter 4. The covered topics include optimization of machining parameters, tooling considerations, and how the material acts while being machined. Prior to full

integration of FFF with milling, it is necessary to understand the fundamental implications and define the appropriate conditions to produce the best surface finish and dimensional accuracy.

Chapter 5 presents a hybrid process planning framework and helpful methods that could be utilized by the planner. All the steps of hybrid AM is summarized, i.e., from the representation of the solid model up to the manufacturing of the objects. Afterwards, the strategies and techniques that allow for the seamless integration of these two processes are discussed in sample virtual manufacturing cases in Chapter 6. Also, the hybrid manufacturing platform serves as a testing ground for the implementation of the described framework in produced simple parts.

Chapter 7 is the last part of the dissertation. It summarizes the most important results, conclusions, and implications from the previous chapters. This chapter also speculates on what the future holds for hybrid additive manufacturing research and development.

CHAPTER 2

REVIEW OF THE STATE OF THE ART

The basics of additive manufacturing are established here, including a definition and a classification scheme. This will assist in clarifying important ideas and key terms in the field. The current discussion then moves on to an in-depth examination of the extrusion-based AM methods, which constitute the central focus of this thesis. The fundamentals of material extrusion additive manufacturing, its main benefits, and an analysis of the most important aspects affecting product quality will all be covered in this discussion. Next, a detailed explanation of the integration of the method with the milling process and its significance is provided, reviewing the current state of the art in this area of research.

Additive manufacturing is the production process in which objects are made from 3D model data by the successive addition of material in a layer-by-layer fashion, in contrast to traditional methodologies such as subtractive or transformative manufacturing.

AM encompasses a variety of approaches; nevertheless, subcategories can be identified based on the nature of the materials used and the methods of material bonding.

The type of feedstock material determines the way of joining those substances together due to the distinct mechanisms of their fusion. The principles used for joining purposes may range from curing to melting, allowing the process to be utilized with a wide variety of materials, from metals to polymers.

In terms of feedstock options, additive processes can utilize materials available in many forms, such as filament, powder, or liquid.

Machines utilized in AM processes, as one might expect, have numerous motion axes to let the primary additive tool move along a specified path. These tools make use of diverse energy sources during production. For instance, deposition nozzles in material extrusion are heated to facilitate thermal reaction bonding, while lasers in vat photopolymerization utilize light energy for chemical reaction bonding.

The following categories of processes is used to classify additive manufacturing technologies [1]:

- **Binder Jetting (BJT):**

This term refers to the processes in which selective deposition of a liquid binder is used to connect powder-based feedstock.

- **Directed Energy Deposition (DED):**

Concentrated heat is utilized in this AM technology to melt substances during the deposition process, fusing them together.

- **Material Extrusion (MEX):**

The processes in this category use a nozzle or orifice to discharge material selectively.

- **Material Jetting (MJT):**

Feedstock material is deposited in droplets in this AM technology.

- **Powder Bed Fusion (PBF):**

This term refers to the processes where targeted regions of a powder bed fuse together with the application of a heat source.

- **Sheet Lamination (SHL):**

In this technology, the products are built by bonding sheets of material together.

- **Vat Photopolymerization (VPP):**

The processes in this category utilize light-activated polymerization to cure photopolymer in a vat of liquid.

2.1 Hybrid additive manufacturing

The benefits of AM include the simplified production of complex shapes, individualized products, optimal use of materials, and minimal waste. The quality of the products, however, needs to go up. These advantages are augmented by hybrid additive manufacturing, which takes the benefits of multiple manufacturing processes and combines them to boost product quality of AM.

Hybrid additive manufacturing has been extensively discussed in the existing literature, with more emphasis on metal additive manufacturing. Two recent works in the field of metal AM, by Flynn et al. [6] and Cortina et al. [7], highlight the importance of hybrid machine tools that integrate AM and subtractive processes. Sealy et al. [8] conducted a literature review, with an emphasis on classifying the many possible combinations of processes. Chong et al. [9] provide insights into digital-manufacturing advancements, emphasizing hybrid-AM's software aspect.

Industry interest in hybrid-AM has led to its implementation in several fields, including the biomedical, aerospace, and molding industries. The main target of the current implementations can be considered in two categories.

The first category is associated with the requirement for prototyping. Today's hybrid-AM technology may not compete with traditional techniques in mass production due to the severe limitations of the AM (particularly on manufacturing speed), unless the coupled process greatly increases the entire output. Even if recent developments may lead the way forward, no existing combination of processes has been able to overcome this challenge until now. However, the current state-of-the-art has shown that hybrid-AM is superior for the purpose of prototyping, customization of the products, and creating complex designs. Hybrid-AM applications are ideally suited for the aerospace industry, which frequently requires complex functional metal parts. Although early implementations have faced challenges in meeting essential part specifications, researchers have attempted to remedy these issues by employing hybrid manufacturing techniques [10]. As a result of its flexibility, hybrid-AM has also found application in the biomedical industry [11]. Clinical devices, hearing aid shells, surgical implants, and tissue engineering scaffolds are just a few of the medical uses that have benefited.

The second main application area for hybrid-AM is the re-manufacture of components. Re-manufacturing is the process of reshaping used components back into their original designs. It has lately emerged as a viable repairing solution. This is due to the fact that it is unreasonable to throw away expensive components in many industries. Instead, restoration conserves resources like time, energy, and money. Repair-type hybrid-AM applications, such as the reincarnation of high-value vital components like turbine blades, have lately gained attention in the aerospace industry [12]. The use of DED technologies combined with multi-axis machining is commonly recommended for remanufacturing.

While much research has centered around hybrid additive manufacturing for metals, the introduction and evolution of MEX have pushed production into our homes and broadened the material spectrum beyond metals. Despite ongoing quality challenges, MEX's substantial influence on personalized production and prototyping has gained widespread interest from individuals and industry. This includes the utilization of materials like thermoplastics as structural components for applications involving lighter loads. However, the existing body of literature primarily concentrates on hybrid additive manufacturing with metals, leaving a knowledge gap in relation to polymers. Recognizing this gap, the dissertation shifts its primary focus toward hybridizing material-extrusion-based AM with milling.

2.2 Material extrusion additive manufacturing

Material extrusion is the primary subject of this research. Other specialized terms for the same process are fused deposition modeling (FDM) and fused filament fabrication (FFF). Moreover, the term "3D printing" is frequently used synonymously in non-technical contexts. These terms will be used interchangeably throughout the dissertation.

The FFF method relies on the layering of molten thermoplastic. Selective deposition of the thermoplastic material is accomplished by means of an extruder head equipped with a nozzle and a motorized, gear-driven delivery mechanism to force filamentous base material through the nozzle. The nozzle, characterized by its orifice of various

sizes, is typically heated by an element located in the extrusion head. It also moves relative to the fixture-free build plate, while the deposition is controlled accordingly.

Thermoplastics are typically used as the feedstock, with polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) being the most common ones. Additional substances that are not used as the building material, such as water-soluble support materials, may be consumed when necessary.

The fused filament fabrication process starts with the design of the CAD model in suitable software, which is then translated into a format readable by an FFF machine. Object surface geometry is typically represented as a tessellation of triangles in STL files, which are used to store model data in terms of faces and vertices. The STereoLithography apparatus was the original inspiration for this file format. The terms “Standard Triangulation Language” and “Standard Tessellation Language” are also used to refer to this type of file format. Recently, more formats have become compatible with AM, including AMF, which provides extra support for storing color, material, and data for other similar attributes in the file. The STL file format is still widely believed to be the de-facto standard format for 3D-printing.

In the following step of FFF, the 3D CAD model is sliced into a number of 2D cross-sectional layers, each of which represents a specific height of the sliced structure. A slicing software is commonly used for this purpose, which takes into account various parameters such as print speed, infill pattern, and support structures.

The FFF machine is then guided on where and how much filament to deposit for each layer by the slicing software. These commands are written in a numerical control programming language called NC-code, or G-code in particular. These instructions not only contain information about the path but also additional details like the extruder or heated build platform temperatures. The G-code is sent to the FFF machines after being generated by the slicing software to carry out the production. The FFF machine maintains the desired temperature of the nozzle, speed, and motion control throughout the printing process to deposit material properly and create a three-dimensional product that represents good enough accuracy compared to the solid model.

Despite its potential and easy implementation, FFF is held back by its inability to

achieve the required level of production quality. As a result, research efforts have focused on finding ways to improve the surface smoothness, efficiency, repeatability, dimensional accuracy, and strength of the final products.

The FFF process has a number of significant error sources, which can lead to problems in surface quality, strength, and dimensional accuracy. Factors like thermal shrinkage and distortions, chordal errors, the staircase effect, and support structure burrs collectively contribute to surface quality problems. Additionally, voids and defects on the extrusion path, variations in road thickness, and delamination of layers are also possible causes of problems related to strength and internal quality [13].

One source of surface quality problems is the stair-stepping, which is quite innate with the layer-by-layer nature of the process. FFF employs layer thicknesses ranging from hundreds of microns to nearly a millimeter in extreme cases, resulting in visible layer lines that downgrade the overall aesthetic. An unfavorable build direction may worsen the stair-stepping effect, while reducing layer thickness partially alleviates it but extends build time.

The representation of 3D designs for FFF also impacts the surface finish and dimensional accuracy. The aforementioned STL format approximates the surfaces of the objects using triangles. This simplifies the geometry but leads to chordal errors or deviations between the original design and the corresponding mesh representation.

Further issues arise from thermal factors. Rapid cooling of thermoplastics results in unpredictable distortions and residual stresses. Dimensional stability is influenced by thermal shrinkage. The effects of shrinkage are magnified in areas such as small features on the parts or near the holes on the objects, whereas components constructed from materials prone to shrinkage are more vulnerable. Applying an offset to the layer's original 2D slice is a common solution to this issue. However, ensuring the exact sizes may present challenges when compensating for dimensions.

There are a number of other issues, such as the defects caused by the seaming spots and the leftover of the burrs from the support structures. Support structures typically create defects on the surface, which impairs the product's look and function, if the user does not adequately balance the support requirement and its post-processing.

Hybrid manufacturing strategies, which include supplementary techniques like machining, are being investigated in response to the aforementioned problems introduced by FFF.

2.3 Hybrid additive manufacturing for FFF-produced thermoplastics

Researchers have paid more attention to FFF in the past decade due to the topic's popularity and the large research gap on many related concerns.

The simplest attempt to resolve the problems of FFF has been the optimization of the processing parameters [14]. The surface quality of FFF parts, for instance, can be greatly enhanced by selecting the optimal build orientation. It is possible that the parts' strengths would improve or that there would not be a requirement for surface-degrading support structures if they were produced along specific suited orientations. Similarly, the stair-case effect can be mitigated by decreasing the layer height, but doing so will slow down the production. Adaptive slicing might also help reduce surface roughness in specific parts. Unfortunately, these solutions are often left as partial remedies.

Integrated methods like milling offer the potential to resolve some of the remaining challenges of FFF. This dissertation primarily focuses on FFF, however, other integrated technologies are employed to tackle these problems as well. The details of other hybrid methods are classified here [15].

Researchers in the field define FFF's manufacturing quality in terms of the smoothness of the part surfaces and the accuracy of its dimensions. As a result, the majority of the recent publications concentrates on the subject of attainable surface quality and dimensional accuracy.

The first applications on hybrid FFF and milling date back to the research of Pandey et al., [16] and continue with subsequent applications of the authors [17]. By implementing hot cutter machining, they have significantly reduced stair-stepping. The FFF parts made of ABS are heated just above their glass transition temperature during processing to provide easier machining and lower cutting forces. The authors

reported 50-times higher cutting forces when performing machining at room temperature as compared to a hot cutter. These results highlight the challenges related to the material properties of the thermoplastic base material.

To perform both FFF and milling processes, Lee et al., [18] have developed a low-cost hybrid manufacturing system. Their machine incorporated both manufacturing tools on the same axis, facilitating easy switches between operations. Nevertheless, the resulting parts imply that the manufacturing quality was impacted by the accuracy of the used machinery.

A similar work has been conducted by Li et al. [19], using a multi-axis robotic arm to carry out those processes in combination. In fact, there are hardware and software problems that must be solved for robotic applications [20]. The robotic arms' software architecture is generally developed for routine tasks and is not optimal for generating smooth tool paths that prevent singularities. The robot arms have poorer stiffness and positioning precision compared to gantry systems, but they have advantages like bigger build volumes and flexible tool configuration. They can only be used on softer materials with lower cutting forces because of their lack of stiffness.

Drilling of FFF components has also been studied by Dezaki et al. [21], who emphasized the role of macrostructure and material behavior. Poor layer adhesion led to cracks in the macrostructure when subjected to high pressure, and drilling into angled surfaces was more challenging. Moreover, thermoplastic materials melt and adhere to the cutting tool at high spindle speeds.

While they have looked for the best milling settings for 3D-printed PLA, their study lacked in-depth investigation [22]. The same authors conducted another similar study [23]. The influence of FFF parameters on PLA workpiece machining optimization has also been studied by Grgura and Kramar [24]. The results of the latter study are also consistent with the hypothesis that high spindle speeds and low feed rates may cause the material to overheat and gum up. Their results have also shown the interdependent effects of FFF and milling. When printing on walls with big nozzles, for instance, the milling depth has essentially no effect on the final surface roughness. On the other hand, when using narrow nozzles, cutting depth is limited. By increasing the size of the nozzles used in the FFF, production could be multiplied by three without

sacrificing quality in the milling that followed.

Boschetto et al. [25] have investigated a method to regulate the milling depth of cut in relation to the object deposition angle of FFF-produced objects. The study indicated the importance of addressing the macrostructural influence to avoid internal defects. This method assures that after the milling process, the adjacent walls remain hidden.

A recent research has surveyed the existing literature on surface enhancement, with a primary focus on FFF's many potential uses [26].

The remaining critical concerns that researchers have been focusing on recently include the following:

- hybrid additive manufacturing platforms for FFF and CNC machining combined [18]
- improvement of material properties [27]
- better dimensional accuracy [28]
- modeling of surface quality [29]

Hybrid additive/subtractive methods either use integrated in-process modifications or sequential post-processing steps in the fabrication. That implies that milling can be employed either concurrently (in-process) or subsequently (post-process). For the latter case, it can be inferred from all these studies that the secondary milling method requires starting with an oversized, near-net-shaped product and then milling it down to the required dimensions.

It is well known that FFF necessitates a trade-off between superior product quality and a high output rate. This trade-off is established by the smallest elements that can be manufactured and the resolution of layering. The nozzle size and layer height are the most important considerations involved. So, when FFF is utilized in tandem with milling, the bottleneck might be overcome by controlling the process resolution and the surface finish independently. That is to say, larger nozzles can be utilized to boost productivity, and subsequent machining smooths out the surfaces and tailors the final dimensions.

2.4 Hybrid manufacturing process planning

Due to its layer-by-layer building process, additive manufacturing offers extensive possibilities for creating intricate designs, no matter how complex they may be, with virtually boundless design and manufacturing options. Furthermore, there is a significant possibility for increasing product quality by merging additive manufacturing with other processes. As a result, multi-axis additive machine tools and supplementary processes have found their way into the manufacturing industry, where they have proved to be highly influential in certain applications. The most common use case is in the AM of metals, but there is also a demand for consumer-grade products made from more accessible and affordable materials.

Researchers and organizations in this field already have a deep familiarity with the necessary hardware because the machines they use are comparable to those used in other production methods. These machines' motion systems, for instance, are generally similar to those seen in conventional machine tools.

Despite this hardware expertise, researchers and industry are unable to fully exploit the potential of hybrid manufacturing due to a lack of knowledge in software and tool path planning. These machines may resemble traditional machine tools at first glance, but the advent of AM has fundamentally altered the way we create products. This change has led to an increased emphasis on developing software solutions for hybrid additive manufacturing, which are essential to realizing the full potential of this novel technology.

Additive manufacturing involves several key steps: (i) pre-process selections like build orientation, machine setup, and nozzle size, (ii) describing part geometry and layers, (iii) planning workflows and tool path, and (iv) generating and executing machine instructions.

The determination of the build orientation is a crucial procedure prior to the main fabrication since it directly affects the accessibility of the AM/SM tool, the fabrication time, and the support volume. The user may be able to execute support-free fabrication in a typical AM applications by optimizing positioning/orientation or using higher degrees of freedom (DOF) platforms [30], [31].

In practice, the order of AM and SM processes has traditionally imposed additional limitations on the build orientation for hybrid platforms. For instance, reaching to a feature surrounded on the inner surfaces in a certain build orientation may pose tool accessibility issues in hybrid additive manufacturing, whereas planar milling of a freshly produced face may become a possibility [6].

Adjustments to the intermediate process planning should take into account the object's reactions against the cutting forces generated at the current orientation, as the base faces function as a fixture during the material removal stage [32]. Similar constraints must be taken into account when constructing on top of an already existing portion or on a stock material [33].

Described as the second stage, STL is typically used to describe the part geometry, where the 3D geometry is expressed as specific triangular meshes. In different production scenarios, the tool path can be generated using either a uniform slicing approach or an adaptive slicing technique of this geometry. The use of hybrid platforms enables manufacturers to implement advanced slicing techniques. For example, the ability to machine the base slice along several axes allows for slices of varying thicknesses and surface normals to be created [34].

Recent research suggests new opportunities for creating highly complex things in hybrid processes can be unlocked by decomposing the part into sub-volumes [35]. This has been used for engineering polymers, where deconstructed subparts (with their own build directions to avoid collisions) are made hierarchically via FFF, machining, and inspection [36].

In the current state-of-the-art, extracting the geometric features in light of the information obtained from 3D models has been achieved by widely known approaches such as volumetric decomposition methods, graphical boundary recognition methods, and rule-based pattern recognition algorithms. The extraction of geometric elements and their respective hierarchy, referred to as feature recognition, promotes the operation's sequencing and selection of proper tools in the course of the process planning for hybrid-AM [37]. For instance, a coupled operation of AM and SM may respectively necessitate a nozzle or a machining tool to form individual additive- or subtractive geometric features defined by certain criteria.

As a further step in the process planning, the generation of the individual trajectories of the AM/SM tools requires lots of effort since the optimal path without any collision and the minimum processing time are desirable. Besides, the process sequences of AM and the secondary operation should be carefully arranged.

Among the limited number of process planning studies regarding hybrid AM, a well-known methodology has been the iAtractive framework, which proposes the integrated use of material removal, inspection, and additive manufacturing [38]. The proposed framework particularly suits additive applications of the extrusion type, i.e., FFF of engineering plastics. With respect to the framework, the artifact is divided into sub-parts in order to perform production without any tool collisions. After the sub-parts are assembled and inspected, the final product is formed with the desired dimensional accuracy.

In the last decade, a highly active field in the literature related to hybrid AM has become the process planning for the reincarnation of the products. Apparently, reincarnation refers to the use of existing products to produce new components, i.e., a geometry that is already available can be reshaped and re-used through additive manufacturing and CNC machining.

Reproduction of end-of-life parts without any recycling step may have a significant impact on the industry by reducing the production cost and shortening the processing duration. Thus, the reproduction approach has expectedly become a popular research area in metal additive manufacturing. In recent literature, it has been shown that re-forming metal substances is possible with specific process planning techniques implemented on enabling hybrid-AM platforms [39]. For instance, Hao et al. [40] developed a hybrid process planning technique for building on existing parts with the help of skeleton tree matching.

The aforementioned iAtractive framework has also been utilized for reuse purposes in 3D printing [41].

2.5 Research gaps and opportunities

Due to the significant advantages of hybrid manufacturing over the conventional- and additive manufacturing operations, researchers have been conducting their works on different aspects of this entirely new method to make it more attractive. Their primary goals include; (i) increasing the number of suitable materials, (ii) achieving a better surface quality of the resulting products, (iii) developing special design tools for better efficiency, and (iv) decreasing the cost of the fabrication and the machinery.

The followings are the main research prospects in hybrid additive manufacturing.

- In-process measurement

Since the overall process is highly sophisticated compared to the other manufacturing operations, there is potential for many unpredicted events. In the course of the fabrication, the broken tools, surface defects, and unaccounted alterations in the process parameters affect the overall quality of the parts. Thus, in-process measurement systems (such as measurement probes, non-tactile sensors like high-resolution cameras) could be incorporated into the hybrid manufacturing systems for registering such events. The accuracy of the fabricated products could be improved dramatically by feeding the corresponding information (on dimensions) to the CNC units dynamically and taking corrective actions regularly.

- Advanced process planning

Due to its higher complexity in comparison with the traditional approaches, hybrid process planning has recently been utilized only for simple topologies. Further research on effective management of subsequent/simultaneous additive and subtractive processes may provide engineers/planners/designers a broader perspective. In fact, the current hybrid process planning practices have highly been governed by manual practices that rely on the expertise of the operator. So, the low level of manufacturing talent may expectedly hamper the industrial acceptance of hybrid-AM. For this reason, specialized software tools are required to face challenges like arranging the tool path and managing the AM process parameters effectively at the same time. Eventually, fully automated

hybrid process planners (armed with AI) might considerably expand the horizon of hybrid manufacturing processes while reducing overall manufacturing cost and fabrication time.

- **Materials**

The number of materials that can be processed on hybrid manufacturing machinery is limited since the material should be both appropriate for machining and AM processes. Therefore, new materials should be tested for hybrid-AM processes, or new types of process combinations capable of handling such materials should be investigated in the near future. Furthermore, new developments in many AM technologies have accelerated the multi-material usage, coming along with a great potential to extend the design domain. However, secondary processing on those composite layers (i.e., machining of multiple dissimilar materials at once) may create unique challenges in the compromised selection of many parameters (e.g., possible conflicts on feed rates and cutting speeds) and the tool (e.g., its geometry and material).

- **Tool design**

The cost of hybrid additive manufacturing may be reduced with an accurately controlled subtractive apparatus, e.g., new tools for forming operations rather than machining tools.

On the AM side of hybrid manufacturing, dynamic heads may be used to increase the capabilities of the process. Instead of having a constant cross-section at the tip of the extruder in the material extrusion processes, it may be modified dynamically during fabrication, which will result in an increase in the complexity of the products and a decrease in the fabrication time.

- **Chip management**

Since subtractive manufacturing is a part of hybrid manufacturing, chip, dust, or swarf production is inevitable. For high-quality parts, these chips should adequately be handled. Otherwise, they will interfere with AM operations. Various new methods need to be developed not only for chip management (including recycling) but also for control of the environment inside the hybrid manufacturing machine tools.

Due to a lack of design tools/experiences and software utilities, hybrid AM/SM platforms have not fully benefited from their hardware capabilities. Some research gaps and opportunities are identified as follows:

- Despite recent field experiments, a fully integrated hybrid AM/SM production system has not yet been introduced.
- The complicated decision-making requirement in hybrid process planning justifies the use of advanced systems but it has not encountered until now.
- A lack of process knowledge on material removal for 3D-printed thermoplastics necessitates proper design of experiments for selecting influential process parameters.
- Extraordinary applications utilizing the unique capability of the developed hybrid platform (such as concurrent AM and SM on either side of axisymmetric objects) may be followed.



CHAPTER 3

MULTI-AXIS MATERIAL EXTRUSION ADDITIVE MANUFACTURING

The preceding two chapters emphasize the significance of hybrid additive manufacturing and review the current state of the art.

This dissertation focuses on the practical implementation of hybrid-AM, which involves the seamless integration of additive manufacturing (i.e., fused filament fabrication) and subtractive manufacturing (i.e., milling). In order to systematically address this research objective, a step-by-step investigation is pursued.

Firstly, an in-depth exploration and experimentation of the FFF process on Hybro was conducted. Subsequently, the focus shifted to the milling of 3D-printed components. The feasibility of each process is carefully examined before the eventual integration. The necessary foundation has been set up for these two processes, and the best possible settings have been attempted and tested for each.

In this context, the present chapter and the subsequent one are dedicated to the independent exploration of the FFF and milling, respectively. The holistic integration of the hybrid methodology is to be addressed after these sections.

The overall pipeline for FFF comprises several sequential steps that can be elaborated as follows: (i) representation of the solid geometry, (ii) analysis of the geometry for determination of build orientation, (iii) slicing, (iv) tool path generation, (v) simulation, and (vi) execution. This chapter provides a detailed expansion of the essential elements that have been studied in the course of this research. Specifically, it explores the typical application of FFF on Hybro and its utilization within a multi-axis context.

3.1 Slicing

Slicing refers to the method used in AM to divide a digital solid model into several thin layers. The FFF platforms use the layers' data as a guide for the nozzle's tool path and deposit material precisely as commanded to create the final product.

Despite the availability of various slicer programs, such as Cura, a more comprehensive inquiry into the subject becomes essential. This is driven by the necessity to easily manipulate the tool path for Hybro, especially during the development of innovative features such as its multi-axis use. A modifiable slicer is particularly advantageous when seeking to implement customized commands on the manufacturing platform. Purposefully, a 3-axis slicer is developed within the MATLAB environment. When creating the slicer, standard practices are followed.

The developed 3-axis slicer uses STL files as the main geometric input, comprising the digital data of the part to be manufactured. Those files contain triangular mesh information representing the 3D design in terms of faces, vertices, and normal vectors. The developed slicer works by (i) reading the STL files, (ii) performing line-plane intersections to calculate layers, (iii) creating tool paths, and (iv) generating motion commands. A simple output of the developed slicer is provided in Figure 1, where a 3D model of a bunny (i.e., a low poly bunny) is sliced into individual layers.

3.2 Simulations

This part of the dissertation was presented as a conference paper at FAIM (Flexible Automation and Intelligent Manufacturing) 2019 [42]. The conference paper mentioned is a good resource for more detailed information. The current part of the study provides a brief overview of the topic at hand.

Once the individual layers of FFF objects are created via slicing, they are converted into tool path trajectories for production. However, especially for multi-axis systems, it is crucial to simulate the tools' trajectory before actual production to notice any potential problems or collisions of axes. A simulator may offer users a preview of the tool path and an interpretation of the overall appearance of the final product.

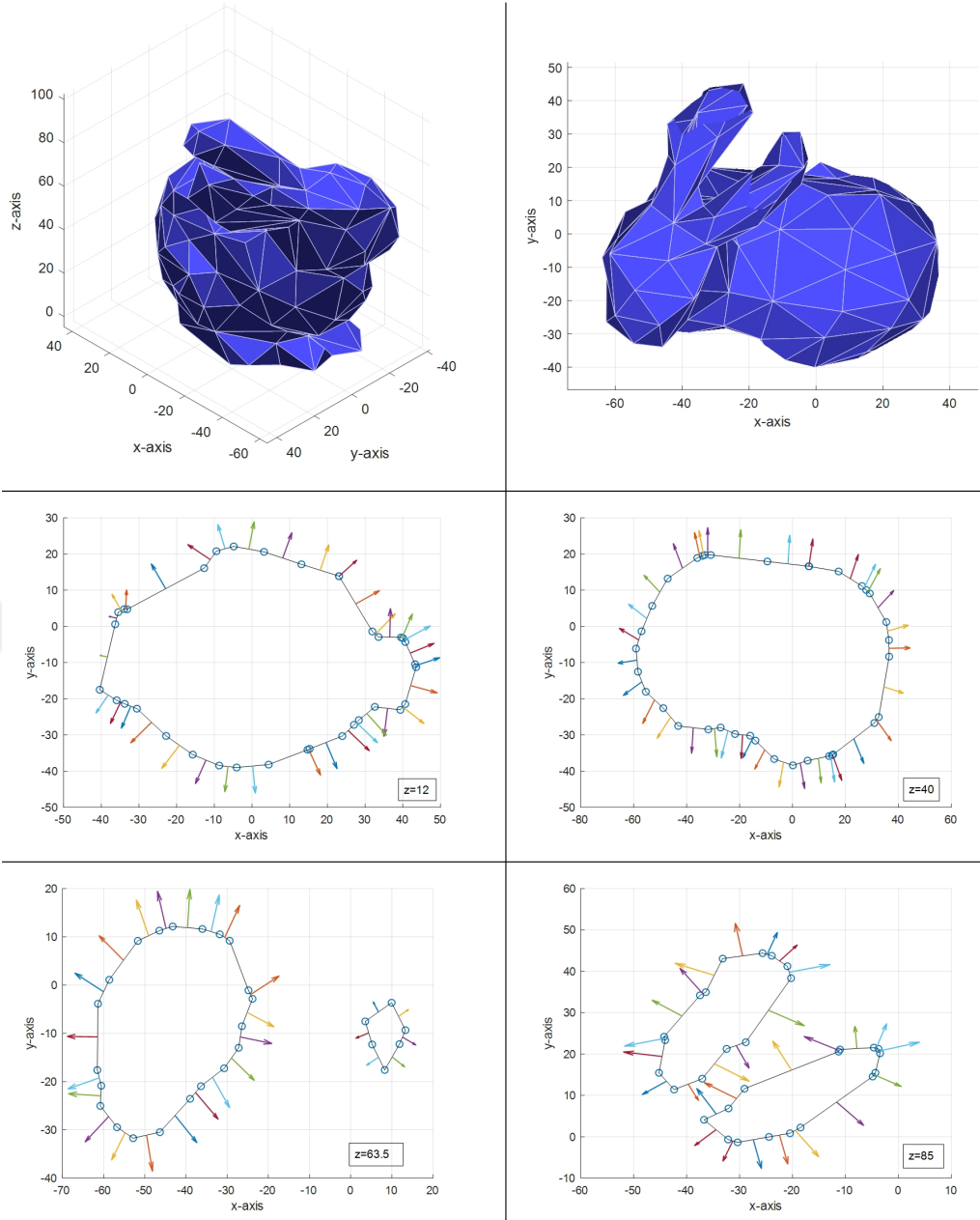


Figure 3.1: Top view and isometric view of the Low Poly Bunny, and arbitrary slices with contour lines and their normal vectors

Developing the simulator begins with establishing the kinematic model of the hybrid manufacturing platform. This model is crucial for controlling the nozzle's or milling tool's location and orientation in relation to the workpiece via coordinate transformations and command inputs. The first step in constructing the kinematic model is to attach the proper reference frames to the relevant mechanical parts.

The kinematic elements of the 5-axis platform are structured in a table-tilting configuration, with linear tables on the X and Y axes, rotational axes on the B and C, a subtractive tool on the linear Z-table, and an additive tool on the linear W-table (in fact, it is also spinning about the nozzle's center with additional Q-axis). The kinematic order and related coordinate frames for these mechanical units are depicted in Figure 3.2.

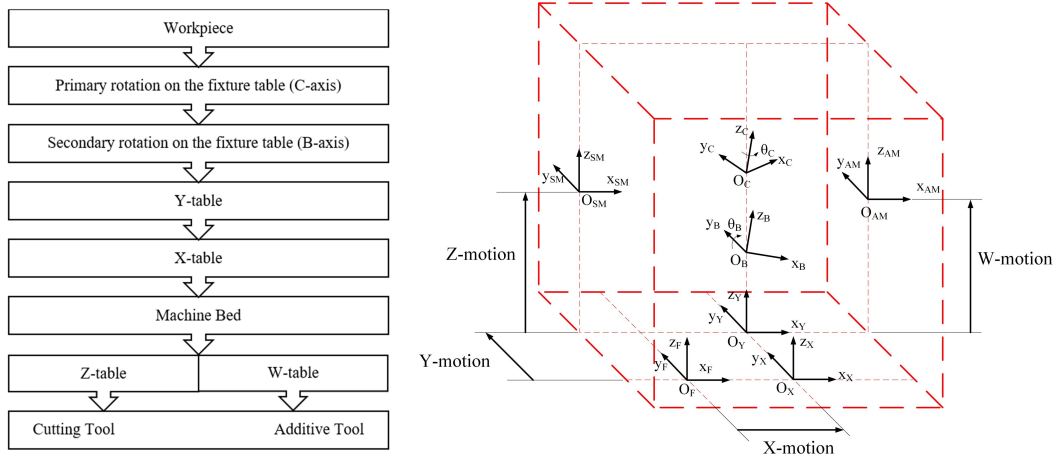


Figure 3.2: Coordinate frames used in the kinematic model

The relative position and orientation of the tools (milling tool or nozzle) as observed with respect to the workpiece (i.e., part) coordinate system can be transformed with the following expressions:

$$^{Part}\mathbf{A}_{Tool} = ^{Part}\mathbf{A}_C \times ^C\mathbf{A}_B \times ^B\mathbf{A}_Y \times ^Y\mathbf{A}_X \times ^X\mathbf{A}_F \times ^F\mathbf{A}_{AM/SM}$$

$$^{Part}\mathbf{A}_{Tool} = \mathbf{T}(L_{P,C})\mathbf{R}(z_C, -\theta_C)\mathbf{R}(y_B, -\theta_B)\mathbf{T}(L_{Y,X})\mathbf{T}(L_{X,F})\mathbf{T}(L_{F,AM/SM})$$

where the transformation matrix representing the relative position and orientation of the reference frame $O_jX_jY_jZ_j$ with respect to $O_iX_iY_iZ_i$ is expressed as follows:

$$^i\mathbf{A}_j = \mathbf{T}(L_{i,j})\mathbf{R}(N, \theta_N) \text{ where } \mathbf{L}_{i,j} = L_x\mathbf{i} + L_y\mathbf{j} + L_z\mathbf{k}$$

Here $\mathbf{T}$ and $\mathbf{R}$ indicates the pure translational and rotational homogenous transformation matrices, respectively. Using the kinematic relations and the known dimension/s/offsets of the motion axes, two versions of simulators are developed on Rhino and Matlab separately, as shown in Figures 3.3 and 3.4.

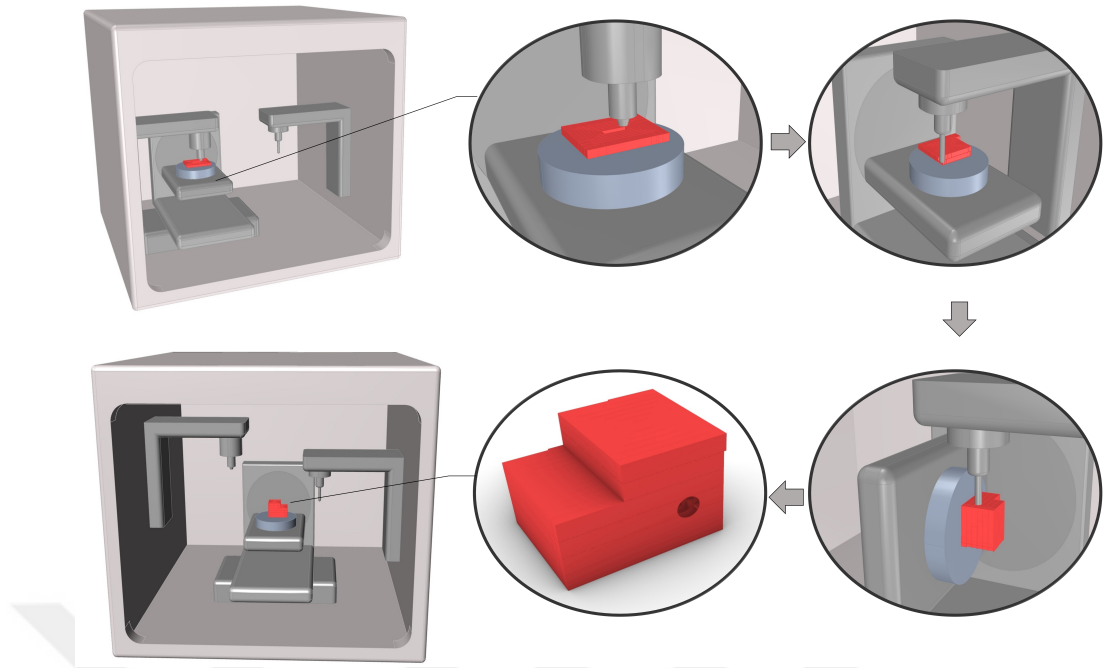


Figure 3.3: Simulator developed in Rhino/Grasshopper

The first version of the simulator was created in Grasshopper 3D software. Because of its adaptability and the fact that its programmable features are executed within a CAD (Rhinceros 3D) environment, it was favored for use in this context. The general framework of the simulations on this platform includes; (i) checking the syntax errors in the motion commands, (ii) executing the commanded translations and rotations using the kinematic relations, (iii) generating BRep (boundary representation) volumes of virtually extruded material, (iv) subtracting the material if milling exists, and, (v) rendering and visualizing the final 3D volume.

The first simulator has limited utility due to its high processing time and high computational resource requirements. This restriction results from the fact that slicing STL files produces a large number of line segments, which must be processed in great detail before being used to represent swept volumes of solids. Executing additional Boolean volume operations also adds complexity and increases simulation runtime.

Matlab is used to come up with an alternative method that will make the simulation run faster. Instead of using volume operations, the other version of the simulator used line segments and mesh structures to perform the necessary tasks.

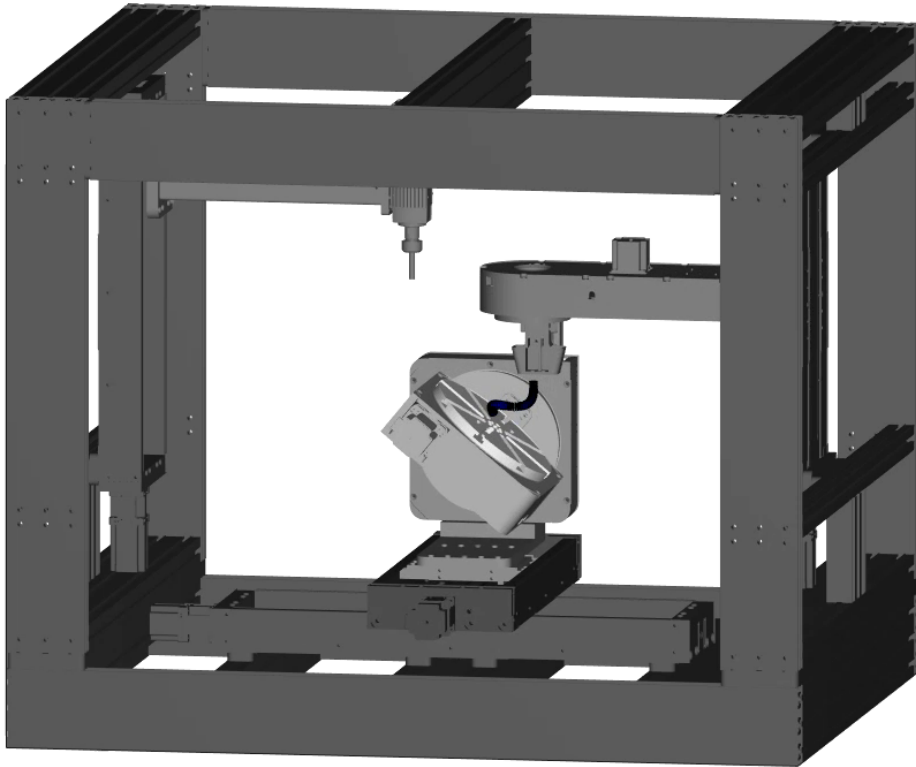


Figure 3.4: Simulator developed in Matlab

Thus, using the accelerated simulations, the planned operations on Hybro may be previewed in detail, allowing for the identification and correction of problems encountered beforehand.

3.3 Motion Commands

Once the tool path has been built using the layers resulting from slicing and this tool path has been checked by the simulator, the next stage is to perform the production with the motion system. At this point, the custom-built drivers using established embedded firmware for Hybro send motion commands to the corresponding axis' stepper motors. Thanks to the coordinated motion of the axes and the feeding of the material, production may proceed.

Using the custom firmware, two distinct operation modes are possible due to the many functions it contains.

Table 3.1: Drivers with their numbers and description

Driver Name	Driver No	Description
X	1	Horizontal motion axis 1 (X-axis)
Y	2	Horizontal motion axis 2 (Y-axis)
Z	3	Vertical motion axis 1
W	4	Vertical motion axis 2
B	5	Primary rotary table (B-axis)
C	6	Secondary rotary table (C-axis)
Q	7	Spindle rotary axis
F1	8	Filament feeding motor 1
F2	9	Filament feeding motor 2
S	10	Spindle motor

The two operation modes can be identified as follows:

- Independent Motion:

Through a graphical user interface developed on Matlab, users can independently control each axis in the system directly via the RS-485 protocol.

- Coordinated Motion:

To achieve a perfectly coordinated trajectory, the motion commands stored on an SD card are continually read and transmitted to the axes.

There are ten independent axes in the hybrid production system. The relevant motion axes, and the functions in the firmware that manage these axes, are given in detail in Tables 3.1 and 3.2, respectively.

The graphical user interface (GUI) for independently controlling the motion axis in jogging mode is shown in Figure 3.5. This GUI is developed in Matlab and facilitates the execution of commanded motions on individual axes through serial communication.

Table 3.2: Functions of the firmware embedded on the drivers

Function No	Function Name	Communication Format	Data Size
1**	Periodic Step Move	!(data)	10 bytes
2*	Motor On	:__0200\n\r	
3*	Motor Off	:__0300\n\r	
4*	Rotate Positive	:__0400\n\r	
5*	Rotate Negative	:__0500\n\r	
6*	System Acknowledgement	:__0600\n\r	
7*	Fast Rotate	:__0700\n\r	
8*	Slow Rotate	:__0800\n\r	
9*	Stop	:__0900\n\r	
10*	Reset	:__1000\n\r	
11*	Absolute Move	:11(data)__00\n\r	8 bytes
12*	Incremental Move	:12(data)__00\n\r	8 bytes
13*	Write to Parameter	:13(data)__00\n\r	6 bytes
14*	Read Parameter	:14(data)__00\n\r	2 bytes

*For Independent motion , ** For Coordinated motion

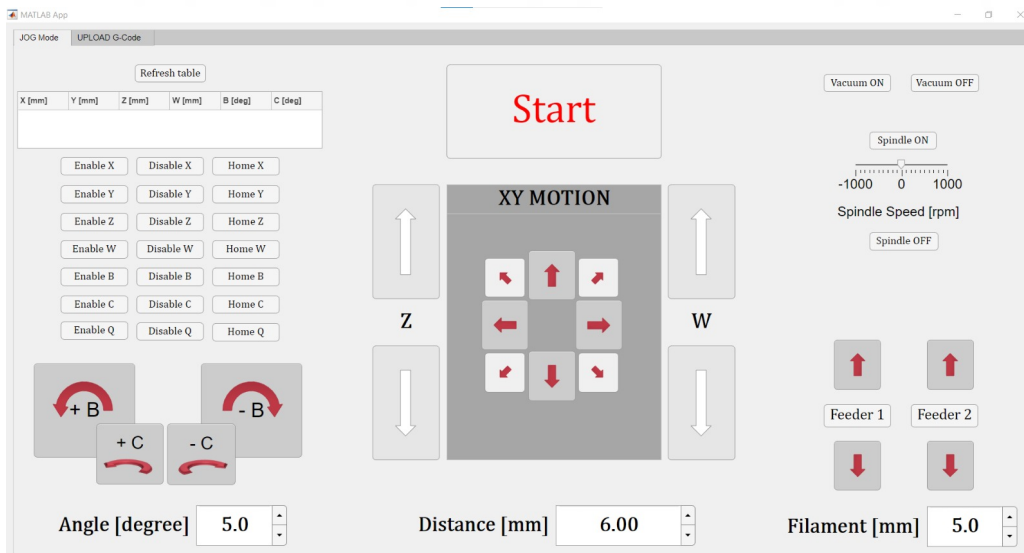


Figure 3.5: Graphical user interface for controlling individual axes in jogging mode

3.4 Multi-axis Fused Filament Fabrication

Once the first steps of slicing, simulation, and motion command design and implementation have been completed, the primary objective, multi-axis additive manufacturing with material extrusion, is pursued. This was presented as a conference paper at the AMCTurkey 2021 [43]. The research looked specifically at the Hybro's multi-axis FFF capability to produce support-free prints. The current part of the dissertation summarizes the important aspects of the mentioned work.

Typical FFF machines involve three orthogonal axes of translation (i.e., X, Y, Z). The tool path is generated by slicing software along a single, specified build direction. Due to the nature of fused filament fabrication, support structures are quite often required, leading to (i) greater material consumption, (ii) decreased production speed, (iii) a reduction in component quality, and (iv) additional post-processing.

Common ways for reducing support structures in FFF include (i) making adjustments to the model's shape [44], (ii) optimizing the build orientation [45], and (iii) partitioning the model into smaller buildable pieces [46]. There have also been interesting hardware solutions proposed to deal with the necessity for support structures, such as a gridded build plate with movable supporting pins [47]. Using multi-axis hardware stands out as a simple and effective approach to tackle FFF's support structure needs [48], [30].

Targeting multi-axis FFF on Hybro is an attempt to learn more about the capabilities of the manufacturing platform in support-free fabrication. With the extra rotational axes on the production platform, the workpiece coordinate system (WCS) (i.e., the build table) can be aligned with the material extrusion unit (i.e., the nozzle) while the process is going on. At the cost of increased motion complexity, it allows for greater freedom in generating tool paths. When the consecutive layers are chosen properly, support-less FFF is possible with continuous orientation changes.

Before the additional rotational axes can be used in the process, some preliminary work, such as slicing along altered directions, must be completed. Tool paths in this context must be created via multi-axis slicing. In addition, objects are skeletonized to allow for multi-axis slicing following a guide curve inferred from the object.

3.4.1 Skeletonization

Two main types of representations are used to embody 3D solid models: (i) volumetric representations and (ii) surface representations.

Solid volumes are typically defined in terms of dense structures in CAD programs, which are represented by volumetric representations. For instance, in constructive solid geometry (CSG), the desired geometry is constructed using Boolean algebra and elementary geometric shapes such as spheres or cubes.

In contrast, surface representations simply reveal the boundaries separating the inside and outside of the objects, which leads to a lower computational cost when working with such models. FFF predominantly employs STL models, which fall under the surface representation method.

While STL representations embody a 3D model well enough, users might not be able to directly access every piece of information they require, such as details like the existence or the orientation of a hole in the structure. Skeletons provide a potential method of characterizing 3D shapes with their core features, as they expose information about the core structure.

The information extracted from 3D objects' skeletons can be intentionally utilized in several FFF tasks:

- Volume decomposition
- Multi-directional slicing
- Optimization of infill patterns

Voronoi diagrams, medial axis transforms, distance field method, and the thinning algorithms are among the many tools for extracting an object's skeleton. Depending on the method utilized, curve skeletons or surface skeletons may be generated. In this study, a thinning algorithm is employed to extract the skeleton of the objects represented by STL models. This method yields curve skeletons of the solids, that will facilitate the subsequent process of multi-directional slicing.

Extraction of a 3D skeleton from sample objects is demonstrated with two instances in Figure 3.6. It's important to remember that the thinning technique may still yield a skeleton with unwanted noise, necessitating additional pruning in order to achieve the desired result.

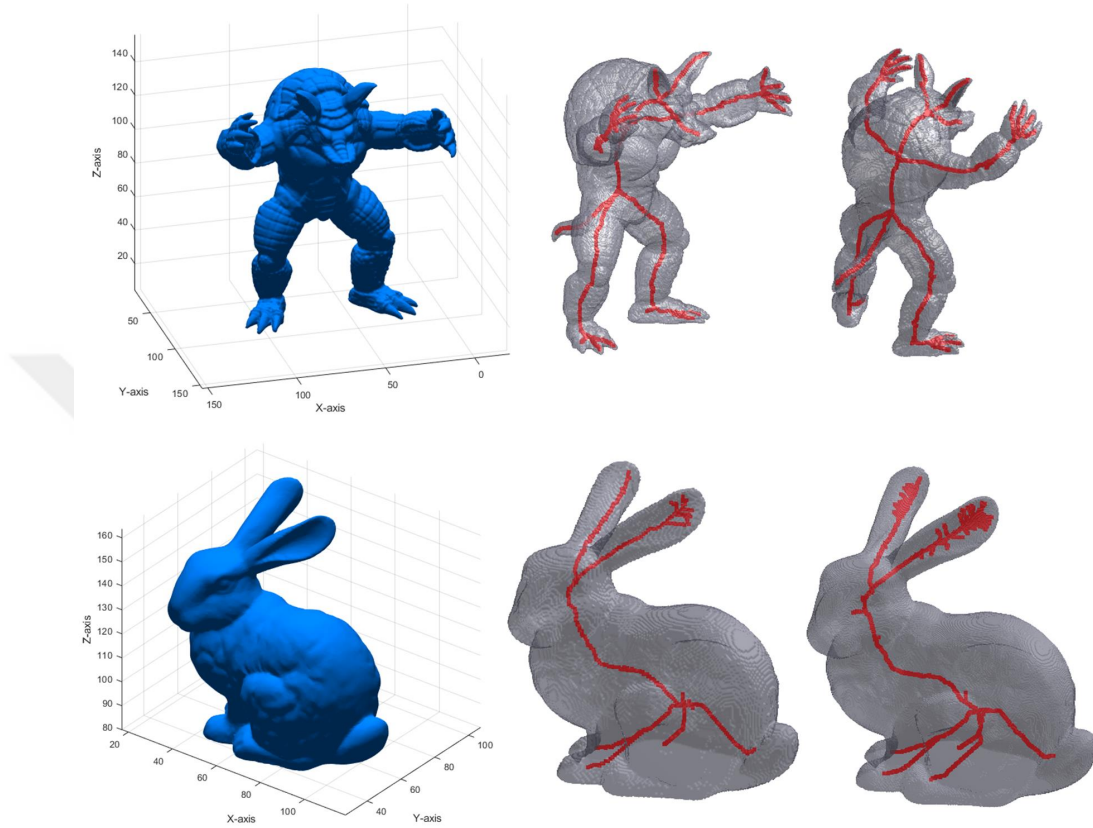


Figure 3.6: Skeletonization examples: Armadillo and Stanford Bunny

3.4.2 Multi-directional Slicing

The extracted skeleton of objects is an important piece of information that can be benefited in multi-axis slicing. When the 3D skeleton is used as a guide curve, slicing can be carried out along that curve, and the desired parts can be produced without the need for a support structure.

In this perspective, the developed 3-axis slicer has been modified, and a new multi-axis slicing approach has been created to facilitate slicing along a guide curve that considers the underlying topology of the objects.

The updated version of the slicer is employed to manufacture a complex sample part in the following example. 3D printing a spiral structure that would need internal and external supports in a regular 3-axis configuration is a useful case of viewing Hybro's multi-axis capability.

The selected sample part, as shown in Figure 3.7, features a hexagonal hollow cross-section following a helical guide curve.

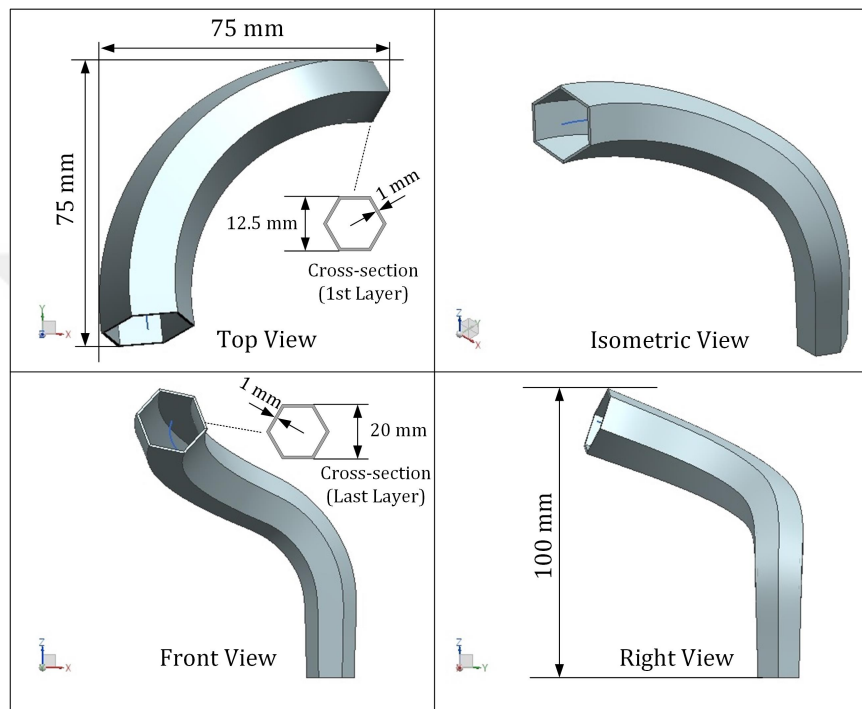


Figure 3.7: The sample part to be produced with multi-axis FFF

To accomplish support-free FFF, the following steps are used:

- Definition of the guide curve through skeletonization
- Division of guide curve into equidistant lengths, determined by layer thickness.
- Identification of slicing planes employing tangential and normal vectors along the guide curve.
- Representation of the slices on these defined planes.
- Application of the previously established coordinate transformation to align the slices with respect to the nozzle.

This methodology, summarized in Figure 3.8, ensures that the normal vector of these layers consistently remains parallel to gravity. The figure also reveals the difference between one- and multi-axis slices of the model. There is no need to use any support structure if the production is carried out on multiple axes. In contrast, a 3-axis platform would require both interior and external support structures for the same manufacturing goal.

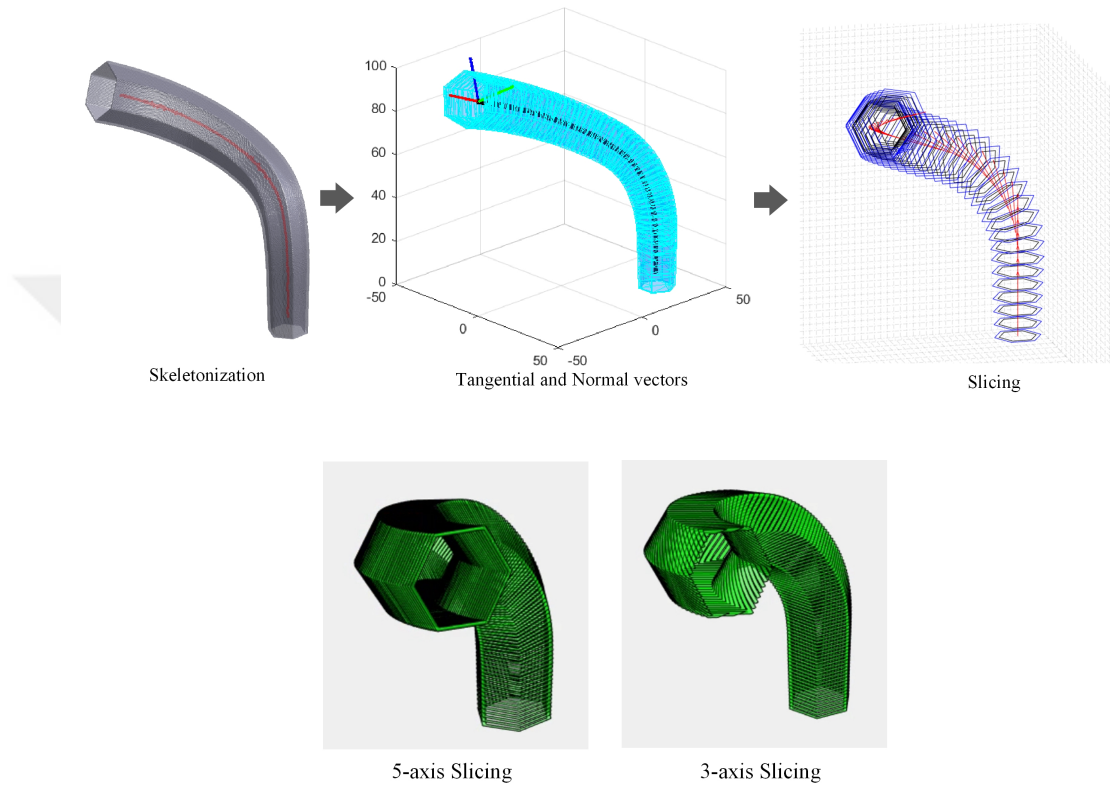


Figure 3.8: Classical slicing method compared to the multi-axis slicing

Production tests are run on a Hybro after the tool path has been generated, making use of the machine's X, Y, W, B, and C motion axes. The identical component is also manufactured on the AnyCubic i3 Mega with similar parameters, so that we may compare the two methods of production. For both the 5-axis (on HYBRO) and 3-axis (on Anycubic) scenarios, the most important process parameters are listed in Table 3.

Using the given process variables, identical sample parts are produced. Instantaneous captures during manufacturing are shown in Figures 3.9a and 3.9b for Anycubic and Hybro, respectively. The key distinction is that in the 5-axis FFF process, the B- and C-axes can be used to continually rotate the WCS into the desired orientation.

Table 3.3: Critical process parameters used in both platforms

	HYBRO	Anycubic
Used Material	PLA	
Process Temperature	205 °C	210 °C
Layer Thickness	0.2 mm	
Nozzle Diameter	0.4 mm	
Number of Shells	2	
Infill Ratio	0%	
Support Overhang Angle	N/A	60 °
Support density	N/A	8%
Consumed Material	~12 g	~23 g
Processing Time	80 min	161 min



Figure 3.9: Instantaneous captures during manufacturing on 3-axis and 5-axis platforms

Figure 3.10 shows the final product of the Hybro's manufacturing process. The final form of the manufactured product clearly demonstrates the potential of multi-axis systems in support-free FFF. The remarkable quality of the printed cross-section is made possible by the ability to dynamically modify layer orientations during production.

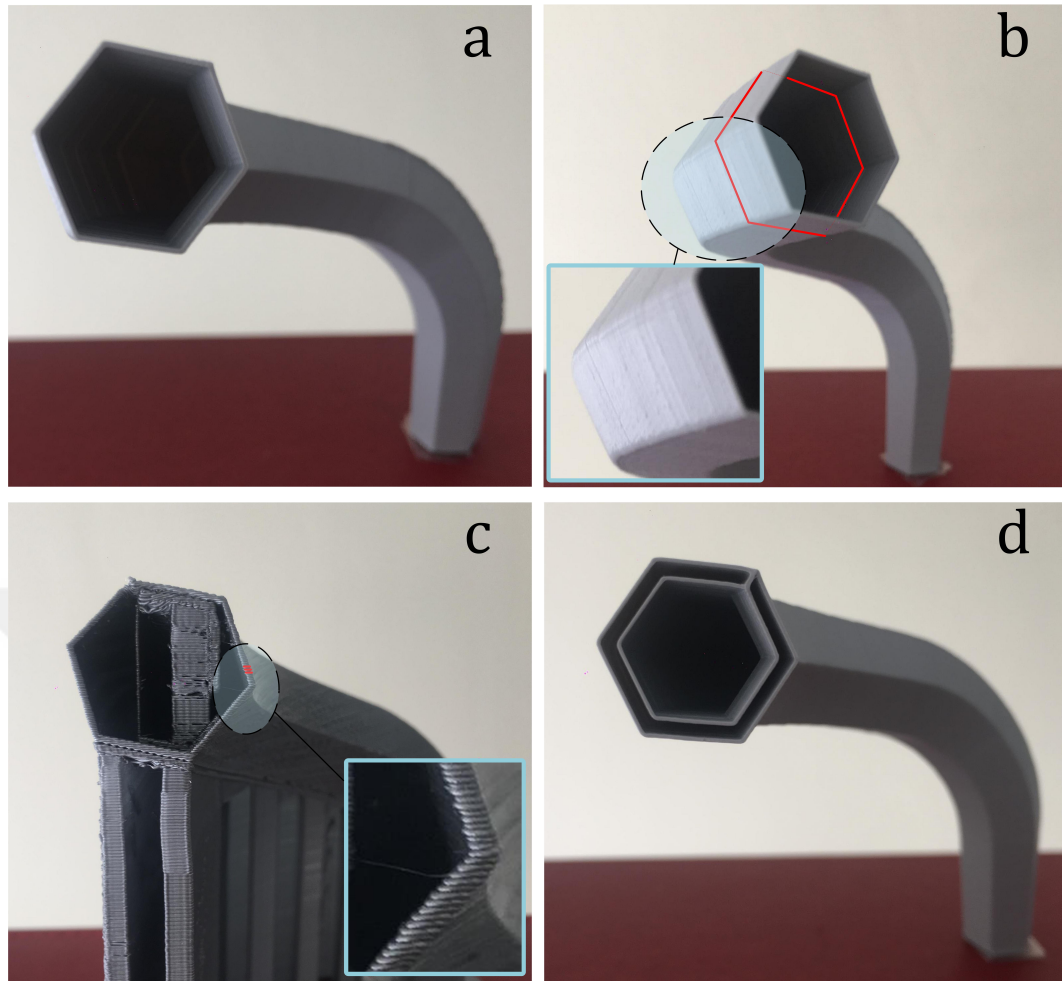


Figure 3.10: (a) Produced part on Hybro, (b) Its alternative view with extra details, (c) Produced part on Anycubic, (d) A modified part produced on Hybro

Figure 3.10b features highlighted cross-section of an example slice. The magnified view reveals how the smooth surface is achieved by stacking successive layers (with normal vectors aligned parallel to gravity). Typical 3-axis FFF can only use layers that are perpendicular to the build plate. In order to maintain contact between newer layers and older ones, it is required to employ both internal and external support structures. Stair-stepping becomes more apparent in 3-axis case.

As can be seen in Table 3.3, 3-axis FFF requires roughly twice as much printing time and material consumption. In addition, the removal of support structures may cause quality problems on touching surfaces. Support removal within inner parts may be impractical due to shape complexity unless a soluble support material is used.

A last example is another huge object produced on Hybro with multi-axis support-free FFF, as shown in Figure 3.11.



Figure 3.11: Support free printing in 5-axis on Hybro

CHAPTER 4

PRECISION MACHINING OF FFF POLYMERS

Objects fabricated via FFF may exhibit several problems, comprising (i) inevitable stair-stepping, (ii) defects and voids on both the surfaces and the inside volume, and (iii) dimensional- and form errors caused by the machinery and the thermal dynamics that show up as shrinkage and distortion.

One potential strategy for alleviating these problems is secondary processing through milling. Since the FFF objects can be regarded as near-net-shaped parts, milling produces planar surfaces and gets their dimensions down to the intended nominal size. Thus, the primary focus shifts towards addressing the challenges related to surface generation on FFF objects.

The guidance for best machining practices for specific engineering polymers relies on the previous experiences of the professionals. But, existing research on polymer machining primarily pertains to solid, dense forms of these materials. Machining FFF objects somehow falls into a separate category since the staircases, defects, and discontinuities present in those objects add extra difficulty to their processing.

Before the exploration of hybrid-AM, it is essential to set the optimized conditions for polymer milling. Thus, this part of the study offers a comprehensive guide to milling techniques for 3D-printed objects made up of the most common FFF thermoplastics. The content presented in this chapter is under consideration for the publication in Rapid Prototyping Journal.

The researchers in the field define the production quality of FFF based on the surface roughness and dimensional accuracy of the produced objects. The related studies indicated that the typical achievable average surface roughness (or predictable by ge-

ometrical models specific to FFF [49] begins at a few microns and reaches up to several tenths with increasing layer height and deposition angle. Moreover, dimensional inaccuracies can be reached up to the order of millimeters with inexpensive machinery and other material-induced problems. In an effort to enhance the overall quality evaluated by these factors, some researchers suggested numerous milling practices.

The prior applications commence with the pioneering works conducted by Pandey et al. [16], [17]. They introduced hot cutter machining, which yielded a noticeable contribution to the elimination of stair-stepping. Purposefully, the FFF parts made of ABS (Acrylonitrile Butadiene Styrene) are processed slightly above the glass transition temperature with the intent to reduce cutting forces by softening during machining. The authors stated that the cutting forces were approximately 50 times higher when machining was conducted at room temperature. These findings shed light on the critical role of the temperature-dependent behavior of thermoplastics under machining conditions.

Lee et al. [18] devised a low-cost gantry hybrid manufacturing system capable of executing both additive and subtractive (milling) operations. Their solution merged both manufacturing tools onto a shared axis, allowing for seamless switching between the two processes. The low manufacturing quality attained in the study emphasizes the importance of machinery performance and optimal application. Still, avoiding part re-positioning makes such hybrid systems convenient for overcoming stacking tolerances. Similarly, Li et al., [19] used a multi-axis robotic arm to carry out additive- and subtractive manufacturing in combination. Nevertheless, robotic applications face challenges in both hardware and software [20]. The software architecture of the robotic arms, designed for repetitive tasks, is not well suited for smooth tool paths and avoid singularities. Despite their advantages, such as larger build volumes and flexibility in tool configuration, the robot arms have lower rigidity and positioning accuracy if compared to gantry systems. The lack of rigidity restricts their use to softer materials with low cutting forces.

Dezaki et al., [21] investigated the drilling of FFF parts, highlighting the effect of the macrostructure and material behavior. Concerning the macrostructure, poor layer ad-

hesion resulted in cracks under high pressure, while drilling angled surfaces proved more difficult. High spindle speeds caused material melting and adherence to the cutting tool. Dezaki and Ariffin [22] searched for optimal milling parameters for 3D-printed PLA (Poly Lactic Acid), but the study lacked a detailed analysis. Grguraš and Kramar [24] also investigated optimizing the machining for PLA workpieces, including the impact of FFF parameters. Similar findings verified the material's tendency to overheat and gum up at high spindle speeds and slow feed rates. The milling depth had almost no effect on the final surface roughness if the walls were printed with large nozzles. Conversely, when working with small nozzles, the depth of cut was constrained to a minimum. This implies inconclusive evidence of the worsening effect of milling unfavorable regions in the 3D-printed macrostructure. Besides, larger nozzle sizes in the FFF phase of manufacturing allowed for tripled output while maintaining the same surface roughness with subsequent milling. Boschetto et al. [25] further explored a methodology to control the depth of cut in milling regarding the deposition angle of the object. The study highlighted the significance of considering the macrostructural effect to prevent the visibility of inner defects. Similarly, Leite et al. [50] proposed a method for improving the surface finish of AM parts by cutting the walls from an intermediate position. This approach ensures that the neighboring walls do not become visible again after the milling process. The offered strategy necessitates the use of an oversized, near-net-shaped product before milling to achieve the desired dimensions.

The existing literature also reveals notable shortcomings. First, there is an over reliance on statistical analysis for parameter optimization, which overlooks an understanding of the underlying cause-and-effect relationships. While statistical methods serve as a valuable tool for quantitative analysis, they divert the emphasis away from the clarification of the fundamental mechanisms in charge towards the insensible correlations between process variables and achieved performance. Second, a significant concern lies in the selection of the performance evaluation criteria. Many studies compare the relative quality of the original and the machined parts, despite the insignificance of the pre-processed state of the products. Instead, a more meaningful evaluation should prioritize assessing the extent to which the final product meets the specified design criteria, such as dimensional accuracy within a tight tolerance.

This dissertation aims to seek a comprehensive understanding of the topic, supported by extra knowledge to move beyond statistical correlations. This shifts the focus towards manageable surface formation. Once the desired surface finish is achieved, dimensional accuracy naturally follows due to the precision of the machinery employed. Insightful ideas are provided in the following part before any experiments are performed, and then the main results are explained in the context of those ideas.

4.1 Polymer Processing - Rule of Thumbs

The high quality of the machining often implies lower surface roughness and tight dimensional tolerances on the finished workpiece. Factors influencing surface finish and product geometry can be divided into three categories: (i) the intrinsic material behavior, (ii) the effect of tooling and processing parameters, and (iii) the effect of machinery and other factors. The material behavior and milling parameters are closely related to the surface formation, whereas the machinery affects the overall dimensions and product shape.

4.1.1 Material Properties

The machining process is inextricably linked to the response of the material to the cutting process. This is particularly relevant when dealing with 3D-printed thermoplastics having unique characteristics at the micro- and macro levels. The former refers to its chemistry and rheologic behavior, such as polymer branching, crystallinity, and viscoelastic properties. The latter refers to the networked structure of the 3D-printed volume, covering the aspects such as wall thickness, layer bonding, and infill density.

4.1.1.1 Material Behaviour

Polymers are known for their viscoelastic behavior, which makes temperature and time critical factors in their response to an external perturbation. The interplay between temperature and deformation rate causes counteracting effects on the behavior of polymers undergoing milling.

The thermal effects result in important physical transitions influenced by the polymer's molecular morphology. Typically, the thermoplastics used in FFF span from semi-crystalline to amorphous morphologies.

An important phenomenon for those thermoplastics is the glass transition temperature, denoted by T_g . At temperatures below T_g , the molecular chains are immobilized, and the material behaves like a glassy solid. Another transition is the melting temperature (T_m) above which the crystalline regions of the material are able to flow like a liquid. A semicrystalline polymer begins to soften above T_g , but it exhibits rubbery behavior until T_m is reached. In short, as the temperature rises, polymers undergo a gradual transition from brittle to ductile, rubbery, and even liquid.

The polymer's viscoelastic response is also influenced by stress relaxation. In essence, the polymer's behavior at high deformation rates is analogous to its behavior at low temperatures. Under excessively high deformation rates, even the polymers with naturally ductile behavior can become brittle.

Milling produces periodic deformations and subsequent heat induced by friction. The low thermal conductivity of the polymers can cause insufficient heat dissipation, thereby resulting in a buildup of heat within the processed material. Consequently, the superposition of the thermal and time-dependent behaviors governs the complex interaction that determines how these polymers react to the cutting process.

For glassy polymers under milling conditions, the quality of the processed surface is dependent on their stress-strain and relaxation attributes. If the material possesses brittleness, milling may yield low-quality surfaces.

Conversely, a more ductile regime under the effect of milling results in relatively smoother surfaces. In instances where cutting occurs when the polymer is in a rubbery state, rough and torn surfaces are anticipated [51].

It is more desirable for cutting action to fall within the soft and tough range as opposed to the hard and brittle range. The material can be made more pliable and easier to cut by heating it slightly (e.g., hot cutter machining) or by attempting to cut at slower deformation rates.

Processing close to critical temperatures may create transition zones (e.g., viscous zones), which introduce localized worsening of the surface quality for materials exhibiting quick physical transitions. Working in near-melting conditions is already pointless.

4.1.1.2 Macrostructure

As mentioned before, FFF involves the selective placement of thermoplastics in strand form along predetermined tool paths. Nozzles are heated and used to extrude the material, resulting in the desired 3D networked structure. The process of building FFF objects entails the formation of a complete layer, followed by the stacking of those layers whose boundaries are determined by the solid model data.

To construct a single layer, semi-molten strands are deposited onto the build surface by the nozzle's relative motion. After the squeezing effect of the nozzle, known as ironing effect, the top and bottom of the extruded cross-section flatten, while the side regions take on a semi-circular shape.

The final dimensions of the solidified bead are referred to as the bead width and layer height, as shown in Figure 4.1.

The nozzle traversal within a layer calls for the adoption of a popular strategy that involves the formation of a basic infill pattern enclosed by several walls (i.e., shells). The macrostructure of a representative layer comprises an infill structure embodied by a cross-hatch pattern, and the walls that enclose the infill are shown in distinctive colors (see Figure 4.1).

Naturally, the bounding surfaces of the stacked layers align with the corresponding surfaces of the solid model. However, due to the stair-stepping effect, the produced surface deviates from the intended plane of the designed object. This deviation can be further intensified by flow irregularities or an imprecise motion system.

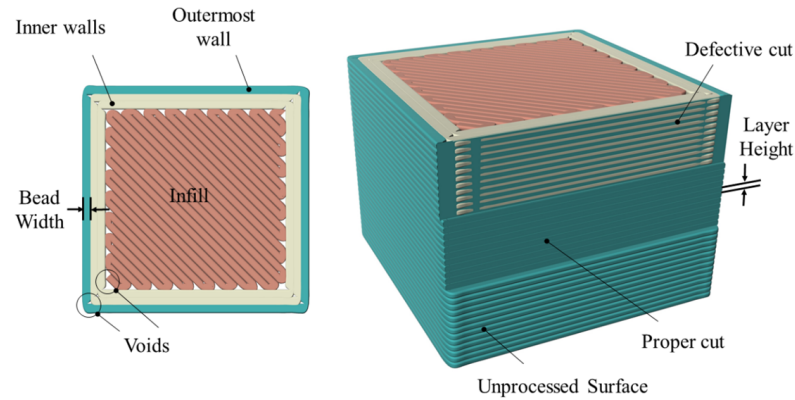


Figure 4.1: A simple layer in FFF and machining on a stack of layers

The occurrence of voids within the layer is a phenomenon that cannot be completely avoided in FFF. This is primarily attributed to the curved profile at both ends of the cross-sectional shape of the flattened beads, which makes it difficult for the nozzle to enter narrow regions. Nevertheless, the void density can be mitigated by reducing the nozzle size, overflowing the material, and overlapping the beads. Severe interlayer voids or layer separation have hardly ever become a problem in FFF due to the flattening by ironing, resulting in a natural fusion of successive layers. In summary, the products of FFF are built as near-net-shaped solids with voids and geometrical deviations from the ideal designs. Thus, the macrostructure directly affects the possible proper cut regions. The surfaces to be processed should be located away from regions with high void density and dimensioned accordingly beforehand. As illustrated in Figure 4.1, this is the key to create void-free and planar surfaces. The figure shows two side milling cases, representative of a proper- and a defective cut, respectively. Some milling parameters, like depth of cut, are closely related to the macrostructure.

4.1.2 Effect of Tooling and Machining Parameters

This study also aims to provide perspective on how best to process thermoplastics with optimized parameter- and tool selection. The users have control over critical milling parameters such as cutting speed, depth of cut, and feed rate, while the tool geometry is often predefined by its manufacturers.

4.1.2.1 Milling Parameters

Milling is a material removal process in which a rotating cutter acts as a wedge-shaped body to push into the material at the microstructural level. Plastic deformation takes place, causing the creation of chips. Ductile materials allow for a natural flow of the material during chip formation (i.e., shearing on the rake face), promoting the surface quality. Conversely, for brittle materials, the applied stress is likely to initiate and propagate cracks in the shear zones that may adversely affect the quality.

Thermoplastics like PLA or ABS, are typically characterized as glassy (somehow brittle) solids at room temperature. But, the milling dynamics may cause these materials to undergo a transition from brittle to a more ductile state or vice versa.

Milling causes both material deformation and heat generation, with the cutting speed serving as a critical parameter that governs their magnitude. Elevated cutting speeds can induce a remarkable temperature rise within the polymer, potentially causing it to enter the softening range and enabling a more ductile behavior.

Nevertheless, augmenting the cutting speed can also adversely impact the process, particularly when stress relaxation fails to keep up with the deformation rate. The dominance of either effect depends on the molecular weight of the polymer and its glass transition temperature [52], [53].

The low thermal conductivity exhibited by polymers provides evidence that the generated heat is not likely to be conducted to the tool, and instead, the chip predominantly carries away the majority of the heat.

Consequently, faster cutting speeds may lead to localized heating due to frequent surface rubbing and the subsequent formation of adhesive residues [53]. The polymers can gum up above the T_g or even melt.

The radial depth of cut (D) represents another controllable milling parameter. Theoretically, a decrease in the depth of cut yields a reduction in deformation and smooths the cutting operation through the alleviation of accompanying forces. Principally, the macrostructure of a 3D-printed object determines the range of acceptable radial depth of cut.

The cross-sectional representation in Figure 4.2 illustrates two adjacent vertical walls fabricated through FFF. The problematic areas arise from the presence of voids resulting from the imperfect contact between the curved bead sections. Even in the case of an ideal wall with sufficient overlap, the filling of these voids is limited by the polymer's viscosity. The profile of a wall, when measured along the build direction, typically exhibits periodic peaks and valleys with a period determined by the layer height (h). The observed peaks and valleys govern the minimum D required to eliminate the roughness profile on the surface (roughly R_t).

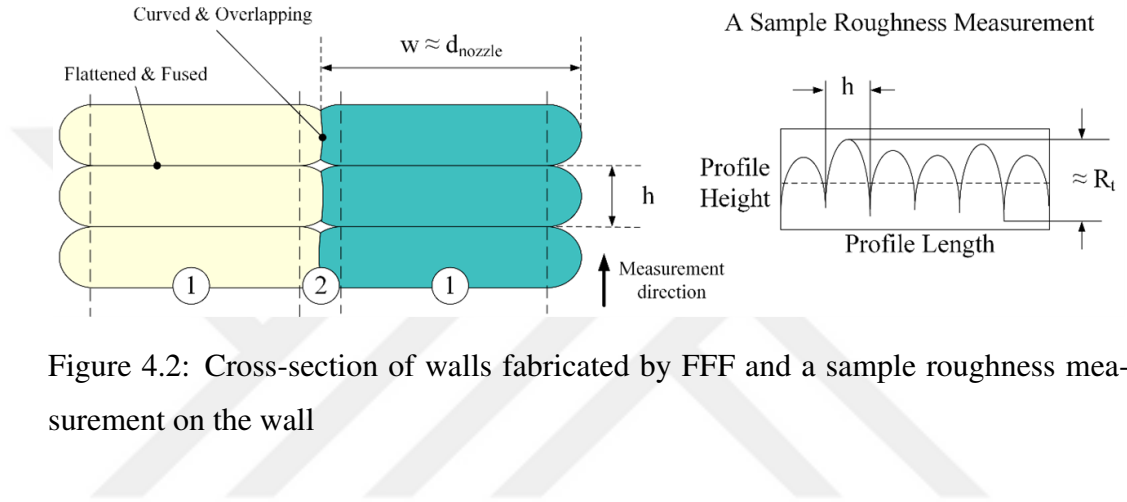


Figure 4.2: Cross-section of walls fabricated by FFF and a sample roughness measurement on the wall

As D increases, a region suitable for achieving proper cuts emerges, referred to as Region 1. However, as it approaches the bead width (w), another region characterized by a high void density is encountered. In Region 2, the anticipated surface quality deteriorates. For a typical FFF object, this recurring pattern is consistently noticed with the gradual increase in the depth of cut. This leads to an obvious recommendation regarding its amount for milling the walls from their middle, which can be expressed with the following simple relation:

$$D = (n + 0.5)w + e$$

where n is an integer that determines the specific location within the object, w denotes the bead width ruled by the nozzle size, and e represents the inaccuracy arising from various error sources as the maximum deviation from the ideal surface. It is also vital to design the near-net shape dimensions to accommodate the depth modifications during the subsequent milling.

The feed-per-tooth (f_z) governs the geometric characteristics of the resultant surface in milling, with lower f_z values naturally tend to produce smoother surface finishes. In instances where the polymer exhibits highly brittle behavior, employing a high f_z can also lead to torn or pulled-out surfaces instead of clean cuts. Conversely, a higher feed-per-tooth may be advantageous for dissipating the generated heat by promoting the creation of sufficiently large chips. Thus, a trade-off must be considered to balance its amount. Moreover, alternative milling types (up-milling or down-milling) can also be explored in this context to evaluate their effectiveness in terms of chip evacuation and susceptibility to issues such as burr formation or gumming-up, and mechanical vibrations.

4.1.2.2 Tool Parameters

Endmills have been a traditional tool for machining due to their availability and extensive experience with them. But these tools are exclusively tailored for metals and might not possess the right geometry for polymer processing. This part discusses the key geometric characteristics of endmills for polymer processing. Same principles can be extrapolated to other types of cutting tools.

A sharp cutting edge is essential for working with polymers, as bluntness is highly prone to generating excessive heat. Standard endmills, generally designed as heavy-duty cutting tools, possess a slightly positive rake angle and a low clearance angle. This particular geometry, although not optimal for polymers, can still be employed provided that milling parameters are finely tuned. But at least, the endmills designed for softer metals like aluminum should be utilized. Such endmills are characterized by a high rake angle and an adequate clearance angle.

Polymer cutting mechanism is identified by slipping on the shear plane, cracking at the tooltip, and tearing with compressive deformation. Largely positive rake angles tend to remove material by slipping, while negative rake angles induce tearing by constantly compressing the material down [52]. For very brittle polymers, the rake angle should be set so that the cutting force is parallel to the cut surface, as this minimizes the crack formation and propagation [51]. Generally, a larger positive rake angle implies reduced cutting forces. Experimenting to set the best rake angle for a

certain polymer can be performed within the recommended range of 10° to 25° , by searching for the indication of smooth chip flow through slip on the shear plane with plastic deformation.

The milling quality is influenced by the clearance angle of the tool in two distinct ways. A larger clearance angle reduces rubbing between the processed surface and the flank face of the tool, thereby reducing heat generation. This helps prevent gumming of the thermoplastic. However, with a significant clearance angle, the tool's cutting edges may make unstable contact with the surface, resulting in unevenly spaced cutter marks on the surface. Thus, a lower clearance angle can also be preferable to dampen induced vibrations and prevent chatter [54]. The optimal clearance angle for a particular polymer can be found by experimenting within a range from slightly positive up to 15° .

Tool's helix angle and the flute type are other critical factors to promote chip removal. Single-flute tools, as opposed to multi-flute ones, are preferable due to the greater area available for the discharge of larger chips while handling low cutting forces. Specific to the drill bits, low helix angles and polished flutes are favored with the pecking strategy [55].

Typically, single-flute endmills exhibit a high rake and a sufficient clearance angle, rendering them well-suited for polymer processing. For multi-flute counterparts, specialized geometries with a preferred rake and clearance angles might be considered. Concerning the helix arrangements, a right-hand spiral configuration is favored, as it directs the formed chips toward the spindle side rather than the processed surface.

4.1.3 Effect of the Machine Tool and Other Factors

Attaining final large-scale dimensions and geometrical tolerances, such as straightness and parallelism, is influenced by the machine tool and environmental factors. High-quality milling assumes the tool is precisely positioned relative to the workpiece. This necessitates suppressing spindle rotational errors and vibrations in addition to the accuracy of the motion system. For polymers, fastening reliability, temperature stability, and swarf management help to achieve the desired level of quality.

But, these factors are of secondary importance when compared to the ones mentioned in preceding parts.

In milling, the stability of the workpiece position is ensured through rigid fixing. In general, adhesive tapes are employed to secure FFF objects to the build plate. The same method can be used for milling if it becomes strong enough to handle the low holding forces required. But any misalignment can cause the processing of unfavorable regions within the macrostructure.

This indicates the indispensability of suitable machinery that permits FFF and milling in harmony. Otherwise, processed parts are subject to positioning errors due to non-repeatable fixturing. Utilizing an integrated setup that enables both post-processing and in-process modifications is the best option.

4.2 Experimentation

In the experiments, the milling function of the HYBRO platform is utilized through the Z-X-Y-B-C kinematic chain. The cutting tools are mounted to a Hertz HMA95 spindle, which serves as the inexpensive milling unit. The integrated FFF function of the platform is not employed intentionally. Instead, the test specimens are fabricated using Ultimaker 3 Extended and Anycubic i3 Mega S, and then clamped onto the main platform to provide a more rigid connection compared to the use of adhesive tapes.

The design of experiments (DoE) principle is not used in this part, but several cutting conditions are searched through a series of experiments. A qualitative methodology is adopted to explore specific observations. Still, the key guidelines are supported by numerical findings when appropriate.

The cube-shaped specimens, comprised of shells and infill structure, are subjected to side milling. The specimens are made of PLA and ABS due to their widespread adoption in FFF. A bunch of test specimens are shown in Figure 4.3, whose properties are provided in Table 4.1.



Figure 4.3: Some test specimens machined during the experiments

During the experiments, spindle speed and feed rate are carefully controlled to correspond with the intended feed-per-tooth and surface cutting speeds. The depth of cut is selected considering the macrostructure and the anticipated peak-to-valley height of the stair-stepped surfaces. Both up-milling (conventional) and down-milling are tested.

Three endmills with dissimilar properties are utilized. With respect to the cutting edge, both single-flute and multi-flute tools are employed. Figure 4.4 illustrates their distinctive cross-sections, highlighting the differences in the primary geometry. Dry-cutting conditions are maintained throughout the experiments. The summary of the milling parameters and tooling is provided in Table 4.2.



Figure 4.4: Cross-sections of the endmills

Table 4.1: The properties of the test specimens

Materials	ABS & PLA
Glass Transition Temperature	~100 °C (ABS) & ~60 °C (PLA)
Color	Red, Blue, Gray, Transparent, Black
Filament Diameter	2.85 mm & 1.75 mm
Basic Dimensions	40 mm× 40 mm × 40 mm
Printing Temperature	230 °C (ABS) & 210 °C (PLA)
Bed Temperature	80 °C (ABS) & 60 °C (PLA)
Nozzle Diameter	0.8 mm (Ultimaker) & 1.2 mm (Anycubic)
Number of Outer Shells	4
Bead-width	1 mm
Layer Height	0.5 mm
Infill Ratio	25 % (zig-zag pattern)

The profile of the machined surface, the types of the formed chips, resulting temperatures, and the formation of apparent flaws are possible indicators for performance evaluation. A profilometer and a thermal camera are primarily employed to collect surface- and temperature data for analysis. Since accurate dimensions are also the intended outcome, the final dimensions are measured by the caliper but receive less attention since they are not the main focus.

Surface profiles are obtained using a MarSurf PS10 surface profiler equipped with a 2 μ m stylus tip. The standard roughness calculation algorithm defined by ISO 4287 is applied, with a cut-off frequency set at 0.8 mm. Micrographs of the resultant surfaces are captured using a Topcon universal measuring microscope featuring an objective lens with 10x magnification. Optris PI 640i thermal camera is utilized to capture radiometric snapshots and real-time videos from the cutting environment. The camera offers an optical resolution of 640x480 pixels and is capable of measuring temperatures in the range of -20 to 900 °C.

Table 4.2: Summary of the parameters used in the experiments

Parameter	Value
Cutting Speed	20-240 m/min
Depth of cut	0.05-0.4 mm
Feed-per-tooth	0.01-0.4 mm
Milling Type	Up-milling – Down-milling
Feed Rate	4-18 mm/s
Spindle Speed	1000-6500 RPM
T1 - Carbide Tool	
Diameter	6 mm
No. of Flutes	Single-flute
Radial Rake Angle	High (20°)
Primary Clearance Angle	High (45°)
T2 - HSS Tool	
Diameter	12 mm
No. of Flutes	3-flutes
Radial Rake Angle	Low (0°)
Primary Clearance Angle	Low (10°)
T3 - Coated Carbide Tool	
Diameter	8 mm
No. of Flutes	4-flutes
Radial Rake Angle	Low (0°)
Primary Clearance Angle	Low (18°)

4.3 Findings

An analysis of the experimental outcomes, examining the machined surfaces and produced chips are provided in that part. Certain factors from several categories demonstrated significant influence on machining performance. The followings are particularly noteworthy: (i) Glass transition temperature, (ii) Tool's flute volume and primary angles, (iii) Feed-per-tooth and surface cutting speed, and (iv) Macrostructure.

4.3.1 Glass Transition Temperature

The experimental observations clearly revealed that the key material property for machining those polymers is the glass transition temperature. The manufacturer-specified T_g values for PLA and ABS are 59°C and 100°C, respectively. This provides inconclusive indication prior to experimentation, suggesting that ABS may be more amenable to processing than PLA.

Due to the polymers' inadequate thermal conduction, chip removal becomes the primary heat dissipation mechanism. Insufficient dissipation induces localized frictional heating on the surface and chip welding. This highlights the importance of maintaining a steady generation of correctly sized chips. Expectedly, multi-flute endmills are not a preferred option for effectively flushing the chips away.

The inferior performance of multi-flute tools is demonstrated by utilizing T2 and T3 in the operation. These tools have low rake and low clearance angle. The total hollow volume in their cross-sections for chip removal is relatively lower. These factors contribute to the poorer milling performance that becomes more noticeable at incorrectly selected parameters. One can gain a sense of the tools' performance by analyzing the chip types encountered and the condition of the machined surfaces. Micrographs of the chips/surfaces and thermal camera recordings provide support to this argument. Figure 4.5 shows thermal captures at selected intervals during machining of a PLA specimen with a multi-flute tool. Localized heat accumulation caused hot spots where the temperatures exceeded material's T_g . Not only the burr formation but also the adhesion of the chips to the processed surface are evidenced.

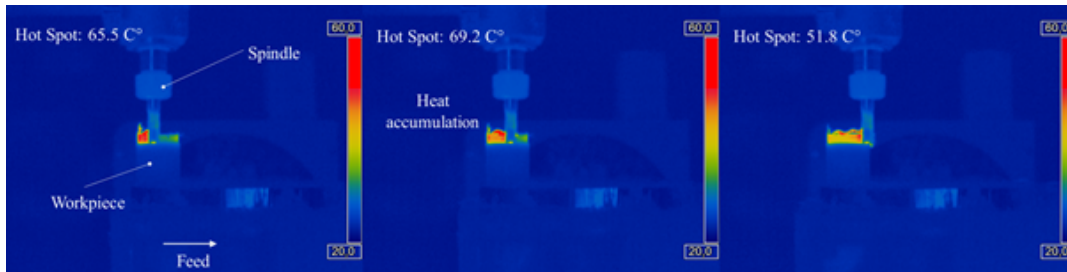


Figure 4.5: Temperature distribution on a PLA specimen – milling carried out with T2, at $v_c = 180m/min$, $f_z = 0.042mm$, $d = 0.1mm$

Milling with very low f_z gives rise to a significantly inferior surface finish since it permits almost no time for chip- and heat removal. As the depth of cut increases, surface quality deteriorates more, leading to coarser chips. These chips unnaturally wrap around the endmill and, once they have grown to a considerable size, they are thrown away over large distances as shown in Figure 4.6.

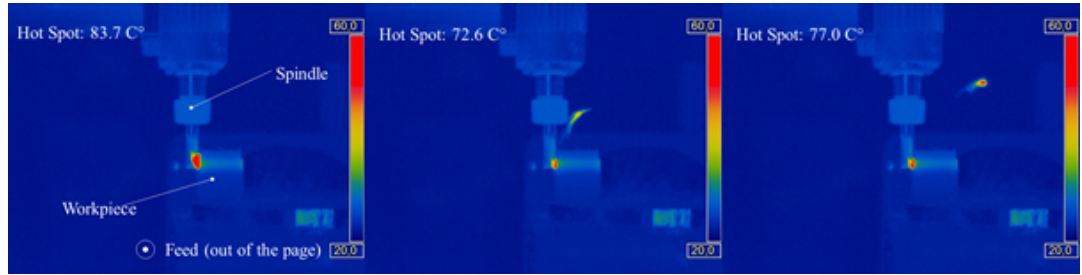


Figure 4.6: Temperature distribution on a PLA specimen – milling carried out with T2, at $v_c = 180m/min$, $f_z = 0.025mm$, $d = 0.1mm$

These glossy chips possess a hard and brittle nature, resembling quenched materials. Figure 4.7 demonstrates welded chips (combination of many small chips) produced during the processing of PLA. When welded chips exist, the resultant surfaces are of poor quality, with some regions being cut while others are almost remelted. The surface temperatures reach above 80°C , leading to an unusual phenomenon. This phenomenon is referred to as viscous folding [56], which emerges as wave-like ridges on the final surface. It is due to the localized temperature gradient and varying viscoelastic material behavior. Under the influence of fluctuating compressive stress caused by machining, regions experiencing viscous flow regime undergo folding. Such patterns were observed as defects encountered whenever the temperatures were recorded above T_g .

Micrograph in Figure 4.8a shows the unprocessed layers of PLA and the surface resulted from milling under unfavorable conditions characterized by viscous folding. The original layers spaced by 0.5 mm are shown at the bottom, whereas the top section is machined in the specified direction. Figure 4.8b clearly highlights the zones of viscous folding. Such patterns imply a worse case of surface formation, concurrent with the incidence of welded chips.

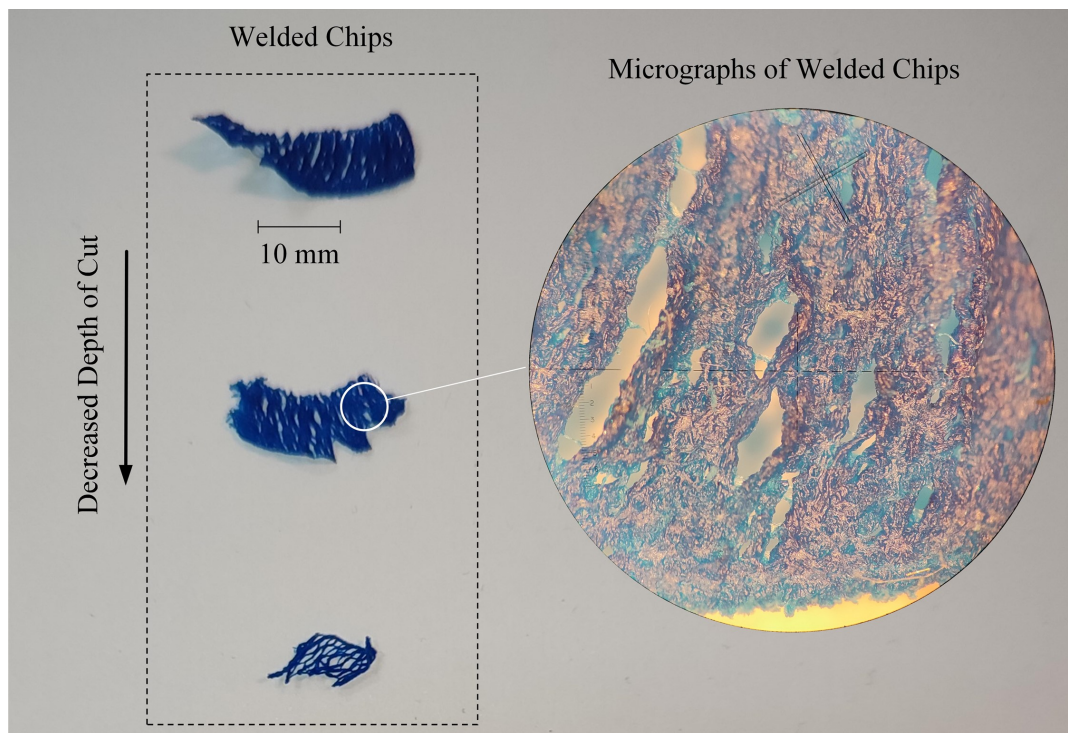


Figure 4.7: Welded chips at different depths of cuts and micrograph of a welded chip

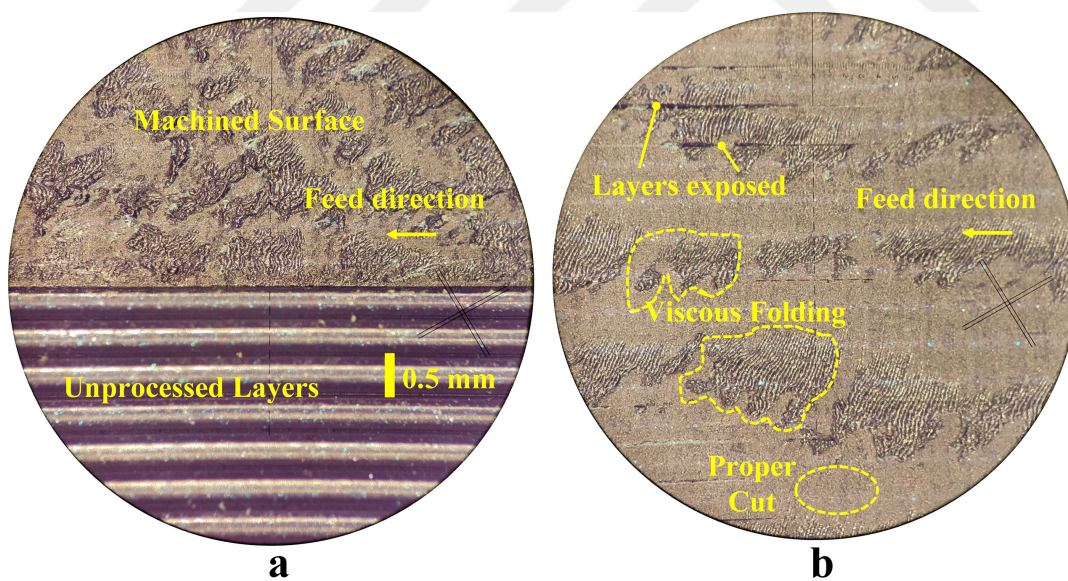


Figure 4.8: Micrographs of (a) machined and unprocessed surfaces, (b) viscous folding spots

Experiments show that this problem is common when milling PLA with multi-flute tools operating at low f_z . There is a tendency towards improved surface quality if the chip shape approaches uniform thickness and flushing become more periodic. With T2 and T3, this is relatively harder but still achievable with favorable milling parameters. Here, the presence of pulverized chips and nearly-uniform chips (see Figure 4.9) is regarded as an indicator of better cutting performance. The former is an outcome of a too-thin depth of cut ($D < 0.05mm$), while the latter is acquired with a higher f_z . Both scenarios yield substandard surfaces, as shown in Figure 4.9, still with the presence of irregularities.

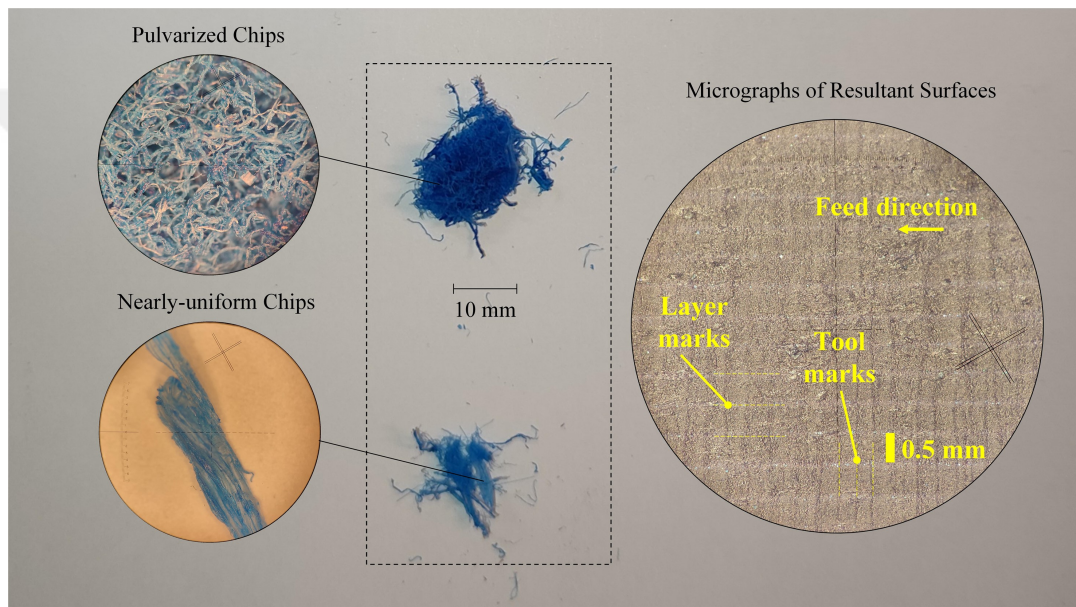


Figure 4.9: Substandard quality achieved with multi-flute tools and associated chip types

Setting optimal milling parameters offered a partial solution for PLA specimens, attributable to its lower T_g . PLA has been machined defectively, while ABS is processed without viscous folding in identical tests. Figure 4.10 illustrates an ABS specimen in milling. The constant scattering of similar chips indicates that the multi-flute endmill was indeed able to remove heat persistently. The temperature record confirms that the highest temperatures are far below the ABS's glass transition. The creation of those uniform chips is the ideal scenario while machining thermoplastics, but it may be challenging in practice.

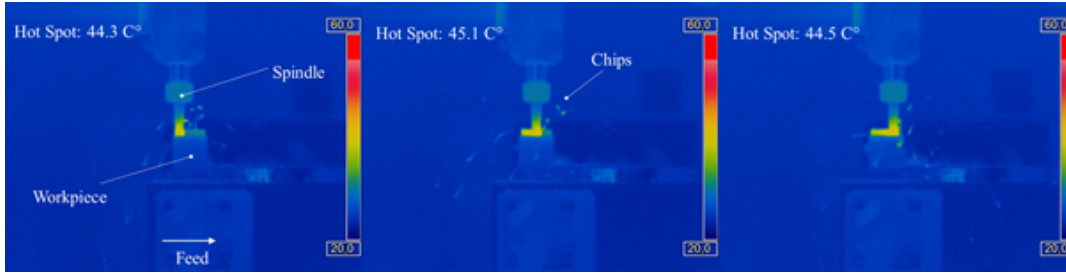


Figure 4.10: Temperature distribution on an ABS specimen – milling carried out with T2, at $v_c = 180m/min$, $f_z = 0.025mm$, $d = 0.1mm$

Table 4.3: Typical temperature conditions associated with the chip types

Chip Type	Condition
Welded	Surface Temp.: $60\text{ }^{\circ}\text{C} < T_{avg} = 80\text{ }^{\circ}\text{C} < 92\text{ }^{\circ}\text{C}$ Chip Temp.: $27\text{ }^{\circ}\text{C} < T_{avg} = 33\text{ }^{\circ}\text{C} < 49\text{ }^{\circ}\text{C}$
Pulverized or Nearly-uniform	Surface Temp.: $34\text{ }^{\circ}\text{C} < T_{avg} = 49\text{ }^{\circ}\text{C} < 60\text{ }^{\circ}\text{C}$ Chip Temp.: $29\text{ }^{\circ}\text{C} < T_{avg} = 30\text{ }^{\circ}\text{C} < 38\text{ }^{\circ}\text{C}$
Uniform	Surface Temp.: $38\text{ }^{\circ}\text{C} < T_{avg} = 45\text{ }^{\circ}\text{C} < 55\text{ }^{\circ}\text{C}$ Chip Temp.: $29\text{ }^{\circ}\text{C} < T_{avg} = 34\text{ }^{\circ}\text{C} < 45\text{ }^{\circ}\text{C}$

The chip types with the typical maximum average temperature conditions are provided in Table 4.3. Maximum temperatures in distinct regions (i.e., chip area and surface area) are recorded to monitor the heat removal from the surface by these chips. Welded chips are characterized by their large size and capacity to carry substantial heat. But, heat buildup on the surface is unavoidable due to the aperiodicity of their flushing. Pulverized- or nearly-uniform chips generally mitigate the highest observed surface temperatures. Uniform chips naturally demonstrate persistent heat removal, reducing the average surface temperature.

The time histories of these conditions are illustrated in Figures 4.11, 4.12, 4.13. The temperature records demonstrates the highest temperatures in the enclosed areas (Chip Area and Surface Area) during machining of one side of the PLA specimen. Snapshots shows the temperature levels at specific points in time.

For further progress in processing both PLA and ABS, switching to an endmill with improved chip removal capability is preferable. Next is the discussion about the favored geometry of the tool.

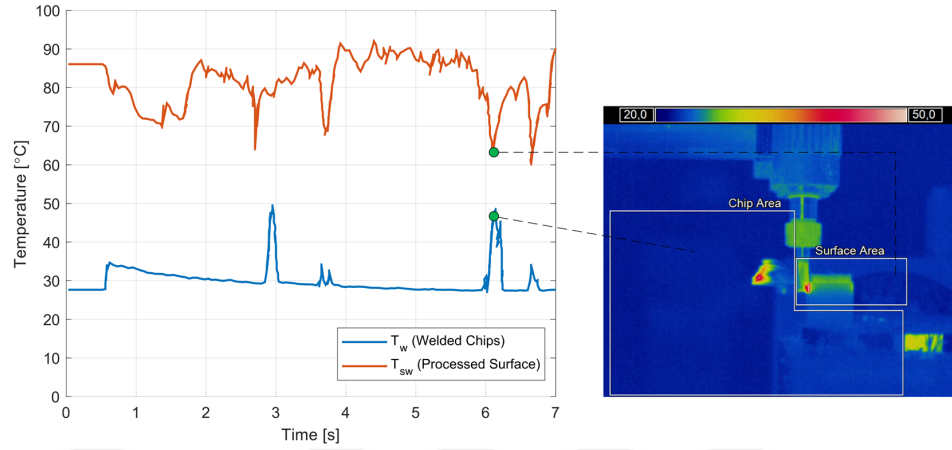


Figure 4.11: Temperature records of the Welded chips

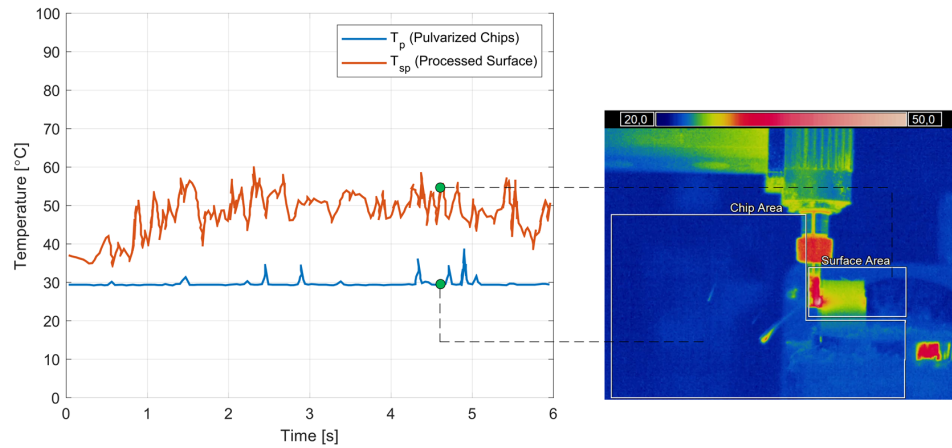


Figure 4.12: Temperature records of the Pulverized or Nearly-uniform chips

4.3.2 Tool's Flute Volume and Primary Angles

The ideal tool for milling thermoplastics is one that unloads its flutes at regular intervals. High flute volume is advantageous for extended capability, making single-flute endmills (O-flute type) a favorable choice. Highly positive rake angles are recommended in the related literature. A sufficient clearance angle can eliminate friction

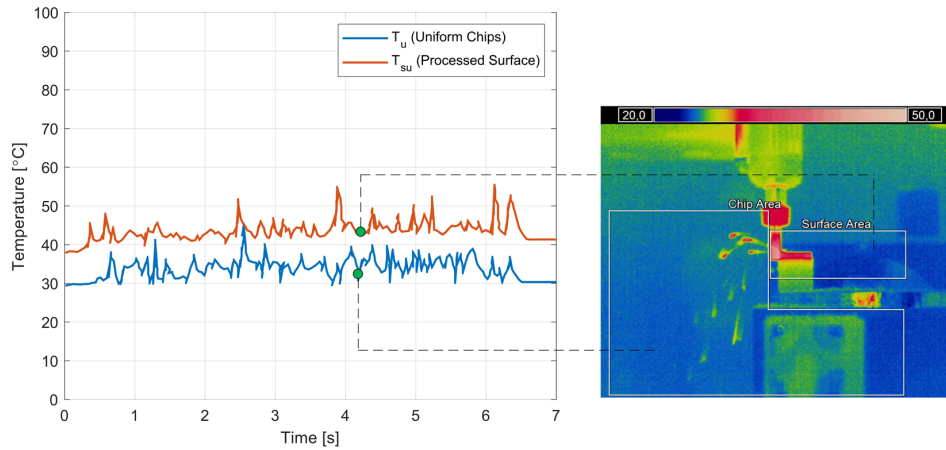


Figure 4.13: Temperature records of the Uniform chips

and minimize heating. Considering these factors, T1 emerged as the most promising option among the alternatives. This is supported by the observations from several experiments conducted. Here is an overview of the key findings:

- T1 generates uniform chips for a wide range of parameters, while T2 and T3 tend to produce welded, pulverized, and nearly-uniform chips;
- In most cases, T1 yields the best surface quality;
- Milling type affects the tool performance, where down-milling is superior;
- T1 is more prone to chatter, especially at high feed-per-tooth;
- Distinct modes of surface formation exist.

The superior cutting performance of T1 is evident from the uniform chip formation in several milling conditions for both materials. Figure 4.14 reveals unvarying chip thickness as an outcome of the smooth cutting process. These tools usually curl the chips that promotes their discharge. When machining the surface for the first time (Figure 4.14c), the chips maintain the stair-steps on one side while the opposite side is straight. Another example (Figure 4.14b) reveals the chips formed when milling a previously cut surface with partially eliminated stair-stepping. Uniform chips imply geometrically predictable surfaces, where the tool marks are clearly apparent. In contrast, such outcomes were not observed when milling with multi-flute endmills.

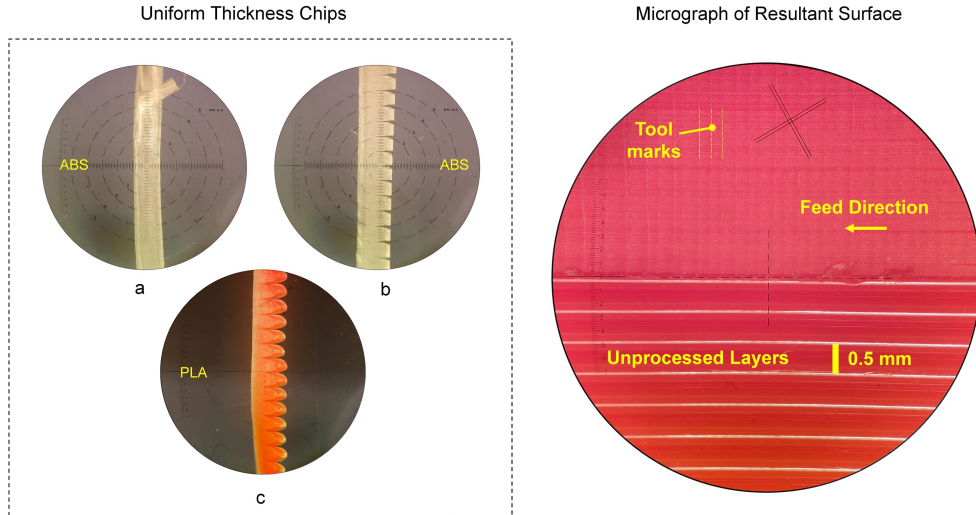


Figure 4.14: Three instances of uniform chips and a micrograph of a resultant surface

The surface quality assessment can be based on various metrics obtained from surface roughness profiles. To carry out a preliminary check of the comparative performance of the available tools, an analysis of average surface roughness (R_a) and maximum profile height (R_z) under identical conditions are conducted. Experiments are carried out using T1, T2, and T3 with parameters $f_z = 0.1mm$ and $v_c = 60m/min$ on ABS specimens. These conditions simulate good enough cutting conditions for all those endmills. Figure 4.15 presents the R_a and R_z values obtained from the experiments. Using down-milling with T1, R_a can be reduced to a sub-micron level. In the absence of a single-flute tool, T2 and T3 may still be used, but at a slightly reduced surface quality. Overall, down-milling tends to outperform up-milling. Multiple observations revealed a recurring trend of vibration and chatter during up-milling specifically with T1, which are much severe while cutting at frequencies close to the natural frequencies of the manufacturing platform. T2 and T3 displayed reduced susceptibility to vibrations with up-milling. Fine-tuning the clearance angle can be investigated as a means to reduce vibrations if the operators have access to alternative tools.

The mode of surface formation is another remarkable factor. A complex elastic and plastic deformation emerges as the outcome of the cutting action and the burnishing effect induced by the tool. The cutting action is governed by the forces acting upon the rake face, while the clearance face can potentially provoke a burnishing effect, particularly pronounced when the material exhibits a tendency to viscous flow.

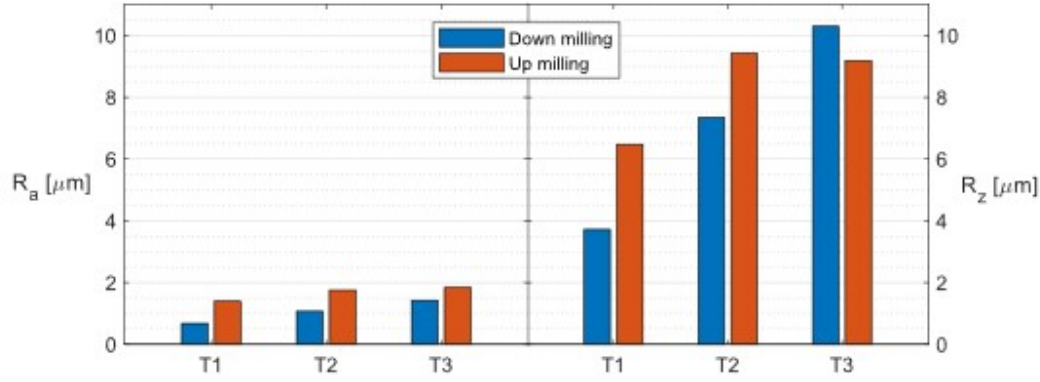


Figure 4.15: Standard metrics showing tools' performance under identical milling conditions

The combination of cutting and burnishing, coupled with subsequent elastic recovery, forms distorted (or vanished) tool marks on the surface. This signifies an inherent lack of control over the resultant surface. Once the relative dominance of cutting and burnishing is identified, the anticipated surface morphology can be recognized.

The roughness profile reflects a natural sense of the existing forces, deformations, and recovery in machining that collectively shape the surface. A perfect profile is characterized by the repetition of the tool-tip shape at a period of feed-per-tooth. The actual profile deviates from the ideal one due to the material's response and mechanical inaccuracies.

Spectrum analysis facilitates the extraction of distinctive components in roughness profiles through frequency decomposition of the data. Since it allows for the isolation of primary contributing factors, the main discussion would be independent of undesirable components like vibration modes associated with the structural stiffness of the machinery or spindle run-out related to the inexpensive spindle. For instance, chatter is typically observed at longer wavelengths and was recognized accordingly. The material-induced geometric deviations are intrinsic (referred to as the swelling effect [57], [58] and can be detected through spectral analysis at frequencies near the feed component. To understand whether cutting or burnishing predominate, a useful suggestion is to inspect the sharpness of peaks or the spread of data in the spectrum. The sharp peaks at multiples of feed frequencies indicate proper cutting while spreading and noisy data shows burnishing.

Tool selection directly influences the mode of surface formation and its extent. In general, T1 demonstrated proper cutting for a wider range of milling parameters. This was expected due to its high rake angle facilitating smooth cutting, and high clearance angle preventing surface rubbing. Conversely, T2 and T3 are prone to significantly burnishing the surface, which may be attributed to their lower clearance, zero rake angle, and relative inability to persistently discharge the chips. Experiments have also revealed that f_z is among the primary milling parameters influencing the transition between the cutting and burnishing modes. When the feed-per-tooth exceeds a threshold (e.g., roughly at 0.2 mm with T1), a complete cutting mode is observed, imprinting the tool's kinematic signature on the surface. Decreasing f_z disrupts the harmony of the chip removal, causing them to get stuck, which intensifies the burnishing effect. This is more noticeable when machining with T2 and T3.

Figure 4.16 exemplifies proper-cut with negligible swelling effect, achieved at $f_z = 0.36\text{mm}$ with T1. Dominant cutting mode is validated by the sharp peak at 2.75 cycles per mm in the spectrum. In contrast, Figure 4.17 illustrates an instance of burnishing experienced at $f_z = 0.33\text{mm}$. In this case, T2 is intentionally employed to exploit burnishing, where the presence of noisy signal in the spectrum is a strong indicator.

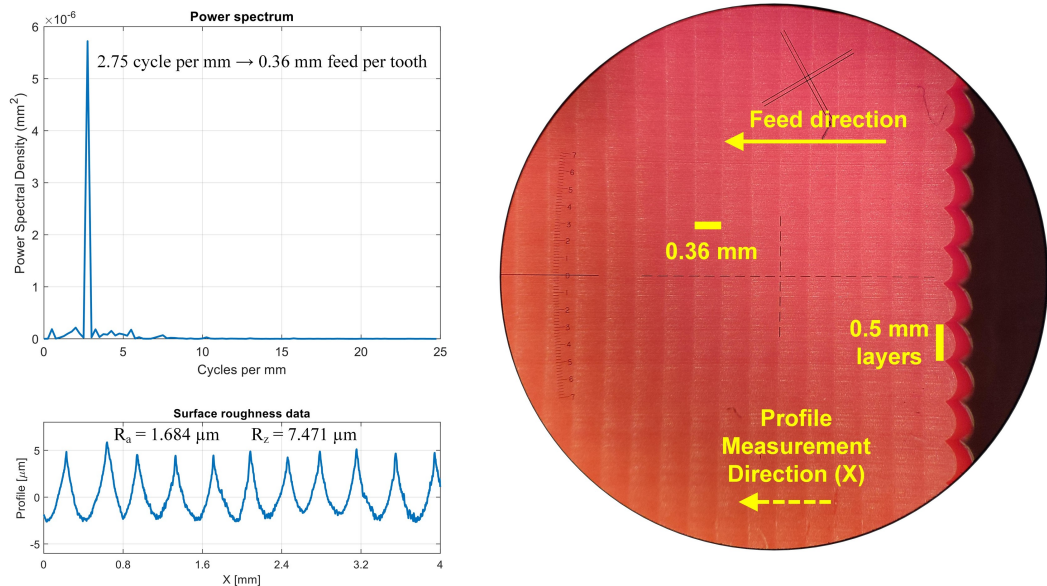


Figure 4.16: The roughness profile, the power spectrum, and micrograph of the surface under a dominant cutting mode

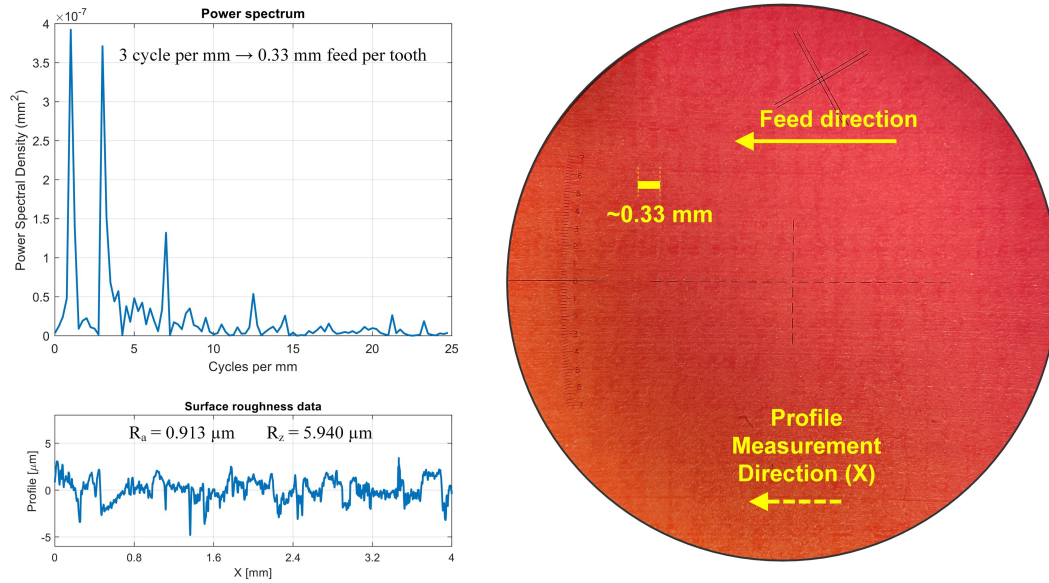


Figure 4.17: The roughness profile, the power spectrum, and micrograph of the surface under remarkable burnishing mode

The discrimination between these modes could also be made by inspecting the distinct surface textures shown in Figure 4.16 and 4.17. Despite the lack of periodic texture in burnishing mode, the average surface roughness may still meet the desired requirements. Therefore, the users may optionally consider triggering the burnishing mode to produce surfaces with low R_a , at the expense of a predictable geometry of the final surface.

Overall, tailoring the surfaces of 3D-printed polymers is easier with T1. It is the clear recommendation among the alternatives. Its performance can be further enhanced through proper configuration. The subsequent section will concentrate on identifying the best milling parameters, exclusively for T1.

4.3.3 Feed-per-tooth and Surface Cutting Speed

After T1's confirmation as a viable recommendation, the emphasis shifts to maximizing its performance. The following is a summary of observations gathered through experimentation:

- Feed-per-tooth has one of the most significant impact on the process;
- Cutting speed affects the quality, with its effect dependent on the material;
- Depth of cut does not meaningfully affect performance unless vibrations are induced.

While T1 allows for dominant cutting mode much easily, burnishing is still possible at low feed-per-tooths. At high f_z , periodic tool marks are undoubtedly visible on the surface (see Figure 4.18a). However, below roughly 0.2 mm feed-per-tooth, they begin to disappear, leading to a gradual transition towards significant burnishing (see Figure 4.18b). If f_z falls below nearly 0.03 mm, the surface quality worsens to the extent that roughness measurements become unreliable.

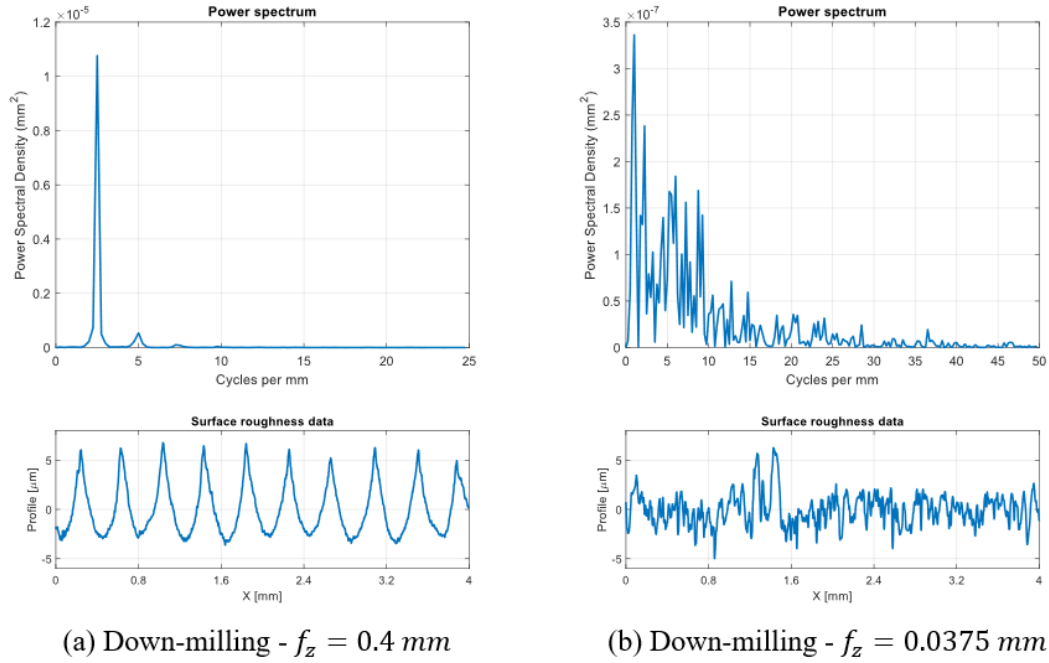


Figure 4.18: The mode of material removal (a) a dominant cutting mode, (b) dominant burnishing effect

Surface cutting speed plays a role in the quality achieved, with varying influences depending on the material. To uncover the optimal milling parameters, preliminary tests were conducted, leading to the identification of the optimal searching space in terms of $f_z(\text{mm})$ and $v_c(\text{m/min})$. Accordingly, the best interval is selected as $f_z = 0.04 - 0.2 \text{ mm}$ and $v_c = 20 - 180 \text{ m/min}$.

Then, 25 experiments are performed with 5 equally-spaced levels of f_z and v_c , and for each material using down-milling. The contour plots shown in Figures 4.19 and 4.20 demonstrate the expected R_a obtained through the best fit to the data collected from these experiments, for PLA and ABS, respectively. The following relations can be used to extrapolate the results.

For PLA specimens:

$$R_a[\mu m] = 0.614 + 0.113v_c + 0.077f_z + 0.062v_c^2 + 0.036v_cf_z + 0.009f_z^2$$

For ABS specimens:

$$R_a[\mu m] = 0.49 + 0.041f_z + 0.005v_c$$

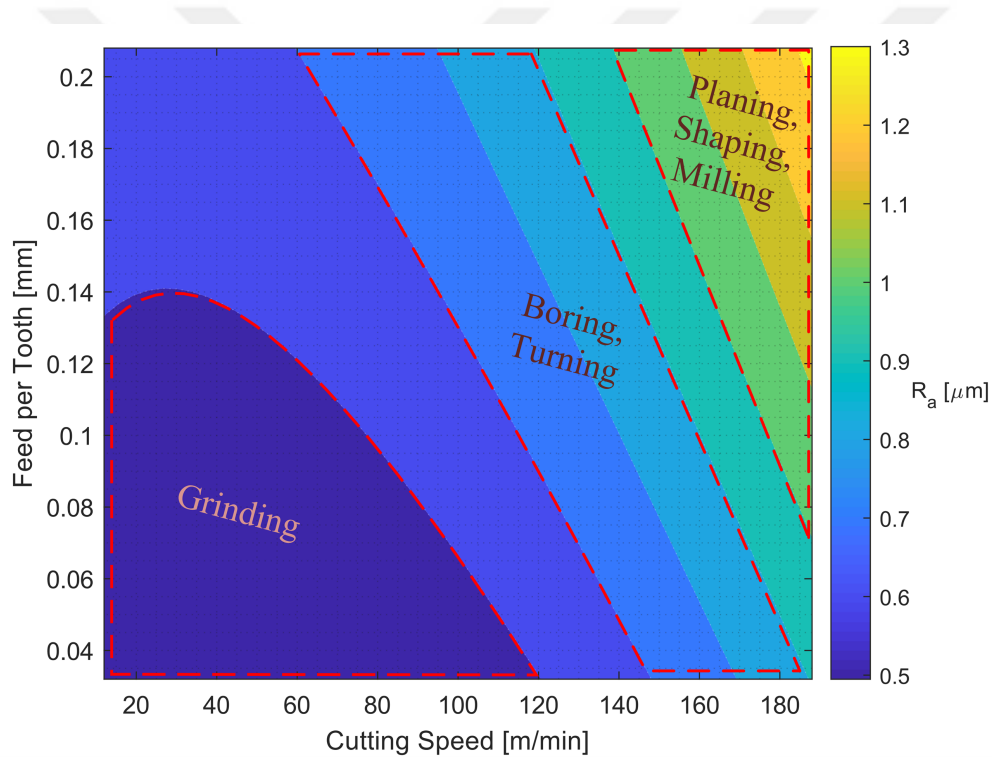


Figure 4.19: Effect of feed-per-tooth and cutting speed, as experimented with T1 on PLA

The contour plots offer a quick benchmark with the typical surface quality achieved through alternative subtractive manufacturing techniques. Accordingly, milling 3D-printed thermoplastics can produce surface finish similar to those obtained with a grinding process. The plots reveal the optimal intervals for f_z and v_c that yield the

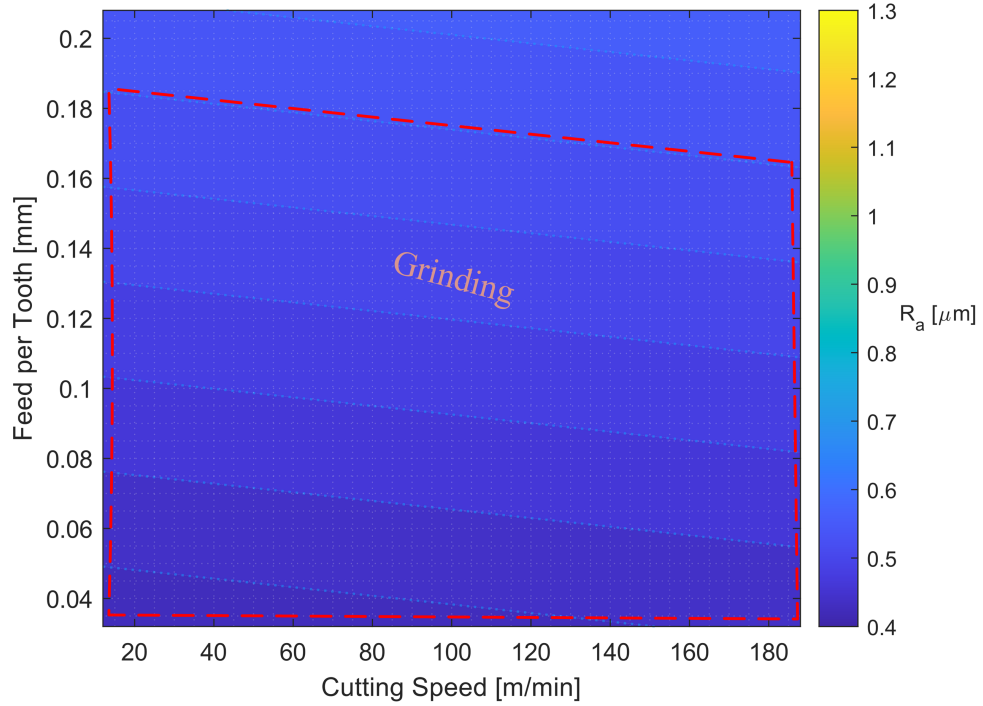


Figure 4.20: Effect of feed-per-tooth and cutting speed, as experimented with T1 on ABS

finest surface finish. While extrapolating the results, one must be cautious about setting the lower limit for f_z , since rapidly generated heat may impair the milling performance. On the contrary, high f_z naturally outcomes rougher surface finish and may not be intended.

Despite the combined influence of f_z and v_c on the surface finish, PLA is particularly sensitive to heat accumulation, which makes v_c a crucial consideration. Surface cutting speed has little discernible impact on ABS, allowing for greater flexibility in processing the material within a broader parameter range. The R_a values can be reduced to a sub-micron level for both PLA and ABS, with ABS reaching a lower level.

Lastly, the depth of cut exerts a minimal effect on the milling process, as the surface finish remains unchanged if milling is held within the shell width. A depth of cut ranging from 0.1 mm to 0.4 mm has been considered safe, but for the purpose of eliminating vibrations, a depth of cut of 0.1 mm was utilized in the experiments. Further discussions about the depth of cut will be addressed in the following part.

4.3.4 Macrostructural effects

The final discussion focuses on the influence of the distinctive macrostructure of 3D-printed objects during milling, particularly when targeting an intermediate position within a single wall. There are two arguments worth emphasizing: (i) excessive depths can lead to defects near the high void density regions, (ii) insufficient depth of cut only partially eliminates stair-stepping.

Figure 4.21 provides illustrative examples of defects observed during the experiments. In cases where the internal volume is reached (Figure 4.21a), the presence of void patterns in the (curved) contact zones of machined walls is observed. Figure 4.21b shows inadequate fusion between the walls and infill structure that led to vibrations and subsequent fracture in the shown area. When the cutting depth exceeds a certain limit, the tool's chatter exposes underlying layers, as shown in Figure 4.21c. These defects highlight the necessity of the macrostructural integrity of the FFF workpieces for milling and the consequences of cutting to a greater depth than necessary.

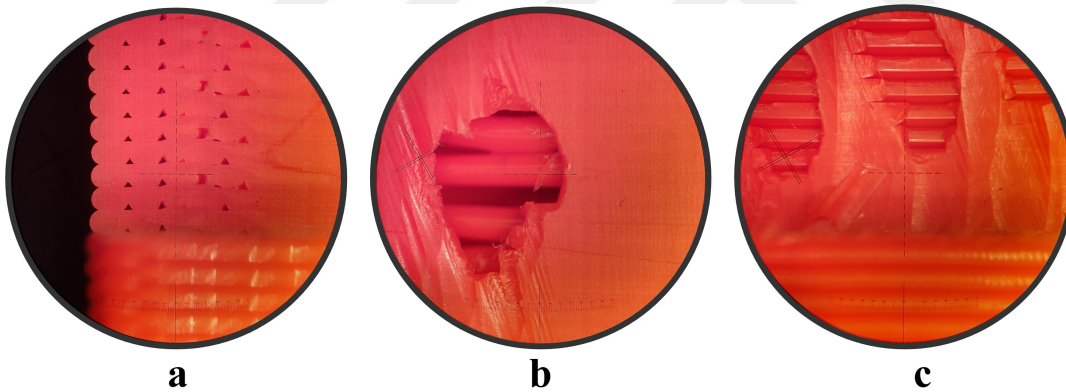


Figure 4.21: Instances of observed defects: (a) Voids , (b) Fracture, (c) Chatter

The effect of insufficient depth of cut can also be experienced with an intentionally misaligned cut in a simple experiment. To demonstrate the progressive elimination of stair-stepping on the surface, an increasing depth of cut along the feed direction is set through misalignment of the workpiece. In Figure 4.22, by examining roughness profiles at different locations (at 1, 2, and 3), separate instances of scaled-down stair-stepping are observed. As D increases, the measured profiles gradually turned into a planar and smooth surface.

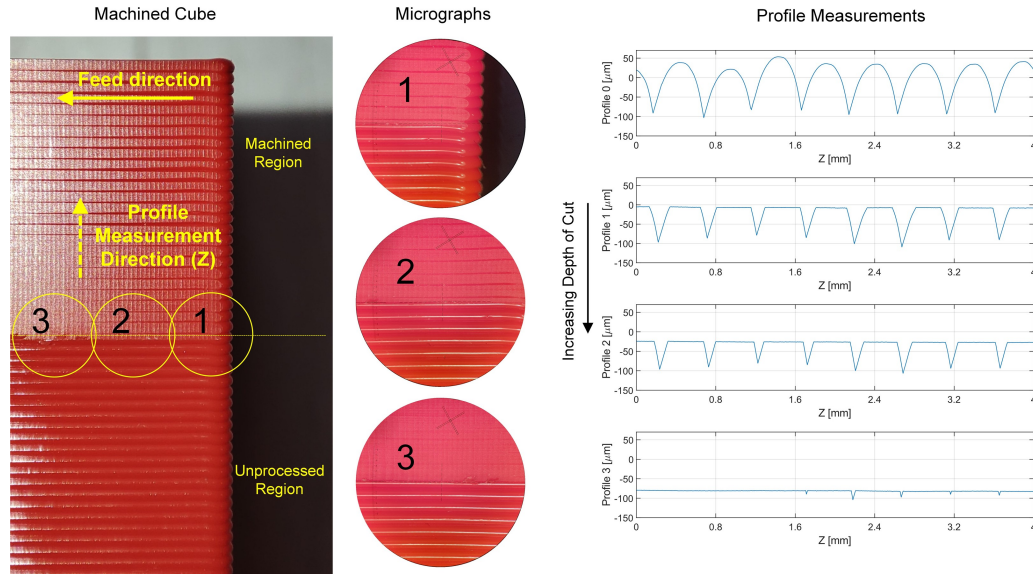


Figure 4.22: The profile measurements from the gradual elimination of stair-stepping

An optimal recommendation about the minimum D should be based on R_t of the measured profile, in the absence of additional positional errors and waviness of the surface. Overall, the suitable depth of cut is highly dependent on the nozzle size (or bead width) used during FFF. Larger nozzles offer advantages by providing extra flexibility in adjusting the depth of cut.

4.4 Summary of the key factors for milling FFF polymers

FFF has natural weaknesses in terms of surface quality and dimensional accuracy. Secondary processing, such as milling, helps to alleviate its shortcomings. For processing thermoplastics, characterization of the critical material properties, choosing the right tool, and setting optimal milling parameters are all key steps.

The detailed guidelines for processing the most popular FFF polymers are presented throughout this chapter. In order to examine key factors, cube-shaped FFF workpieces are subjected to numerous milling conditions. Based on the analysis of the experimental evidence, many factors—including glass transition temperature, tool geometry, feed-per-tooth, surface cutting speed, and macrostructural effects—have remarkable influence on machining performance.

The glass transition temperature is a useful criterion for determining the optimal milling parameters. Its importance comes from the indispensability for efficient heat dissipation. Otherwise, temperatures exceeding that point might cause problems on the surface like viscous folding, especially while processing PLA.

Effective chip removal is key for heat dissipation. The heat dissipation performance can be predicted by analyzing the types of chips generated. In general, the worst case of chip formation occurs in the form of welded chips, where many small chips cannot be flushed away, heated, and fused together. A moderate milling performance can be observed concurrently with the generation of pulverized and nearly-uniform chips. Ideally, the operators should aim to remove the heat persistently through the generation of uniform chips.

Endmills are widely accessible on the market, but they are often designed for metal cutting. Their multi-flute geometry and modest rake and clearance angles characterize them. But, their performance is moderate in polymer processing. On the other hand, single flute endmills (in the form of an O-flute like T1) generally offer a much advantageous geometry. If possible, tools similar to T1 but with even more favorable angles may be sought.

The surface formation modes can be classified into cutting and burnishing, each contributing to the final surface quality. Cutting mode produces periodic texture at a period of feed-per-tooth, while burnishing creates shiny polished surfaces via compressive deformations and surface rubbing. Both options are viable, depending on the specific demands.

Milling on 3D-printed specimens can yield a surface quality comparable to that obtained from a typical metal grinding process. Using a single-flute, high rake angle tool with down-milling achieves the best surface finish, at the submicron level in terms of R_a .

The ideal milling parameters for alternative tools and setups could be sought by taking into account the aforementioned theoretical and practical concerns. Here, a recommended starting point for optimizing them could be selected within the interval of $0.05 - 0.1\text{mm}$ feed-per-tooth and $40 - 80\text{m/min}$ cutting speed for both PLA and

ABS. Moreover, the depth of cut should be set between 0.1mm and half the size of the nozzle used in FFF to avoid possible flaws caused by macrostructural effects.

A limitation of the study is the dependence on the type and state of the used material, as thermoplastic filaments vary in material properties based on the manufacturer and environmental effects. To ensure consistent results, it is advised to utilize fresh filaments for FFF before milling such workpieces. Nevertheless, these guidelines serve as an excellent starting point for processing similar materials with analogous tools. Further progress would pave the way for hybrid systems with seamless integration.





CHAPTER 5

A PROCESS PLANNING FRAMEWORK FOR HYBRID ADDITIVE MANUFACTURING

The flexibility of FFF and the precision and surface finish capabilities of milling can be combined in hybrid additive manufacturing. Nevertheless, it is necessary to solve a number of issues brought up by the integration of those processes. Understanding the distinct potentials of these technologies is the foundation for properly connecting them. The preceding chapters focused on utilizing multi-axis fused filament fabrication and optimizing milling parameters for thermoplastic materials to achieve this goal.

This chapter focuses on creating a comprehensive process planning framework for hybrid additive manufacturing with the goals of improving surface quality, increasing overall production efficiency, decreasing material waste, and maximizing component utility, especially for assembly structures.

An outline of the fundamental components involved in a typical hybrid manufacturing process framework is first summarized before delving into the details. These key steps cover (i) the design and analysis of part geometry crucial for identifying manufacturability challenges, (ii) the selection of part orientation, which influences both functional and aesthetic aspects of the final product, (iii) the slicing process that is essential for the additive stage of the production, (iv) the strategic selection of manufacturing approaches and their sequence to balance the quality and the processing time or other performance factors, and (v) the tool path planning, which is vital for performing the intended movements with the manufacturing tools. Refer to Figure 5.1 for a detailed visualization of these critical steps and how they are integrated into the hybrid manufacturing process planning pipeline.

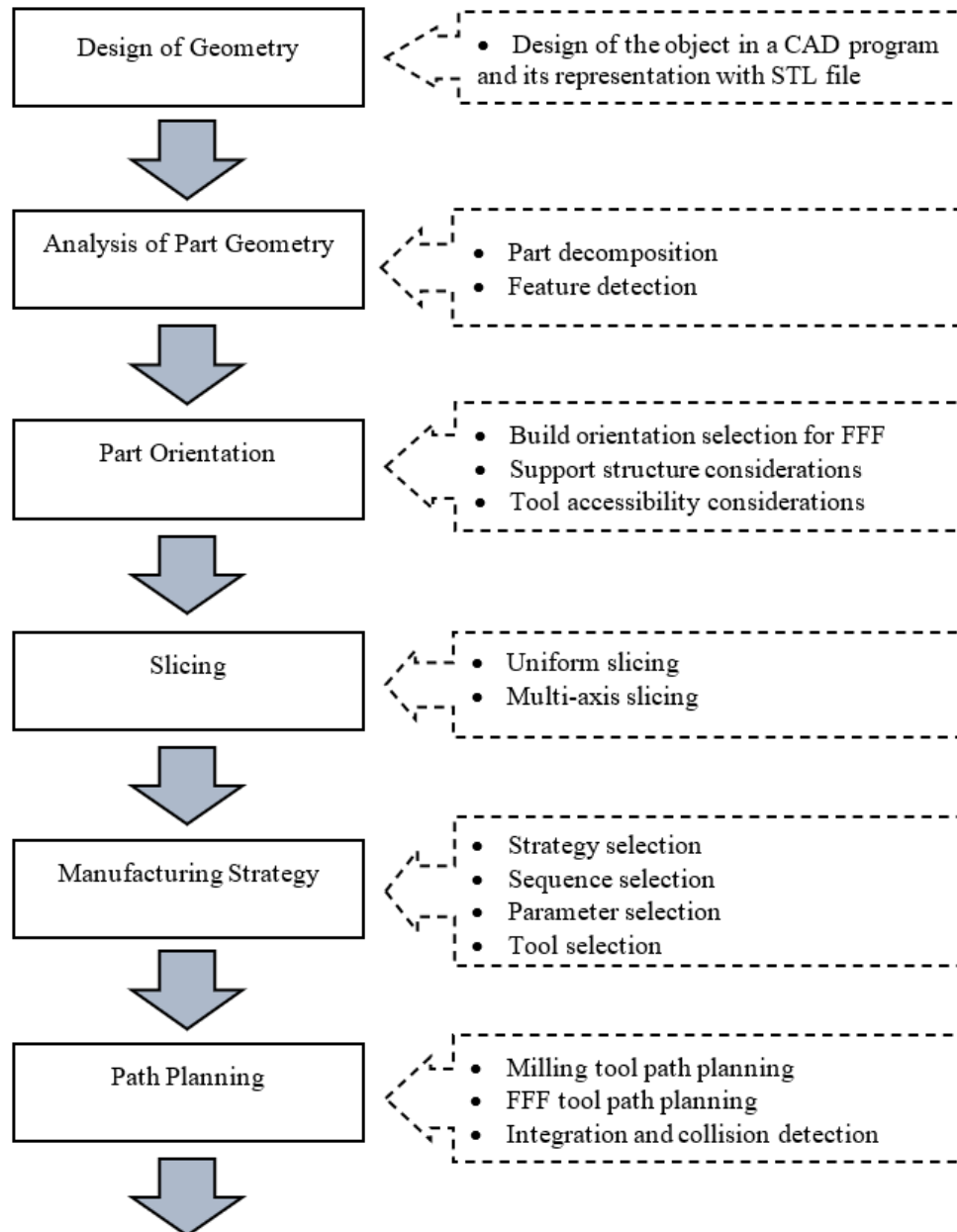


Figure 5.1: Hybrid process planning framework

The design of the geometry can start from scratch in a CAD environment or with the use of an existing solid model, preferably in STL format, which makes computation much easier. Part analysis entails feature recognition and part decomposition, which allows for step-by-step manufacturing planning for separate regions of interest on the workpiece. Depending on the feature type, either an additive operation (i.e., FFF) or a subtractive one (i.e., milling or drilling) could be employed. The selection of

the build orientation is crucial for FFF, ensuring layer support and tool accessibility, with multi-axis systems offering greater flexibility and enabling inclined planes for subsequent steps.

Slicing, whether uniform, adaptive, non-planar, or multi-axis, depends on the part's geometry and is integral to the part's decomposition and build direction selection. An example in Figure 5.2 illustrates how these components rely on one another, showing a part decomposed into sub-parts, each with a hierarchical structure for process sequencing and slicing orientation.

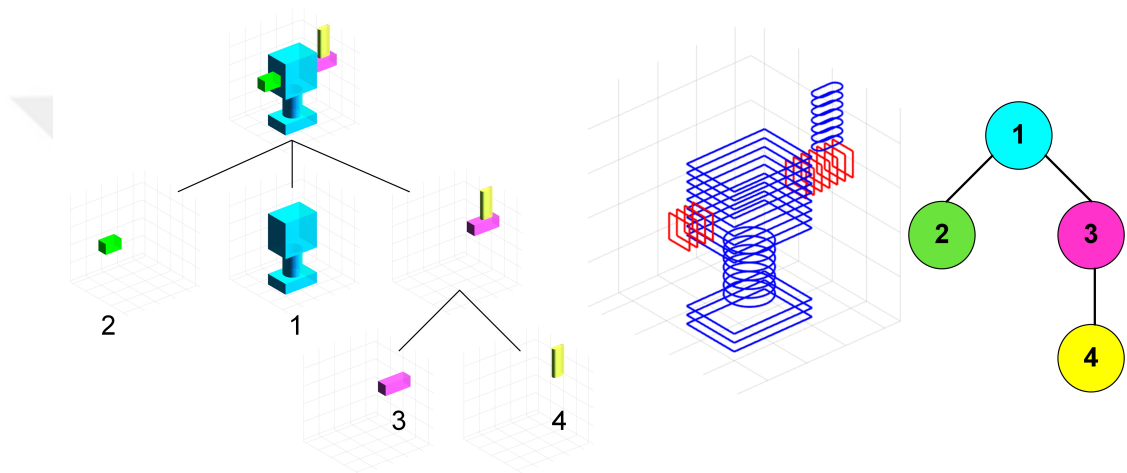


Figure 5.2: Decomposition of the solid model into manufacturable sub-parts having individual slicing directions

Selecting the manufacturing strategy involves multiple considerations, including process sequencing, parameter selection, and the choice of the manufacturing tool. Determining the optimal sequence of FFF and milling operations also requires extensive geometry analysis.

The final step involves developing algorithms or software for generating toolpaths for both FFF and milling. Optionally, simulations can be employed to foresee outcomes and evaluate different manufacturing strategies. Other developments may incorporate in-process monitoring, employ feedback loops, and make real-time modifications to the process plan, ensuring the end product aligns with intended specifications. Nevertheless, these potential developments fall outside the scope of the current study.

Among the aforementioned components, the manufacturing strategy selection, which is inseparably linked to the sequence planning governed by the part's geometric analysis results, is the most crucial. The success of hybrid additive manufacturing relies on the strategic timing of additive manufacturing (AM) and subtractive manufacturing (SM) processes. The effectiveness of hybrid process planning (HPP) is largely determined by the order of these operations, where a typical AM-then-SM sequence can be represented as $HPP = \{AM_1, SM_1, AM_2, SM_2, \dots, AM_n, SM_n\}$ for n decomposed sub-parts of the workpiece.

The manufacturing sequence, often alternating between AM and SM, is not static but depends on the evolving geometry of the workpiece. For instance, an empty initial state calls for starting with AM for material build-up, while a starting state with excess stock material requires beginning with SM to reduce it to the desired size and shape. Thus, the adaptability of the sequence is crucial, tailored to the unique geometry and requirements of every manufactured object.

Alternative sequence patterns in hybrid additive manufacturing could simply be classified into three categories: (i) AM-then-SM pattern, (ii) SM-then-AM pattern, (iii) their integrated use.

AM-then-SM pattern in hybrid additive manufacturing begins with an additive buildup of the part using FFF and then employs milling for surface finish enhancement, feature refinement, and dimensional accuracy. The sequence of the processes can be denoted by $HPP = \{AM_1, SM_1, AM_2, SM_2, \dots, AM_n, SM_n\}$. This method might be used to accelerate production by utilizing thicker FFF layers, with subsequent milling mitigating the stair-stepping effect. This approach would be notably effective for solid mechanical parts featuring multiple holes and distinct, non-merged features. For example, parts with numerous holes can be initially created smaller through FFF and later precisely drilled to size using milling or drilling. Parts that typically require supports can also be finished by milling to remove unnecessary regions.

A subcategory of this pattern can be applied in a layer-by-layer fashion. Each layer, or a predetermined number of layers, is first 3D printed and then milled before building up the next layers. It ensures dimensional accuracy and access to intermediate features, but the frequent process switching can extend fabrication time. Although it may

be slow and impractical for most applications, this pattern becomes useful for cases needing precision in small, localized regions. Specifically, for each layer or set of layers, the HPP could be denoted as: $HPP = \{..., AM_m, SM_m, AM_{m+1}, SM_{m+1}, ...\}$.

SM-then-AM pattern is useful for establishing a stable foundation for subsequent FFF operations. It follows a specific sequence in the process plan, represented by $HPP = \{...SM_m, AM_m, SM_{m+1}, AM_{m+1}...\}$. In multi-axis hybrid manufacturing, for instance, this involves milling to form a slanted base on which tree-like structures with various branches can be 3D printed.

A subcategory of this approach is the use of milling as the first option on an existing part. This method combines FFF and milling to modify an existing object or a stock material. It involves identifying the object's current elements and the necessary alterations to attain the desired final product. This approach is beneficial for repurposing old parts, repairing them, or starting from raw materials, significantly cutting down on waste and production time by leveraging an existing build. It could be represented as $HPP = \{ExistingPart, ..., AM_m, SM_m, ...\}$.

A third pattern that integrates both the AM-then-SM and SM-then-AM approaches in hybrid additive manufacturing can be conceptualized as a versatile, adaptive process. This integrated pattern is designed to maximize the strengths of both methods, allowing for greater flexibility and precision in creating complex parts.

For integrated use, the process sequence is not rigidly set to start with either additive AM or SM techniques. Rather, it flexibly alternates between FFF and milling, adapting to the part's specific needs at each step of fabrication. This advanced strategy involves the selective use of AM and SM on certain features, dictated by a thorough geometry analysis. It requires a detailed computational effort for the part decomposition. Key benefits of this approach are optimized material usage and increased efficiency in production by reducing the frequency of switching between processes.

Overall, regardless of the approach used, individual processes naturally fulfill two primary goals while forming a solid object. Additive manufacturing primarily builds up solid volumes where none existed (i.e., volume creation), while subtractive manufacturing removes excess material to form final surfaces (i.e., surface creation).

Once the process planning is complete, the applications could be operated on a hybrid manufacturing platform. The range of possible manufacturing applications can be expanded by existing multi-axis capabilities while utilizing AM and SM. The potential applications encompass five-axis simultaneous additive manufacturing or milling, planar or non-planar layers in manufacturing, support-free additive manufacturing, and the production of entirely new parts or the repair of old ones.

But, considering the unlimited potential, the complexity of the process planning, and the technical difficulties associated with integrating those processes, it is crucial to constrain the scope of the investigation to ensure a detailed analysis and realistic results. Thus, this chapter pragmatically narrows its focus to the unique capabilities of the manufacturing platform and to the best of the researcher's knowledge.

This study, in addition to support-free 5-axis additive manufacturing as in the case of the previous chapter, concentrates on combining 3+2 axis AM and SM while utilizing uniform and planar slicing in accordance with intended process plans. Part decomposition achieved as a consequence of object's features is the primary determinant of the process plan and strategy selection. Products developed to be manufactured via milling will constitute the majority of the objects studied in this section. This is because, out of the two methods, subtractive manufacturing is the most trustworthy among the two processes when it comes to producing high-quality items. In other words, the accuracy and quality of the output might ultimately be dictated by the manufacturability limits of the SM stage of production. The overall goal is to create reliable and efficient methods for a manufacturing planner to use for achieving superior outcomes in hybrid additive manufacturing, with the additional aim of implementing these techniques on the developed machine for some sample parts.

5.1 Analysis of Part Geometry

The initial step in creating products begins with designing functional geometries, which has been referred to as Computer-Aided Design (CAD) in today's technology. Prior to the rise of CAD, engineering drawings were the primary means of representing intended geometries for manufacturing. CAD replaces the engineering drawings

with 3D models represented as wireframe objects (e.g., STL file) or solid geometries (e.g., CSG models). These representations provide an unambiguous, and comprehensive definition of an object's shape. Compared to traditional engineering drawings, solid models serve as a superior data representation due to their containing other details such as material properties, the mass or volume of the object, or the ability to visualize interacting solids like assembly structures [59].

Process planning, the next stage in product creation, entails developing high-level process representations corresponding to the designed model. During this stage, planners assess the geometry of the products in great detail with the goal of matching the intended output with the capabilities of physical manufacturing processes available. Thus, a human expert or an automated system can select and develop a full sequence of production operations. This systematic practice ensures that the CAD model is created by utilizing the best manufacturing plan based on process knowledge and experience.

The geometric analysis of designed models stands as a crucial element impacting both design and manufacturing processes. The selection of manufacturing processes for a solid model involves analyzing the physical shape and dimensions in the CAD model and the essential attributes of the finished workpiece. Some criteria while performing decision-making in manufacturing planning include shape complexity, size, local elements, tolerances, tool accessibility, etc.

The first considerations that come to mind when planning to use SM, AM, or both may include the following criteria: The overall complexity of the solid model may be a selection criterion since simpler shapes might be suitable for SM, while more complex geometries, repetitive patterns, or internal structures could necessitate AM. Sometimes, the overall size of the objects or the minimum size of manufacturable local elements in a model determines the feasibility of certain processes [60]. Tighter tolerances might necessitate SM methods or other additional finishing processes. Tool accessibility is crucial for both SM and AM. But a comprehensive strategy necessitates the incorporation of geometric reasoning, which is not an easy task [59].

The geometric reasoning used to select manufacturing processes involves a detailed examination of the solid model and how the geometry aligns with the capabilities

and limitations of AM and SM. This examination is simpler when considering local elements of the designed solid model rather than considering the overall shape as a whole. Thus, identifying and categorizing geometric and topological characteristics of solid models, known as feature recognition, has been important for interpreting and analyzing the solid models.

Part decomposition and feature recognition are essential activities in geometric reasoning and for the effective planning of hybrid additive manufacturing.

In solid modeling, a feature refers to a significant region of interest within the model. Features on a designed object fundamentally serve various objectives, ranging from meeting essential design requirements to addressing functional needs. The aim of designing features in solid models may be to ensure specific physical properties like rigidity or reduce weight through strategic subtractions in local areas. Certain features of the solids are incorporated as essential regions to facilitate assembly processes.

The manufacturing planners can utilize feature information to generate necessary instructions after isolating those important local areas/substructures of solid models. Thus, the role of features is to effectively bridge manufacturing-specific knowledge with object representation so as to simplify certain planning challenges. For example, when the solid model of a milling workpiece is reduced to its machining features, the process planning phase evolves into a searching problem for the best sequence [61]. This is due to the direct association of machining features with specific manufacturing processes.

Features can either be recognized within existing solid models or, alternatively, they can be utilized to create desired volumes through the application of Boolean algebra operations. The former is referred to as **feature extraction** or **recognition**, whereas the latter is known as **feature-based design**.

In feature recognition, it is presumed that the ultimate shape of the solid model provides the only source of information for the manufacturer. Conversely, the feature-based design approach operates on the premise that feature information is explicitly incorporated into the model by the designer.

In fact, these methods complement one another and, in theory, may work best when used in combination. Nevertheless, in the current chapter, the basic emphasis will be on feature recognition.

Feature recognition methods generally aim to detect and classify features. Several feature recognition methods are effective for simple features, yet they sometimes struggle to manage non-isolated or interacting features. Automated feature recognition confronts two major challenges. The first challenge is the diversity of features observed in many designed solids. Existing methods are generally designed to find specific, pre-determined features. Nevertheless, it is not feasible to recognize every possible feature for every solid part beforehand. The second challenge is the high computational complexity, as identifying features can become time-consuming with intricate features and large models. Therefore, this field remains actively engaged in exploring new possibilities and methods.

The popular types of automated feature recognition methods can be classified as surface-based methods, volumetric approaches, medial axis transforms, etc [62]. Those methods can be utilized for feature recognition of a known object represented in many classical ways. Feature recognition takes inputs from the 3D objects represented in two common ways: (i) Using information about faces, edges, and vertices (Boundary representation i.e., B-rep, or mesh models). (ii) Using information about body primitives (Constructive Solid Geometry i.e., CSG representation).

- Surface-Based Techniques:

B-rep, or Boundary Representation, models are a way to represent designed shapes using the surface boundaries. B-rep models may become particularly useful in feature recognition as they provide detailed information about the geometry and topology of a solid's limiting surfaces. This information includes vertices, edges, and faces, all of which are crucial for recognizing and classifying features. Edge classification involves categorizing the edges of a solid in B-rep models as either concave, convex, or smooth/tangent [63]. The classification is typically based on the angle between adjacent faces. This classification is critical in recognizing features, as it helps in identifying the nature of transitions between different surfaces of the solid. Similarly, face classification

involves analyzing the faces of a solid to determine their nature and relationship to other features. This can include identifying faces as planar, cylindrical, spherical, etc., and understanding their orientation and position relative to other faces. Similarly, mesh representation represents 3D objects as interconnected vertices, edges, and faces, forming polygons, often triangles. This method is prevalent in 3D printing and reverse engineering but may introduce inaccuracies. Mesh models approximate surfaces and might not capture fine details, as in the case of B-rep models. Features are not inherently represented in mesh models. Some approaches to mesh model analysis involve clustering triangles to identify basic shapes.

- **Volume Decomposition Techniques:**

Feature recognition through convex hull applications involves decomposing a solid into a set of convex components. These components can then be analyzed to identify associated features. Convex hull applications are a kind of volumetric decomposition method. A similar idea is applicable in Constructive Solid Geometry (CSG) applications [64]. CSG is a method used to create complex solids by combining simpler ones through operations such as union, intersection, and difference. In feature recognition, CSG tools (i.e., CSG-based solid modeling software) automatically provide the decomposed volumes of a solid and its constituent shapes. By understanding how these simpler shapes combine to form the overall solid, it may become easier to identify and classify the features of the solid. Thus, intentionally, the information gathered directly from the CSG of designed solids can be utilized in purpose.

- **Medial Axis Transforms and Skeletonization Methods:**

Medial axis transform is a computational geometry method to represent shapes in a manner that captures the skeleton or the medial axis of the structure [65]. By identifying the set of all points inside a shape that have similar distances to the shape boundaries, the medial axis transform may effectively reduce complex shapes into simpler skeleton-like representations. Skeletal representation may be useful as it provides insight into the structure and symmetry of the shape, helping to identify key features based on their geometric properties. Thus, it may facilitate feature recognition by highlighting the topological char-

acteristics of the object. This method is particularly useful for identifying and classifying the intrinsic features of a volume containing channels, holes, protrusions, etc.

While this overview does not encompass all existing methods in the current state of the art for feature recognition, each described method presents a distinct approach to identifying and classifying features within CAD models. These methods can be employed independently or in conjunction with one another to attain a thorough understanding of the features present in solid models.

A primary advantage of feature recognition lies in its independence from the object creation method, allowing for the selection of the most suitable manufacturing technique based on the object's type. Still, challenges arise in universally implementing a single method effectively for all types of objects. A significant limitation for a generalized feature recognition method is the problem of interacting features. While several methods have achieved moderate success in recognizing isolated features, the difficulty of detecting overlapping features remains a challenging barrier. Thus, this study will mainly concentrate on non-overlapping features of solids.

An alternative approach to hybrid process planning may somehow be the inverse of feature recognition, which is referred to as feature-based design.

Feature-based design involves directly integrating feature information into a model instead of extracting it from existing models. This process typically utilizes feature operations to incorporate primitive elements into a solid model. Generally, an object's feature description is stored within a history tree, a comprehensive record of the operations executed to construct a part, essentially serving as an outline for the object's creation. This particular approach is also beyond the scope of the current research.

In this study, the researcher may aim to learn about the identification of various AM and SM features and then utilize that knowledge to formulate feature operations and build operational rules for them, while also tackling challenges like defining transition criteria from different alternatives. The transition criteria are important when there exist different alternatives. This is because feature-based decomposition sometimes inadvertently creates features, a byproduct of certain feature operations (e.g.,

the unintentional creation of a slot when adding neighboring parallel bosses distant from each other).

In the current chapter, the researcher will establish some examples of selection criteria for alternative feature operations, guiding designers in choosing the most appropriate manufacturing methods, whether additive or subtractive, based on the specific design and manufacturing requirements. The following paragraph provides a clear example of this situation:

Since the features on the objects do not specify unique geometric properties, alternative detection of features is possible. As a simple example, consider a cube with a boss on its top, which can be created using two different methods. The first approach, typically preferred by designers, involves manufacturing the cube as a solid block and then employing AM to extrude the boss on the top surface. Alternatively, the cube can be formed by starting with a larger block and then subtracting the unnecessary material to achieve the desired shape. Thus, it is important to define a clear selection criteria and methodology for choosing between such alternative features and the alternative feature operations that correspond to them.

A significant limitation that may be encountered is the inadequacy of existing manufacturing methods to accommodate certain specific features. If the feature cannot be manufactured, it is also crucial to recognize and emphasize it.

In summary, features play a crucial role in solid modeling and manufacturing by significantly improving object understanding and offering a method by directly referencing specific localized sub-parts. While many feature recognition methods exist, a universally applicable and straightforward solution for all object types has not yet been discovered. For part geometry analysis, two key areas are significant: (i) feature recognition, which involves analyzing an object's shape to extract feature information, and (ii) feature-based design, which entails the utilization of primitive features to construct solids. This study will primarily focus on the former, aiming to explore the identification and use of various AM and SM features. The researcher will utilize this knowledge to establish operational rules while discussing the selection among different possibilities. The forthcoming part explores the features and their classification.

5.1.1 Feature Classification

The term feature denotes a significant area of interest within a model, as mentioned before. To better understand the terminology, it will be beneficial to review the feature classification before moving on to the fundamental features found in solid models. There are a lot of attributes that we can categorize the features. It is possible to summarize their distinctive characteristics using a number of categories shown in Figure 5.3.

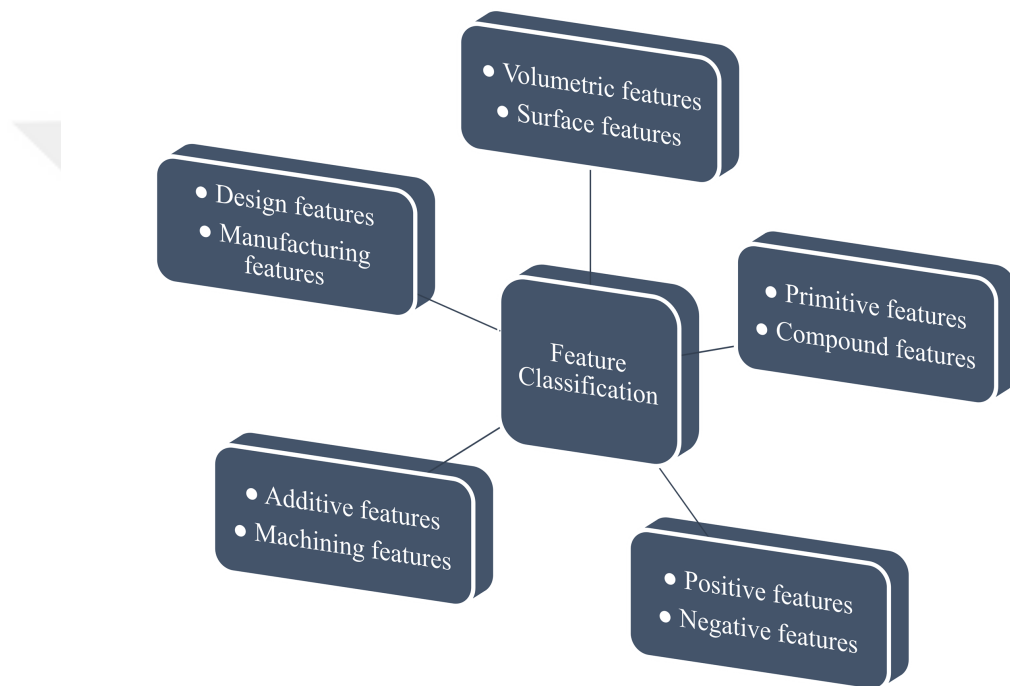


Figure 5.3: The classification of features in terms of many attributes

Design features are functional areas within a solid as conceptualized in its design, focusing on its intended use and characteristics. On the other hand, **manufacturing features** refer to the features that could be manufacturable by a specific production technique. In other words, the former implies the ones shaped by the designer, whereas the former highlights the practical and technical considerations of the production process. In terms of the operation that we use to create them, a manufacturing feature may further be categorized as an **additive manufacturing feature** or a **subtractive manufacturing feature** as distinct sub-classes.

In today's world, design engineers have mostly been inspired by traditional manufacturing methods, which means that CAD models frequently incorporate elements that are well-suited to subtractive manufacturing. Usually, designs are tailored for production through milling and turning, leading to a prevalence of machining features in solid models, such as pockets, slots, and holes, etc. In other words, most design features have been adapted as a subtractive feature or so-called **machining feature**.

Materializing a product physically involves creating a net positive solid volume, which is achievable either through material accumulation (i.e., AM) or by removing material from a pre-existing stock (i.e., SM). Due to the aforementioned motivation behind traditional design practice, subtractive features often take the form of known primitive geometries or volumes. In contrast, a feature built by additive manufacturing may produce volumes of any shape (such as an organic form) with ease, which will radically transform the way the engineers design the products in the future. Those arguments lead to the following conclusions: A widespread adoption of 3-axis machining is usually sufficient in the case of SM features that usually possess a planar cross-section with a specific depth. On the other hand, AM features are not inherently limited by shape or form if the volumes are constructable along a specific build direction. Also, the ability to alter the build direction makes 5-axis motion potentially useful for both processes.

SM features and AM features naturally create a negative and positive volume of material, respectively. In other words, **positive features** and **negative features** may exist on an object depending on its volumetric characteristics. Thus, a regular CAD part can be represented by the summation of a set of those positive and negative volumes of the design features.

Another geometric aspect of features can also be used for classification. Accordingly, the features of a solid part could be classified into two distinct types: (i) **volumetric features** that can be represented by solid volumes created by sweeping the manufacturing tools, (ii) **surface features** that are the collection of faces on the workpiece that resulted from the applied processes at the boundary of volumetric features [61].

The final classification criterion for features is their level of simplicity, allowing them to be categorized as either **primitive** or **compound**. Primitive features are basic,

unique shapes or forms that serve as the building blocks in the design and manufacturing process. Compound features, on the other hand, are more complex, consisting of two or more primitive features combined to form a single, integrated element.

In order to better understand some of the aforementioned terminology, Figure 5.4 illustrates a visual explanation of the characteristics of the features under discussion. Figure 5.4a depicts a cube-shaped base part with a boss design feature on top of it, added for a specific functional aspect by the designer. When this design feature is realized with a specific manufacturing operation, it can also be referred to as a manufacturing feature. This feature can be fabricated using alternative methods, which is resulted from a sequence of volume addition or subtraction. The addition of volume introduces a positive design feature, while the removal of the volume means the addition of a negative design feature to the existing part (see Figure 5.4b).

The fabrication of the boss feature presented in Figure 5.4a could be carried out in two distinct ways: (1) the incorporation of a single (green-colored) positive feature onto a smaller base part, (2) the application of two separate negative features to a larger prior state of the base part. These two alternatives are also shown in Figure 5.4e and 5.4f, respectively. The addition of a positive feature is referred to as the AM feature in the figure, while the integration of a negative feature is termed the SM feature.

Moreover, features that embody 3D volumes are classified as volumetric features, whereas features referring to 2D entities are identified as surface features, as demonstrated in Figures 5.4c and 5.4d. These illustrations show the difference between a surface-only representation and a fully filled 3D volume.

What follows is a detailed description of the principles for producing the AM and SM surface and volumetric features. The subject concludes with the critical functions offered by those features.

Volumetric design features are typically represented geometrically through extrusions, involving the sweeping of a specified contour (i.e., cross-sectional profile) along a vector or any other path. On the other hand, surface design features can be created through Boolean operations of volumetric design features. While the design features are to be transformed into manufacturing features, it is necessary to consider

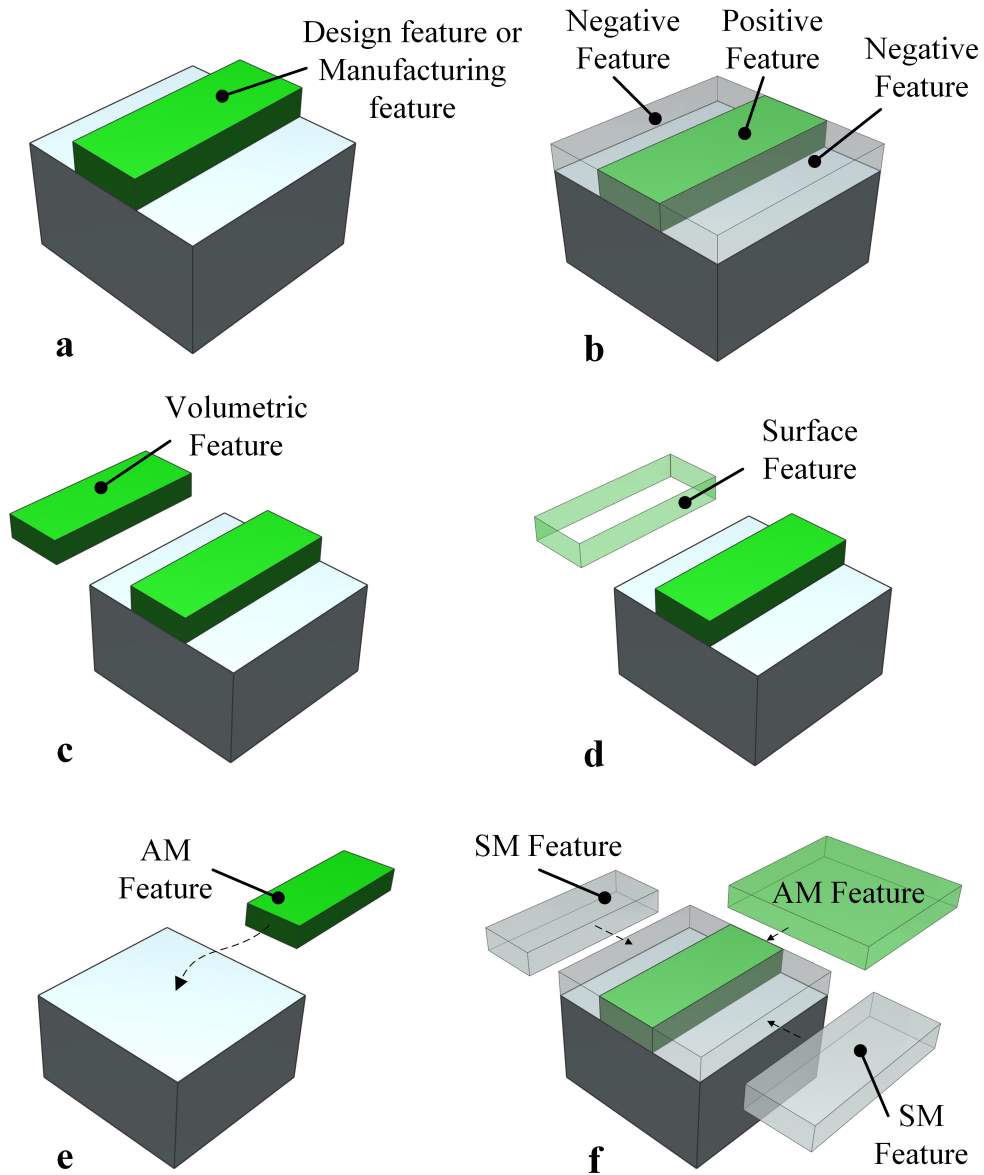


Figure 5.4: The illustration of the characteristics of the described features

the constraints due to the characteristics of the manufacturing processes.

When it comes to manufacturing, a volumetric SM feature might be conceptualized as a solid volume that is systematically removed through a subtractive operation characterized by the tool's sweeping motion. In this case, knowing the cutting tool's shape is an essential assumption. For instance, the use of specially shaped tools, such as a T-slot cutter, can carve out a T-shaped slot through its sweeping action. The manufacturing operation might involve multiple passes, while the definition of the volumetric

feature is still unaffected. Similarly, a volumetric AM feature is constructed through the deposition of material as the extrusion nozzle follows a predetermined tool path, laying down the thermoplastic material in a controlled manner. An already available stock of material can be considered a pre-existing volumetric additive feature that is ready for modification or development.

Through the interaction of volumetric AM and SM features, a set of faces can be developed to construct a surface manufacturing feature. In the context of additive manufacturing that starts from scratch, a volumetric AM feature inherently produces a series of surfaces at the end of the process, which are collectively referred to as a surface AM feature. A notable characteristic of surface AM features is the stair-stepping, which occurs along the build direction due to the layer-by-layer building method. If the surface quality, with its stair-stepping imperfection, meets the manufacturing requirements, a surface AM feature produced by a volumetric AM feature can be left as is. However, if a higher-quality surface finish is necessary, a surface feature created through subtractive manufacturing techniques must be employed to achieve the desired level of surface quality. For a surface SM feature to be realized, a pre-existing volumetric feature is necessary. This serves as the foundation upon which the addition of a volumetric SM feature can shape and refine the surface.

Based on the above-mentioned aspects, the main strategy would be to leverage AM to establish the basic volume of the part, followed by employing SM techniques to enhance the surface finish and dimensional accuracy. Through the proper integration of AM and SM features, it is possible to produce virtually any solid volume, ensuring both surface quality and dimensional accuracy meet acceptable standards. This approach highlights the cooperative relationship between AM and SM processes in achieving the desired outcomes in manufacturing complex solid volumes. Then, the following summary could be expressed for the most fundamental functions of those features:

- Volumetric SM Feature: A negative solid volume added to the workpiece
- Volumetric AM Feature: A positive solid volume added to the workpiece
- Surface SM Feature: Surface at the boundary of a volumetric SM feature

- Surface AM Feature: Surface at the boundary of a volumetric AM feature
- Stock of material: A pre-defined volumetric AM feature, serving as the initial material for further manufacturing processes

5.1.2 Common features:

In the earlier part, we covered the simple description of features, their importance in the analysis of solid models, and reviewed the methodologies for feature extraction and the classification of them. In this part, we go into further detail on the common features that we addressed throughout the investigation. This part will specify the details of both the (i) mathematical definition and (ii) visual representation of features. The former will make use of set theory to provide the definition in a formal sense. We will list and illustrate the standardized features for the latter.

Historically, as mentioned before, the evolution of design features has been closely aligned with SM, with the standardization of certain geometries like pockets, slots, holes, etc. In contrast, AM introduces new flexibility by enabling the fabrication of virtually any shape. This transition may change the concept of the design features, suggesting a future where new norms might emerge. As the industry continues to adapt AM's capabilities, part design might evolve to include novel design features (in fact, infill patterns, lattice structures, or topology-optimized segments could be considered in this context). At the moment, we are still designing our products in the tradition of SM, and this novel approach has not yet resulted in the establishment of totally AM-specific design features.

Assuming the designers' tendency towards traditional, well-established design features and considering the manufacturing setup resembling a 5-axis CNC machine, the focus of the research will be on a family of products designed mostly with standard machining features. This is not just sticking to tradition, but about gaining from the accuracy and reliability of SM while finishing the products. At the same time, we will benefit from the ability to fabricate complex base shapes with the use of AM.

Formal definition of AM and SM features:

The description of an AM feature might involve any volumetric form, as long as the specific constraints do not restrict the process. With usual practice for FFF, designed models are simply manufactured by a union of their internal volume and outermost shell. Thus, the 3D volume that an AM feature occupies $V_{AM,k}$ can be conceptually divided into two distinct parts, which are the outermost shell/contour $C_{AM,k}$ and an infill volume $I_{AM,k}$. Here, $V_{AM,k}$, $C_{AM,k}$, and $I_{AM,k}$ stand for related volumes of k^{th} feature or segment of an object that is to be manufactured by AM. The outer shell represents the perimeter of the feature in each layer, so it is the continuous boundary that defines the external surface of the feature (recall surface AM feature). Note that the shell has a certain thickness, depending on the nozzle size. It can mathematically be expressed as $S_{AM,k} = \partial C_{AM,k}$, where ∂ is the topological boundary operator.

Typically, an AM feature is divided into n layers, $\{L_1, L_2, \dots, L_n\}$, where each layer specifies a 2D cross-section of the feature at a specific height. A layer L_i is then represented as a set of points to be traced by the nozzle. The infill volume $I_{k,i}$ is actually defined by the sweeping the nozzle's unit material output along a guide curve given by an ordered set of points $G_{I,k,i} = \{\mathbf{P}_{I,k,i} \in \mathbb{R}^2\}$ within the boundary defined by the outer shell. The outermost shell/contour $C_{k,i}$ can be defined in a similar manner, except the guide curve is now an ordered set of points $G_{C,k,i} = \{\mathbf{P}_{C,k,i} \in \mathbb{R}^2\}$ that describes the perimeter of the layer. Overall, each layer can be defined as the union of the infill volume and the contour, which represents the complete set of points that will be traced and filled with material in the layer. A layer will have a finite height, usually created in terms of equally distributed layers, i.e., uniform slicing. The AM feature is thus represented as

$$V_{AM,k} = \bigcup_{i=1}^n (I_{k,i} \cup C_{k,i})$$

where $\bigcup$ is the union operator, assuming that each layer L_i is positioned directly on top of the preceding layer L_{i-1} as long as the process ensures continuity, supporting structure, and adherence between layers. To conclude, the AM process can physically generate both volume ($V_{AM,k}$) and surface ($S_{AM,k} = \partial V_{AM,k} = \partial C_{AM,k}$).

Subtractive manufacturing, in contrast to AM, involves taking an already existing material and removing it to shape the final feature. This implies SM could physi-

cally generate functional surfaces only, as a result of the union of volumetric SM and AM features. Let B_k represent the initial base material (i.e., $V_{AM,k}$ or any existing volume) to which the SM volumetric feature will be added. A surface SM feature is the boundary of what volume remains of B_k after the union of all the volumetric SM features R_k (i.e., material removal actions). The material removal action is implemented in a volume described by the sweeping of the cutting tool along a guide curve $G_{T,k} = \{\mathbf{P}_{T,k} \in \mathbb{R}^3\}$, which is represented as follows:

$$V_{SM,k} = \bigcup_{G_k} T_{G_k}$$

where T_{G_k} represents the volume of the tool at a different point along the guide curve.

Provided that there is no restriction about implementation (e.g., tool accessibility), the surface SM feature can be described as

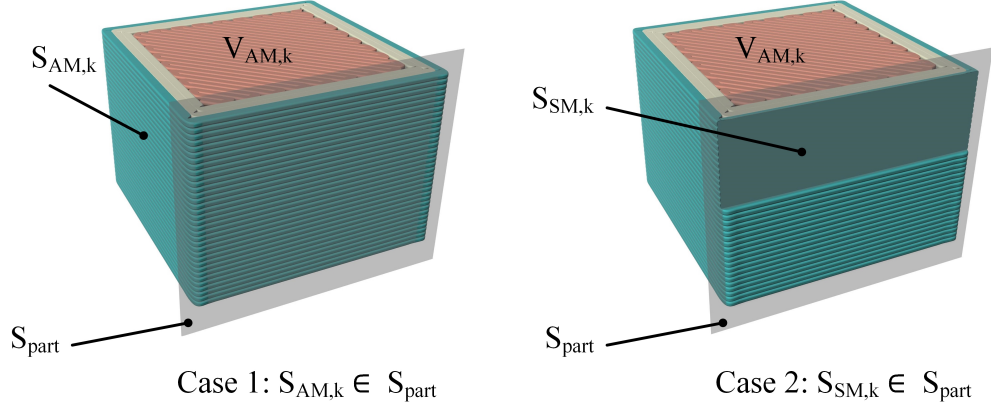
$$S_{SM,k} = \partial(B_k \bigcup R_k) = \partial(B_k \bigcup V_{SM,k})$$

In Figure 5.5, one can see how the surface AM and SM features appear. The plane that touches the peaks of the stair-stepped surface is considered the manufactured part's boundary in case 1. The AM-created surface could be acceptable, but it wouldn't be ideal because of the stair-stepping. In case 2, the produced part's boundary is defined as the plane that intersects the boundary of the volumetric SM feature. This production option is highly favored for its superior surface quality and accurate dimensions. It should be noted that in both cases, the tool path needs to be different from each other. In order to generate a delta volume for the material removal in case 2, the volumetric AM feature should be slightly larger than in case 1 (i.e., offset by half the width of the bead approximately).

Examples of common features:

This section presents examples of common features found in solid model designs, such as planar faces, pockets, slots, steps, holes, etc.. These features are well-defined in the design of the solid models and integrated into the real products as elements of subtractive manufacturing, mostly. Prior to summarizing these features, it is essential to explain certain terminologies here.

Here, we define the normal vector of a feature to establish a plane on which the feature's cross-section is projected. The boundary of the feature's cross-section is



$I_{AM,i}$ (Orange & yellow) , $C_{AM,i}$ (Green) , $V_{AM,i}$ (Orange & yellow & green)

Figure 5.5: Appearance of the surface AM feature and the surface SM feature

defined as the contour of the feature. For instance, a hole feature can be defined by a circular contour extruded along its normal vector. The size and depth of the feature are defined by the size of the contour and the amount to which the contour is extruded, respectively, which is determined by the designer's intention.

It is worth noting that during the design phase, those design features are often recognized as an extrusion operation followed by related Boolean operations. In the fabrication phase, the associated manufacturing features are often formed as a result of the tool's movement by accumulating material volume (in AM) or subtracting the tool's swept volume (in SM). In this regard, it may be stated that it does not always provide a design feature in one step.

Consider a hole design feature conceptualized as the extrusion of a circle along a normal vector. The corresponding SM feature could be achieved by the drilling or milling tool's motion, cutting along the specified normal vector in one step. Conversely, a pocket design feature, defined by the extrusion of a specific area along a normal vector, may require the manufacturing tool to traverse the pocket's interior multiple times to achieve the desired outcome. These examples shows the relationship between design features and their manufacturing counterparts.

The following are the most prevalent design elements observed in CAD models and some guidelines that should be implemented in hybrid process planning.

- **Planar Face:**

A planar face feature is essential in describing the workpiece boundary face. Defined by its boundary contour and depth, it is manufacturable as an SM feature by removing material around the contour of existing material, resulting in a finely-finished surface on the object. While typically used for creating flat outer contours with high-quality finishes, it is not restricted to planar surfaces alone. For instance, an irregularly shaped contour results in a profile face. Although both planar and profile faces can be produced as an AM feature, this method is limited if the build direction exceeds the critical overhang angle, and often resulting in a stair-stepped surface texture. A planar/profile face design feature is preferred to be realized with a corresponding SM feature rather than an AM feature.

- **Boss:**

A boss design feature is characterized as a protruding feature formed by extruding a contour along its normal plane. As an SM feature, a boss is not created through a separate manufacturing step; rather, it is the material left untouched during the machining of adjacent features. This means a boss is not an independent SM feature but is produced in combination with other SM features. Conversely, as an AM feature, a boss can be directly created by adding material, as long as the build direction is favorable to its formation.

- **Pocket:**

A pocket design feature indicates a recessed area on a workpiece generated by subtracting the associated extrusion, i.e., the profile of the pocket is subtracted from the workpiece in the direction of its normal up to a specific depth. This feature is classified as a closed pocket if it is entirely surrounded by material, or as an open pocket if one of its side walls is open. As an SM feature, the tools approach the pocket along the normal vector to the plane of the contour. However, due to the finite radius of SM tools, creating sharp corners in pockets is not achievable. In contrast, an AM feature in the shape of a pocket can be generated practically with sharp corners, because to the small nozzle diameters utilized, which allow for tracing just beyond the target contour, assuming no other limits exist.

- **Slot:**

A slot design feature is a subset of the pocket feature that is distinguished by its manufacture using a single sweep of a subtractive manufacturing tool. This yields a volumetric SM feature whose width is equal to the tool width. In most cases, the tool's travel path aligns with the slot's centerline at the desired depth. Slot features, like pocket features, can be closed or open. The method of producing a basic slot with SM and AM features is similar to that of a pocket.

- **Step:**

A step design feature is a specialized form of pocket, characterized by the absence of surfaces from both the top and sides of a workpiece. This feature shares similarities with an open pocket in that its contour is open on the sides. Thus, it is easier to realize this design feature as an SM manufacturing feature since multiple directions are available for tool accessibility. The manufacturability of a step as an AM feature is also simple.

- **Hole:**

A hole design feature is a recessed feature with a circular contour and an orientation defined by a normal vector along the center axis. As an SM feature, tool access is in the direction along the center axis of the hole. Conversely, as an AM feature, a hole feature can be manufacturable by depositing material around it, which is not really a preferable option due to the shrinkage problem and its being unsupported in some build direction. Different types of holes, such as blind holes, counterbores, and countersinks, might have somewhat different geometries with minor modifications. Certain specialized hole types, like tapered holes, may only be feasible with AM if appropriate SM tools are unavailable. Additionally, threading within a hole represents a more complex feature, requiring specialized tools and essentially SM process.

- **Fillet and Chamfer:**

A chamfer design feature serves as a transitional design element between surfaces, essentially acting as a flat planar connection between adjacent faces. As an SM feature, a chamfer is typically external. Fillets, while similar to chamfers in their transitional role, differ by offering a rounded, rather than flat, transition

between surfaces. Overall, they resemble planar or profile face design features. Due to the problem of stair-stepping, using AM to manufacture such relatively small features is not a good decision.

- **Compound Feature:**

A compound design feature is defined as a complex volume consisting of two or more individual features merged together. Its overall boundary volume is the total of the volumes of its constituent elements, seamlessly integrated where these sub-features intersect or overlap. Examples include a T-profile or T-slot, which combines the characteristics of an open pocket and an open slot; or a countersunk hole, representing the integration of a fillet with a hole. Such compound features illustrate how distinct geometries can unite to form a unified, functional design element in a solid model. Those design features could be created as AM or SM manufacturing features, or with a proper combination of them.

Figure 5.6 reveals some of the features observed in solid models, whereas Table 5.1 summarizes their characteristics:

5.2 Part Orientation

Part orientation in hybrid manufacturing is a critical step in process planning. It involves determining the optimal orientation of each decomposed sub-part of a design within the manufacturing environment. This decision impacts not only the manufacturability of each sub-parts but also the overall speed and quality of the manufacturing process.

The orientation of parts influences several key aspects of manufacturing: (i) surface quality, where the build orientation affects the surface finish, especially in AM stage of production in which layering can lead to visible stair-stepping effect, (ii) support structures, where certain orientations in AM require supporting structures that increases material usage and post-processing time, (iii) manufacturing time and cost, when optimal orientation can reduce manufacturing time and material waste, directly impacting the cost-effectiveness of the process.

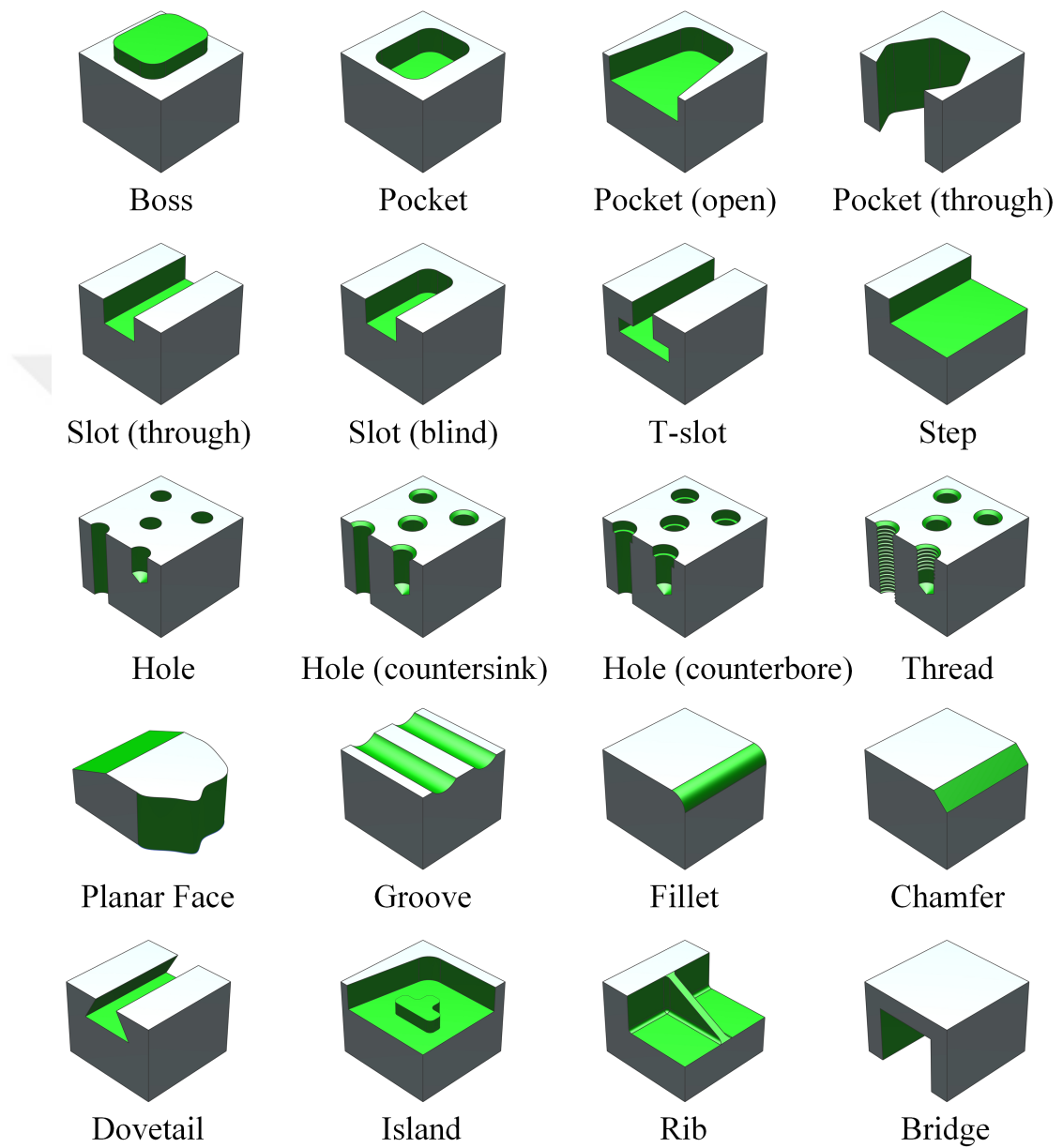


Figure 5.6: Detailed visualization of well-known design features observed in solids

Table 5.1: Summary of common manufacturing features

Feature	Definition	Detail
Boss	Protruding feature on a workpiece	A closed contour extruded normal to its plane
Pocket	Recessed feature in a workpiece	An extruded subtraction of a closed contour into the workpiece
Slot	Special kind of pocket	Pocket with its width often equals the tool size
Step	Special kind of open pocket	An open contour accessible from side surfaces
Hole	Recessed feature with circular profile	An extruded circular subtraction into the workpiece
Thread	Intricate feature applied on circular features	A modified hole or its complementary
Profile	Face or boundary of a surface feature	Planar or curved surfaces
Groove	Channel cuts on the workpiece	Slot with a narrower or smaller geometry
Fillet/Chamfer	Transitional features between surfaces or edges	Chamfer: A flat wall transition Fillet: A rounded transition
Compound	Combination of two or more connected features	Composed of united volumes from constituent feature

Decomposing a complex part into smaller sub-parts simplifies the decision making in manufacturing process, as mentioned previously. Each sub-part can be analyzed for its geometric and functional features to determine its ideal orientation. This decomposition must consider the limitations and strengths of AM and SM methods. Geometric considerations are related to the analysis of the complexity of sub-parts, possible overhangs, and internal structures of each sub-part. Functional considerations needs understanding the practical requirements, like mechanical load directions which influence the orientation for optimal strength. Thus, following aims can be targeted. First, the build orientation should be set to minimize overhangs to reduce the need for support structures. Second, considering the layer adhesion and strength, the AM stage of production should be implemented to maximize layer adhesion in

high-stress areas or thin features. Last and the most important one, the process plan should consider the stair-stepping effect to offer the best aesthetic and also to create functional surfaces for assembly purposes.

Similar restrictions have to be considered to orient the decomposed sub-parts for subtractive manufacturing, as well. Tool accessibility is an important consideration, where the orientation should facilitate easy access for the tools to reach all the surfaces that require machining. To ensure that the part is oriented for stable clamping and minimal vibration during machining, the selected orientation should be stiff enough to handle resulting cutting forces.

When considered in combination, balancing for AM and SM operations that minimize the overall effort is also important. Determined build orientations should be compatible with AM and SM phases, reducing the need for reorientation between processes. For this purpose, it may be necessary to employ iterative procedures to find the optimal build direction, considering factors like build time, material usage, and structural integrity. The selected build orientation will also affect the next step, slicing.

The selection of build orientation could be carried out based on the experience of the process planner, or some other methods may be useful. A method for build direction determination can be applied through the application of skeletonization of the solid model [66]. This methodology offers insights for planning by interpreting the inherent structure of models. To ascertain the optimal build direction for components, a systematic approach, guided by a set of criteria, could be proposed.

The current research typically inputs the solid geometries in STL file format. Objects are positioned within a three-dimensional space, oriented in any chosen direction. Prior to fabrication, an initial assessment could be undertaken to identify the faces necessitating support structures based on their orientation relative to the currently selected orientation. For instance, as depicted in Figure 5.7, the build direction of the object is represented by the unit vector $\vec{B}$. Identification of faces requiring support involves analyzing the unit normal vectors $\vec{n}_k$ of k different faces of the geometry. The criterion for requiring support is determined by the dot product between $\vec{B}$ and $\vec{n}$, which should not exceed a predefined critical threshold that reflects the process

dynamics, such as $\vec{B} \cdot \vec{n} > -0.707$ for maintaining an angle below a 45° inclination threshold. This methodology could also be used as a generic method in analyzing unsupported faces at any phase. Figure 5.7 reveals the STL representation of the solid, its build orientation, and the analysis of the faces in terms of the support structure requirements. Definitely, the faces in red color (except the base surface) necessitate support structures.

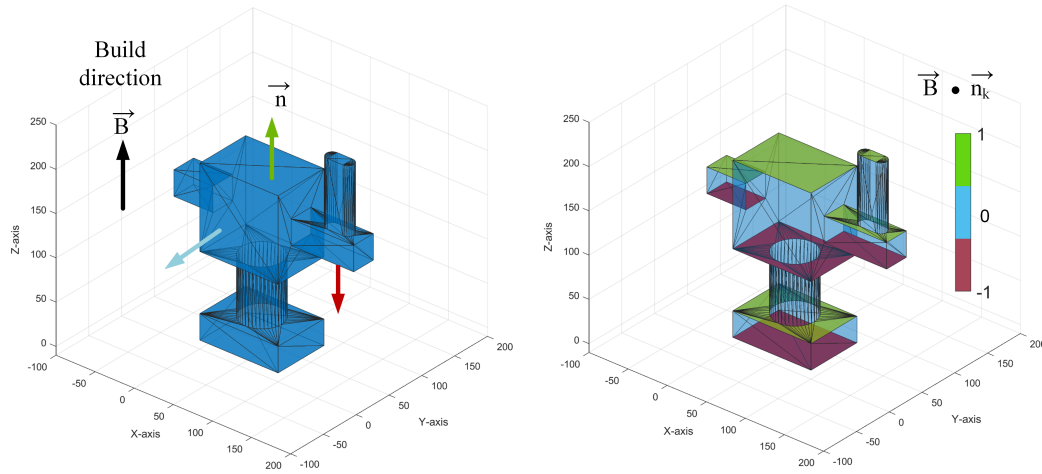


Figure 5.7: STL representation of an object and the identification of unsupported faces with respect to the given build direction

Subsequently, the geometry simplification step involves the reduction of unnecessary triangles through face merging, achieved by eliminating the shared edges of neighboring faces having the same normal vectors. Figure 5.8 demonstrates this process by highlighting the eliminated edges in a local feature as well as the resultant merged faces after geometry simplification. These faces serve as potential base planes or division faces for segmenting the part into sub-parts.

The next phase involves skeletonization, which can extract valuable information for planning purposes. While multiple methodologies exist for skeletonizing a solid, this study employs a thinning method. It could be carried out by generating a binary volume of the solid. It is important to note here that critical information about the topology can be gathered by focusing not only on the skeleton of this binarized volume itself but also on the skeleton derived from its complementary portion. This dual analysis targeted determining optimal build directions for the whole structure as well

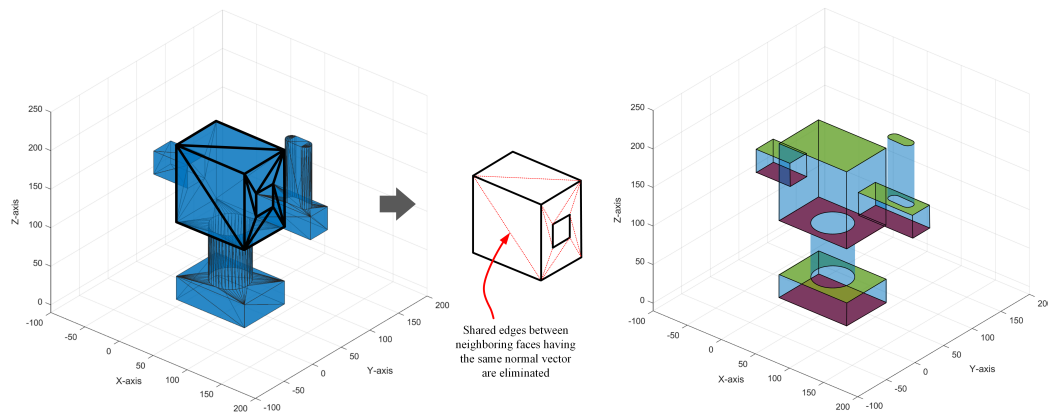


Figure 5.8: Geometry simplification through merging of redundant faces

as the individual features. For example, the presence of an internal hole feature in a part allows planners to utilize the skeleton of the solid's complementary binary volume. This involves virtually filling the volume of the hole to exclusively extract the skeleton of the hole feature, thereby identifying its centerline. This method could be extended to other features as well.

Utilizing graph data structure facilitates queries regarding the topology of both the skeleton and the object. The endpoints of the skeleton and the related faces at their adjacency, can serve as potential base faces. Likewise, branch points and their corresponding faces may be employed to divide the part according to various build orientations. The planner may then refine the skeleton, utilizing this data to segment the object into sub-parts and establish a hierarchy.

As illustrated in Figure 5.9, the binary volume and its corresponding skeleton for a sample object are illustrated. The object is then sliced in two different build direction to eliminate the need for support structure.

In conclusion, the method allows for the identification of potentially useful faces and potential build directions for planning purposes. When production processes facilitate multiple solutions, the planner must formulate an effective plan. For instance, the planner might employ an objective function that prioritizes the use of the largest faces as base faces to increase stiffness and provide greater design freedom. If there is an absence of viable solutions, segmenting the part and manufacturing separate parts in

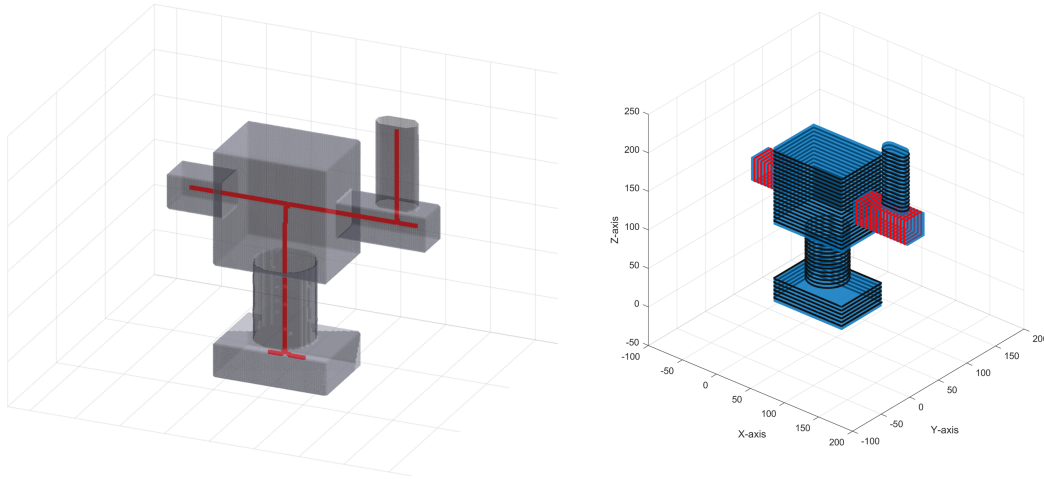


Figure 5.9: The skeleton extraction from the binary volume and an example configuration for the multi-axis slicing of the object

different setups becomes an alternative.

Finding a build direction using this strategy may be particularly effective for prismatic objects. The type of extracted skeleton yields essential information about the part, which holds potential for integration into automated systems in future research. For example, the extraction of a part's skeleton on a plane could imply that the part's main body is positioned between two planes or possesses a kind of symmetry. For such parts, a distinct build direction perpendicular to the identified plane may be chosen automatically. Likewise, in the case of tubular objects with an extracted 3D curve skeleton, direct multi-axis slicing along the skeleton arc length is feasible, as discussed in the previous chapter. However, given the nature of the discussed problem, which inherently lacks a definitive optimal solution, it is reasonable that multiple alternatives exist. Consequently, this methodology may not be universally applicable across all part types. In scenarios where the method cannot help, manual assistance by the planner may become indispensable.

5.2.1 Skeletonization

This part of the study will cover detailed information about skeletonization. Skeletons can be a possible description of 3D shapes that reveals the minimal structure of the

main branches of the decomposed volumetric units. The information extracted from the skeleton of 3D objects can be intentionally utilized in 3D printing applications for such purposes: (i) decomposition of volume into sub-structures, (ii) multi-directional slicing, and (iii) optimization of the infill pattern. The first two targets are useful for the content of the work discussed in this study.

The basic properties of skeletons could be identified as follows. First of all, regardless of the way of extracting the skeleton, the extracted skeletons should have similar structures (i.e., homotopy). The skeletons should be smooth and have connectivity of their all branches. The number of segmentable parts of a volume can be related to the branching points of the skeleton. In fact, some skeletons should have nearly the same shape, but unnecessary branches can result from the deviations. This is sometimes called the noise of the skeleton. The elimination of such noises is referred to as regularization or pruning and results in a stable skeleton and should be implemented. The skeleton definition should be dependent only on the input geometry, so it should be invariant due to the way of skeleton extraction.

With respect to the type of method implemented, the skeletonization may yield a curve skeleton or a surface skeleton. With respect to the input to those algorithms, skeleton extraction methods can be categorized into voxel-based or mesh-based techniques [65].

In 2D, the extraction of the skeleton needs less computational effort than in 3D, with the customary techniques listed as medial axis transforms, voronoi diagrams, distance fields, grassfire analogy, etc.

The medial axis skeleton can be extracted by using the locus of the center points of a bunch of maximally inscribed balls in 2D contours of the objects. The global or local symmetry axis of contours can also help us capture the skeleton of 2D shapes. The idea behind this approach is very simple, but not easily generalized for every 2D shape since the method may not work for intricate contours. Moreover, Voronoi diagrams are a well-known approach in mathematics, together with the use of Delaunay triangulation. Those diagrams have been used for partitioning the 2D or 3D regions into cells with respect to the closeness values among all neighboring cells. Thinning is another method of skeleton extraction applicable to pixel- and voxel-based shapes.

The general connectivity guidelines applied in thinning applications lead to the extraction of 3D curve skeletons. In this study, the thinning approach is implemented in skeleton extraction of some sample parts.

5.3 Slicing

Following the determination of the build orientation, slicing emerges as the subsequent phase. It is possible to slice the whole part at once or detach the sub-features from the main workpiece, each assuming its own distinct build direction. However, regardless of the type, the slicing approach is the same as long as uniform slicing is applied. In the case of multi-axis slicing with a continuous variation in the build direction (as in the case of the previous chapter), slicing types may introduce a slight nuance in the resulting output, leading to slices of non-uniform thickness. That is, the thickness of a slice for an arbitrary layer may depend on the specific location within the layer.

The slicing process starts with the STL model of the solids, available in either binary or ASCII format. These formats contain the object's external surface in a triangulated mesh of faces and vertices, offering simplicity but with a certain degree of approximation. Thus, the representation of complex geometries may be particularly problematic, such as non-flat or curved surfaces.

The methodology employed involves reading the content of STL files, enabling object translation or rotation to achieve the desired positioning. This includes automatic adjustments of the object's base surface at the zero level of the machine as well as its automatic translation to an approximate central location. Subsequent slicing utilizes a standard method involving the calculation of intersections between the model's triangular facets and parallel planes at changing levels, defining each layer's contours. This process benefits from graph data structures, enhancing efficiency and computational speed. Parameters such as layer height and outer shell count are specified by the planner, leading to the extraction of layer contours and the construction of shell structures or simple infill patterns.

Beyond conventional techniques, i.e., uniform slicing, the study explores advanced methodologies, including multi-axis slicing. The principle used for the multi-axis method is actually rather similar, i.e., the faces extracted from the STL file intersect with planar levels. Examples of both approaches are illustrated in Figure 5.10. While acknowledging the existence of non-planar and helical slicing methods, this study focuses exclusively on planar slicing for both uniform and multi-axis applications.

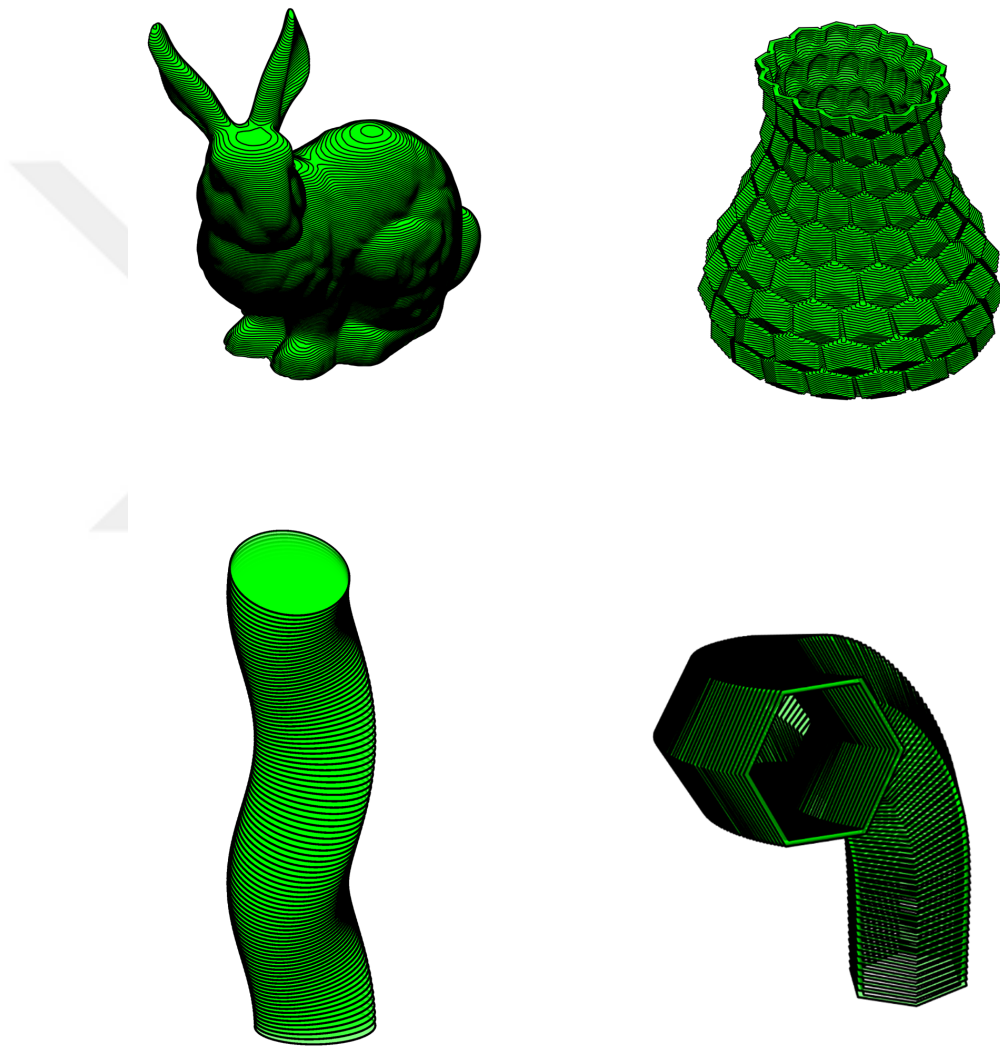


Figure 5.10: Some examples of the sliced object having uniform layers (top) and non-uniform layers (bottom)

5.4 Manufacturing Strategies

Until now, we have explored the geometry of solids, analyzed them through features, and discussed the part orientation and slicing as well. The next critical aspect of hybrid manufacturing process planning involves the manufacturing strategy. Given the capability to both accumulate and remove material in a multi-axis environment, optimally selecting and sequencing the manufacturing processes for a generic part presents a challenging (i.e., NP-hard) problem [67]. Consequently, this section aims to establish a set of rules, identify supportive methods, and develop a knowledge base to facilitate the automation of this process in future research. While the proposed rules and operations may only apply to a specific subset of solid objects, primarily focusing on prismatic parts, they represent a foundational step towards organizing the manufacturing strategy in hybrid manufacturing. The strategies presented in this section reveal the possible options applicable on the developed manufacturing platform. Some fabrication cases have been carried out to realize these strategies later.

The manufacturing strategies can be outlined in Table 5.2. Subsequently, the details of these strategies will be elaborated upon in the following sections.

Table 5.2: Summary of the manufacturing strategies

Strategy	Target	Sub-type of the strategies
D	Direction selection	Type 1: Tool orientation for SM
		Type 2: Build direction for AM
S	Segmentation	Type 1: Feature detection (for one segment)
		Type 2: Locating pins or other inserts (fixed)
		Type 3: Interlocking joints (movable)
A	Additive manuf.	Type 1: Volumetric and surface AM features
		Type 2: Preformed geometry for SM (offsetted)
		a: Use of circular orifice nozzle b: Use of rectangular orifice nozzle
M	Machining	Type 1: Volumetric and surface SM features
C	Combined operation	Type 1: Layer-by-layer AM and SM

5.4.1 Strategy D: Direction selection

This strategy refers to the methods related to the determination of the build orientation for AM and SM processes. For additive manufacturing, the main constraint is the self-supporting principles of the layers and performing manufacturing as the nozzle axis approximately points towards the gravity vector. For subtractive manufacturing, the main constraint is tool accessibility. Thus, the determination of the proper orientation for the sub-parts could be summarized as follows:

- Type1: For SM, this action corresponds to the choice of the orientation of the block or a semi-finished part (i.e., preform) with respect to the table such that the number of tools to be used is minimized while providing easier access for the cutting tools to machine the features of interest.
- Type 2: For AM, this action corresponds to the selection of the build orientation, which minimizes (or eliminates all together) the support structures and/or provides easier access for the nozzle to fabricate the features of interest.

An SM feature's build direction is basically a direction for ensuring that the utilized tools are accessible. Thus, this part basically addresses the prerequisites for the tool's accessibility and summarizes several situations, including inaccessibility, accessibility, and partial accessibility.

In order to add a volumetric SM feature to a workpiece (i.e., material removal), the cutting tool needs to be able to approach the workpiece from the outside while keeping enough clearance for itself and other components of its holder.

Since the milling tools are used by rotating the tool relative to its own central axis, this results in a symmetrical effect while traversing a tool path. That makes the centerline of the tool a significant location while moving on a tool path. A physical cutting tool must have a finite radius (or profile); thus, the corresponding volume of the tool must contact all the points of a volumetric SM feature to be able to generate it.

The accessibility of a tool can be conceptually evaluated by projecting a feature's volume along directions perpendicular to its surfaces. A feature may be considered

accessible if the resulting swept volume neither intersects the feature nor any other part of the workpiece. Conversely, the intersection of the swept volume with the workpiece denotes inaccessibility. In certain cases, a feature is defined as partially accessible when only a specific portion of its volume is approachable by a tool in a particular orientation without causing intrusion.

In order to create a volumetric SM feature, it is essential that there exists at least one direction from which the tool can access the workpiece without interfering with any other area. The movement of the tool can be facilitated in several ways: (i) through another accessible direction, (ii) across a partially accessible volume, or (iii) inside the feature's cross-section that is perpendicular to the accessible direction and bigger than the tool's cross-section in width. For instance, a through slot may be accessible from its top face, allowing sweeping movements along both sides. Similarly, a closed pocket may only be accessible from its top face, necessitating the sweeping of the tool within its own cross-section.

Figure 5.11 illustrates a dovetail feature along with its extensions in potential tool approach directions [61]. While the feature is inaccessible from the vertical direction, it remains accessible horizontally. The figure also reveals the partially accessible volume.

The available space for the tool's approach from the horizontal axis enables the sweeping movement along this accessible direction if the profile of the cutting tool is suitable (i.e., a dovetail cutter). Also, this arrangement ensures that the partially accessible volume accommodates the tool's shank on the trajectory. Here, it is crucial to distinguish between machinability and accessibility. Note that machinability also requires a comparison between the feature's dimensions and the tool's shape.

In this study, the process planner can easily check whether the planned build direction/part orientation for SM is reasonable or not, by applying extrusion operations to the related faces. This is possible by shifting the faces of an STL using homogeneous transformation matrices, followed by the capping of the resultant empty space. Then, the SM tool can theoretically be able to move along the trajectories where the condition holds for accessibility. A physical constraint for selecting the orientation for SM operation is regarding the machining forces resulting from the material removal.

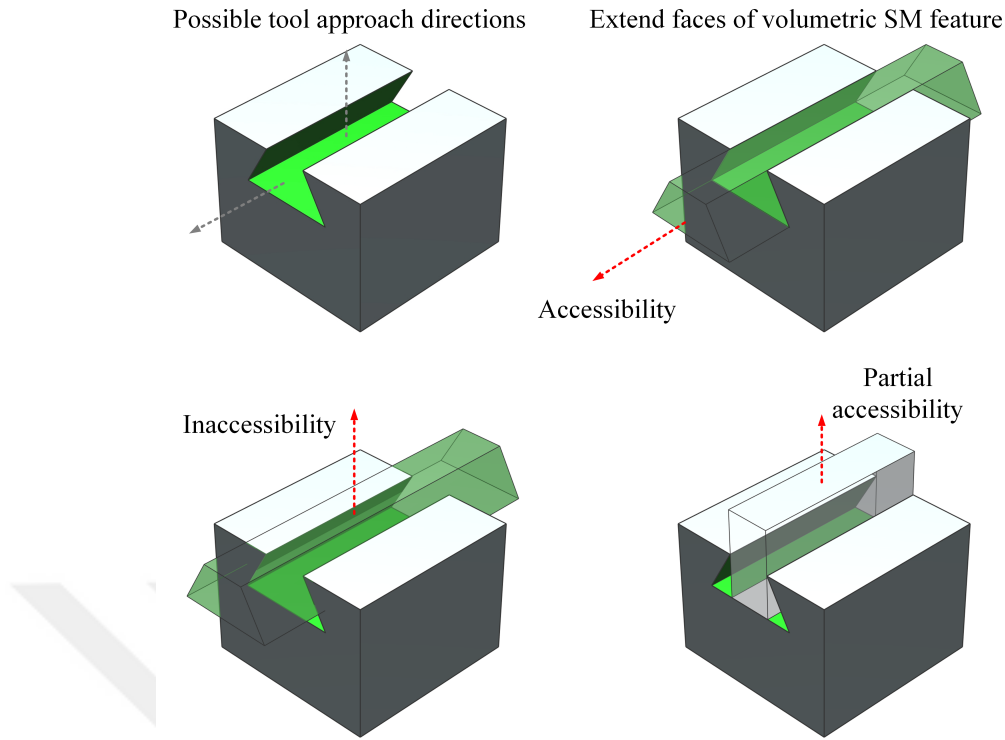


Figure 5.11: Accessibility cases

This part of the study does not involve a model for predicting the stiffness of the part subjected to machining and associated forces. Instead, a planner should manually determine possible weak regions of the sub-part that may not handle the applied forces in the current or upcoming operations.

For the AM operation, the determination of the build orientation is related to the support requirements of the layers. The applied principle is also mentioned in the previous part since the setting of the build orientation is also an essential step before the slicing for AM (refer to Figure 5.7). To summarize the aforementioned method, the normal vectors of the STL faces can be utilized to find the unsupported faces of the objects. Thus, the build orientation can be set accordingly.

In determining the build direction, it is essential to first identify the required process for the intended feature. While some features can be fabricated using both, the choice of production process should be based on the method best suited for the specific feature. Once the process is selected, the build orientation must be adjusted to match.

Figures 5.12 and 5.13 serve as detailed illustrations of this decision-making process. Figure 5.12 demonstrates the use of AM or SM to create a bridge feature, highlighting that, to avoid support structures, the feature must be oriented as shown. For SM, the feature can be directly removed from a preformed solid block without limitations. Similarly, Figure 5.13 shows how an unsupported hole can be fabricated in specific orientations with either AM or SM.

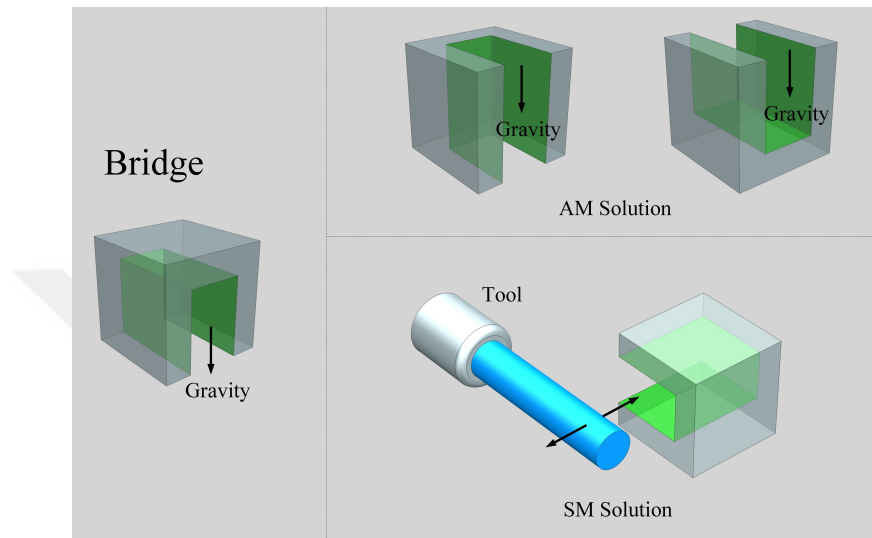


Figure 5.12: Determination of the build direction for a bridge feature

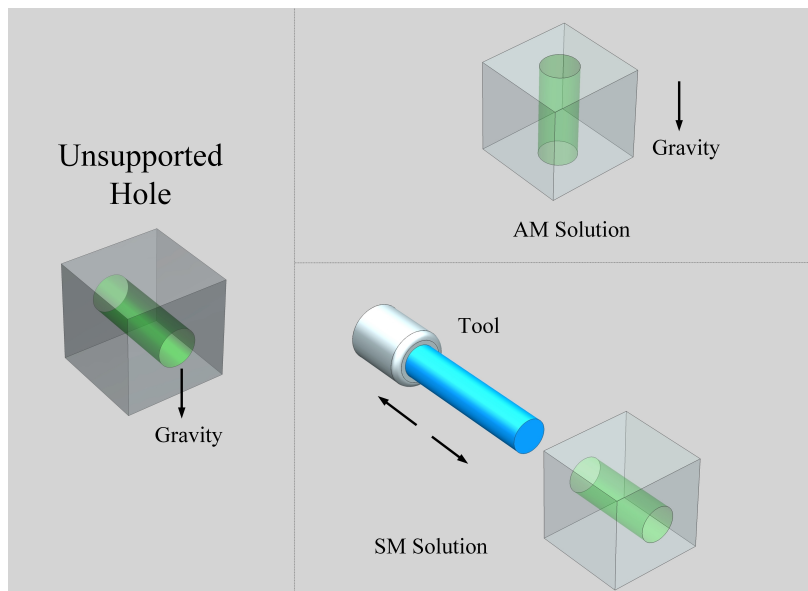


Figure 5.13: Determination of the build direction for a hole feature

5.4.2 Strategy S: Segmentation

This strategy is used to segment the object into its sub-structures such that each segment can be produced independently and the number of segments is minimized:

$$S = \bigcup_{k=1}^N S_k$$

such that

$$\bigcap_{k=1}^N S_k = \emptyset$$

where S is the infinite set containing all the points residing inside the volume of the object while $S_k \subset S (k \in \mathbb{N}_{\leq N})$ denotes the subset representing the volume of the (k^{th}) component.

The segmentation process entails dividing the main object into either its individual features (Type 1) or its suitable sub-parts (Type 2 and 3). In the former case, as these features are manufactured in succession, they compose the main object without any limitation. In the latter case, segmentation permits the partition of the object into independent sub-parts, especially when manufacturability problems are encountered. In such instances, each distinct sub-part is further segmented into its constituent features, manufactured separately, and subsequently integrated. This iterative process results in the decomposition of the part.

It is essential to determine appropriate connecting interfaces and joints among the pieces. When parts can be made in sequence using both AM and SM, the use of locaters or joints is eliminated, resulting in a monolithic manufacturing method. If segmentation requires the use of numerous sub-parts, there are several alternatives available.

- Locating pins, requiring complementary blind holes on each interface of the sub-parts;
- Keys, wedges, or inserts, necessitating complementary pockets on each interface;
- Interlocking joints, such as dovetail joints, which mandate complementary features on each joint.

The manufacturing planner has the flexibility to employ any of these joints to integrate the independently manufactured segments/parts.

For instance, when a number of identical locating pins is to be used, this operation can be described as follows. Let $H_i \subset S (i \in \mathbb{N}_{\leq N_i})$ define the infinite subset defining the volume of the i^{th} locating pin element situated at the desired position and orientation inside the part:

$$H_i(R_i, B_i) = \{h_i = R_i p + B_i : \forall p \in H\}$$

$$H(r_0, L_0) = \left\{ \begin{bmatrix} x & y & z \end{bmatrix}^T \in \mathbb{R}^{(3 \times 1)} : x^2 + y^2 \leq r_0^2 - L_0/2 \leq z \leq L_0/2 \right\}$$

where $r_0 \in R^+$ and $L_0 \in R^+$ refer to the radius- and the length of the locating pin, respectively. The rotation matrix $R_i \in [-1, 1]^{3 \times 3}$ and the bias vector $B_i \in \mathbb{R}^{3 \times 1}$ in the equation are defined for the i th pin as

$$R_i(\theta_{x,i}, \theta_{y,i}) = \begin{bmatrix} \cos \theta_{y,i} & 0 & \sin \theta_{y,i} \\ \sin \theta_{x,i} \sin \theta_{y,i} & \cos \theta_{x,i} & -\sin \theta_{y,i} \cos \theta_{y,i} \\ -\cos \theta_{x,i} \sin \theta_{y,i} & \sin \theta_{x,i} & \cos \theta_{y,i} \cos \theta_{y,i} \end{bmatrix}$$

$$B_i = \begin{bmatrix} x_{0,i} & y_{0,i} & z_{0,i} \end{bmatrix}^T$$

Here, $\theta_{x,i}, \theta_{y,i} \in R$ refer to the rotation angles (Euler) of the (i^{th}) locating pin around the principal axes X and Y respectively while $x_{0,i}, y_{0,i}, z_{0,i} \in R$ denote the Cartesian coordinates of the (i^{th}) pin's center. All in all, each pin has 5 degrees of freedom. Notice that an algorithm associated with the given strategy can automatically select the above-mentioned parameters, or it could be done manually.

When the pins are extracted from the artefact, the resultant volume can be represented as

$$S' = S - \bigcup_{i=1}^{N_i} H_i$$

Next is the segmentation of S' using linear dichotomies:

$$Q_{k,j} = \left\{ \begin{bmatrix} x & y & z \end{bmatrix}^T \in S' : z > a_{k,j}x + b_{k,j}y + c_{k,j} \right\}$$

$$S_k = \bigcap_{j=1}^{M_k} Q_{k,j}$$

Here, $a_{k,j}, b_{k,j}, c_{k,j} \in R$ refer to the plane parameters for the j^{th} dichotomy of the k^{th} component while $M_k \in N$ denotes the total number of dichotomies associated with the k^{th} component or segment. It is critical to notice that the center points of all locating pins must reside on the planes that form the boundaries among the adjacent components. A similar approach is applicable to the other alternative interfaces as well.

A segmentation, classified as Type 2 or 3, utilizing the pin interface or other alternative interfaces, is usually suitable for parts that have manufacturability constraints. Conversely, if a part can be produced seamlessly in a single operation (Type 1) without necessitating an interface, this can be achieved by identifying its features. The segmentation process, thus, should be viewed holistically, encompassing feature decomposition and manufacturability assessment together.

To further explore this concept, the full segmentation framework (including feature recognition), can be explained using two separate flowcharts. Figure 5.14 shows the process of breaking down the primary object into its individual features. The secondary flowchart in Figure 5.15 explains how the segmentation approach is utilized based on the feasibility and manufacturability of the extracted features.

To elaborate, Figure 5.14 outlines the progression from defining an object as an STL file to the process of decomposing the features it includes. Initially, corresponding surfaces are generated by merging triangular geometries defined in STL file. The local exterior features can be disregarded in the feature extraction process since they can easily be manufactured with a flawless final touch. The remaining faces are used in the feature extraction process thereafter. The object's features are identified through a procedure involving convex volume decomposition and concave volume decomposition techniques.

It is worth noting that the fundamentals of the methods referenced here will be thoroughly examined in subsequent discussions. Note also that this method, taken and adapted from [68], results in many alternative features, so the manufacturing planner should select among them according to a decision criterion.

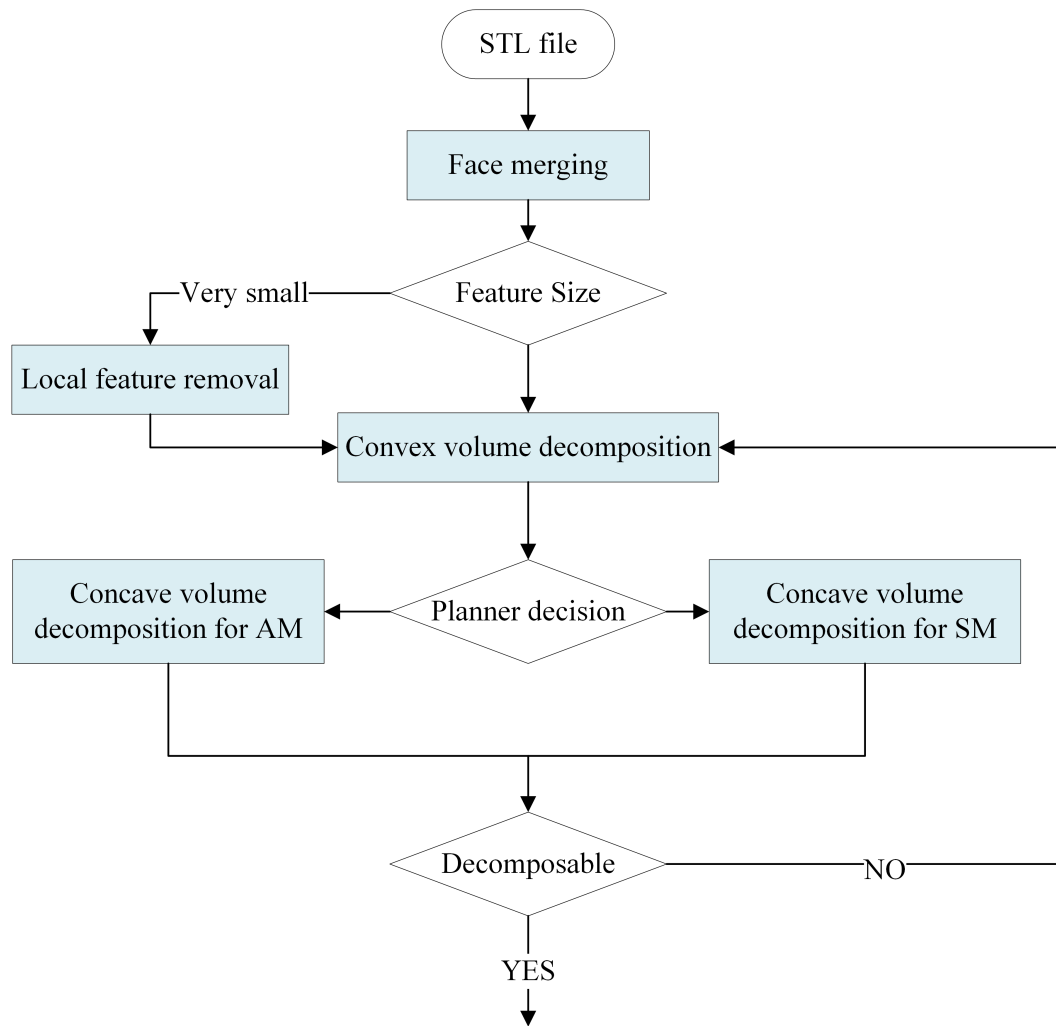


Figure 5.14: Decomposition flowchart

Following the assessment of the part's decomposition and the construction of its features, the feasibility of producing those features through specific operations must be verified. If the object is considered suitable for single-part production, the process can be finalized by employing a Type 1 connection, as illustrated in Figure 5.15. Conversely, in instances where manufacturability issues arise, the part is segmented into sub-parts to explore alternative options (i.e., Type 2 or Type 3 connection). These stages are performed for each sub-part recursively. Upon the completion of all steps, production proceeds seamlessly from start to finish in the reversed order.

Both flowcharts can be seen holistically to trace the journey of the design, represented as an STL file, through to the manufacturing steps. The details about the convex and concave decomposition methods are described in the next part.

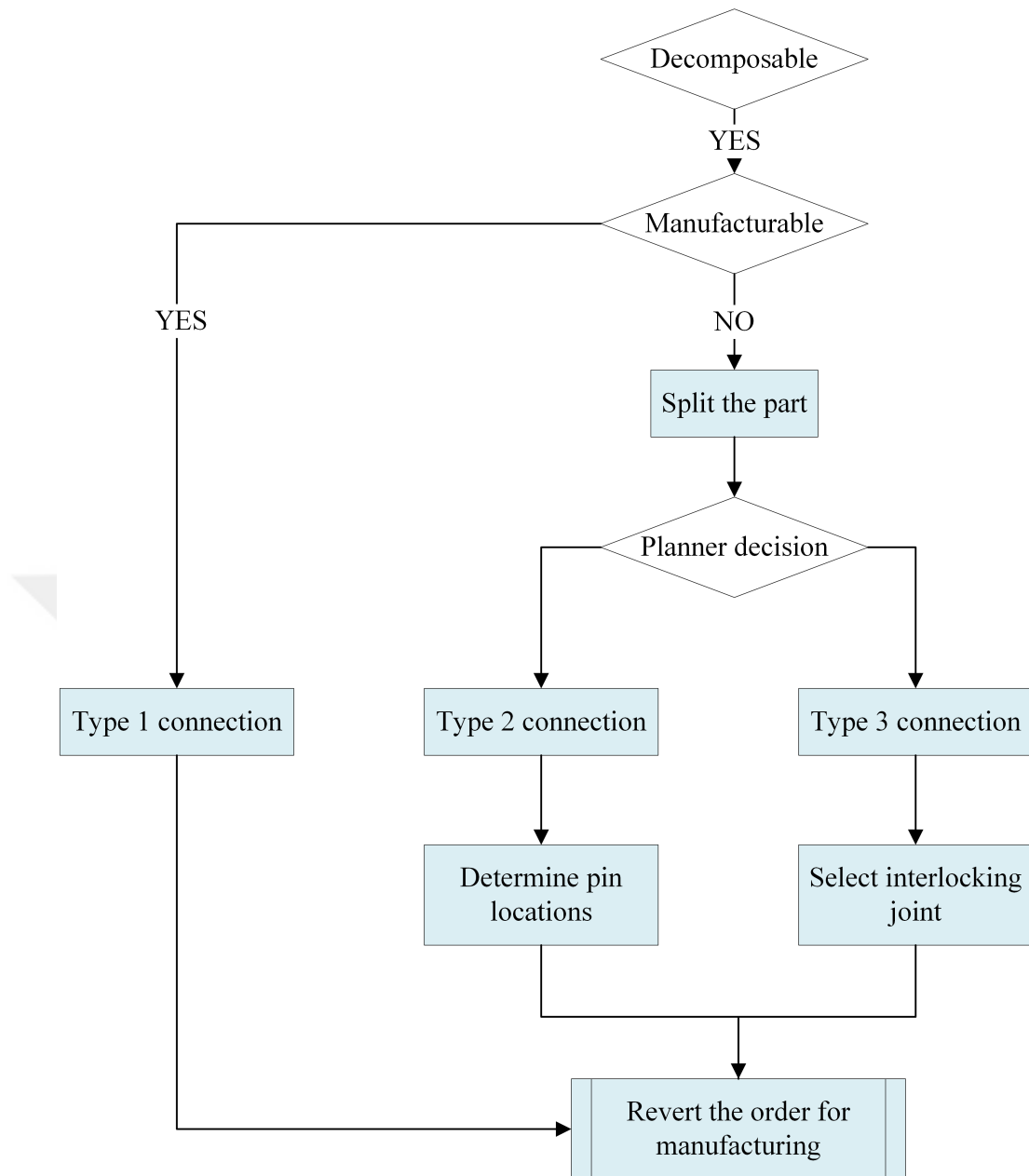


Figure 5.15: Manufacturability flowchart

5.4.2.1 Segmentation method

For the segmentation of parts (especially for prismatic ones), it is possible to apply the convex and concave decomposition strategies. Initially, it is imperative to define the fundamental terminology prior to going into the analysis of convex and concave decomposition of volumes. Understanding the characteristics of edges and loops is crucial for subsequent phases.

The classification of an edge is determined by the angle (denoted as α) formed between the external surfaces of two neighboring faces. Accordingly, the definitions can be stated as follows [63]:

An edge is identified as convex edge if $0^\circ < \alpha < 180^\circ$,

An edge is considered tangent edge if $\alpha = 180^\circ$,

An edge is classified as concave edge if $180^\circ < \alpha < 360^\circ$.

A surface with a closed contour composed entirely of concave edges is recognized as a concave loop, whereas a contour exclusively formed by convex edges is termed a convex loop. A contour that incorporates both types of edges is referred to as a hybrid loop. Additionally, these loops may be located on the surface's exterior or interior, thus being categorized as external or internal/inner loops, respectively. The terminology is summarized in the illustration provided in Figure 5.16.

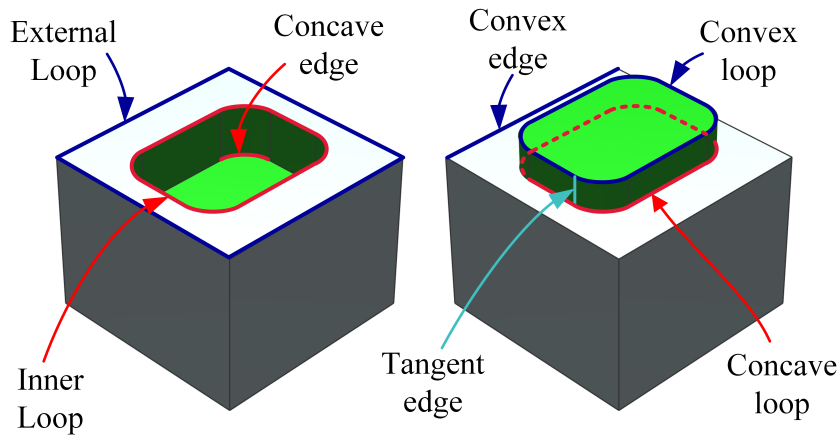


Figure 5.16: Identification of convex-concave edges and type of the loops

The use of two basic operations could be employed to collect information regarding the volumetric additive and subtractive features: (i) **convex volume decomposition** and (ii) **concave volume decomposition** [68]. The former allows us to identify volumetric SM features, while the latter may be applicable to both SM and AM features. Therefore, the next step is to specify the method of their implementation.

Convex volume decomposition process involves the following steps:

- Find and remove the convex inner loops and removable single faces on the solid,

- Identify the surface features of individual faces,
- Modify the surface features by extending them to form a closed volume, exclude the faces not contributing to the solid's closure,
- Use Boolean operations to identify the difference between the original and modified closed volume.

Thus, possible volumetric SM features can be identified quickly with the use of convex volume decomposition, as shown in Figure 5.17.

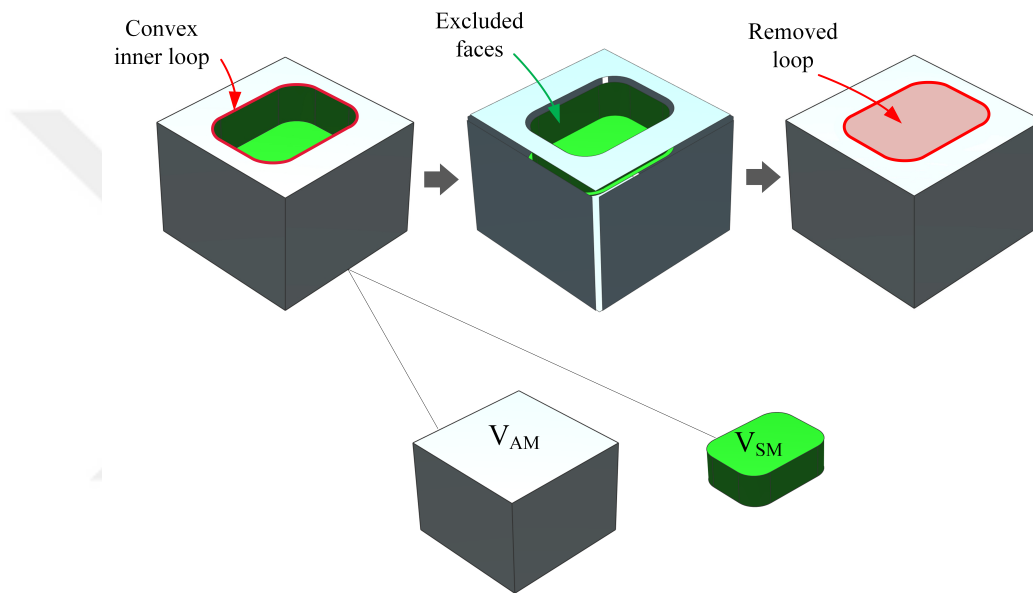


Figure 5.17: Convex volume decomposition

For the implementation of concave decomposition, on the other hand, the planner needs to determine the type of feature volume to obtain for the concave region because it might be viewed as either additive or subtractive.

The following steps constitute the concave volume decomposition procedure for obtaining possible volumetric SM features:

- Identify and remove the set of faces that share concave edges/loop,
- Extend the remaining faces that are adjacent to the removed ones to form a closed solid,

- Use Boolean operations to identify the difference between the original and modified closed volume.

This approach does not ensure feature identification for all features/geometries. The inability to always produce a closed volume following the face removal and extension implies that not all face sets are suitable for removal in some cases. A visualization of the procedure is illustrated in Figure 5.18

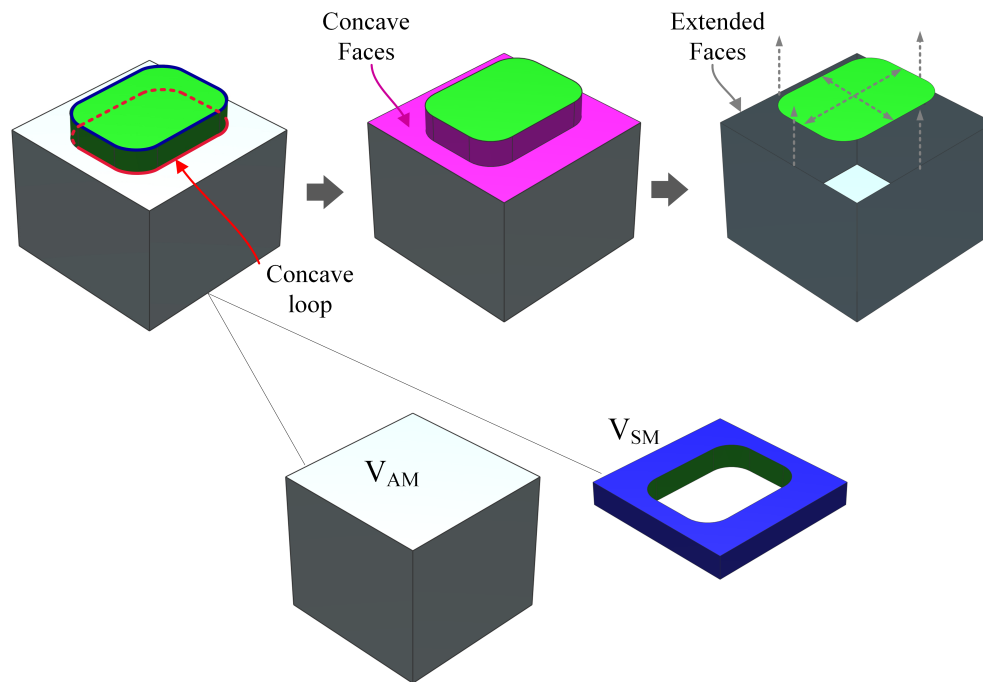


Figure 5.18: Concave volume decomposition for SM

In addition, the following is a description of how concave volume decomposition can also be utilized for recognizing volumetric AM features (see Figure 5.19):

- Identify the set of faces that share a concave loop,
- Split the part using the concave loop as separate volumetric AM features.

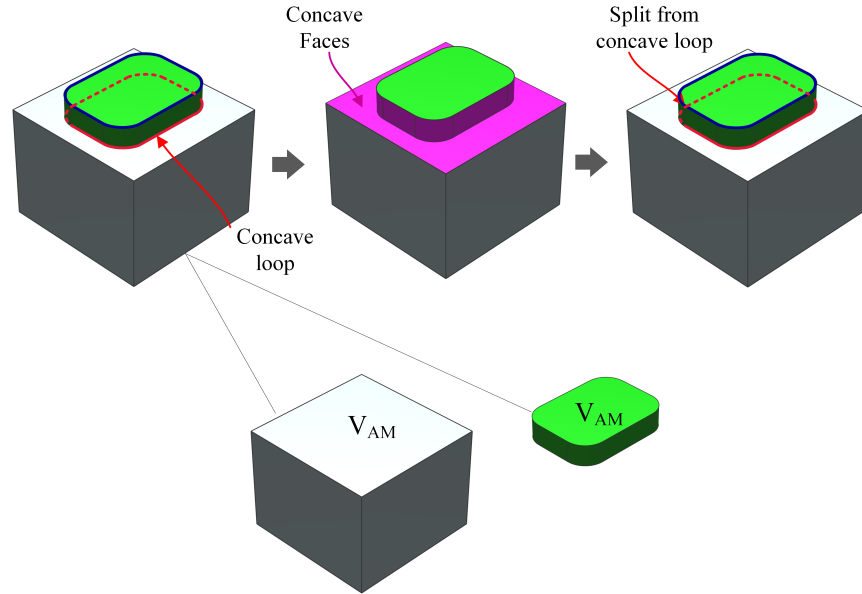


Figure 5.19: Concave volume decomposition for AM

5.4.3 Strategy A: Additive manufacturing

This process is the main method required to generate solid volumes. The sub-parts or features produced by FFF can be considered as the additive manufacturing features mentioned previously.

The volumetric AM features produced by Strategy A can be left as they are if the surface quality and dimensional accuracy satisfy the intended properties (Type 1). This implies that a surface AM feature arises at the boundary of the volumetric AM feature. Alternatively, the volumetric AM features can also serve as a base volume for volumetric SM features. The strategy needs to modify/alter/extend the fabrication plan by considering the precision geometric features (i.e., holes, slots, grooves, pockets, surfaces, etc.) to be later finished via machining (Type 2).

This strategy can build the part from scratch by employing all applicable AM strategies to obtain the desired geometry while imparting certain mechanical attributes with the utilization of (a) a nozzle with a circular orifice (fixed bead width), or (b) a nozzle with a rectangular orifice (variable bead width). This strategy can also fabricate the part over a preformed object using the two types of nozzles mentioned.

5.4.4 Strategy M: Machining

This strategy is used to machine the object to the desired accuracy and surface quality. That implies the creation of surface SM features, as a result of the union of volumetric AM and SM features. Here, the object may refer to the following volumes:

- An existing rectangular block or a cylinder made from the material of interest, i.e., usually thermoplastic polymers,
- A preformed object or segment whose shape is suitable to obtain the desired solid geometry via machining.

The preformed object can be produced via the additive manufacturing method (or, namely, Strategy A). This object can be a reincarnated object or a recycled product. The preformed object can also be roughly produced by attaching a number of standard blocks with predetermined sizes, similar to building a rough shape via LEGO blocks, which accelerates the machining process.

Here, special emphasis has to be made to minimize the number of tools to be used in the process.

5.4.5 Strategy C: Combined processing

The methods described thus far encompass all necessary steps for planning a hybrid AM/SM process. Furthermore, various combinations can emerge by mixing these steps, applicable to parts regardless of their features.

An important observation is that while producing typical prismatic parts with features, one can utilize the aforementioned operations. However, some operations are also applicable to parts without clear features, such as organic parts. These options involve combining the previously mentioned operations. For instance, in manufacturing a bunny object, operations can be directly applied to layers without needing to identify features. This involves conducting AM every few layers of the bunny, followed by a subsequent SM process at regular intervals. By repeating this process, the final product can be completed.

Therefore, the combined method aims to produce the part via a series of interweaved AM- and SM operations (i.e., Strategy A and Strategy M). This requires the fabrication of a number of layers at a time with FFF. Then, the desired portions of those slices (i.e., interfaces, boundaries, precision surfaces, etc.) can be machined. Repeating these steps sequentially will eventually lead to the manufacturing of the object.

Note that since the AM operations are expected to follow the SM ones that create chips to clutter the fabrication site, the chip evacuation requirement needs to be addressed at this point for the success of the proposed strategy.

Overall, the strategies outlined in this section encompass all available options that could be used on the developed hybrid production platform. By synergizing these strategies, a comprehensive planning methodology can be formulated. However, automating this process remains a subject for further investigation. Figure 5.20 illustrates the primary framework for integrating all strategies and explains their potential implementation.

5.5 Tool Path

After all the groundwork has been performed in the previous steps of production, tool path planning comes to carry out the fabrication. By controlling the motion and synchronization of the tools along the determined trajectories, this phase is essential for turning production plans into real products. In AM, the nozzle's detailed paths through each layer are specified, whereas in SM, the cutting tool's trajectory and orientation are calculated.

Conventionally, machine tools utilize standardized formats like G-code to specify tool paths, ensuring consistency and ease of implementation across different devices. The developed platform has also been capable of working with G-codes. However, it employs an alternative approach to speed up communication and enhance motion resolution, deviating from the traditional G-code methodology.

Accordingly, the machine's movements, consequential from slicing and planning processes, are programmed into ".txt" files. These files, stored on an SD card, are format-

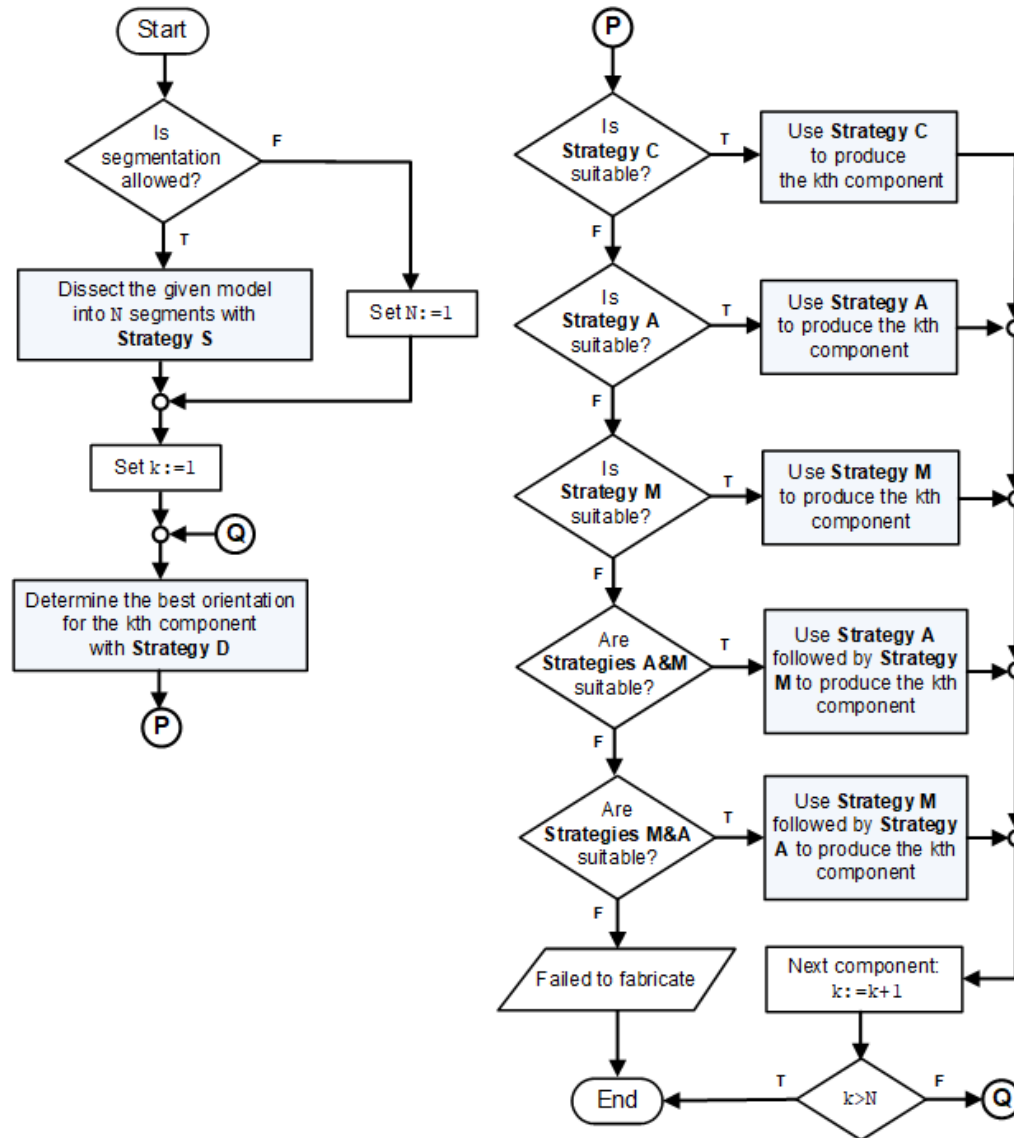


Figure 5.20: The flowchart of the manufacturing strategies

ted for compatibility with the machine’s embedded software. The system periodically retrieves these tool paths from the SD card through a communication protocol (RS-485), facilitating their transfer to the manufacturing platform. This setup is designed with integrated functionalities to interpret and execute the production codes effectively, ensuring the system’s ability to carry out its intended operations proficiently.

Prior to executing the tool path on the machine, simulating the tool path is crucial, especially due to the 5-axis capability of the manufacturing platform, to prevent any unintended collisions.

Figure 5.21 presents the pipeline of the tool path planning process for an organic part, detailing the steps from design representation and the associated tool paths for individual operations to the virtual simulation. This part is designed to be manufactured in Strategy C, where layers are initially printed and subsequently milled at specific intervals. Thus, the tool paths of the extrusion (FFF) process and the machining process are combined at certain levels.

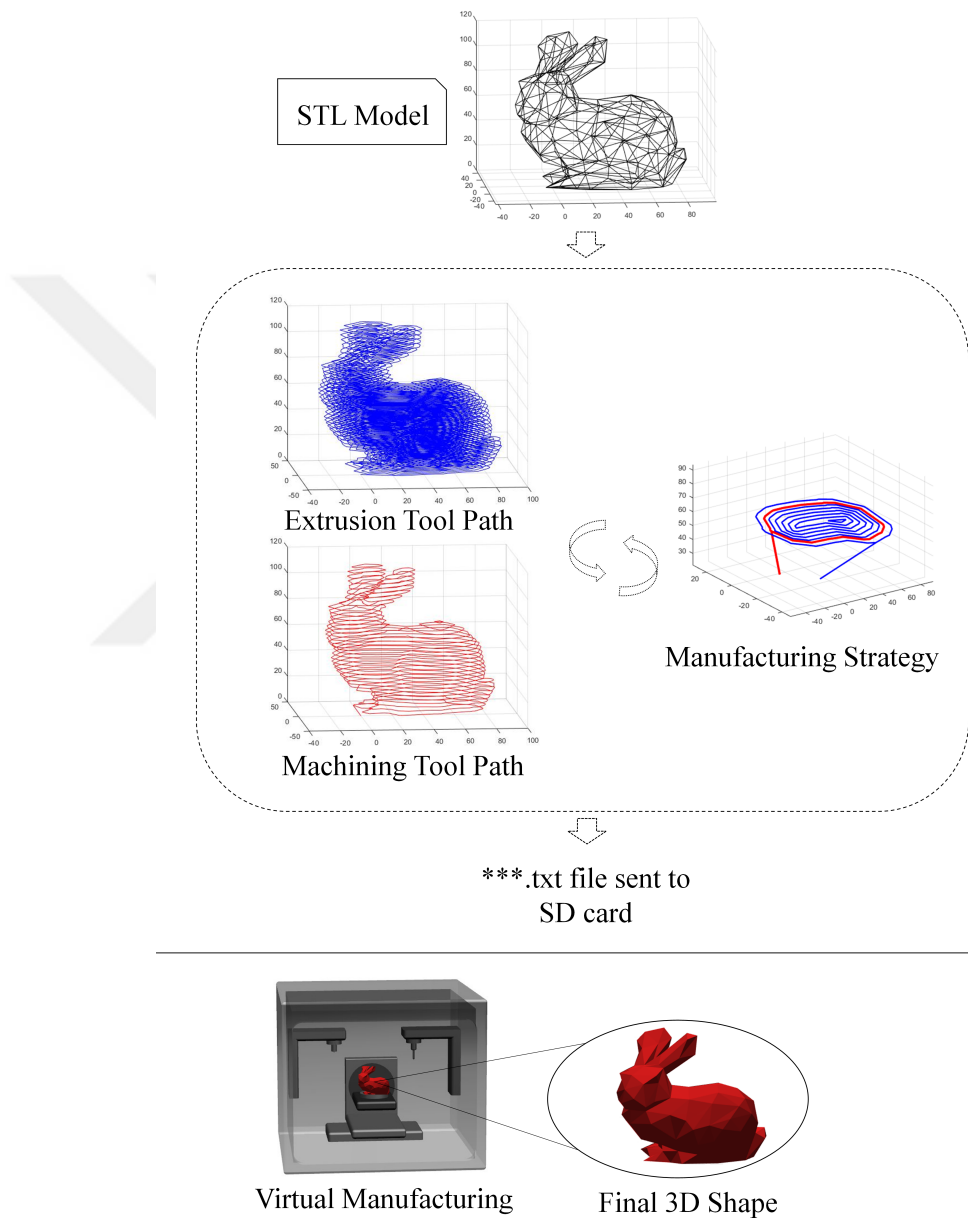


Figure 5.21: The tool path generation and simulation



CHAPTER 6

VIRTUAL MANUFACTURING SCENARIOS AND PRODUCTION TRIALS FOR HYBRID ADDITIVE MANUFACTURING

This chapter focuses on implementing the hybrid-AM methods and strategies outlined earlier, exploring the cases using virtual process plans for sample parts and practical experiments as well. At first, various scenarios are simulated through virtual manufacturing cases to evaluate the practicality of the chosen manufacturing method. Following this, the hybrid manufacturing platform was used, enabling the production of sample parts. The processes, outcomes, and methodology of these experiments will be clearly explained. We will demonstrate the benefits of combining additive and subtractive manufacturing by analyzing individual scenarios. The primary goal is to validate the process plans and suggest improvements for broader use.

6.1 Virtual test cases

This section will discuss how some of the previously listed strategies can be adopted through sample cases. The first example part includes an object that incorporates dovetail joint geometry. An STL model of the part was initially built for the fabrication planning of this object. The solid model was initially represented with triangles, and later surfaces were formed by merging these triangles, as described in Figure 5.8. Subsequently, features of the object are identified and analyzed using these surfaces.

Figure 6.1 displays the volume and surfaces of the solid model being discussed. While all designed surfaces are theoretically expected to be of high quality, those surfaces that will be paired with others in an assembly and require exceptional production are highlighted in green.

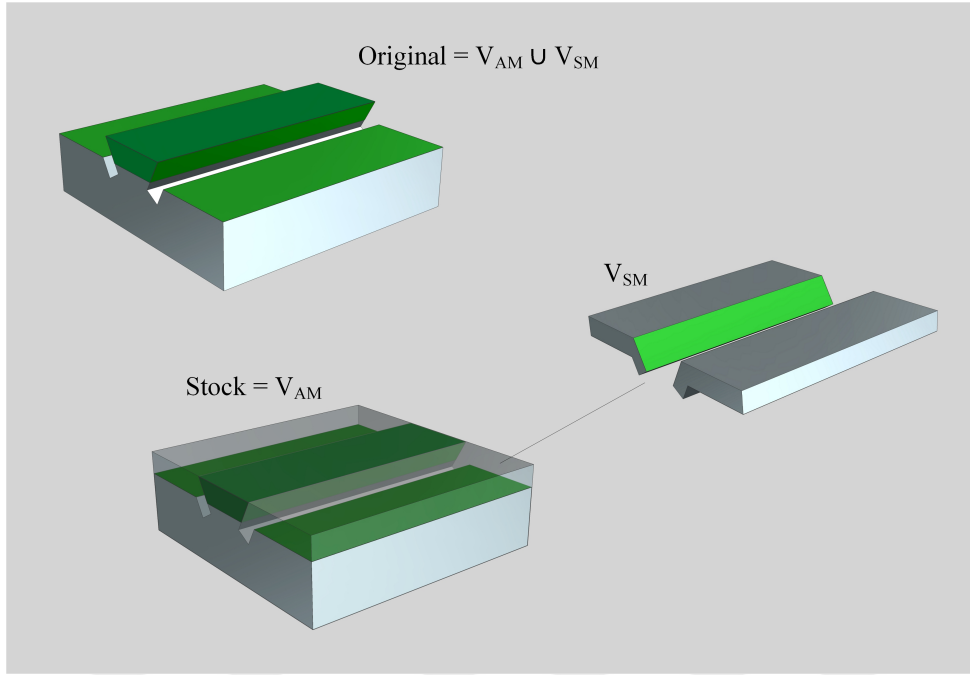


Figure 6.1: Sample virtual part - Scenario 1

The creation of concave, sharp corners is considered a constraint due to the assumption that only the endmill will be used throughout the finishing process. To prevent this issue, the regions around the surfaces that can serve as dovetail joints are designed to be machined using an endmill. The component depicted as the original part in Figure 6.1 contains channels in the dovetail joint area for this specific purpose. Thanks to these channels, the object is both decomposable and manufacturable and can be machined just with an endmill, of course in 5-axis in the specified build orientation. The build orientation can be simply selected by the user, where the existing orientation is the most reasonable choice (skeletonization is unnecessary for this part).

The designed object can be represented as a combination of many design features in different scenarios. In this regard, the very first scenario that comes to mind is expressing the original part as a combination of a volumetric AM feature within its own bounding box of the part and a volumetric SM feature integrated with this feature. Combining the volumetric AM feature (referred to as Stock) with a corresponding volumetric SM feature will provide surface SM features. The features present in the first scenario can be extracted using the concave volume decomposition method outlined in the preceding section.

Another possible scenario during production is the ability to generate the object's volume from the beginning. The part can be built utilizing several volumetric AM features in the initial phase. The final surfaces can be constructed by combining the volumetric SM feature with the generated volume. The part with the given design features can be fabricated in the order shown in Figures 6.2: (1) Combining 4 volumetric AM features or a portion of stock material, (2) adding another volumetric AM feature (i.e., a boss), (3) adding a volumetric SM feature to the previous state, and (4) union of them results in the desired product.

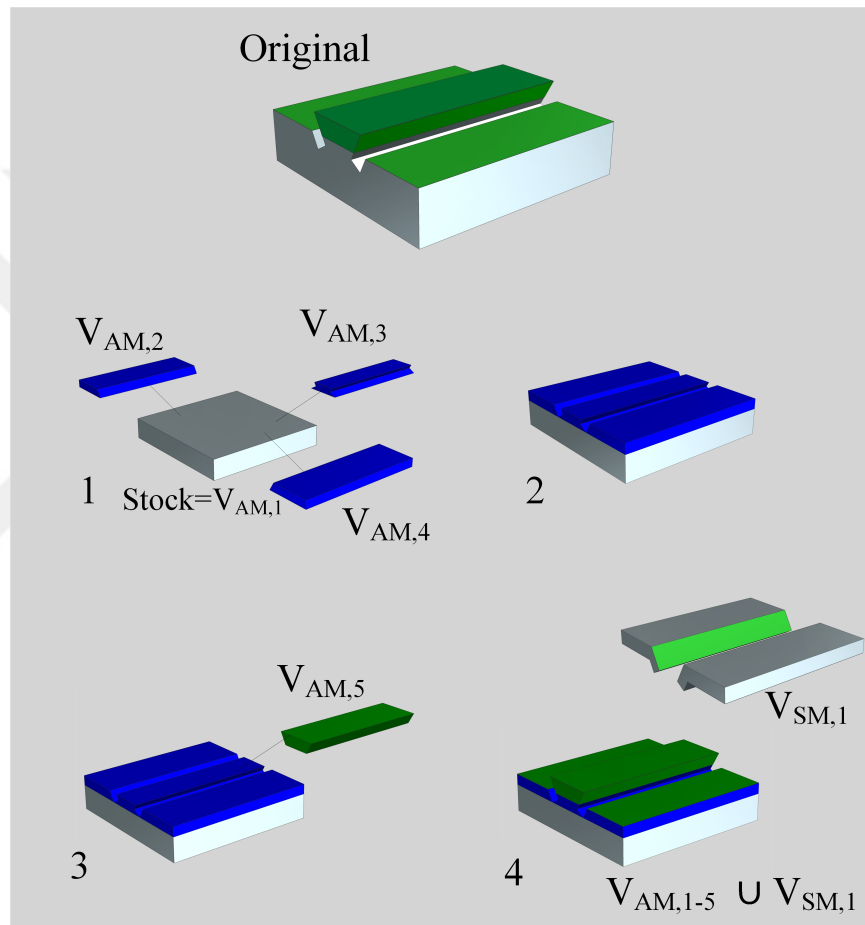


Figure 6.2: Sample virtual part - Scenario 2

To develop comprehensive hybrid process plans in both scenarios, further decision-making is required, relying on knowledge of particular processes and other crucial factors. Having a knowledge base or manual process planner is essential for making informed decisions. Table 6.1 and 6.2 display the outcomes of the initial work in creating a list of rules that defines the constraints and knowledge about the procedures.

Table 6.1: Summary of useful knowledge and constraints about the processes

Aspect	AM Knowledge	SM Knowledge
Accessibility	Requires nozzle access for material deposition	Demands tool access for material removal
Dimensional Accuracy	Utilize strategies to enhance layer adhesion and resolution	Utilize precision tooling and techniques for exact dimensions
Feature Size	Minimum feature size is constrained by nozzle size, bead size, or layer height	Minimum feature size constrained by tool geometry and accessibility, and due to cutting forces
Feature Spacing	Minimum spacing ensures adequate distance between AM features to maintain structural integrity	Chip removal rule optimizes SM feature sequencing for efficient chip evacuation
Unsupported Volume	Limit overhangs to maintain structural integrity between layers	Ensure minimal tool deflection for accuracy via appropriate support and stiffness
Priority	Loop rule encourages processing in loops rather than layer by layer to save time	Compound SM rule dictates machining the base feature before secondary features, considering depth and size for efficient removal
Tool Efficiency	Favor larger nozzles for rough builds where detail is less critical	Aim for minimal passes to expedite the manufacturing process
Build Speed Optimization	Set build direction ensuring the minimum dimension along its z-axis	Omit finishing details on features that will undergo further rough processing

Each scenario demonstrates a different application of the rules established in the knowledge base, focusing on optimizing the manufacturing process through a hybrid use of AM and SM. Scenario 1 emphasizes achieving high surface quality for critical features, whereas Scenario 2 focuses on a balanced approach combining AM for rough builds and SM for finishing, and it highlights material conservation. The decision among these scenarios would ultimately depend on the specific requirements for surface quality, material efficiency, and manufacturing time constraints.

Table 6.2: General rule of thumbs about the hybrid process planning

Aspect	Generic Knowledge
Accessibility	Child-parent rule: the manufacture of parent before the child to favor accessibility
Dimensional Accuracy	-
Feature Size	Presence Rule: Every volumetric operation should contribute to at least one volumetric or surface feature, ensuring no action wasted
Feature Spacing	Dimensional Limits: Avoiding efforts on unachievable dimensions
Unsupported Volume	Design features to avoid reliance on unsupported geometries
Priority	Feature Size Rule: Prioritize larger non-intersecting features at the same hierarchical level for SM due to chip, heat, and force considerations
Tool Efficiency	Tool Type Rule: Sequence feature creation by using the same tool type at the same hierarchical level to minimize tool changes
Build Speed Optimization	Segment Minimization: Reduce the number of segmented parts

The first scenario uses stock material and utilizes SM for high-quality surface finishing on critical (green) surfaces. It aligns with the dimensional accuracy rule for achieving high surface quality through SM and the accessibility rule by ensuring tool access for finishing the inclined surfaces. The second scenario begins with a smaller stock or construction from zero, which emphasizes efficient use of material. The planner may also look into using bigger nozzles for rough builds under the build speed optimization rule in AM. Still, the use of stock material may greatly speed up the overall production in the first scenario. In both scenarios, it adds an SM feature that maintains the accuracy of dimensions and quality for important surfaces.

Likewise, let us demonstrate how the production scenario may vary when considering an object sharing a geometry analogous to the initial part. The new shape includes concave, sharp edges, as shown in Figure 6.3. The features of this structure can be retrieved in a way similar to the first case, leading to a decomposable part once more. But, the existence of concave, sharp edges make the part not manufacturable.

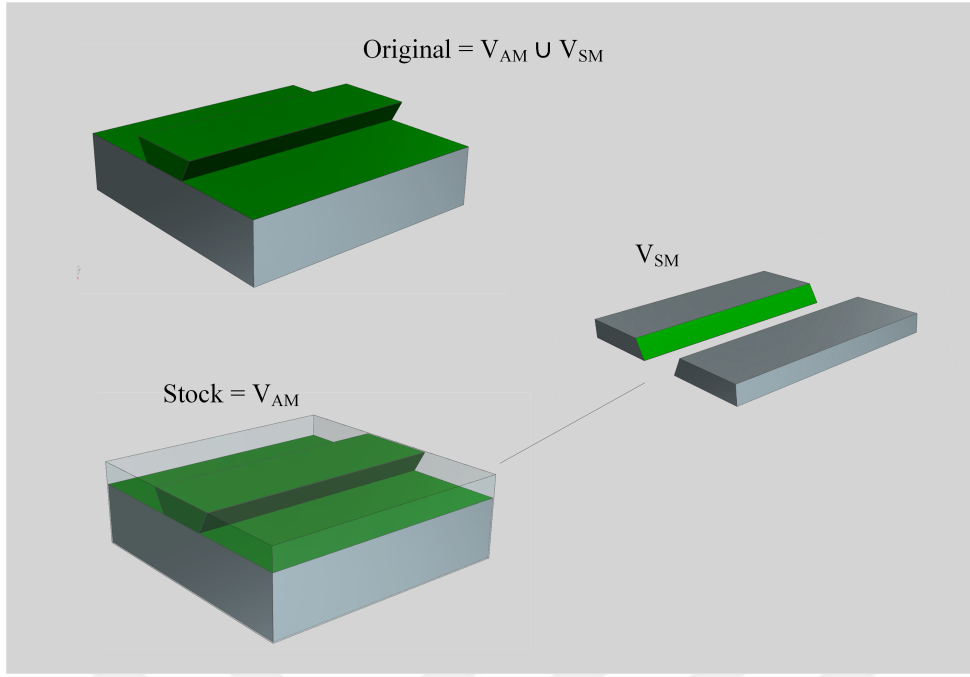


Figure 6.3: Modified sample part

To manufacture this component, it is essential to segment it into sub-parts. Through the employment of the mentioned framework, such as Strategy S, Type 2, we can split the component into two distinct sub-parts, subsequently reunifying them through pin-based connections (see Figure 6.4). A sub-part may undergo fabrication as a union of a volumetric AM feature with a volumetric SM feature. Similarly, the second sub-part is to be manufactured in a similar way. Pin connection interfaces shall be integrated into both sub-parts, at appropriate locations. Consequently, upon the separate production and eventual consolidation of these sub-parts, the primary object can be realized.

Let us also investigate two build orientation alternatives for another basic part shown in Figures 6.5 and 6.6. The features of the parts can be segmented using concave and convex volume decomposition. The possible regions of the parts that need support structures are identified by red color in the figures. Those regions could be found using the method mentioned in the previous chapter. Moreover, the skeleton of the part is a straight 3D curve that suggests two different candidates for building directions. One possible build direction is along the (long) axial direction of the object, whereas the second one suggests one of the hexagonal faces becomes the base face.

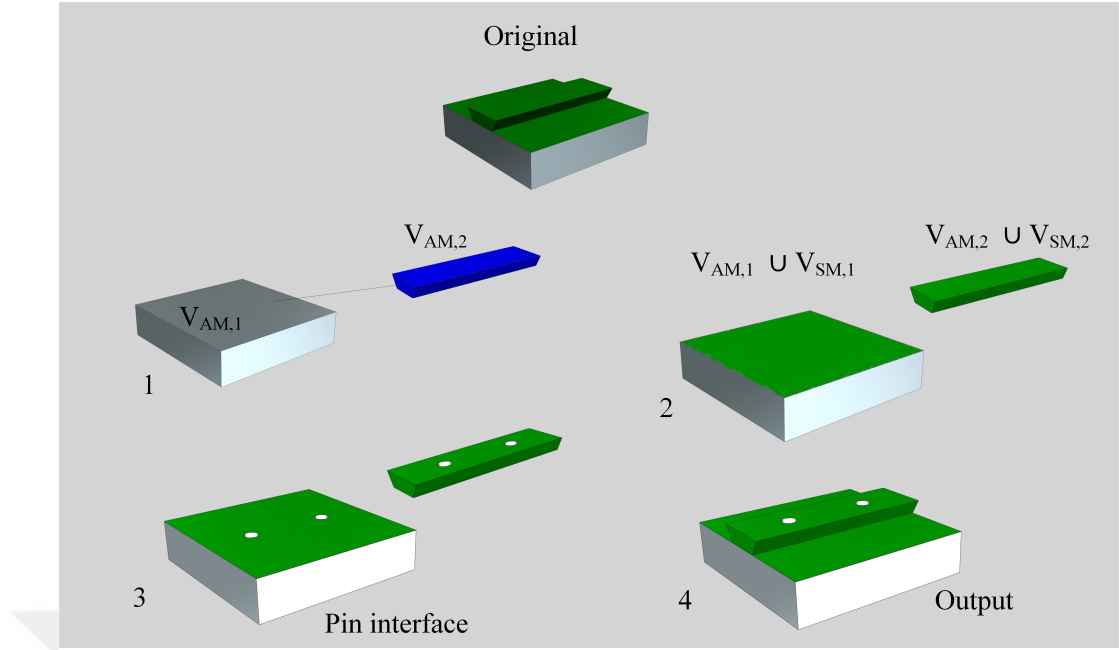


Figure 6.4: Segmentation of the modified sample part

If the part is to be built on one of its hexagonal faces, there is much more need for support structures. Also, the volumetric SM features cannot be fabricated due to the finite radius of the tool with the current build direction. Instead, the orientation of the tool should be matched to carry out side milling on the triangular surfaces. This indicates the base of the endmill will create the green surface. But, still, the support structure requirement cannot be eliminated due to the step where the volumetric AM feature is fabricated.

In another scenario, the build direction is now upright while the volumetric AM feature is being constructed. The upper area of the red triangle needs support structures. But, if we segmented the two volumetric AM features as illustrated, an intermediate SM operation could be conducted on the rough surfaces of the previous state of the part. Afterwards, the two small volumetric AM features can be fabricated along another axis perpendicular to the previous build direction. At the end, another volumetric SM feature can be used to finish the surfaces that become rough due to the latest material deposition. Thus, the second option suggests a better solution.

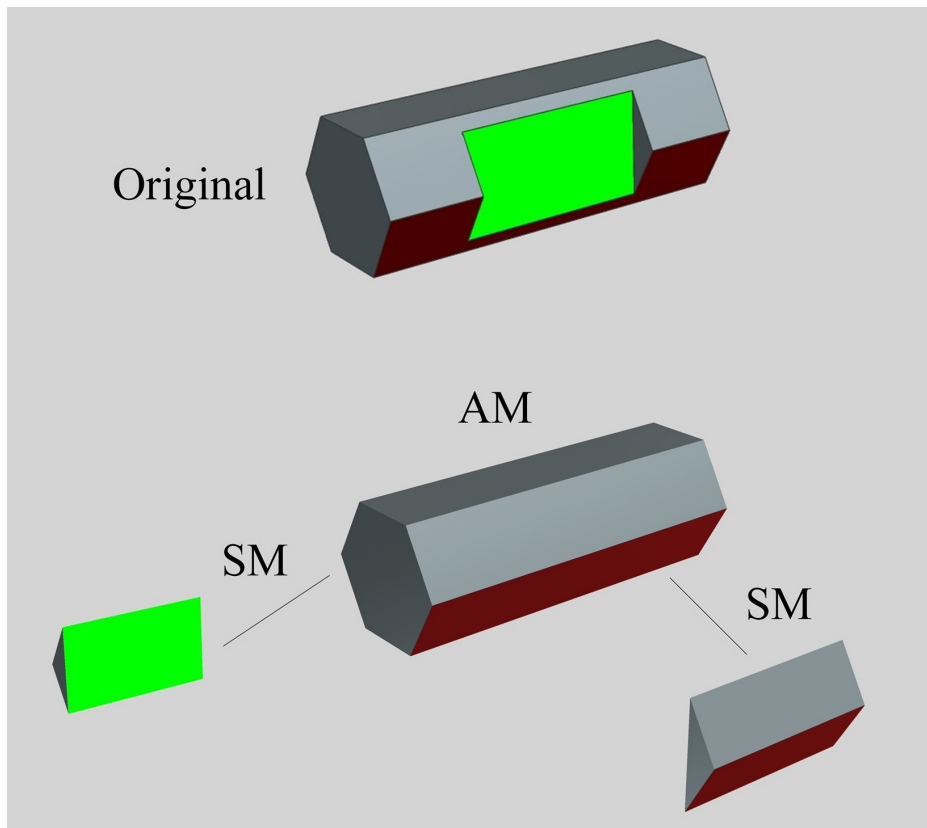


Figure 6.5: Initial built orientation of a virtual manufacturing case

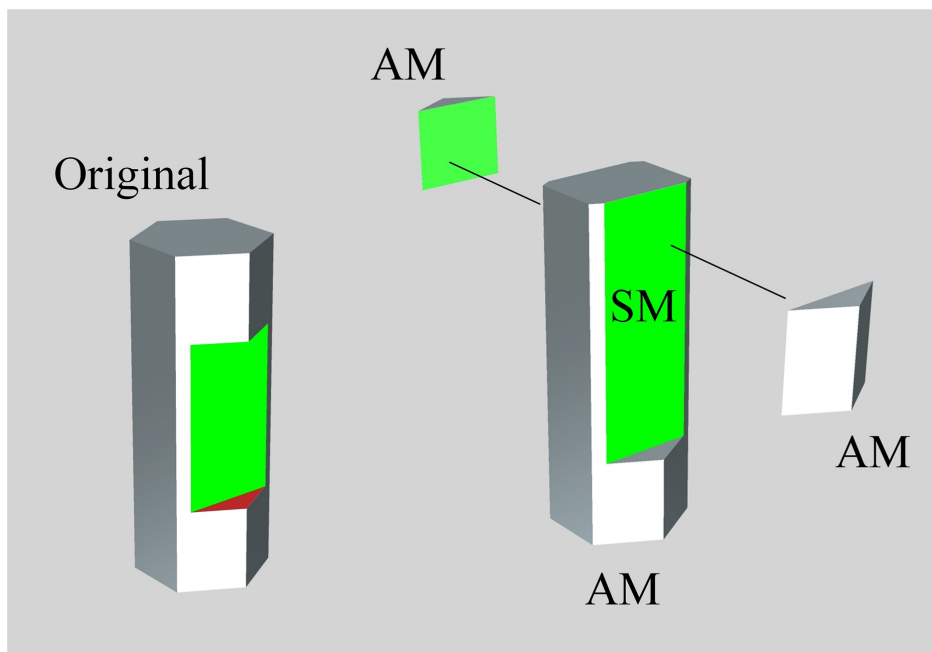


Figure 6.6: An alternative built orientation of a virtual manufacturing case

6.2 Experiments on Hybro

In this section, we explore the production trials conducted on a hybrid AM-capable machine, where sample parts were manufactured. The key highlights of these produced samples include the capability to achieve sharp corners, eliminate the staircase effect, and attain high dimensional accuracy, facilitated by SM. Several of these capabilities are revealed in Figure 6.7.

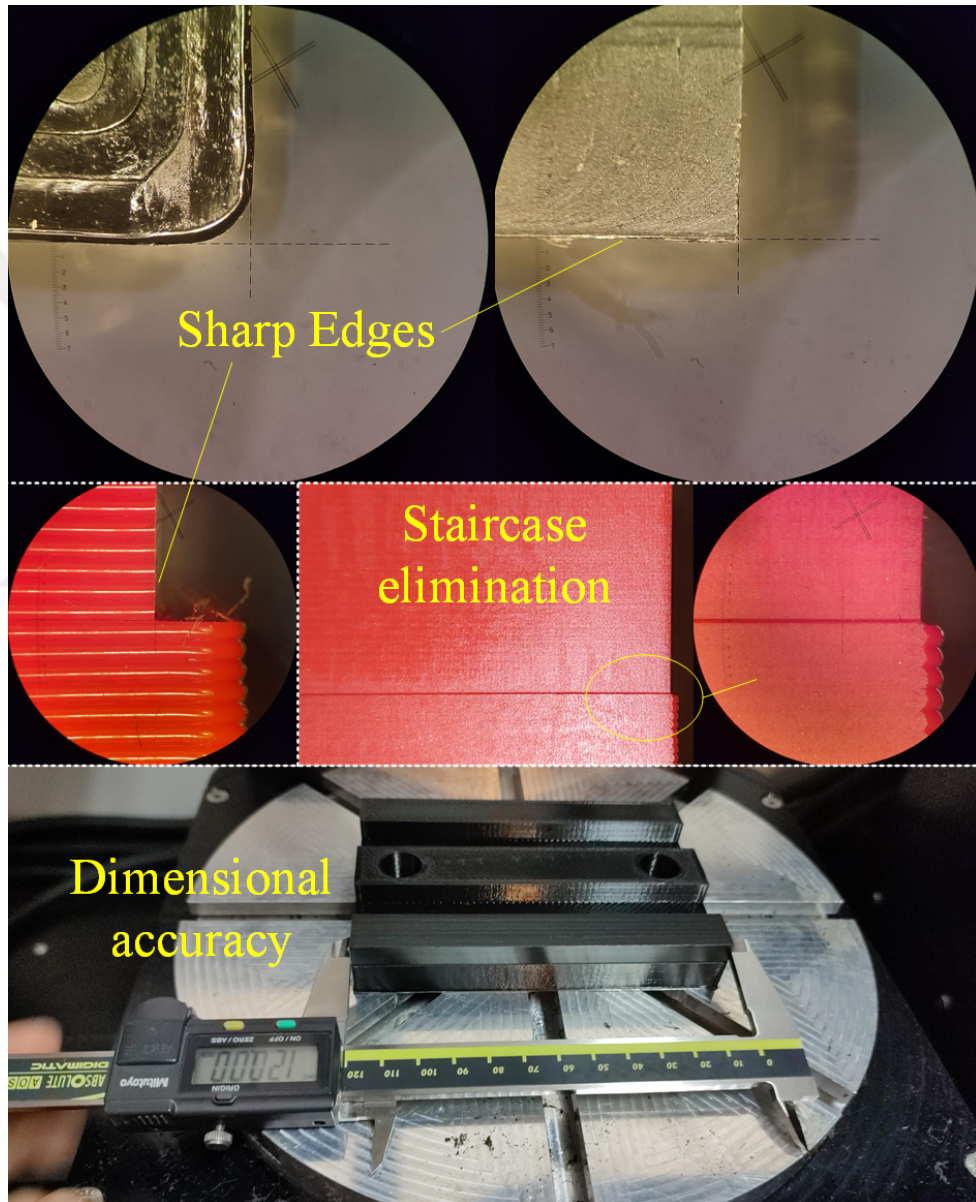


Figure 6.7: Application of SM on thermoplastic objects and its influence

Sample Part 1: Gear

This part demonstrates the steps involved in producing a sample component using hybrid additive manufacturing. The object is to be manufactured using fused filament fabrication followed by milling.

It is well known that FFF produces undesirable results in terms of the surface roughness of components supposed to work together in assemblies. A gear is chosen to be manufactured because it would serve as a particularly difficult case study. The selected sample part is shown in Figure 6.8.

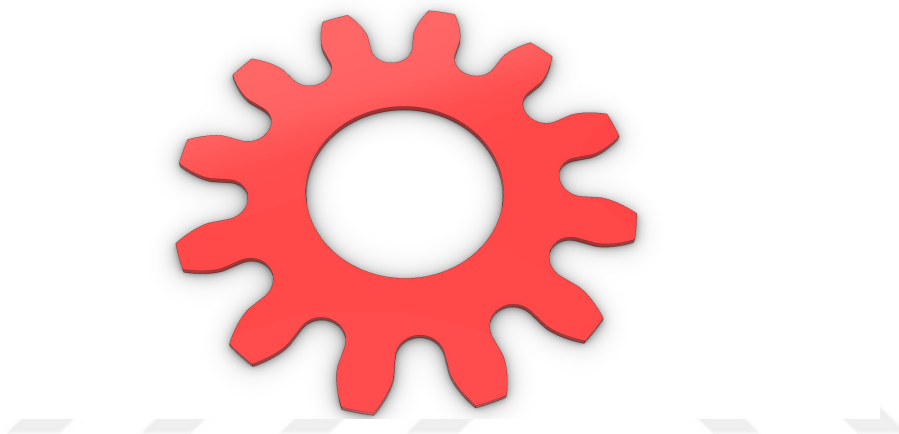


Figure 6.8: A sample part: Gear

For the production of this object, there are many steps required for the FFF process and the milling process.

For the FFF process, (i) reading the solid model represented by the STL file, (ii) creating layers of the model with the developed slicing software, (iii) filling in each layer using an appropriate infill pattern, and (iv) creating the toolpath by stacking the sequential layers are the essential steps.

Additionally, while determining the trajectory for the FFF process, the nozzle diameter and internal pattern must be decided by the user in advance. In Figure 6.9, an example trajectory is shown on a single layer.

The tool path for the milling operation should similarly be determined by the outer contour lines of the layers produced by slicing the STL model. Moreover, necessary

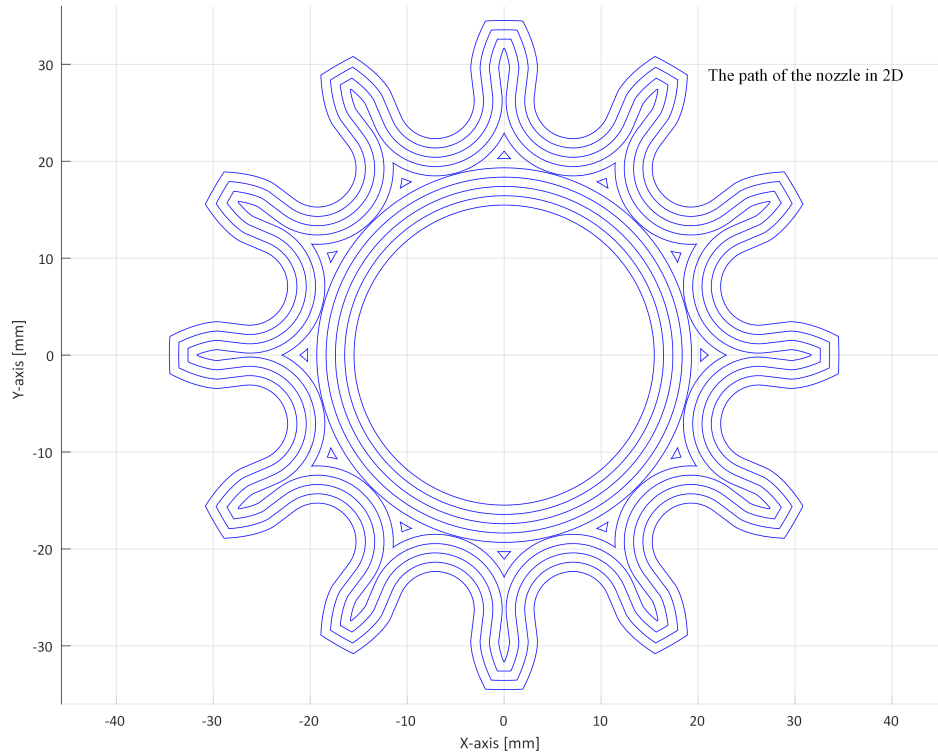


Figure 6.9: The trajectory for the FFF process on a single layer

adjustments like tool radius compensation must be made before the milling stage.

After individual trajectories have been determined separately for FFF and milling, they need to be combined, taking into account a manufacturing strategy C. In this context, since first FFF and then milling strategy is implemented, these trajectories are added successively.

Figure 6.10 depicts the combined additive and subtractive manufacturing paths needed to make the sample gear.

The important thing to note here is that the corresponding coordinate transformations are made by means of homogeneous transformation matrices during the conversion of operations to machine commands. Because the extrusion head and the milling head are equipped on separate axes.

Since fully coupled processes are essential for hybrid additive process planning, the Gear example utilizes both AM and SM tools and the related axes in the process. This

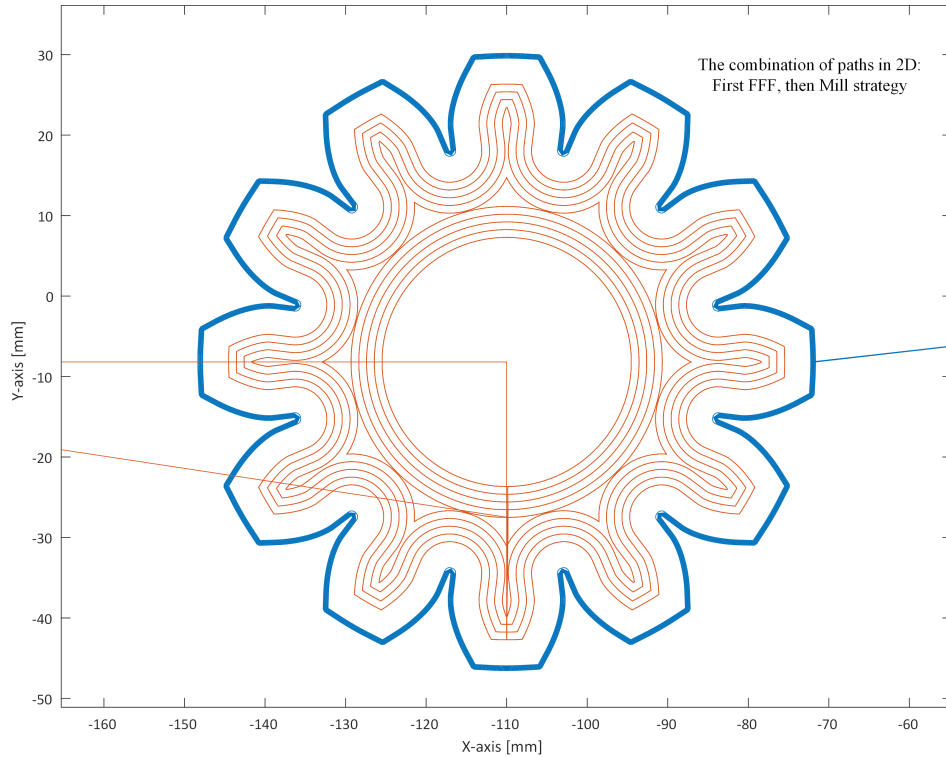


Figure 6.10: The combined trajectories of FFF and milling on a single layer

implies in-process switching between the two processes.

The aforementioned strategy needs to generate an oversized product to build the near-net shape of the object. Then, the unnecessary part of the FFF object is removed by milling thereafter. The Strategy C is utilized here.

The amount of oversizing is frequently applied to the size of a single bead, which varies in the range between 0.5 mm and 1 mm. Under these conditions, the positioning accuracy of the hybrid manufacturing platform enables cutting the workpiece from the inside of the walls or shells. The second important consideration is to make the part as dense as possible so as to avoid further problems if the high void density regions are reached. When the amount of overlapping in the AM process increases, the layers as well as the walls fuse strongly.

After determining the tool path required for production, the remaining parameters related to the extrusion are selected. The production table is prepared for production using adhesive tape. PLA was chosen as the filament material. Since this material can provide good adhesion by penetrating the adhesive tape, no fixturing is required during the milling phase of production.

Figure 6.11 illustrates the additive and subtractive stages of the fabrication of the gear example on Hybro.

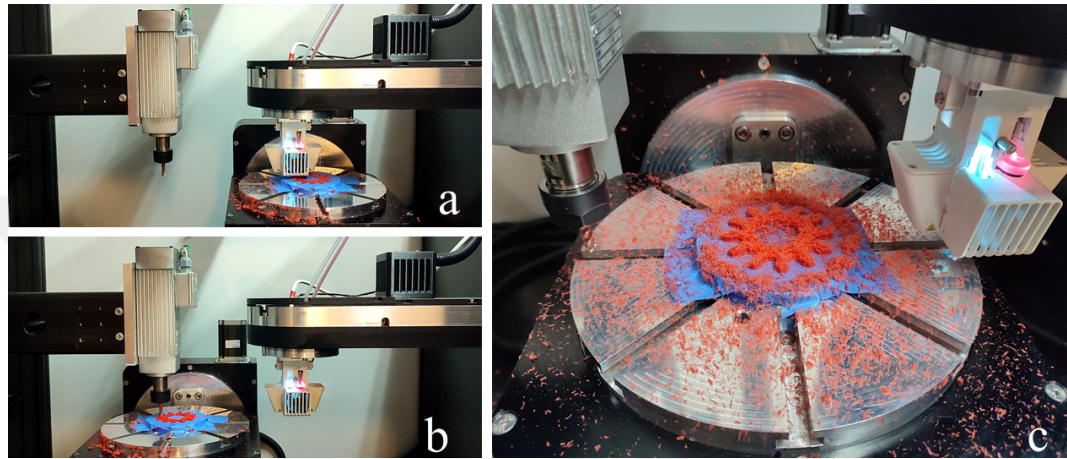


Figure 6.11: An integrated hybrid production of the gear, (a) AM stage of the production, (b) SM stage of the production, (c) The end of the process

Sample Part 2: Rail and Carriage

The production of another sample part involves milling over existing 3D-printed thermoplastic objects to yield the final product with improved surface finish and dimensional accuracy.

Since it is not a fully integrated application and the entire process is not applied at once; it is necessary to fix the intermediate part to the table of the platform. Conventional vise clamping methods, or fixing by bolting through deliberately created holes on the part can be considered as alternative options. Consequently, it is inevitable that there will be errors related to the fixing of the part. Therefore, the issue of compensating for fixing errors should also be considered, especially for avoiding the milling of high void-density regions.

Rail and carriage assembly is a group of two parts, as shown in Figure 6.12. Both parts are produced with a greater size to compensate for the subsequent material removal, taking into account the anticipated sources of errors. Both of these parts can be connected to the table through the holes on them.

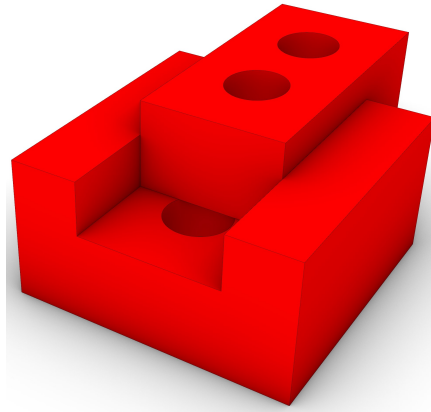


Figure 6.12: Linear rail and carriage

Due to the inherent inaccuracies in the dimensions as well as the natural stair-steps, it was difficult for two identical components that have not been treated to fit together properly. On the other hand, this can be solved by the application of SM. The reference surfaces of both parts were then milled in separate processes after being attached to Hybro. Thus, flat surfaces are created by processing the corner areas that should normally be circular. In this way, it is ensured that the parts can be combined harmoniously with each other since the stair-stepping effect is eliminated. The resulting parts are shown in Figure 6.13.

Sample Part 3: Column with many holes

Another sample item is manufactured and mounted on Hybro, where a number of holes are drilled on each of the object's four distinct surfaces. Producing the original part with the holes without making use of support structures is a challenging task. On the other hand, the holes on the object can be drilled using the multi-axis capability of the workstation with an accurate size (see Figure 6.14).

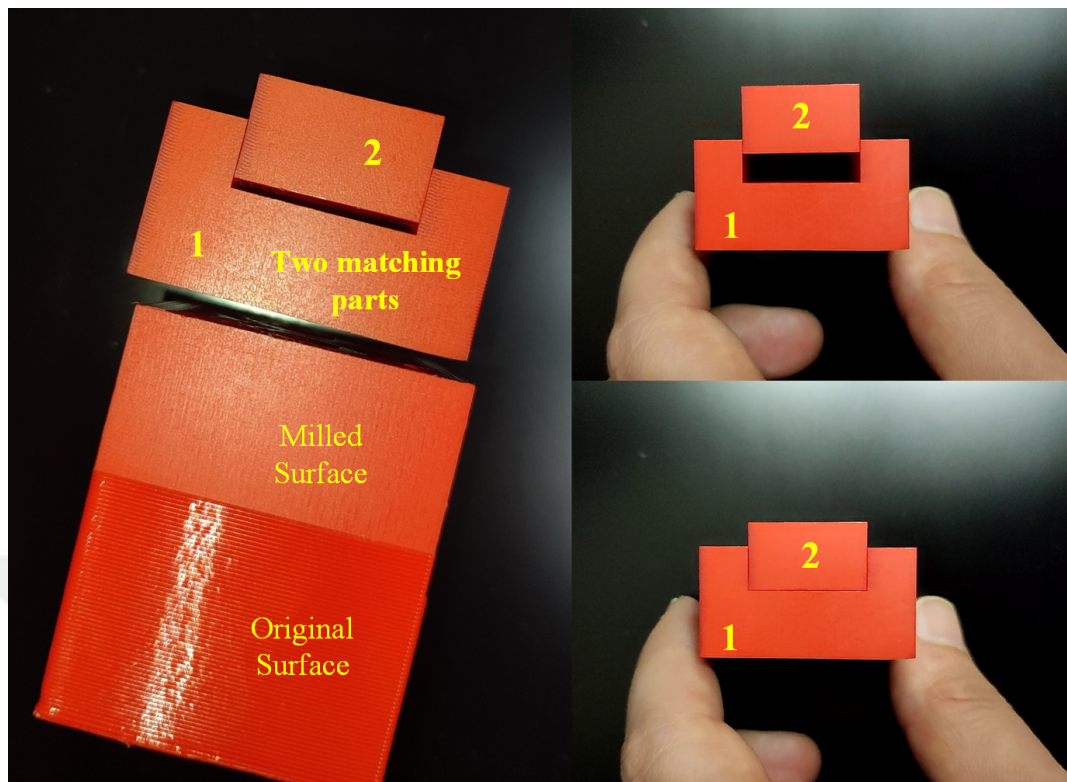


Figure 6.13: Fabricated linear rail and carriage

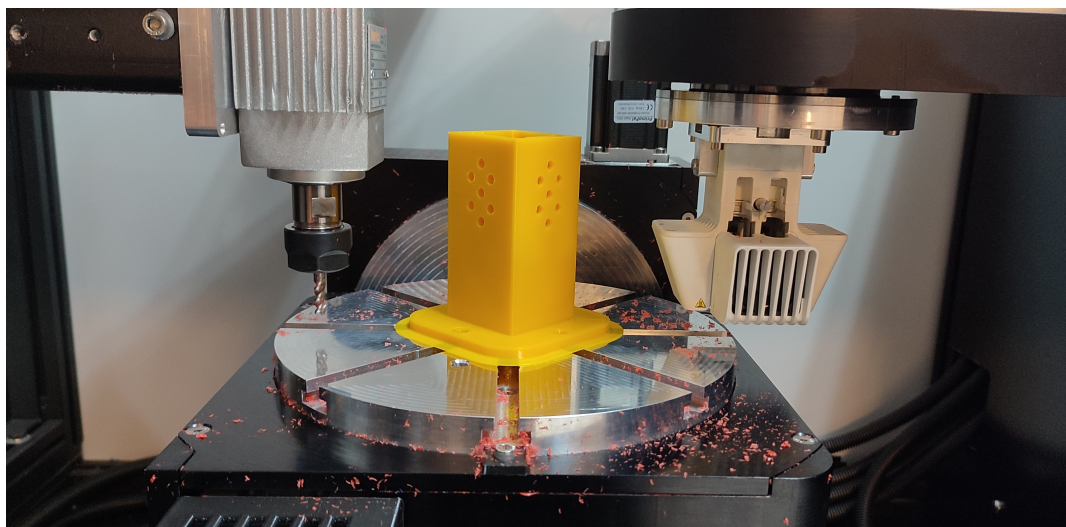


Figure 6.14: Drilling of several holes on a column in multi-axis

Sample Part 4: Dovetail parts

Another example demonstrates the precise machining of surfaces intended as dovetail joints, aiming to eliminate the stair-stepping effect using multi-axis milling. This particular sample part can be produced using an endmill due to channel-shaped regions in the design (similar to the first virtual manufacturing sample). To create the inclined side surfaces, milling was adjusted by changing the tool approach direction and angle. Other surfaces are easily processed with the endmill. This process results in smooth surfaces, as illustrated in Figure 6.15.

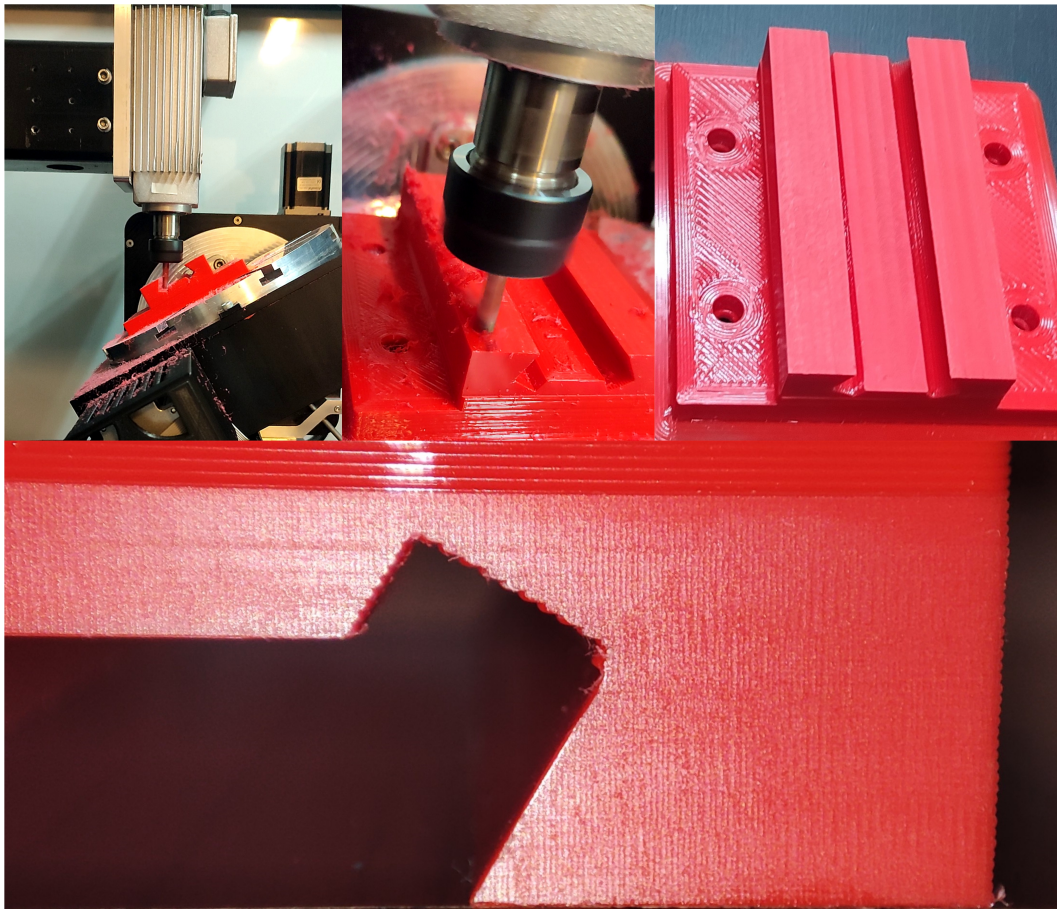


Figure 6.15: Finishing of the surfaces of a part for dovetail joint

Producing such a part without channels becomes unattainable, as the endmill cannot access sharp concave edge areas (as observed in the modified virtual sample part). In such scenarios, segmentation of the part into distinct sub-parts becomes feasible, using strategy S - Type 2. Moreover, employing different tools presents itself as a viable solution. As mentioned earlier, volumetric SM features are essentially generated by

the tool volume following a specific trajectory via sweeping, enabling these parts producible using a dovetail tool. As illustrated in Figure 6.16, dovetail assembly can be directly produced using a suitable tool, avoiding the need for multi-axis operations. Thus, planners should consider not only strategies but also alternative facilities for optimal outcomes.

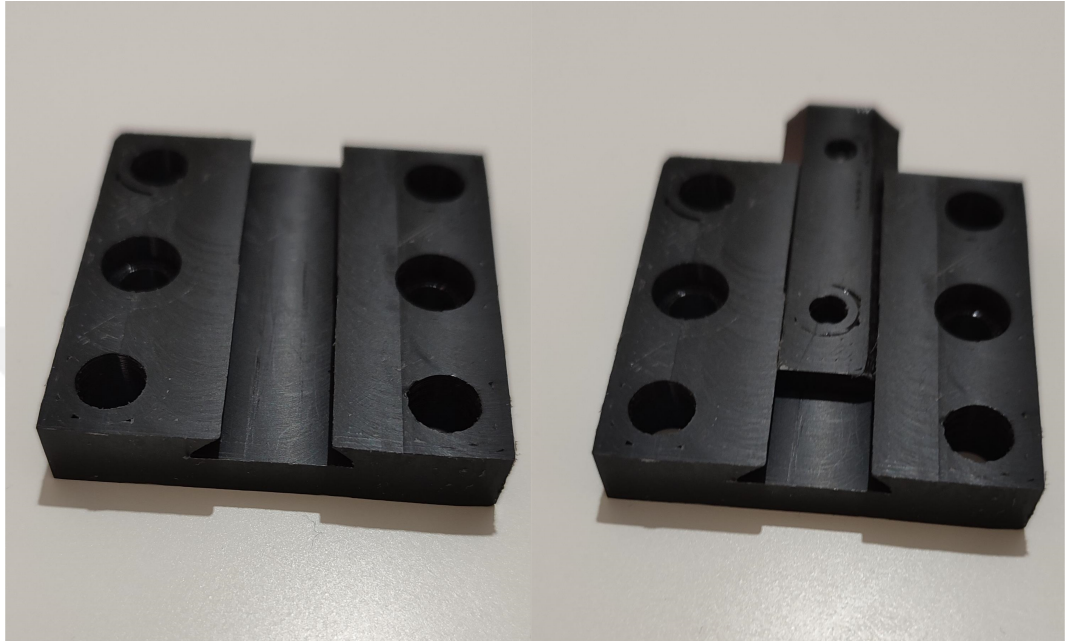


Figure 6.16: Dovetail assembly



CHAPTER 7

CONCLUSION AND FUTURE WORK

Conventional manufacturing methods have historically served as the core of industrial manufacturing. Milling, molding, sheet metal forming, and other similar operations are examples of typical traditional manufacturing processes utilized in mass production. Because of their expertise in the production of large quantities at low cost, these methods have the capability to satisfy the needs of the industry.

The introduction of AM has recently revolutionized modern manufacturing by changing the way products are shaped. Its unusual method of manufacturing objects, immediately creating them layer-by-layer from digital designs, transformed today's production industry. In contrast to traditional methods of production, modern manufacturers may quickly put their creative ideas to the test while benefiting from remarkable flexibility in product design and development. Nowadays, AM makes it feasible to create intricate geometries that were previously considered unfeasible.

Metals have long been the preferred material for engineering projects due to their durability, strength, and structural performance. On the other hand, with the rise of AM, production is now accessible to home users, and the list of usable materials has expanded well beyond metals. As a result, many people are interested in it because of its impact on customized manufacturing and prototyping.

Nevertheless, there are typically quality issues with the products made with FFF, such as apparent stairsteps, surface imperfections, and size and shape variations. These issues stem from the fact that the process and parts are built layer by layer, which makes them difficult to resolve. Other contributing difficulties include part build resolution, inaccurate machinery, and thermal dynamics that cause shrinkage and distortion.

A promising approach to tackling these problems is through secondary processing, referred to as hybrid additive manufacturing. Hybrid manufacturing is a relatively new area that combines FFF with subtractive processes in a way that could increase design freedom, quality, and efficiency. A workable alternative is milling, which refines surfaces to provide flat, smooth surfaces and the required dimensions after treating/processing FFF products as near-net-shaped items.

Incorporating FFF and precision subtractive milling into a hybrid additive manufacturing framework is the primary goal of this dissertation. This research seeks to overcome the constraints of FFF and show a realistic way to improve output quality by robustly merging additive and subtractive processes. This goal is accomplished by doing research into individual processes such as implementing multi-axis FFF and optimizing machining settings for thermoplastic parts, along with exploring a new hybrid process planning framework thereafter.

While additive manufacturing in its simplest form allows nearly net-shape fabrication with practically no material waste, the precision and surface quality it produces might not be up to high standards for certain uses. Increasing the resolution alone is not enough to achieve the precision required in FFF. In comparison to FFF, hybrid AM would eliminate the AM staircase effect while simultaneously increasing product quality, dimensional accuracy, and surface finish. Post-processing the AM-produced surfaces using various methods after production could enhance part quality; nevertheless, processing freedom is significantly reduced owing to the inaccessible surfaces after production. In contrast, in-process approaches, such as merging AM and SM in an integrated manner, provide high levels of flexibility but present an entirely novel challenge to process planners.

Particularly for general complex geometries, the current state of the art is still far from complete automation for hybrid additive manufacturing. The enhanced flexibility of combining AM and SM techniques means that there are endless possibilities to think about when planning a hybrid manufacturing process. It is quite challenging to propose a generic approach for hybrid process planning that works for all kinds of objects. So far, no prior method has tackled this issue in the context of general process planning scenarios; therefore, the researchers focus on specific subgroups of

the problem and examine them in case-based scenarios.

Given the multi-axis degree of freedom offered by the developed hybrid platform, many potential applications emerge, including flat or curved print layers, five-axis simultaneous fabrication strategies, support-free multi-axis FFF, and object remanufacturing. However, comprehensively covering all these aspects within this study is not feasible. Therefore, the study's focus shifts towards investigating the groundwork for regular and multi-axis support-free FFF, as well as optimizing milling for thermoplastic parts produced by these methods. The primary objective is to establish a hybrid process planning framework for integrating AM and SM processes.

Throughout the first part of the dissertation, we explored regular 3-axis FFF processes and multi-axis support-free FFF, along with investigating the optimal application of SM on thermoplastic parts. The subsequent chapters propose a framework for integrating AM and SM processes, outlining essential steps in hybrid manufacturing process planning. Additionally, sample procedures are provided to aid manufacturing planners in formulating alternative process plans, along with a list of implementation strategies. The final part of the study includes sample plans for simple parts, as well as illustrations of the results of trial experiments carried out on the developed platform.

The study outlines the fundamental components of a typical hybrid manufacturing process framework, comprising the following key steps: (i) designing and analyzing part geometry to identify manufacturability challenges, (ii) selecting part orientation, which influences both functional and visual characteristics of the final product, (iii) conducting the slicing process for the AM stage of production, (iv) selecting manufacturing approaches and their sequence to balance quality, processing time, and other performance factors, and (v) planning the tool trajectories. Throughout the dissertation, methodologies are developed concerning these critical steps of hybrid additive manufacturing.

During the development of process plans, a significant aspect involves analyzing the parts to be produced, heavily influenced by the feature-based method due to the following reason. Traditional part design heavily leans on SM, even for parts intended for AM. Process planning, according to conventional SM understanding, is all about figuring out the best order in which to do various machining operations (such as

milling, drilling, and turning) in order to create various features (such as slots, holes, pockets, and bosses) that go into the fabrication of the product. Here, AM could play a role in the process plan by generating the 3D solid volume, which is to be shaped to corresponding surfaces ultimately by machining. While doing this, a feature-based approach can provide a good method to break the problem down into smaller ones. Key challenges include recognizing interacting/intersecting design features and selecting the most appropriate feature for a region where multiple interpretations between additive and subtractive features are possible. Hence, planners must consider various decision criteria, such as preferring SM for small-sized hole features or minimizing process switches to reduce overall manufacturing time. Therefore, creating a knowledge base about all sub-components of hybrid process planning is essential.

In future studies, the aim is to establish a comprehensive knowledge base and contribute to the literature on hybrid process planning by leveraging this information to automate the strategies outlined in this thesis.

Among these strategies, Strategy C, which involves periodic SM processing on layers produced with AM, will probably gain widespread adoption in the future. Particularly effective for parts highly amenable to AM, such as organic components, this approach offers advantages in terms of surface roughness and dimensional accuracy.

Another pivotal strategy with significant potential for innovation is Strategy S, which involves segmenting parts and connecting them using pins or other interfaces. This method is well-suited for hybrid applications, as SM enables the creation of interfaces like pin holes or dovetail geometry. Segmented parts can be produced to be dimensionally compatible with each other, facilitating repeatable production processes.

As clarified in one part of the study, the proficient implementation of SM processes facilitates the production of parts with exceptional dimensional accuracy and surface roughness reaching below the micron level. Such precision holds promise for accelerating the industrialization and advancement of additive manufacturing.

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Curriculum Vitae - M.Uğur Dilberoglu

Ankara, Turkey

EDUCATION

Middle East Technical University, Ankara, Turkey

PhD, Mechanical Engineering, 2015-2024

Middle East Technical University, Ankara, Turkey

M.Sc., Mechanical Engineering, 2012-2015

Middle East Technical University, Ankara, Turkey

B.Sc., Mechanical Engineering, 2007-2012

EXPERIENCE

Turkish Aerospace Industries, Ankara, Turkey

Space Systems, Opto-mechanical Design Engineer, 2023-Current

Middle East Technical University, Ankara, Turkey

Research Assistant, 2012-2022

Türk Traktör, Ankara, Turkey

Intern, Quality Assurance Engineer, July-August 2011

Pi Makina, Ankara, Turkey

Intern, Manufacturing Engineer, June-July 2010

PUBLICATION

Gharehpapagh, B., **Dilberoglu, U.M.**, Yaman, U., & Dolen, M. (2024). A rotary extrusion system with a rectangular-orifice nozzle: toward adaptive resolution in material extrusion additive manufacturing. *Journal of Intelligent Manufacturing*, 1-17. URL: <https://doi.org/10.1007/s10845-023-02288-w>

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with Rectangular Orifice. Additive Manufacturing, 78, 103873. URL: <https://doi.org/10.1016/j.addma.2023.103873>

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Yaman, U., Dolen, M., **Dilberoglu, U.M.**, Gharehpapagh, B.(2017). A New Method for Generating Image Projections in DLP-type 3D Printer Systems, Procedia Manufacturing, Volume 11, 490-500, URL: <https://doi.org/10.1016/j.promfg.2017.07.142>.

Production Method with Molten Filament on a Powder Bed, EP3820674B1

Bir Toz Yatağı Üzerinde Eriyik Filament ile Üretim Yöntemi, TR2018 14270 B

PROJECTS

Developing a Hybrid and Intelligent Manufacturing System Using Additive and Machining Methods (117M429), TÜBİTAK 1001 project, Engineering Research Support Group, Project Start/End Dates: 11/1/17 - 8/1/20.

INTERESTS

Additive Manufacturing, Computational Geometry, Robotics

CAD/CAM, Dynamics and Control Systems, Automotive Engineering

SOFTWARE SKILLS

Computer Programming: MATLAB, Python.

CAD/CAE: Siemens NX, SOLIDWORKS, Rhinoceros/Grasshopper, Simulink

LINGUISTIC SKILLS

English, Turkish.