Design, Dimensioning, and Optimization of a fixture for CNC machining a pump housing part

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Abstract

This thesis focuses on developing and prototyping a fixture for CNC machining a housing part from a bent axis piston pump manufactured by ABER Hydraulics. The research encompasses an analysis of the previous defective fixture, followed by the design, structural calculation, manufacturing, and testing of a new fixture system.

The thesis begins with a comprehensive analysis of the processes and components involved in manufacturing a pump housing. A detailed study of fixturing systems is conducted to understand the fundamental principles and devices necessary for fixture design.

Based on the acquired knowledge, an analysis of the defective fixture is performed to identify the errors and their root causes. Subsequently, a new fixture is developed, applying the principles of literature review to ensure a successful outcome. Additionally, a structural analysis is carried out to verify the strength and resistance of the fabricated components under machining forces.

Finally, after the production of the developed fixture, to validate the effectiveness of the new fixture, extensive measurements were performed using a Coordinate Measuring Machine (CMM). A comparison was made between the measurements obtained from the old fixture and the ones from the new fixture.

Overall, this thesis aims to address the challenges associated with fixture development for CNC machining processes, providing insights into fixture technology, identifying, and rectifying previous fixture deficiencies, and validating the performance of the new fixture through testing and inspection.

Resumo

Nesta tese é realizado o desenvolvimento e prototipagem de um dispositivo para realizar a fixação de um corpo de bomba de pistões de eixo inclinado fabricada pela ABER Hydraulics para ser maquinado em uma Fresadora CNC. A pesquisa abrange uma análise do dispositivo anterior que apresentava inconsistência na produção, seguida pelo projeto, cálculo estrutural, fabrico e testes de um novo dispositivo de fixação.

A tese começa com uma análise abrangente dos processos e componentes envolvidos no fabrico de um corpo de bomba. Um estudo detalhado dos sistemas de fixação (fixturing) é realizado para entender os princípios fundamentais e principais dispositivos utilizados nesses sistemas.

Com base no conhecimento adquirido, uma análise do dispositivo com defeito é realizada para identificar os erros e suas causas fundamentais. Posteriormente, um novo dispositivo é desenvolvido, aplicando os conceitos da revisão da literatura para garantir um resultado bem-sucedido. Além disso, uma análise estrutural é realizada para verificar a resistência do corpo de bomba e dos componentes desenvolvidos submetidos as forças de aperto e as força de corte, respectivamente.

Por fim, após a produção e montagem do dispositivo desenvolvido, para validar sua eficácia, foram realizadas medições extensivas usando uma Máquina de Medição por Coordenadas (CMM). A partir dos resultados foi feito uma comparação entre as medições obtidas do dispositivo defeituoso antigo e as do novo dispositivo.

Portanto, esta tese tem como objetivo abordar os desafios associados ao desenvolvimento de dispositivos de fixação para processos de usinagem CNC, fornecendo uma revisão literária sobre os mesmos, identificando e corrigindo deficiências do modelo anterior e validando o desempenho do novo dispositivo projetado por meio de testes e inspeção.

Contents

1 Introduction 20
1.1 Motivation 20
1.2 The company 20
1.3 Objectives 21
1.4 Structure 22
2 Literature Review 23
2.1 Pumps Manufacturing and Types 23
2.2 Casting 26
2.2.1 Cast Iron 28
2.3 Machining Process and Cutting Parameters 29
2.4 Cutting Tool 37
2.4.1 Coated Tools 39
2.4.2 Cast iron machinability 40
2.5 Fixturing 41
2.5.1 Supporting and Locating Principle 42
2.5.2 3-2-1 Locating Principle 43
2.5.3 Locators 45
2.5.4 Locating Devices 46
2.5.5 Clamping principle 48
2.5.6 Modular Fixture systems vs Dedicated Fixtures 51
2.5.7 Design economics 52
2.5.8 Hydraulic Clamping 54
3 Development 56
3.1 Methodologies 56
3.2 Old Middle Housing Fixture Design 58
3.2.1 Pump Housing 60
3.2.2 Casting Process 60
3.2.3 Machining Process 62
4 Fixture Analysis 64
4.2 New Middle Housing Fixture Design 78
4.2.1 Casting Mold Protrusions design 80

4.2.2 Fixtures ... 81
4.2.3 Cutting parameters optimization and Clamping Forces Calculation ... 88
4.2.4 Fixture Mechanical Resistance ... 99
4.3 Finite Element Method Analysis for Middle Housing Clamp Forces ... 106
4.4 Heat treatment ... 108
4.5 Assembly and fixture testing ... 109
4.5.1 Sinter Grips heights ... 109
4.5.2 CMM Final Measurements ... 110
5 Conclusion and Future works ... 115
5.1 Conclusion ... 115
5.2 Future works ... 116
6 Bibliography ... 117
7 Annex ... 121

List of Figures

Figure 1 - Centrifugal Pump [3] 24
Figure 2 – ABER Bent-axis piston pump CAD (a) and sliced view (b) 25
Figure 3 - ABER Lathe machine with auto feeding [11] 30
Figure 4 - Lathe Operations [12] 31
Figure 5 - ABER Drill Press 32
Figure 6 - Face Milling Operations [12] 33
Figure 7 - Horizontal Milling Machine [11] 34
Figure 8 - ABER Vertical Milling Machine [11] 34
Figure 9 - Surface Grinder [17] 36
Figure 10 - Cylindrical Grinder [18] 36
Figure 11 - ABER 4 Axis CNC Mazak (HCN-4000) 37
Figure 12 - Cutting Tool Material, Hardness x Temperature [21] 38
Figure 13 - Jig with bushings used in drilling operation [30] 41
Figure 14 – 12 Degrees of Freedom 43
Figure 15 - 3-2-1 Locating Principle [36] 44
Figure 16 - Types of Locations [27] 46
Figure 17 - Shoulder Pin [37] 47
Figure 18 - Diamond Serrated Face Gripper [38] 48
Figure 19 - Clamping Force Optimization Process 49
Figure 20 - Modular system with dowel-pin fixing style [27] 51
Figure 21 - Types of Hydraulic Clamp Tubing [27] 55
Figure 22 - BI cast iron ABER pump 58
Figure 23 - BI series ABER Catalogue 59
Figure 24 - BIM Middle Housing 60
Figure 25 - BIP Middle Housing 60
Figure 26 - Pump Housings for BIP (Rear Cover, Middle Housing, Fixation Housing) 60
Figure 27 - Pattern and Mold of BIM Middle Housing 61
Figure 28 - Technical Drawing Middle Housing for Casting 62
Figure 29 - Palletech and 3 horizontal CNC 64
Figure 30 - P size middle housing old fixture 65
Figure 31 - Hidraulic Clamp for Clamping BIM Middle Housing 65
Figure 32 - Locator Pins for Supporting BIM Middle Housing 65
Figure 33 - Vertical Dimension for BIP Middle Housing 66
Figure 34 - Clamping Tool 69
Figure 35 - Forces and lever dimensions 69
Figure 36 - Forces directions and positions 70
Figure 37 - Fixed constraints positions 70
Figure 38 - Von Mises Stresses 70
Figure 39 - Displacement 70
Figure 40 - Von Mises Stresses of Machined Part 71
Figure 41 – Displacements of Machined Part 71

Figure 42 - Technical Drawing, BIP Middle Housing Pump 72
Figure 43 - ABER CMM, Global model 07-07-05 74
Figure 44 - BIP housing mounted at Global 07-07-05 75
Figure 45 - Angularity Tolerance Measurements 75
Figure 46 - Flatness Tolerance Measurements Front Face 76
Figure 47 - Flatness Tolerance Measurements Rear Face 76
Figure 48 - H7 Tolerance Measurements for Ø84 Hole 76
Figure 49 - Circularity Tolerance Measurements for Ø84 Hole 76
Figure 50 - G8 Tolerance Measurements for Ø105 Hole 77
Figure 51 - Circularity Tolerance Measurements for Ø105 Hole 77
Figure 52 - BIP housing solution with Protrusions 78
Figure 53 - Scheme of base locating vs axial locating. 79
Figure 54 - Protrusions dimensions 80
Figure 55 - CAD project fixture Assembly 81
Figure 56 - Fixture sub-assemblies layout 82
Figure 57 - PS1/PS2 Sub Assembly 83
Figure 58 - Sinter Grip Technical Drawing 84
Figure 59 - PS3 Sub Assembly 85
Figure 60 - Locating Pin Sub-Assembly 86
Figure 61 - Spring Loaded Support Sub-Assembly and Sectioned View drawing 86
Figure 62 - Intermediate Aluminum Plate 87
Figure 63 - BIM Base Plate, BIP Base Plate 87
Figure 64 - Sandvik square shoulder milling cutter, model 490-050Q22-08M [48] 89
Figure 65 - Width of cut definition [48] 91
Figure 66 - Engagement angle definitions [48] 91
Figure 67 – Reaction forces PS’s FEM analysis 94
Figure 68 - Forces diagram for protrusion section 97
Figure 69 - Force Diagram for Sinter Grip and Protrusion relation 98
Figure 70 - Free Body Diagram for Lever component 99
Figure 71 - Shear (Qy) and Bend Moment (Mx) Diagrams 102
Figure 72 - Lever screw hole cross-section 103
Figure 73 - Mohr's Circle for Neutral Axis 104
Figure 74 - FEM analysis for PS3 Lever V1 105
Figure 75 - FEM analysis for PS3 Lever V2 106
Figure 76 - Rib detail, FEM analysis Lever V2 106
Figure 77 - Von Mises Stresses 107
Figure 78 - Displacement 107
Figure 79 - Final Fixture Assembly 109
Figure 80 - Old vs New Flatness Tolerance Measurements Front Face 112
Figure 81 - Old vs New Flatness Tolerance Measurements Rear Face 112
Figure 82 - Old vs New Angularity Tolerance Measurements 112
Figure 83 - Old vs New H7 tolerance Measurements for Ø84 Hole 113
Figure 84 - Old vs New Circularity tolerance Measurements for Ø84 Hole 113
Figure 85 - Old vs New G8 Tolerance Measurements for Ø105 Hole 114

Figure 86 - Old vs New Circularity tolerance Measurements for Ø105 Hole 114

List of Tables

Table 1 - Casting Types Advantages and Disadvantages 27
Table 2 - HCN-4000 specifications 62
Table 3 - Rejection Rate BIP and BIM Middle Housing 64
Table 4 - Tools and Cutting Parameters for BIP housing machining 68
Table 5 - EN-GJS-400-15 mechanical properties [40] 69
Table 6 – Stresses and Displacements for Casted and Machined BIP Middle Housing 71
Table 7 – Face Mill 50A Parameters 89
Table 8 - $mc\ and\ kcx$ values for ISO K, Cast Iron [28] 92
Table 9 - Reaction Forces Rear Face Roughing 94
Table 10 - Reaction Forces Front Face Roughing 95
Table 11 - Drill Bit 10.2 Parameters 96
Table 12 - Force distribution values 98
Table 13 – Old x New displacements and stresses comparison 107
Table 14 - CMM measurements and calculations for Shim Rectification, BIP fixture 110
Table 15 - CMM measurements and calculations for Shim Rectification, BIM fixture 110

Nomenclature

BIM - Bent axis piston pump (Medium)

BIP - Bent axis piston pump (Plus)

CAD - Computer-aided design

CAM - Computer Aided Manufacturing

CMM - coordinate measuring machine

CNC - Computer Numerical Control

CVD – Chemical Vapor Deposition

DoF – Degrees of Freedom

FEM – Finite Element Method

LPS - Locating Pin Support

PS1 – Protrusion Supports 1

PS2 – Protrusion Supports 2

PS3 – Protrusion Supports 3

PVD - Physical Vapor Deposition

SLS - Spring Loaded Supports

F_A – Clamping force

F_c - Cutting force

F_{Acs} - Clamping force with the safety factor

f_n - Feed per revolution

F_f – Feed force

F_s – Static friction force

F_{fn} - F_f projection to F_{TN} direction

F_{fA} - F_f projection to F_A direction

F_{TN} – Teeth normal force

1 Introduction

1.1 Motivation

With the advancement of technology, companies are increasingly compelled to modernize. Failure to do so results in losing market share to competitors who embrace technological advancements. In the competitive landscape of companies, investing in technology is crucial for maximizing production efficiency, reducing labor costs, and achieving competitive pricing.

In manufacturing facilities that rely on machining to obtain the final product, this concept becomes a reality, as the recent years have witnessed significant advancements in this field. Those who oppose technological progress are bound to fall behind in the competition. One of the major breakthroughs in this area has been the implementation of computer control in various machining machines within a production line, commonly known as CNC machines. Through this implementation and the evolution of CAD/CAM technologies, factories have been able to achieve unprecedented levels of productivity and product quality.

Although these modern machines are highly advanced, they are designed for use by a broad range of companies producing a diverse array of final products. Consequently, they adhere to certain standardization, requiring user companies to adapt their production to the technology provided by CNC machines. This adaptation involves the creation of auxiliary machining tools to maximize the return on the significant investment made in purchasing a CNC machine.

One aspect that needs to be considered when making such an investment is the development of tools that assist in securing the workpieces during machining. The fixation process must be carefully studied to ensure proper machining, requiring consideration of various factors. The literature related to this topic explores the technology of Fixturing, covering the main types and standards of workpiece fixation. It also examines the principles that must be considered, the clamping force required for workpiece fixation, and the economic implications involved in tool development and the final product.

Another area that assumes greater importance when owning a modern CNC machine is knowledge related to cutting tools. As production volumes increase, the selection of the correct tool and its cutting parameters have a significant impact on the overall economy of the factory. Analyzing and studying ways to reduce costs, tool life, minimize operation times, and utilize the most suitable tool for each operation becomes essential. Since the machine's operating time is considerably higher and process automation is achievable, the investment in studying this area can be quickly recovered due to the high production rate.

1.2 The company

The thesis was conducted in a business environment, at ABER Hydraulics, located in Maia, Portugal. Founded in 1972, this Portuguese company has been operating in the oil hydraulic industry for over 50 years, manufacturing various mechanical components such as piston pumps, gear pumps, hydraulic motors, and power take-offs. These components are used in diverse industries and applications worldwide. The company primarily exports its products to countries in Europe and South America.

ABER executes the mass production of these components, overseeing the entire process from raw material procurement to the final product assembly. To meet the growing market demand, the company has invested significantly in cutting-edge CNC machinery, enabling high-volume production. Moreover, ABER Hydraulics has been actively pursuing financial incentives to introduce new technologies and innovative solutions to further enhance their production line.

The factory floor is now filled with state-of-the-art Mazak machines, which have become an integral part of their operations. Notably, the CNC Centers play a crucial role, encompassing five individual vertical centers. In addition, the implementation of a pallet organizer known as PALLETECH has revolutionized their workflow. PALLETECH facilitates the supply of three Mazak horizontal CNC machines, specifically the HCN-4000 model.

Within these pallets, workpieces are securely fastened using a variety of fixturing techniques tailored to the unique requirements of each component produced in the factory. Due to the diverse shapes and sizes of the workpieces, the development of specific fixture tools becomes essential to ensure proper and efficient clamping during the machining process.

1.3 Objectives

The internship in which this thesis is conducted will allow to study and develop new fixtures for machining on the Mazak HCN-4000 machining centers, coupled with the PALLETECH pallet changer system. This should help the company utilize its new technology more efficiently, maximizing production capacity and profitability. Additionally, the internship will provide valuable professional experience and give the opportunity to apply the knowledge acquired over the past five years in various engineering fields such as design, manufacturing processes, finite element analysis, materials, among others.

The main objective of this dissertation is to design, develop, and optimize a fixture system for machining a bent axis piston pump housing. To achieve this, the following specific objectives must be fulfilled:

- Conduct an in-depth study of fixturing technology.
- Analyze the limitations encountered with the previously used fixture system.
- Design the fixture system using CAD software and consider the stresses present in the system.
- Manufacture a prototype to test the developed fixture.
- Analyze the results and validate the project accordingly.

By accomplishing these objectives, the dissertation aims to contribute to the improvement of machining processes and the development of an efficient fixture for one specific workpiece, benefiting the company's productivity and overall performance.

1.4 Structure

This thesis is structured into 4 chapters, each divided into subchapters to ensure an organized presentation of the topics and a logical flow of the dissertation. This structure is designed to help the reader understand the progression of the dissertation.

Chapter 1: Introduction

In this chapter, a brief introduction is provided to acquaint the reader with the subject matter and provide a general overview of the dissertation. A summary of the company where the research was conducted is presented, along with the objectives and structure of the dissertation.

Chapter 2: Literature Review

The main objective of this chapter is to gather existing knowledge from the literature, necessary for a better understanding of the topic. It is designed to start with broader subjects and then progressively delve into more specific aspects. The chapter begins with a literature review of hydraulic pumps and their components. A brief overview of the casting process and the main machining processes is discussed. Later, one of the subchapters focuses on different cutting tools, and finally, the topic of fixture tools is thoroughly explored, including principles, key tools, design economics, and other relevant topics.

Chapter 3: Development of the New Fixture

This chapter focuses on the development of the new fixture. To achieve this, the old fixture for machining the specific workpiece is studied in order to understand existing limitations. A study and optimization of the cutting parameters are carried out to comprehend the clamping forces required for the fixtures. The design of each component of the new fixture for machining the pump housing is then accomplished, and finally, the implementation and verification of the developed project are analyzed.

Chapter 4: Conclusion and Future works

The final chapter brings together all the information and presents a conclusion on the work carried out throughout the dissertation. Additionally, future work and potential areas of study related to the research are proposed.

2 Literature Review

To manufacture a pump housing, several production stages must be undertaken, each requiring significant background knowledge. The component, to reach its final form, needs to be conceptualized, designed, cast, machined, assembled, and tested.

To achieve the casting process, the mold for the housing must be developed. Once the cast piece is obtained, before proceeding with machining, appropriate cutting parameters need to be selected to achieve the desired dimensions and finish. During machining, the fixture used to secure and locate the part must also be studied, designed, and developed. Finally, the workpiece must be assembled with other components present in the desired pump model and subsequently subjected to testing.

This dissertation will address some of the processes above mentioned, with a particular focus on the development of fixtures. It is noteworthy that the project conducted in a business environment was entirely executed by the author throughout the duration of the dissertation semester with the assistance of many employees experience.

In order to facilitate a more comprehensive study of the processes presented, this chapter will provide a brief overview of each stage, accompanied by a general exposition on the subject matter.

2.1 Pumps Manufacturing and Types

Pumps are mechanical components capable of adding energy to fluids (gases or liquids). With this added energy, fluids are used by humans in various ways. Therefore, pumps are present in several engineering fields and are constantly used in everyday life. The water pressure during a shower, the hydraulic systems on trucks and fuel pumps for vehicles are some examples where we can observe the presence of pumps.

Fluid can have energy added to it in different ways. According to Equation 1, also known as Bernoulli's equation, named after the Dutch-Swiss mathematician Daniel Bernoulli, it is evident that there are three possibilities. Energy can be added by increasing the fluid's velocity, height, or pressure. Pumps are responsible for increasing the pressure in this equation. The method used to achieve the desired pressure can also vary depending on the type and construction of the pump [1].

$$P_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = P_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 \tag{1}$$

Where:

P - *Pressure*

v - *Speed*

ρ - *Density*

h - *Height*

g - *Acceleration due to gravity*

Pumps can generally be categorized into two primary groups: dynamic pumps and positive displacement pumps. Dynamic pumps function by converting kinetic energy into potential energy, utilizing centrifugal force to move the fluid. These pumps incorporate a rotating impeller that generates a vortex, drawing in the fluid and subsequently expelling it through a discharge port via centrifugal force. Dynamic pumps find common applications with low viscosity fluids like water, thin oils, and chemicals. The main types of dynamic pumps include:

- Axial pumps: These consist of a propeller (known as an axial impeller) enclosed within a pipe, driven by a motor.
- Centrifugal pumps, Figure 1: These employ a shaft connected to an impeller, which, through its spinning motion, imparts centrifugal force on the fluid, causing it to acquire velocity and subsequently convert it into pressure at the discharge port [2].

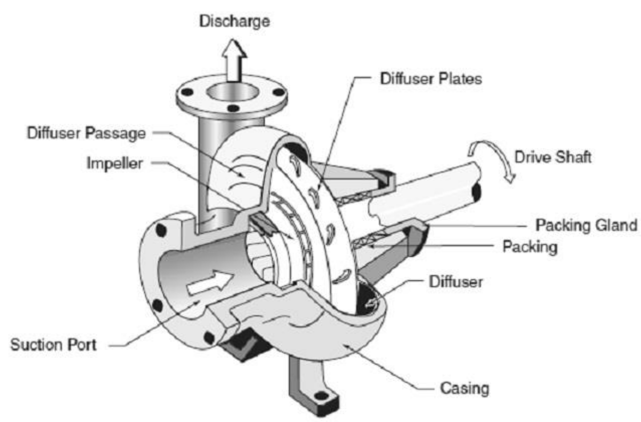
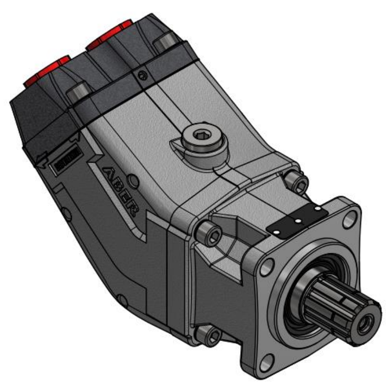


Figure 1 - Centrifugal Pump [3]

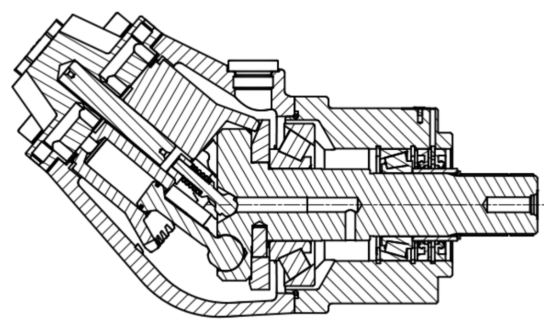
Positive displacement pumps, in contrast, operate by capturing a fixed quantity of fluid and subsequently forcing it through the system. These pumps are specifically designed for handling high viscosity substances like crude oil, thick chemicals, and slurries. Positive displacement pumps can be further divided into two categories: reciprocating pumps and rotary pumps.

Reciprocating pumps employ a piston or plunger mechanism to displace the fluid. The piston or plunger moves back and forth within a cylinder, creating a vacuum that draws the fluid into the cylinder and then propelling it out through a discharge valve. Reciprocating pumps find applications in various fields, including high-pressure water blasting, oil and gas production, and chemical processing [2].

One specific type of reciprocating pump is the bent axis pump. It utilizes a rotating cylinder block and a bent axis piston to facilitate fluid movement. As the cylinder block rotates, the piston reciprocates along the bent axis, forming a displacement chamber that captures the fluid and transports it through the system. Bent axis pumps are commonly utilized in mobile equipment such as construction machinery, agricultural machinery, and heavy-duty trucks due to their compact size, high power density, and efficiency. They are also employed in hydraulic systems for industrial applications. Depending on the specific requirements of the application, bent axis pumps can be constructed from various materials, including cast iron, aluminum, and steel [4]. The pump housing under investigation in this thesis belongs to this type of pump, as shown in Figure 2.



(a)



(b)

Figure 2 – ABER Bent-axis piston pump CAD (a) and sliced view (b)

Rotary pumps, on the other hand, use a rotating element such as a gear or screw to move the fluid. These pumps are also used for high viscosity fluids and can handle abrasive fluids and slurries. Rotary pumps can be further classified into gear pumps, lobe pumps, screw pumps, and vane pumps.

- Gear Pump: A gear pump consists of two interlocking gears that create a sealed chamber, enabling the transfer of fluids by trapping and forcing them through the pump's rotation.
- Lobe Pump: A lobe pump utilizes two or more lobes to generate fluid movement by intermeshing and creating chambers that transport fluids through the pump, providing smooth and pulsation-free flow.

- Screw Pump: A screw pump uses an Archimedean screw rotating inside a cylindrical cavity to transport fluids, pushing them axially along the screw's threads for efficient pumping.
- Vane Pump: A vane pump employs rotating vanes within a cylindrical chamber to create suction and push fluids through the pump, providing consistent and reliable fluid transfer [2].

In terms of the internal components of positive displacement pumps, they typically consist of a housing, a rotor, and some form of sealing mechanism. The housing is the outer shell of the pump that contains the rotor and seals the fluid inside. The rotor is the rotating element that moves the fluid through the system, and the sealing mechanism is used to prevent leaks and maintain pressure. Positive displacement pumps can be made of a variety of materials, including metals, plastics, and composites, depending on the fluid being transported and the conditions of the application [2].

When discussing pump housings made of metal, which is the case for most pumps on the market, including those produced by ABER, the initial step involves the casting process. This is an efficient and fast method to achieve a similar shape to the post machining housing shape.

2.2 Casting

Casting is a manufacturing process in which a liquid material is poured into a mold, where it solidifies and takes the shape of the mold cavity. The cast part is then removed from the mold, and any excess material is removed. Casting is used to produce a wide range of products, like simple door handles to complex components for aerospace industries [5]. Using this method, it is easier to achieve complex shapes that would be harder or uneconomical to make utilizing other methods like machining. Some of the main casting process utilized are described next and Table 1 compares its main advantages and disadvantages:

Sand casting is an incredibly versatile method of casting capable of producing metal alloys, whether they are ferrous or non-ferrous. This process finds extensive application in industrial settings, particularly for mass production purposes. For example, it is frequently employed in the manufacturing of automotive parts like engine blocks and crankshafts.

The technique involves the utilization of a mold composed of silica-based materials, such as naturally bonded or synthetic sand, which can achieve a smooth mold surface. The mold itself consists of two parts: the cope, which forms the upper half, and the drag, constituting the lower half. To achieve the desired shape, molten metal is poured into the pattern via a pouring cup and allowed to solidify. Upon solidification, any excess metal is removed through a trimming process to attain the desired finish for the final metal casting product [5].

The **Gravity Die Casting Process** involves the direct pouring of molten metal into the mold cavity, utilizing the force of gravity. To ensure optimal coverage, the die can be tilted, allowing for control over the filling process. Once poured, the molten metal cools and solidifies within the mold, resulting in the formation of various products. Consequently, this method has contributed to the increased prevalence of casting materials such as lead, zinc, aluminum, and magnesium alloys, certain bronzes, and cast iron.

This casting process adopts a bottom-up approach to fill the mold. While it boasts a higher casting rate compared to sand casting, its relatively higher cost is attributed to the utilization of expensive metal molds.

Investment Casting, alternatively referred to as **Lost-wax Casting**, is a technique that involves coating a wax pattern with refractory material and a binding agent. For this process a temporary ceramic mold is created, into which molten metal is subsequently poured, resulting in the creation of metal castings. Known for its high cost and requiring substantial labor, investment casting is used for a wide range of metal casting products, such as gears, bicycle trunks, motorcycle discs, and spare parts for blasting machines.

Centrifugal casting is an industrial process used to manufacture cylindrical parts by utilizing centrifugal forces. This metal casting method involves pouring molten metal into a preheated spinning die. The centrifugal forces generated during rotation push the molten metal exerting high pressure. Centrifugal casting is typically used for producing cylindrical shapes, such as bush bearings, clutch plates, piston rings, and cylinder liners. The pouring of metal in the center of the mold helps minimize defects like blow holes, shrinkage, and gas pockets [6].

Table 1 - Casting Types Advantages and Disadvantages

	Sand casting	**Gravity Casting Process**	**Investment Casting**	**Centrifugal casting**
Advantages	Inexpensive	Good Accuracy	Complex Shapes	Good Surface Finish
	Large components fabrications	Good Surface Quality	High accuracy	High Density and Low Defects
Disadvantages	Low Accuracy	Mold Cost Expensive	Expensive	Specific Shapes Production
	Bad Surface Finish	Difficulty for Complex Shape	Longer Production Cycle	Skilled Labor

The materials used in casting can vary widely, depending on the desired properties of the finished product. Common materials used in casting include metals like aluminum, brass, and steel, as well as non-metallic materials like ceramics and polymers. The choice of material depends on factors such as the required strength, temperature resistance, and chemical resistance of the finished product [7].

Casting is a versatile manufacturing process that has been used for centuries to produce a wide range of products. Advances in casting techniques and materials have made it possible to produce complex components with high precision and accuracy. As the demand for high-quality castings continues to grow, the industry will always be trying to evolve and improve casting techniques [8].

2.2.1 Cast Iron

The class of materials most commonly used in current foundry processes is cast iron. Cast irons are iron-carbon alloys with a carbon content greater than 2%. They are widely used in foundries due to their low melting temperature.

The eutectic phase in cast iron manifests in two primary forms: stable austenite-graphite and metastable austenite-iron carbide (Fe3C). These two eutectic types display substantial variations in their mechanical properties, encompassing strength, hardness, toughness, and ductility. As a result, the principal aim of metallurgical processing in cast iron is to effectively manipulate the type, quantity, and morphology of the eutectic structure to attain the desired mechanical characteristics. By controlling these factors, engineers and metallurgists can manipulate the characteristics of cast iron to meet specific requirements [9].

Cast iron, mainly composed of iron and carbon, is typically brittle and non-malleable. However, it possesses excellent compressive strength and is commonly used for structures that require this property. The composition and heat treatment applied to cast iron can shape its mechanical characteristics to suit the desired application [10].

Historically, the classification of cast iron was based on its fracture. Two types of iron were initially recognized:

- **White Iron**: This type of cast iron exhibits a white, crystalline fracture surface because the fracture occurs along the iron carbide plates. It is the result of metastable solidification (Fe3C eutectic). White iron is known for its high hardness and wear resistance, making it suitable for applications requiring excellent abrasion resistance.
- **Gray Iron**: Gray iron, on the other hand, displays a gray fracture surface because the fracture occurs along the graphite plates (flakes). It is the result of stable solidification (Gr eutectic). Gray iron possesses excellent castability, good machinability, and high damping capacity. These properties make it widely used in applications such as engine blocks, pipes, and automotive components.

With the advancement of metallography and the increased knowledge about cast iron, other classifications based on microstructural features became possible:

- **Ductile Iron**: Also known as nodular or spheroidal graphite cast iron, ductile iron contains nodular graphite in its microstructure. This graphite structure imparts improved ductility, toughness, and tensile strength compared to gray iron. Ductile iron finds applications in components that require high strength and impact resistance, such as crankshafts, gears, and suspension components.

- **Malleable Iron**: Malleable cast iron undergoes a heat treatment process called annealing, which transforms the carbon in white cast iron into graphite nodules. This results in improved ductility and toughness, allowing malleable iron to be easily bent or deformed without fracturing. It is used in applications that require formability and impact resistance, such as pipe fittings and automotive parts.
- **Compacted Graphite Iron**: This type of cast iron possesses a unique microstructure with elongated graphite structures, lying between gray and ductile iron. Compacted graphite iron offers a balanced combination of strength, thermal conductivity, and damping capacity. It is used in industries when a high strength-to-weight ratio is required, such as the automotive sector.

For selecting the cast iron material, it is essential to understanding the characteristics and applications for each of these different types as well as its machining capabilities. Each type has its own advantages and is tailored to meet different mechanical and performance requirements [10] [9].

As observed, cast iron is widely employed in the production of mechanical parts through casting. However, traditional casting processes such as sand casting do not ensure the required dimensional and geometric precision for proper functioning when interacting with other mechanical components. Therefore, the procedure that typically follows casting is machining.

2.3 Machining Process and Cutting Parameters

Currently, machining is widely used in various fields, ranging from the production of parts for machinery and equipment to the manufacturing of jewelry and art objects. Technology continues to advance, and machining becomes increasingly sophisticated, incorporating advanced materials such as ceramics and composites, as well as unconventional machining techniques like laser machining and electrochemical machining.

Each machine has specific cutting parameters that must be precisely chosen according to the tool, shape of the final product and the material being used. Optimizing these parameters can increase production efficiency, reduce tool wear, and enhance product quality. Therefore, such studies are of great importance, ensuring cost savings for companies that use them wisely.

A machining factory may utilize a series of machines to transform raw materials into the final shape. Here are some of the main machineries used in a machining factory, along with a brief description of their operations and their key cutting parameters:

2.3.1.1 Lathe

A lathe, Figure 3, is a machine tool used for shaping metal, wood, or other materials by rotating the workpiece against a cutting tool. It can be used for cutting and drilling operations. The cutting tool is typically held in place by a tool post that can be adjusted to achieve different cutting angles. By moving the tool post, it is possible to remove material from the part to give it the required shape. Different tools are used for different operations, each of them can have some variations of application.

Figure 3 - ABER Lathe machine with auto feeding [11]

Turning is the most common lathe operation. It is used to remove material from the outer diameter of the rotating workpiece in order to acquire the desired diameter. Turning can be divided into roughing or finishing. While the first aims to remove a thicker layer of material at the lowest time possible, finishing tries to end with the best surface finish by using suitable cutting parameters.

Facing is another operation that determines the length of the rod being machined. The movement of the tool on this operation is perpendicular to the rotating axis. In Figure 4, it is possible to see the descripted and other types of lathe operations indicating the movement of the tool for each of them. By mixing these operations the lathe is a powerful machine that can achieve a variety of shapes, normally with an infinite number of symmetry planes.

To carry out turning operations, the chosen parameters need to be determined. These are:

1. n - Spindle speed (RPM): This parameter refers to the rotational speed of the spindle to which the workpiece is attached.
2. V_c - Cutting speed (m/min): It represents the velocity of the cutting tool's tip in relation to the surface of the workpiece with diameter (D). The cutting speed can be calculated using equation (2).

$$V_c = \frac{\pi D n}{1000} \tag{2}$$

3. s - Feed rate (mm/rev): This parameter determines the tool's movement in the direction of the rotation axis. The operator should select the feed rate based on the machine capabilities, surface finish, and cutting tool material.

4. a_p - Depth of cut (mm): It is defined as half of the difference between the uncut diameter and the diameter of the machined cylindrical surface. This parameter indicates the radial distance that the cutting tool penetrates the material.

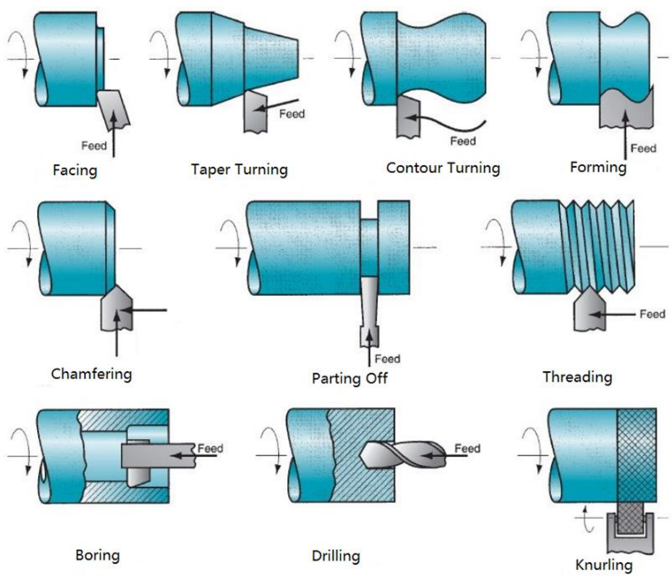


Figure 4 - Lathe Operations [12]

2.3.1.2 Drill Press

A drill press, Figure 5, is a versatile machine tool that is commonly used in manufacturing processes. It is designed to drill precise holes in a variety of materials, including metal, wood, and plastic. The machine consists of a spindle that holds a cutting tool, and a table that supports the workpiece. The drill press can be used to drill holes of various sizes and depths, making it a valuable tool in many industries [13].

To define the drilling strategy, certain parameters need to be chosen to produce parts with the desired quality. These parameters are explained as follows [14]:

- V_c - Cutting speed (m/min) - Corresponds to the peripheral speed of the cutting tool.
- n - Spindle speed (rpm) - Represents the number of rotations the drill performs per minute. This value depends on the machine's capacity and is calculated based on the recommended cutting speed for a specific drilling operation.

- f_n - Feed per Revolution (mm/rev) - Is a crucial value for performing cutting calculations, such as the feed rate.
- V_f - Feed rate (mm/min) - Refers to the tool z-axis movement of the tool. It can be calculated using the equation (3).

$$V_f = f_n * n \tag{3}$$

In addition to drilling, there are several other operations that can be performed with a drill press. Reaming is a process that creates a smooth, polished surface inside a drilled hole, which is important when the dimensions of the hole need to be the same size as a dowel or other precise component.

Tapping is another process that can be done with a drill press. This involves cutting threads into a hole so that a screw can be inserted and tightened securely into the workpiece.

Counterboring and countersinking are two operations that are often performed with a drill press to create recesses in the surface of a workpiece aligned with a threaded hole. This allows a screw to be inserted and tightened so that its head is below the surface of the material. The first results in a cylindrical recess and the second in a conical shape.

Overall, a drill press is a reliable and essential tool in many manufacturing processes, offering precision and versatility in drilling and other operations.

Figure 5 - ABER Drill Press

2.3.1.3 Milling Machine

Milling machines are the most versatile machines. They are used to remove material from a workpiece by feeding the workpiece into a rotating cutting tool. The cutting tool is held in a spindle that can move up and down and side to side. Sometime even the table where the workpiece is mounted can rotate and move. Milling machines can be used for a variety of materials such as metal, wood, plastic, and more. There are two types of milling operations, for each one many different variations give the possibility to achieve different results [12]:

- Peripheral Milling: On this type, the axis of the tool is parallel to the surface, this is done by using mainly the outside cutting edges of the tool. By using this method these are some of the operations possible: Slab Milling, Slotting, Side milling.
- Face Milling: In face milling, the cutting tool's axis is perpendicular to the workpiece surface. It removes material from the surface to create a flat, even finish, by using peripheral and end tool cutting edges. These are various forms of face milling:
    - Conventional face milling (a) - Diameter of the tool bigger than the workpiece width.
    - Partial face milling (b) – Diameter of the tool smaller than the workpiece width.
    - End milling (c) – Is when the cutter diameter is smaller than the allowing for slots to be made on the part surface.
    - Profile milling (d) – Shapes the periphery of the part.
    - Pocket milling (e) – a type of endmill that is capable of machining pockets into flat surfaces.
    - Surface contouring (f) – In which a ball nose cutter is capable of creating a 3-dimensional surface shape by using all directions of movement of the milling machines at the same time [12].

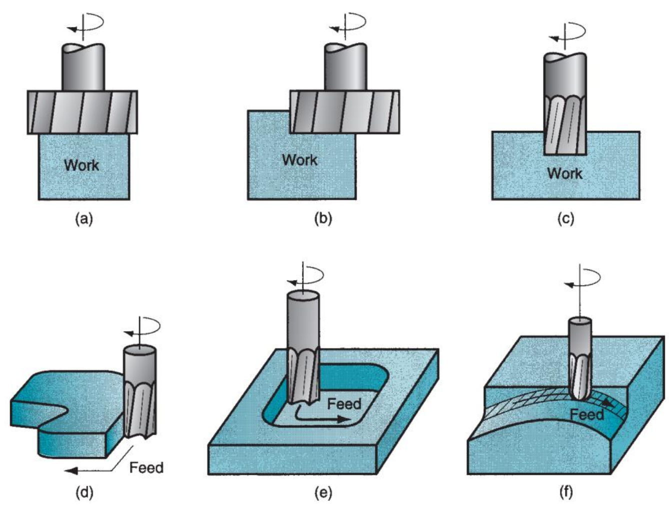


Figure 6 - Face Milling Operations [12]

Milling machines can be classified based on the orientation of the tool axis relative to the worktable. Therefore, the horizontal milling machine, as shown in Figure 7, has the tool axis parallel to the worktable. On the other hand, the vertical milling machine, as shown in Figure 8 is similar to a drill press and has the tool axis perpendicular to the work plane.

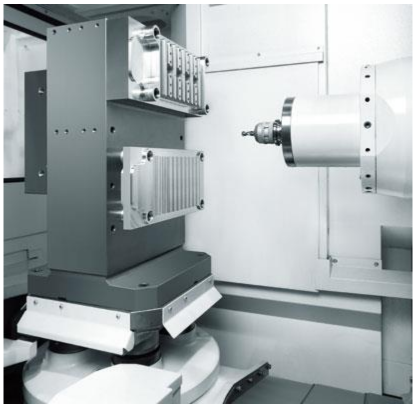


Figure 7 - Horizontal Milling Machine [11]

Figure 8 - ABER Vertical Milling Machine [11]

Depending mainly on the cutting tool and finishing grade, these are the main cutting parameters that must be defined for milling machines operations:

- n - Spindle speed (RPM): This parameter refers to the rotational speed of the tool.
- V_c- Cutting speed (m/min): It refers to the speed at which the cutting tool moves across the workpiece surface. The appropriate cutting speed depends on factors such as the material being machined, the tool material, and the desired surface finish.
- V_f - Feed rate (mm/min): It represents the speed at which the cutting tool advances into the workpiece. The feed rate is determined by the desired material removal rate and the capabilities of the machine and tool. Sometimes this information is expressed with the f_z parameter, which represents the Feed per Tooth, measured in millimeters per tooth (mm/tooth). The relationship between these two values can be calculated using equation (4).

$$f_z = \frac{V_f}{n * Z} \tag{4}$$

Where:

Z is the number of teeth

- a_e- Width of cut (mm): Is the parameter that defines the width of the material that is removed by the milling cutter in a single pass. It represents the distance between the outer edges of the milling cutter's path as it cuts through the material.
- a_p - Depth of cut (mm): It refers to the distance between the original and final surface of the workpiece, parallel to the tool axis, for one single pass of the milling cutter. Both depth of cut and width of cut are crucial in determining the material removal rate and the cutting

forces. It should be chosen carefully to avoid excessive tool wear and ensure dimensional accuracy [15] [14].

In addition to the cutting parameters, other decisions are necessary to ensure optimal interaction between the machining process and the tools:

Coolant/lubrication: Proper coolant or lubrication is essential to dissipate heat, reduce friction, and prolong tool life. It also helps in chip evacuation and improves surface finish. The selection and application of coolant/lubricant should consider the specific machining requirements and the compatibility with the workpiece material.

Tool path strategy: The tool path strategy determines the path the cutting tool will follow during the milling process. Various strategies, such as contouring, pocketing, and profiling, can be employed based on the part geometry and the desired machining objectives. Optimal tool paths can improve efficiency, reduce tool wear, and ensure accurate machining.

These parameters should be carefully analyzed and adjusted based on the specific requirements of the milling operation to achieve the desired quality of the machined parts. It is important to consider the capabilities of the milling machine, the characteristics of the workpiece material, and the available cutting tools to optimize the milling process.

2.3.1.4 Grinding Machine

The grinding machine is capable of removing material through abrasion, where tiny chips are removed from the workpiece by the abrasive surface of the grinding wheel. This wheel while rotating at high velocity, typically composed of geometrically non-defined cutting, with a very precise distance from the workpiece, can achieve a fine tolerance and roughness. The material utilized for the wheel is commonly an aluminum oxide or other abrasive materials.

With this machine it is possible to have a very good surface quality (i.e., low surface roughness) and high accuracy of shape and dimension. There are two main applications that grinding machines are used for. The first is related to the surface finish of the part, other machining methods usually leave some roughness depending on the tool and cutting parameters utilized. When low roughness is important to the project due to mechanical interaction or appearance, the grinding wheel can remove a thin layer of material giving the part a very fine roughness grade. The other is to acquire exact dimensions important for fittings, as the accuracy in grinding operations is in the order of 0,002 mm on most grinding machines and sometimes can achieve 0,000025 mm for precision grinding. The grind wheels are constructed of different materials such as Aluminum oxide, diamonds, or Ceramic.

There are 2 main types of grinding machines, the plane surface grinder, and the cylindrical grinder. The first is used to grind flat surfaces, as a moving table makes the part pass between the table and the grinding wheel in a defined distance, giving the part an exact dimension, Figure 9. The second, Figure 10, used for cylindrical shapes have the grinding wheel placed alongside the part.

With a defined distance of the part axis, the workpiece axis is held in place by a chuck or a fixture. The part is rotated while to achieve the desired diameter dimension and surface finish done by the abrasive grinding wheel spinning at a fast rate [16].

Figure 9 - Surface Grinder [17]

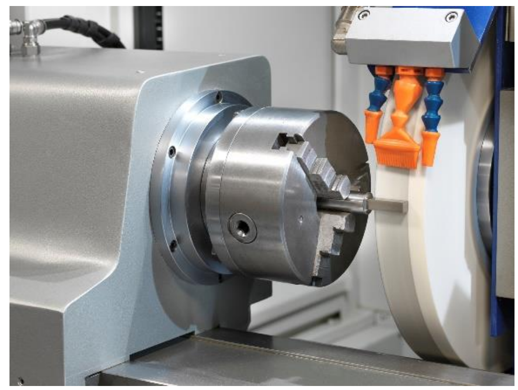


Figure 10 - Cylindrical Grinder [18]

The grinding process is a cutting process that is geometrically undefined due to the undefined number and geometry of cutting edges interacting with the workpiece. The load on the workpiece as well as the load on the grinding wheel is a result of the programmed actuated variables, the cutting tool properties, and the workpiece properties. Due to the complex relationships during grinding process, parameters have been defined to describe the process behavior. These parameters are described as follows [19]:

- V_c - Cutting speed (m/min) – Circumferential speed of the grinding wheel
- a_e - Depth of cut (mm) – the engagement of the grinding wheel in radial direction
- V_f - Feed velocity (mm/min) – Is related to the feed direction and depends on if it is a tangential or axial grinding.

2.3.1.5 CNC machine centers

Machine centers are modern machines used for high-precision machining of metal parts and other materials. They are capable of performing a variety of machining operations, such as milling, drilling, threading, turning, and other cutting operations, all in a single machine. These machines typically have multiple axes of movement and all of them move accordingly with Computer Numerical Control (CNC). CNC is an automated control following a coded programmed instruction, without the need for a machine operator, allowing the machine to have an incredible productivity.

- 3 axes: This implies that the machine/tool has control over three directions (X, Y, Z)
- 4 axes: In addition to the three axes mentioned earlier, typically the fourth axis refers to a rotational axis of the table on which the workpiece is mounted.

- 5 axes: The fifth axis may consist of an additional rotational axis of the worktable, ensuring that the workpiece can be machined from any direction, except for the face in contact with the table.

Modern machining centers are highly automated and can perform complex tasks quickly and accurately. They are equipped with automatic tool changers, which allow for rapid tool changes for different machining operations without the need for human intervention.

They are fundamental for modern manufacturing and are used to produce a wide range of parts and components, from airplane engine parts to medical implants and electronic components. Due to their automation, machining centers can operate for hours without the need for constant observation by an operator. Modern centers are capable of detecting tool wear and can alert the operator to replace the worn tool, ensuring the most efficient production process without the risk of damaging the workpiece [20].

Figure 11 - ABER 4 Axis CNC Mazak (HCN-4000)

2.4 Cutting Tool

Cutting tools are an essential component in the machining industry, used to remove material from workpieces through cutting, drilling, and milling operations. The efficiency and effectiveness of cutting tools play a vital role in determining the quality and precision of the finished products.

Cutting tools used in machining processes are made from a variety of materials. The selection of the material depends on the type of material being cut, the desired cutting speed, the cutting forces generated, and the expected tool life [8].

Some of the commonly used materials for cutting tools available on the market are:

- High-speed steel (HSS)
- Carbides
- Ceramics
- Diamond

- Cubic Boron Nitride (CBN)

When cutting through metal, the cutting tool needs to be made from a material that can withstand the elevated temperatures and forces generated during the cutting process. The material properties required for cutting tools used in metal cutting include high hardness, wear resistance, toughness, and thermal stability.

High hardness is necessary to ensure that the cutting tool can withstand the high compressive forces generated during the cutting process without deforming or breaking. Figure 12 relates in a graph the hardness and temperatures for the main materials. Wear resistance is crucial to prevent the tool from wearing out prematurely due to the abrasive nature of the metal being cut. Toughness is essential to prevent the tool from fracturing due to the high impact forces generated during the cutting process. Thermal stability is necessary to ensure that the tool does not overheat or undergo thermal fatigue due to the high temperatures generated during the cutting process.

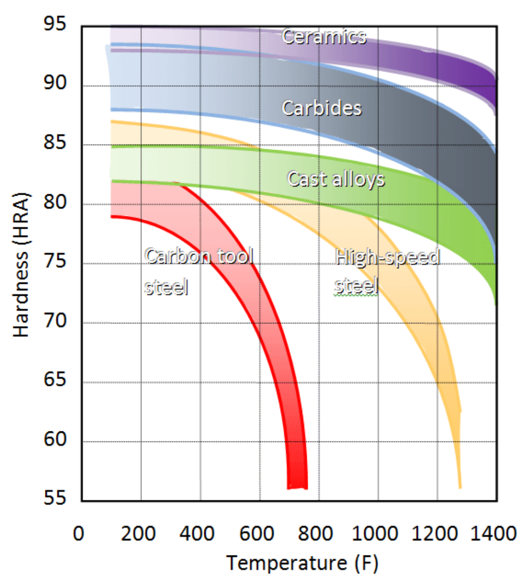


Figure 12 - Cutting Tool Material, Hardness x Temperature [21]

High-speed steel tools, developed at the early years of 20th century, were designed to withstand high cutting speed and temperatures, as 200°C, at that time, while maintaining their cutting edge, making them ideal for use in high production environments when combining with its low cost.

The composition of HSS typically includes high levels of carbon, tungsten, chromium, and vanadium, which gives it the necessary mechanical properties to withstand high cutting speeds and temperatures. The high carbon content provides hardness, while the alloying elements provide additional strength and wear resistance [22].

To improve the high-speed steel tool properties, it is common to have surface treatments such as case hardening for improved hardness and wear resistance. Another option is to have a coating, further explained in the next subchapter.

With the advancement of cutting technology, sintered carbide, also known as hard metal or cemented carbide tools became the most utilized type of tools in the machining industry, due to its superior performance and durability. They are made from a compound of carbon and metal (tungsten, titanium, or tantalum). Compared to the High-speed steels, carbide tools are extremely hard, with values from 600 to 2100 HV and have excellent wear resistance [23].

Tungsten carbide is known for its high hardness and are able to withstand high cutting temperatures and maintain its cutting edge for longer periods. The heat resistance property also allows for increased machining speeds since the material doesn't loses its hardness when subjected to the extreme cutting temperatures like 1000°C. Carbide tools are ideal for machining hard and abrasive materials.

Cutting tools are a critical component in the machining industry, and the selection of the appropriate material depends on the composition of the material being cut, desired cutting speed, cutting forces, and tool longevity. Material properties essential for cutting tools utilized in metal cutting encompass high hardness, wear resistance, toughness, and thermal stability, which can be achieved through the utilization of materials like carbide, ceramics, diamond, and CBN.

2.4.1 Coated Tools

Coating a tool is the process of giving a superficial layer, ranging from 2 to 15 µm thickness, with different material properties in order to enhance its quality and lifetime. It provides better hardness, thermal protection, and chemical stability. By applying a coating, with the increasing durability of the tool by 50%, only 1% is reduced to the component cost, since in all machining costs just 3% of it is related to cutting tool cost. But when considered the possibility to increase machining parameters and consequentially productivity, coating results in a reduction of costs of 15% per machined part [24].

CVD and PVD are two early developed, at the 1970s, techniques used in coating technology to deposit a different substance creating a thin layer of materials onto a surface.

CVD (Chemical Vapor Deposition) involves the reaction of gases to form a thin film on a surface. During the process, a gas mixture containing the desired coating material is heated and allowed to react with the surface. The process occurs in a vacuum, and the coating material is deposited on the surface in a uniform and controlled manner.

PVD (Physical Vapor Deposition) is a process in which the coating material is evaporated and then condensed onto the substrate or surface. This is done in a vacuum chamber where the coating material is heated to a high temperature, causing it to vaporize. The vapor then condenses onto the surface to form a thin film.

Within the PVD process, different techniques such as EB-PVD and HiPIMS can be used. These techniques enable the deposition of various coating materials, including titanium nitrides (TiN), titanium aluminum nitride (AlTiN), aluminum oxide, among others, and result in a considerably harder, smoother, and more adhesive coating. The choice of technique depends on the specific requirements of the desired coating, such as the tool material and machining conditions.

Both CVD and PVD processes are continuously improved and widely used in the manufacturing industry to create coatings with specific properties, such as hardness, corrosion resistance, and wear resistance. The choice of method depends on the specific application and the desired properties of the coating [23] [24].

2.4.2 Cast iron machinability

The machinability of cast iron materials is significantly influenced by the amount and formation of dispersed graphite within the material. The presence of graphite has two main effects on the machining properties: reducing friction between the tool and the material and interrupting the metallic structure. These factors contribute to more favorable machining properties compared to steel, leading to the formation of short brittle chips, low cutting forces, and longer tool life.

The graphite shape and matrix type of cast iron also play a crucial role in determining its mechanical properties and, consequently, its machinability. Each type of cast iron exhibits unique characteristics that influence its machinability.

When machining malleable cast iron (MCI), the predominant wear mechanism is adhesive wear. To mitigate tool wear and improve machining efficiency, the optimal cutting tools are coated with materials that have a low affinity and a low friction coefficient. The selection of suitable cutting tool materials, such as ceramics, cemented carbides, or PCBN (polycrystalline cubic boron nitride), is essential in achieving optimal machining outcomes.

On the other hand, compacted cast iron (CGI) exhibits a different wear mechanism, mainly abrasive wear. In this case, the best cutting tools are coated with tool materials that possess high hardness and excellent impact resistance. The coating on the cutting tool plays a significant role in enhancing cutting performance and reducing tool wear during the machining of CGI [25] [26].

In general, cast iron machining requires tools that are resistant to abrasion, possess high toughness, and are chemically inert to avoid any unwanted reactions with the work material. To enable high-speed milling, cutting tools have been equipped with high hardness coatings. The TiAlN coating on cemented carbide tools of the K material grade, i.e., Cast iron group, has become widely adopted for machining cast iron, as it enhances productivity and reduces costs. This coating maintains its high hardness and oxidation resistance even when exposed to high temperatures. By using these tools, manufacturers can achieve greater productivity and obtain superior surface finishes on the machined parts, especially when operating at high cutting speeds and low feed rates.

2.5 Fixturing

In the early days of manufacturing, each part was crafted individually. These pieces were handmade, and the manufacturing process was time-consuming and inconsistent. Eventually, a formula for mass production was discovered: standardized parts. Based on this concept, the use of guides and workholders allowed less skilled workers to perform repetitive tasks. With the advancement of this technology, these manufacturing aids are now referred to as Jigs and Fixtures.

Jigs and Fixtures are devices developed for production purposes to manufacture parts accurately. When machining a part, it is needed to have precision positioning between the cutter and the part being machined. To achieve this, jigs and fixtures are designed and built to locate and support the part being machined [27].

A jig is a manufacturing tool designed to not only secure and position the workpiece but also to guide the cutting tool during the operation. Typically, jigs are equipped with hardened steel bushings to guide drills or other cutting tools. Is mostly used in drilling, reaming and boring operations. In Figure 13 it is possible to see a jig example used to fix and direct a drill to the workpiece [28] [29]. Jigs are more utilized in manual machining since the guiding of the tool is more necessary because of human limitations, with the CNC machines they are not very common since the control of modern machines can already provide the accuracy needed to the cutting tool.

Figure 13 - Jig with bushings used in drilling operation [30].

Fixturing is the process of designing and manufacturing fixtures, i.e., devices or equipment developed to hold, support, and locate the workpiece in place during a manufacturing process. The purpose of fixturing among many others is to ensure that the workpiece remains in a fixed and stable position, allowing for accurate and repeatable production or measurement. It gives industry the capability of standardization for the manufactured parts needed for today's high-speed, high-volume production [29].

The fixture design will depend on the specific application and the type of workpiece being manufactured or inspected. Fixtures may be designed for a single use or for multiple uses, and can be made from a variety of materials, including metal, plastic, or composites [29].

Regarding machining, fixturing is essential for a good result. It is crucial to spend time and money to develop a good working fixture when producing a part on a large scale. A badly fixed part during machining operations can cause many different problems. The minor of them is the loss of the part being machined. If this happens, work, money and time that was invested on is lost. But the consequences can be worse, a loose part accelerated with the great speed necessary for cutting hard material on an expensive CNC machine can damage the equipment as well as hurt someone.

With the advancement of technology in the world, industry is constantly evolving in terms of production systems. The evolution of modern manufacturing concepts demands that the fixturing systems keep pace with this progress, becoming more efficient and precise. However, even with all the advancements, the fundamental principle of workpiece fixturing remains the same. During machining operations such as milling or drilling, the workpiece must be precisely positioned and securely clamped throughout the entire process.

In the pursuit of achieving the maximum productivity each workpiece sometimes may require a different costume fixture, but for each fixture the principles of fixturing remain constant. In addition to fulfilling their basic role, fixtures can also, based on intelligent design, help streamline the production process. Therefore, current advancements in this area focus on reducing setup times for workpiece machining.

The following sections will present a literature review related to the principles of workpiece positioning, clamping, and support. The main types of fixtures components available in the current market will also be discussed.

2.5.1 Supporting and Locating Principle

Referencing the workpiece is crucial for any machining operation to achieve precision. It involves properly aligning the workpiece with the cutter or tool. To attain the desired level of accuracy, the tool designer must ensure that the part is held in a precise location and supported rigidly. In addition to positioning the part correctly, locators guarantee effortless loading and unloading of the tool and ensure that the tool is mistake proof, this means that the tool can only be mounted in one position, making it impossible to the operator to make a mistake, this concept is sometimes called ***"Poka-yoke"***.

"Poka yoke" is a Japanese term that means mistake proofing. It refers to any device or mechanism implemented in a process to avoid, (yokeru), mistakes, (poka) and defects caused by human mistakes. These mechanisms work by alerting the operator, correcting the error, or preventing it from happening altogether [31].

It is pointless if parts take too long to get clamped or unclamped, or if they are put in the tool incorrectly. The tool designer must also incorporate a robust support system for the part. With proper design, the part locators can act as supports as well as locators.

Accurate referencing of a workpiece involves the restriction of all twelve degrees of freedom. When a workpiece remains unrestricted in space, it has the capability to move in an infinite number of directions. Nevertheless, this motion can be broken down into twelve distinct directional movements, commonly referred to as "degrees of freedom" (DoF).

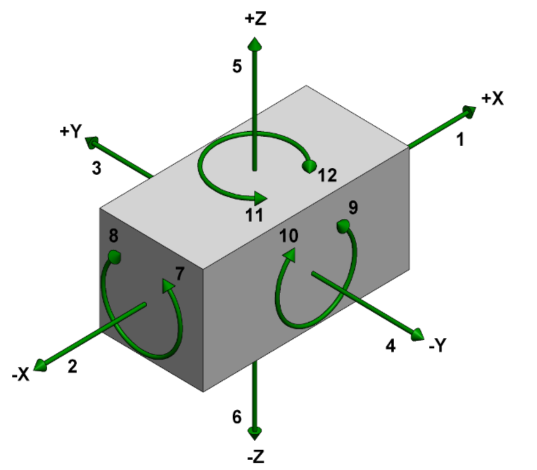


Figure 14 – 12 Degrees of Freedom

Figure 14 provides a visual representation of these twelve degrees of freedom. They are associated with the central axes of the workpiece and are split up into two groups, six axial degrees of freedom and six radial degrees of freedom. The axial degrees of freedom enables linear movement along the x, y, and z axes. On the other hand, the radial degrees of freedom allows for rotational movement around the same axes, clockwise and counterclockwise.

Typically, to ensure stability and precision, at least nine degrees of freedom are constrained through the utilization of supporters and locators. These components work together to restrict the majority of the workpiece's potential movements. However, the final three degrees of freedom necessitate a different type of component. To accomplish this, clamps are employed to apply force against the existing locators, effectively constraining the remaining degrees of freedom [32] [33].

By restricting all twelve degrees of freedom, engineers can achieve enhanced accuracy and control over the positioning and manipulation of a workpiece. This meticulous approach to referencing ensures that the workpiece remains firmly fixed and stable, enabling precise and reliable operations in various industrial applications.

2.5.2 3-2-1 Locating Principle

The 3-2-1 principle is a widely used technique in fixturing development that involves three steps for prismatic parts. It is named after the number of fixed points used at each step, first 3, then 2, then 1, totalizing six fixed points.

In the 3-2-1 method, as illustrated in Figure 15, each step introduce locating points for a datum plane. These planes play a crucial role in determining the position of the workpiece. Along with opposing clamping forces, they provide complete constraint to the part [34].

The minimum number of points to define a plane is 3. So, for the first step 3 points need to be located on a plane surface. Spreading the points apart helps to increase workpiece stability. The workpiece 12 degrees of freedom after this step is reduced to 7 [35].

The second step consists in defining a second plane perpendicular to the first. For this is necessary to have 2 more points as shown in Figure 15, since the rotation in axis that connect these 2 points is limited by the first plane. In this step DoF are reduced to 4.

The third plane, perpendicular to the other two first planes, can be defined with just one more point of location. So, the “y- axis” translation is no longer available.

For the last 3 DoF, movement on the direction of the locators but to the opposite sense, it is not possible to restrict it utilizing locators, since they are static in general, and the part need to be mounted and removed. This is when a clamping mechanism is needed to restrict some of the last DoF’s [34].

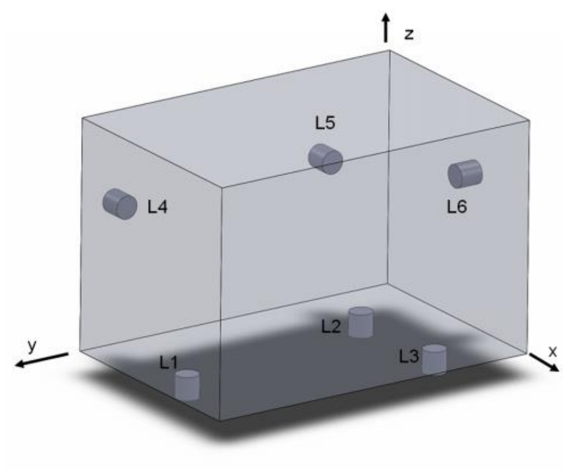


Figure 15 - 3-2-1 Locating Principle [36]

In the other hand, for non-prismatic parts several components may be considered for properly supporting and locating the part. The techniques utilized are often dependent on the workpiece shape because there are no generalized fixture-design principles for non-prismatic parts, but the 3-2-1 principle should still be considered to understand fixturing workpiece relationship [35].

2.5.3 Locators

Locators are the devices used to restrict the movement of the workpiece and ensure repeatability to the manufacturing process. They must be strong enough to withstand the cutting forces and hold the workpiece in place. Workholder design is critical, and it is important to note that locators, not clamps, are responsible for holding the workpiece against the cutting forces. Locators acts like a physical limitation for the workpiece, ensuring that it cannot move when placed against the stop. On the contrary, clamps operate by utilizing the friction between the clamp and the surface being clamped. Their primary purpose is to secure the workpiece against the locators. By applying pressure or force, clamps prevent unwanted movement or displacement of the workpiece during the manufacturing or machining process.

A technique to guarantee precise positioning is to include spring-loaded devices in the workholder. These components are placed in a way that they exert a force to the workpiece, pushing it against the fixed locators and by consequence locating it before clamping. The spring-loaded components guarantee a better repeatability since it facilitates the location step in a way that it helps the setup procedure for the operator.

Another important factor during the fixturing designing is related to chips that comes off from the machining process. These debris can cause interference with the locators when accumulating between the locator and the workpiece. An effective way to control the chips is to try to position the locators far away from the machining area. To guarantee that a chip will not affect the location of a machining part an intensive cleaning between setups should be carefully done.

In general, there are three types of locating, Figure 16. The first one is plane location (a), which refers to the ability to locate based on a single surface. The second type is concentric location (b), where locators rely on internal surfaces of the workpiece being machined. The most common approach in this case is to use a pin inserted into a hole created in a previous operation to locate the part in the current operation. This type of location is very useful as it restricts movement of the part in two directions and rotation in two others. The last type of location complements the previous one. Radial locators (c) prevent rotation of the part in the plane on which it is supported. Typically, a well-designed fixture makes use of a combination of the three methods described [27].

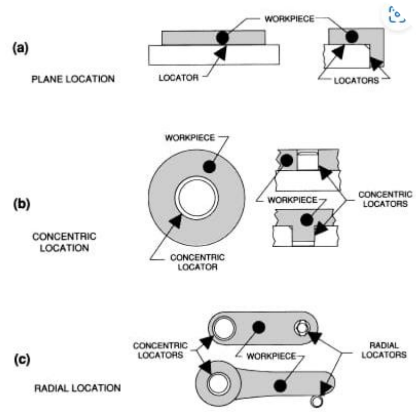


Figure 16 - Types of Locations [27]

2.5.4 Locating Devices

Both locator and support elements can be described by locating devices. Support is typically used to refer to locators that hold the weight of the part, they are generally larger and positioned below the part. These devices can be divided into two major groups: those that are fixed and those that are adjustable. The adjustable ones are capable of moving to accommodate the workpiece not relying on any dimensional variations from previous manufacturing processes [27].

2.5.4.1 Locating pins

These pins are the most common type of locator devices. They are normally threaded so they can be tightened to the tool plate. They can have two different styles, either plain or with shoulder. The second means that it has a section with bigger diameter to make a stop, Figure 17, this way the locators are not pushed inside the tool plate when a force is applied to it.

Figure 17 - Shoulder Pin [37]

To localize the body being machined the locator can utilize the outer surface or the tip of the Locator to localize it. There is no right way to utilize them, as long as they localize the workpiece and stay fixed. The tip can have different shapes depending on the model and the applicability, bullet nose dowel, round, or cone.

Rest buttons are the support counterparts of locating pins. They have a similar shape but are designed to always be above the Tooling Plate, underneath the part, providing support to it. They are usually hardened to resist wear making it superior to machined surfaces for supporting the workpiece, as the machined surfaces tend to wear out over time. Furthermore, Rest Buttons can be easily replaced and have a dimensional accuracy of approximately ±0.001 mm.

2.5.4.2 Grippers

Grippers are another family of support and locating tools. They are made of hard material and are usually replaceable inserts. The contact faces can have different types of textures and geometry to provide additional holding force to the workpiece. They are designed to slightly indent the workpiece's surface resulting in an increase gripping force and not just relying on static friction. There are many different types of grippers. They can be round, square, swivel contact bolts for example. One of the most common is the diamond serrated face as illustrated in Figure 18.

Figure 18 - Diamond Serrated Face Gripper [38]

2.5.4.3 Spring Loaded Devices

Spring-loaded devices are used to position the part before clamping it. They are employed to push the part against fixed locators, ensuring that the locators make contact with the workpiece to be machined. While these devices move under force application, technically they are not considered locating devices. However, they assist in the location process and facilitate the setup.

Spring plungers are one type of spring-loaded device that is used when longer strokes are required. They can apply high pressures and are typically threaded on the outside so that they can be easily mounted on a fixture body [27].

2.5.5 Clamping principle

The clamping mechanism serves the purpose of securely holding the workpiece to be machined with a specific level clamping force against the previously mentioned locators. To fulfill this task, the clamps must be strong and resistant to deformation under high stress. Additionally, they must not deform the workpiece they are clamping; instead, the force applied should be directed towards the locators. In order for a fixture to fulfill its purpose, the clamping mechanism should allow for quick tightening or loosening, minimizing setup time during operations [27].

Another important aspect for clamping design is to minimize the contact area between the clamp and the workpiece resulting in increased pressure on the workpiece. However, if the pressure becomes too high, the workpiece may be indented. When designing the fixture this indentation needs to be taken into account, as they may be unwanted, especially if any imperfection on the surface in contact with the clamp is not machined in a subsequent operation and or could be detrimental to the final product.

In addition, when designing a clamp mechanism, is important to check for the cutting tool paths, and make sure the there is no interference between the components, since with all the movements that an CNC is capable, occasionally the tool path is not considered leading to damage [27].

2.5.5.1 Clamping Forces

During machining, cutting tools exert forces known as cutting forces on the workpiece. These forces are caused by the resistance encountered during the machining process. These forces with the advancement of cutting tools and increasing of drastic cutting parameters needs to be proportionally bigger every time to support the cutting forces. They should primarily be countered by the locators, but a portion of the force may be resisted by the clamps. In such cases, it is necessary to calculate the clamp force to ensure that the workpiece does not move.

The position where the clamps are located must be carefully chosen to avoid deformation of the part when the support and clamps are not well-designed. Even elastic deformation caused by clamping forces can lead to improper positioning of machining holes. Once the workpiece is released, the required tolerances specified in the design may not be followed. Therefore, all the force exerted by the clamps should be directed towards the locators to ensure proper positioning.

The study conducted by Chen et. al [39] proposes an optimization method for clamping force and fixture layout to minimize workpiece deformation during machining. The position of locators, clamps, and supports, along with the clamp force, is typically strategically chosen by the tooling designer. However, there is no guarantee that the chosen solution is the optimal one for the problem. Therefore, the proposed method aims to minimize the maximum elastic deformation of the workpiece and achieve a more uniform deformation.

The study follows the process presented in Figure 19 to reach the optimal result. For a fixture with ***p*** fixture-workpiece contacts and ***n*** machining load steps, a multi-objective optimization model is established to minimize the maximum deformation of the machined surfaces under clamping and cutting forces while achieving uniform deformation.

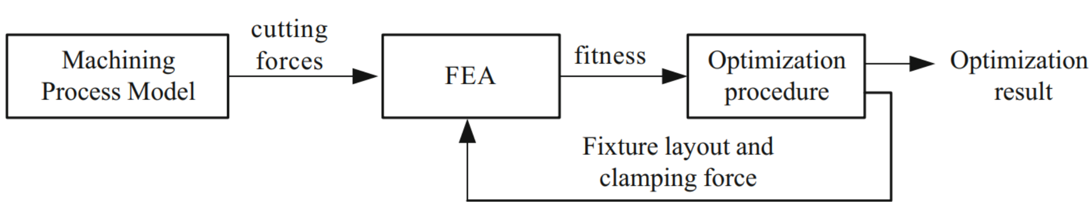


Figure 19 - Clamping Force Optimization Process

To determine the maximum cutting force, a finite element analysis model is employed. The iteration process is carried out using a Genetic Algorithm (GA), which simulates the "survival of the fittest" phenomenon. The optimization process for fixture design involves using the GA, where the design variables are the fixture layout and clamping force. The GA generates strings that represent various layouts, which are then compared to chromosomes in natural evolution. The GA identifies the optimal string, which corresponds to the optimal fixture design scheme. MATLAB's Genetic

Algorithm and Direct Search Toolbox are utilized for implementing the genetic algorithm and conducting direct searches, as further explained in the article.

In conclusion, the study demonstrates that utilizing a multi-objective optimization method is more effective than relying solely on experience-based fixture design. Real examples presented in the study show the superiority of this approach in minimizing workpiece deformation [39].

2.5.5.2 Clamping Devices

There are various ways to clamp a workpiece against its locators. The clamping design method depends on the shape and size of the workpiece primarily. The designer must make this choice in a way that ensures the clamp is as simple and efficient as possible.

One example of a clamping mechanism is the strap clamp, which functions as a lever system. It consists of three components: the lever, the screw, and the heel support. By tightening the screw, which is usually positioned between the workpiece and the support, the lever is imposed by the heel support reaction force and is pressed against the workpiece, creating a clamping motion. The distance between the components determines the distribution of pressure on the screw. If the screw is positioned exactly in the center of the lever, the pressure is evenly distributed between the workpiece and the support [29]. Another design choice that should be studied is the point of the lever that contacts the workpiece since it has a big importance on the functionality of the clamp. There are three main contact shapes: the radius nose, flat contact, or padded. With the first one the contact area is reduced so the pressure applied to the workpiece is increased, this can lead to unwanted deformation or be necessary depending on the cutting forces applied.

Cam clamps are divided into two groups, the direct-pressure clamping has the cam apply direct pressure to the workpiece when activated. In the indirect pressure clamp system, the clamp operates in a similar style as the strap clamp, but instead of a screw, they feature a cam that when activated, pushes the lever. Cam clamps are faster to be activated but are more complex built and have results in more space occupied.

Swing clamps have a rotating arm that can be positioned above the workpiece. When a screw at the tip of the arm is tightened, it makes a pad at the tip of the screw go down and secures the workpiece. This mechanism is useful as it provides space for easier workpiece exchange compared to other clamping methods.

Grippers can also be utilized in clamping devices. Here, their purpose is to reduce the contact area and increase the point pressure to ensure greater gripping force, rather than relying solely on friction. This way, the surfaces provide stability without requiring excessively high clamping forces that could result in workpiece deformation, and more robust mechanism.

2.5.6 Modular Fixture systems vs Dedicated Fixtures

Fixture systems can be classified into 3 different types: modular, dedicated, or a mixing of both, hybrid.

In a dedicated fixture system, a specialized fixture is custom-made to match the specific shape of the workpiece. The production of such fixtures is costly and time-consuming, making it economically viable only for high quantities of production or when the sales of the product can offset the fixture's manufacturing cost.

Fixturing modular systems, Figure 20, are highly adaptable and efficient solutions used in manufacturing to securely hold and position workpieces during machining operations. These systems consist of standardized components that can be easily interchanged and reconfigured to accommodate various workpiece sizes, shapes, and machining requirements. Fixturing modular systems offers several benefits that contribute to improved productivity and cost-effectiveness, but they are not as customizable as a custom designed dedicated fixture.

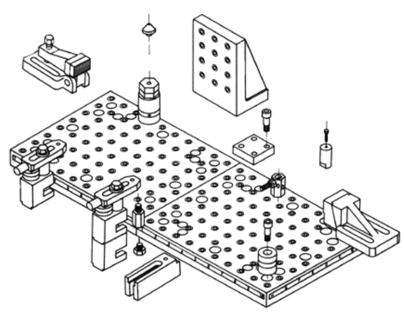


Figure 20 - Modular system with dowel-pin fixing style [27]

One key advantage of fixturing modular systems is their flexibility. The standardized components, such as base plates, clamps, and supports, can be quickly assembled, and rearranged to meet changing production needs. This adaptability allows for easy setup and reconfiguration, reducing downtime between machining operations and improving overall workflow efficiency [35].

Fixturing modular systems also contributes to cost savings. The standardized components are often more cost-effective compared to custom-made fixtures. Additionally, the versatility and reusability of modular systems reduce the need for multiple specialized fixtures, resulting in lower fixture design and manufacturing costs [35].

Moreover, fixturing modular systems facilitate quick and efficient setup times. By eliminating the need for extensive fixture design and fabrication, manufacturers can streamline their production processes, reduce lead times, and increase overall productivity [35].

2.5.7 Design economics

The fixture designer has the responsibility to find ways to keep the cost of fixture low as possible otherwise the parts machined will increase its price proportionally.

The simplicity when designing a tool is one way to keep the low price, saving time and materials. Buying standard components for jigs and fixtures instead of machining yourself is another option that should be considered when possible. The suppliers can achieve economies with large-scale producing, which reduces the final cost per unit. Additionally, they have the expertise that allows them to produce high-quality components while optimizing production and reducing costs. By buying the fixture components it's possible to save time and resources to spend on the areas that the company has expertise. Of course, there may be cases where manufacturing fixture components in-house makes sense, particularly if the fixture needs specialized requirements, unique designs, or cost advantages due to specific circumstances. However, for many businesses, buying fixture components from reliable suppliers offers numerous benefits in terms of cost, quality, time savings, and overall efficiency.

By utilizing the methodology presented in the [29], to estimate the tool cost and productivity first is necessary to calculate the total cost of the development of the fixture, this is the material cost, and labor needs. Next, the Equation (5) is necessary for calculating the parts per hour that the fixture will be able to produce.

$$Ph = \frac{1}{S} \tag{5}$$

Where:

Ph = parts per hour

S = single-part time

The cost of labor can be calculated using the equation (6):

$$L = \frac{LS}{Ph} * w \tag{6}$$

Where:

L = Cost of labor

LS = Lot size

Ph = Parts per hour

w = Wage rate

Finally, the cost per part of the fixture is determined by the equation (7), this marker is necessary to evaluate the viability and true economic potential of the design.

$$Cp = \frac{TC + L}{LS} \tag{7}$$

Where:

Cp = Cost per part

TC = Tool cost

L = Cost of labor

LS = Lot size

The previously described method is capable of evaluating if the fixture idealized is a good investment or not. An economics study to validate the investment can be done to more than one fixture option in order to choose the one that has the best results. Also, the method can be applied to an existing fixture that is being used to assess whether it is worth developing a new, more modern fixture with lower cost per and how many parts need to be produced using the new fixture until the break-even point is reached, equation (8).

$$BP = \frac{TC}{(Cp1 - Cp2)} \tag{8}$$

Where:

BP = Break-even point

TC = Tool cost

Cp = Cost per part

2.5.8 Hydraulic Clamping

In fixturing, power work holding systems, particularly hydraulic systems are progressively replacing mechanical clamping systems. This trend is driven by the need for faster production and the automation of processes. However, implementing a hydraulic system is not as straightforward. It requires a significant initial investment in hydraulic pressure supply systems, as well as constant maintenance and monitoring.

Nevertheless, power workholding systems offer several advantages in manufacturing operations. They enable faster clamping, reducing non-productive time during loading and unloading cycles. These systems also contribute to faster machining by providing consistent clamping forces and adjustable holding forces, allowing for heavier feeds and faster speeds.

Consistency and repeatability are crucial features of power work holding systems. They eliminate the reliance on operator strength and diligence by providing consistent clamping forces controlled by a power source, resulting in fewer scrapped parts and improved quality. Additionally, power work holding systems include automatically adjusting work supports, which enhance stability and precision during machining operations.

Beyond these advantages, power work holding systems offer remote clamp operation for enhanced operator safety, reduced operator fatigue through power-actuated clamps, automatic sequencing for improved efficiency, fixture compactness, and increased machine-tool productivity due to consistent holding forces.

A hydraulic clamp can be single-acting or double-acting. Single-acting clamps are simpler and cheaper to install as they have only one hydraulic chamber. When not actuated, a spring returns the clamp to its original position. However, double-acting clamps are more suitable in certain situations:

- When utilizing flood coolant, a single-acting clamp may face difficulties as the coolant can enter the spring compartment, potentially causing malfunctions. This compartment needs to be open to allow the air inside to escape, preventing pressure buildup from the opposite side.
- Sometimes, it is simpler to have the second acting force to move the weight of the fixture, especially when dealing with heavy loads and larger clamping mechanisms.
- With large fixtures that have long tubing lines and hydraulic components, the return of the fluid can present some resistance due to fluid viscosity or frictional forces at piston seals.

Another variation in hydraulic clamping systems is how the liquid reaches the clamping mechanism. There are four options in this case:

1. Passing tubes over the fixture base: This option does not require machining of the base and has a low implementation time. However, the tubes are exposed and susceptible to impact.
2. Passing tubes under the fixture base: This requires the base to be elevated compared to the pallet tooling plate.

3. Manifold mounting: It involves machining the base plates to create passages that align with O-ring ports underneath the hydraulic clamps.
4. Cartridge type of manifold mounting: The hydraulic clamp is embedded in the base plate through specially prepared mounting holes.

Each approach has its advantages and considerations, and the choice depends on factors such as the specific requirements of the application, ease of implementation, and maintenance considerations.

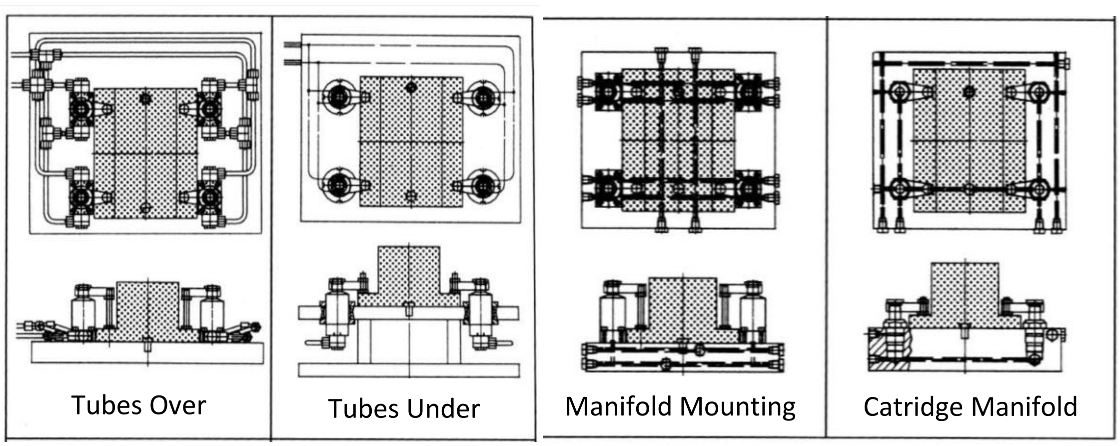


Figure 21 - Types of Hydraulic Clamp Tubing [27]

3 Development

3.1 Methodologies

The following methodology will be employed during the development in this thesis:

1. General Study (Fixturing):
    - To utilize the literature review knowledge about fixturing to gain a comprehensive understanding of the principles, types, and standards of fixturing.
    - Understand ABER's products manufacturing process.
2. Analysis of Defects:
    - Analyze the defects and limitations of the previous fixture to identify areas for improvement and optimization.
3. Development:
    - Develop a new clamping system design based on the identified requirements and fixturing principles.
    - Utilize CAD software to create detailed designs of the new fixture components, considering factors such as dimensional accuracy, alignment, and functionality.
4. Production:
    - Ensure that quality control measures related to dimensional tolerance are well implemented during the production process to maintain the accuracy needed for the fixture system.
5. Assembly:
    - Assemble the manufactured components into the final fixture system according to the designed specifications.
    - Verify proper alignment, fit, and functionality of the assembled fixture.
6. Testing:
    - Perform testing and evaluation of the newly developed fixture to validate its performance, stability, and reliability.
    - Measure and analyze the accuracy of workpiece positioning and deformation achieved with the new clamping system.
7. Conclusion and Future Work:

- Conclude analyzing all the previous information and the success of the fixture developed.
- Present future work that could be done to complement and continue the tool development.

Based on the information contained in literature review, it is evident that the machining of mechanical parts encompasses various aspects. To produce a product, a series of factors must be taken into consideration and studied beforehand to achieve the best possible outcome.

Therefore, the current chapter will follow the following logical progression:

Firstly, the main characteristics of the current fixture responsible for machining the pump housings in cast iron, which is experiencing issues during production, will be addressed. Subsequently, the problems will be analyzed, and potential solutions will be explored. During this analysis, a study of the cutting parameters and previously used cutting tools employed during the machining process will be conducted to acquire necessary information for the development of new fixtures. Factors such as material strength calculations and material selection will also be considered.

Finite element simulations will be performed at different stages throughout the process with the intention of identifying the problem and testing the results to ensure that the issue has been solved before making the necessary investment in alterations. Finally, the practical changes in the production line will be observed, requiring the assembly of new fixtures and verification of the findings.

By following this logical sequence, it will be possible to address the current issues with the machining process and implement effective solutions. This approach aims to improve the production line and achieve the best possible outcomes for the final product.

3.2 Old Middle Housing Fixture Design

On ABER's company website, it is possible to find a catalog featuring all the components that are commercialized by the company. Since the number of products is extensive, this catalog is organized into modules that separate each type of developed product. In the module related to Piston Pumps, it is possible to find different models. Each of them represents a family (series) of pumps with specific characteristics for distinct purposes. The families present in the catalog are: Variable Displacement Pumps (VDP), Bent Axis Piston Pumps (BI series), Figure 22, Double Bent Axis Piston Pumps (BID series), Straight Piston Pumps, and Double Straight Piston Pumps. For each of the mentioned types, through variations in the internal or external components of the pump, they acquire specific qualities that are chosen to meet the needs of each buyer.

Figure 22 - BI cast iron ABER pump

The main characteristics that can vary are:

• Pump displacement - Similar to the displacement of a combustion engine, this indicates the volume displaced with one rotation. To vary the displacement, it is possible to increase the number of pistons or increase the diameter of the pistons as well as their stroke.

• Pressure range - This indicates the range within which the pump is capable of operating.

• Flange standardization - Essentially, this refers to the hole layout on the flange that ensures the connection of the pump to different power take-offs, for example. Usually, these standardizations correspond to the destination country of the pump.

Therefore, to serve the largest number of customers, it is up to the company to produce different configurations. The pump under study in this dissertation is the Iron Cast Bent Axis Piston Pump, as shown in Figure 22. Unlike the BI and BID pumps, these are made of cast iron, which allows them to reach much higher pressures while still being very compact due to the superior properties of iron compared to aluminum. Compact design is often a requirement for buyers, especially in applications such as trucks, which is one of Aber's main markets. The available space for component assembly is limited, and there may be contact between the rear axle truck transmission and the hydraulic pump. The Aber customer may choose among the available flange and axle options, as well as the pump displacement and operating pressure, as indicated in Figure 23.

DISPLACEMENT cc/rot (in³/rot)	FLANGE AND AXLE OPTIONS					
	DIN 5462 ISO 7653 (EN)	DIN 9611 AGRICULTURAL (DA)	DIN 5482 MULTIPLIER (DM)	DIN 5480 ISO 3019-2 (IA1)	SAE B* 4 BOLTS (B4)	SAE B* 2 BOLTS (B2)
UP TO 400 bar (5800 psi)						
17 (1.0)	BIF17M	BIF17MDA	BIF17MDM	-	BIF17M5B4	BIF17M5B2
26 (1.6)	BIF25M	BIF25MDA	BIF25MDM	-	BIF25M5B4	BIF25M5B2
32 (2.0)	BIF30M	BIF30MDA	BIF30MDM	-	BIF30M5B4	BIF30M5B2
42 (2.6)	BIF40M	BIF40MDA	BIF40MDM	-	BIF40M5B4	BIF40M5B2
50 (3.1)	BIF50M	BIF50MDA	BIF50MDM	BIF50M5IA1	BIF50M5B4	BIF50M5B2
60 (3.7)	BIF60M7	BIF60M7 DA	BIF60M7DM	BIF60M7IA1	BIF60M7B4	BIF60M7B2
UP TO 350 bar (5000 psi)						
81 (4.9)	BIF80M7	BIF80M7DA	BIF80M7DM	BIF80M7IA1	BIF80M7B4	BIF80M7B2

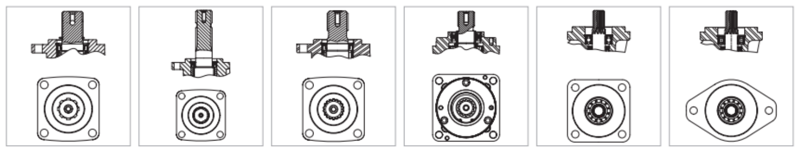


Figure 23 - BI series ABER Catalogue

When making such a choice, it is possible to notice a change in the reference name of the pump. For example, **BIF17M7DM**, has all its components represented in Annex 1, in the form of an exploded view, allowing to see where each component is fitted.

- **BIF** indicates that it is a cast iron bent axis piston pump.
- **80** is related to the liquid displacement per rotation, i.e., 17 cc/rot.
- **M** is linked to the pump size.
- **7** is related to the number of pistons present in the model. For the Iron Cast Bent Axis Pumps, that number can also be 5 instead of 7.
- **DM** is the type of flange and axle used, which defines the connection with the selected power take-off (PTO). As shown in Figure 23, ABER needs to produce a variety of different standards to enter different parts of the world market.

Depending on the choice, the pump components vary to ensure the desired correct operation. One of the components that can change during this selection process is the middle housing, which surrounds the pump and provides a separation between the external and internal environments. It is produced in two different sizes and changes according to the chosen displacement, as it will affect the size of the internal cylinders. The smaller size is referred to as M (medium), as shown in Figure 24, while the larger size is referred to as P (plus), as shown in Figure 25. Both housings are the main focus throughout the thesis, as they frequently present defects at the end of the production line. Therefore, their production must be reformulated as they bring losses to the factory in various ways.

Figure 24 - BIM Middle Housing

Figure 25 - BIP Middle Housing

3.2.1 Pump Housing

The pump housing's main functionality is to house all the other components. Additionally, it protects the internal components by preventing interference from the external environment with the interior of the pump, thus preventing the infiltration of liquids and solids, damage to components due to undesired impacts, among other things.

In this case, the pump casing is divided into three parts, as shown in Figure 26. The middle part is called the Middle Housing, which houses the majority of components such as pistons, shaft, and piston housing. The Fixation Housing is the casing that protects the shaft section. Various components are assembled in this housing, including bearings that ensure the proper housing of the shaft and seals that prevent any external elements from entering the pump and causing defects when interacting with the mechanical parts. On the side where the liquid enters and exits the pump, the casing that houses these elements is called the Rear Cover.

Figure 26 - Pump Housings for BIP (Rear Cover, Middle Housing, Fixation Housing)

3.2.2 Casting Process

In order to produce the pump casings described earlier, ABER employs an external casting process, which is a common approach for manufacturing large-sized and intricately shaped components. The casting process is needed to significantly reduce the need for extensive machining. The castings are already close to the final shape, requiring minimal machining to achieve the desired specifications. This results in reduced tool wear and shorter production times.

The Middle Housings are cast using a sand mold casting technique. Prior to casting, molds need to be manufactured, as shown in Figure 27, which accurately capture the Housings shape with slight modifications as explained next. This mold and pattern presented are ABER property as when is needed to contact a new casting company, the company will use this set to create its own Mold and Pattern for sand casting the part.

Figure 27 - Pattern and Mold of BIM Middle Housing

One important distinction is that the pattern does not include the cavity found in the casing. This design allows for easy removal of the mold from the sand once it has acquired the desired shape. The cavity is created using a separate component called sand core.

Furthermore, it's worth noting that the dimensions of the pattern differ slightly from the final cast product. During the casting process, metals undergo shrinkage as they solidify. To compensate for this phenomenon, the dimensions of the pattern need to be slightly larger, ensuring that the resulting mold cavity is of the correct size. This is an essential consideration, as shrinkage occurs due to variations in density during solidification.

ABER typically utilizes EN-GJS-400-15 as the material for casting all their components, adhering to the European standard DIN EN 1563 or GGG40 according to the DIN1693 standard. It is important to account for a 1% shrinkage in volume during the cooling process, as specified by the supplier. This information is crucial for designing the patterns used in the casting process.

Lastly, the mold contains excess material in all needed regions, which will undergo machining. The machining process will remove material of the cast part to achieve the desired dimensions, tolerances, and surface finishes in the final product. These changes can be visualized in Figure 28, which shows a portion of the technical drawing of the casting product.

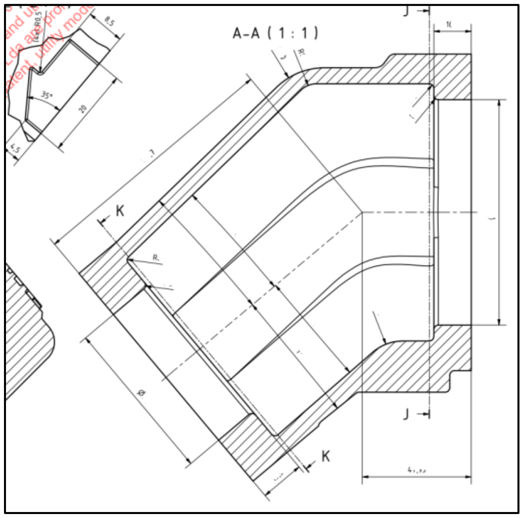


Figure 28 - Technical Drawing Middle Housing for Casting

3.2.3 Machining Process

At ABER factory territory, the middle housings are machined using one of the three CNC centers linked to Palletech, model HCN-4000 from Mazak. The main specification of these machines can be seen in Table 2 [11].

Table 2 - HCN-4000 specifications

Stroke	X axis / Y axis / Z axis (mm)	560 / 640 / 640 mm
Table	Table dimensions	400 mm x 400 mm
	Load capacity	400 Kg
Spindle	Max. spindle speed	12000 RPM
	Spindle acceleration	1,48 sec (0 → 12000 RPM)
Feedrate	Rapid transverse rate	60000 mm/min
	Cutting feedrate	1 – 60000 mm/min
Motors	Spindle motor (30-min / continuous rating)	18,5 kW/15 kW
	Flood coolant pump motor	730 W / 1210 W (50 Hz / 60 Hz)
Machine size	Height / Width / Length	2713 / 2400 / 5454 mm
	Weight	10720 Kg

Thanks to the advanced technology involved in these machines, fewer operators are required at this stage. However, several departments need to coordinate to ensure that this process is executed with excellence. This includes developing machining codes, studying tool selection and cutting parameters, analyzing the tool's lifespan, and refining fixtures. To support these efforts, a quality control team works utilizing various machines such as CMM machines.

The machining process transforms the cast component into the machined piece, as shown in Figure 25. Once machined, the part is ready to be assembled with other components, requiring only a cleaning and painting process.

The use of the rotary table on the HCN-4000 machines allows the part to be machined in a single setup. This is made possible because there are three directions that the CNC spindle can take to machine all the required areas: the front face, the back face, and the side hole. These three directions are situated on the same plane. By aligning this plane parallel to the fixing table's plane, access to each axis can be achieved with just one indexing movement of the rotary table.

This feature greatly enhances efficiency and productivity in the machining process. It eliminates the need for multiple setups or repositioning of the part, saving time and reducing the possibility of errors. With the ability to access different machining directions with a single indexing movement, the HCN-4000 machines optimize the machining process, ensuring accurate and consistent results for the finished component.

3.2.3.1 Palletech

The Palletech system, Figure 29, is a flexible solution designed to increase production efficiency and productivity. It consists of an intermediate machine in the form of a corridor with doors for each CNC center, as well as an entrance door for the Palletech system. Developed by Mazak, this system incorporates intelligent software for operator control.

Using an intelligent automated rail system, the pallets, each with a tool plate above it, located within the corridor can be transported by a movable station to one of the three machines or to the machine's entry/exit point. The Palletech system is equipped with information about the machining times for each machine and the content to be machined on each pallet. This allows it to manage the entire workflow without the need for operator intervention. The operator's responsibility primarily involves removing and feeding the machine with the correct pieces, which includes placing and clamping the parts on the pallet with the corresponding fixture. The operator also inputs the necessary information related to the respective pallet into the machine's system.

In this way, the Palletech system operates as an automated waiting queue with multiple pallets waiting to be machined or to have their machined parts swapped for non-machined ones. The system streamlines the production process by efficiently managing the flow of workpieces, minimizing downtime, and optimizing the utilization of the CNC machines. It enables seamless transitions between different machining tasks and maximizes productivity by reducing manual handling and setup times.

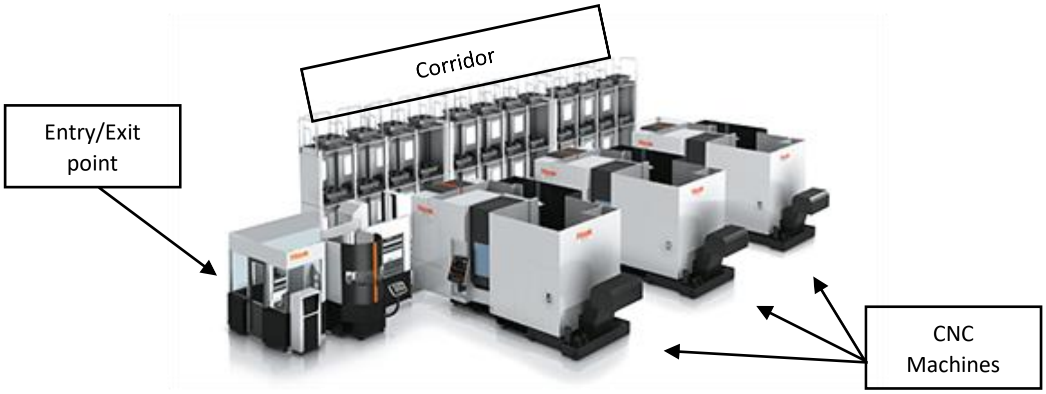


Figure 29 - Palletech and 3 horizontal CNC

3.3 Fixture Analysis

The fixture used for securing the middle housing to the CNC machine should be designed to ensure proper fixation and alignment, as discussed in the literature review chapter. However, it is evident from the analysis of the rejection rates, i.e., percentage for each housing unit that was not accepted due to any issue identified by the quality control department, for both the BIP and BIM middle housings in the last 2.5 years , as shown in Table 3, that the current production model for these housings needs to be redesigned.

Table 3 - Rejection Rate BIP and BIM Middle Housing

Middle Housing\Status	**Rejected**	**Accepted**	**Rejection Rate**
BIM	154	2239	6,88%
BIP	38	164	23,17%

Given that quality control does not identify a high rejection rate for cast parts before machining and that other parts with similar machining operations also do not have high rejection rates, it is possible to affirm that the origin of the higher rejection rate for these two references indicated by the quality control sector comes from the fixture system used. Therefore, it is necessary to reevaluate and modify the fixture design to improve the production process and reduce rejection rates. To improve the fixture is necessary to analyze it and understand the mistakes made.

Figure 30 - P size middle housing old fixture

The concept behind the old fixture, Figure 30, makes use of two hydraulically clamps, as shown in Figure 31, to apply a clamping force on the intermediate section of the pump housing, perpendicular to the surface. The location of the piece is achieved using four support pins positioned at the four corners of the housing, as shown in Figure 32.

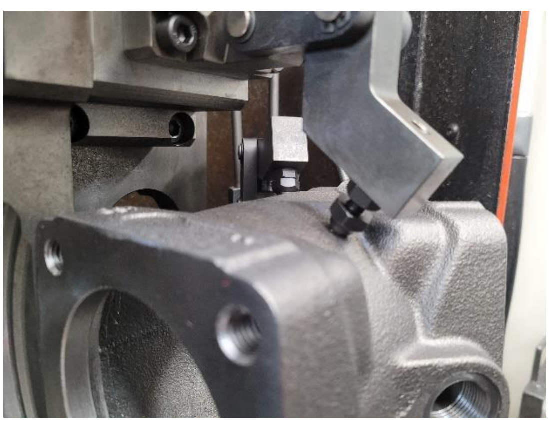


Figure 31 - Hidraulic Clamp for Clamping BIM Middle Housing

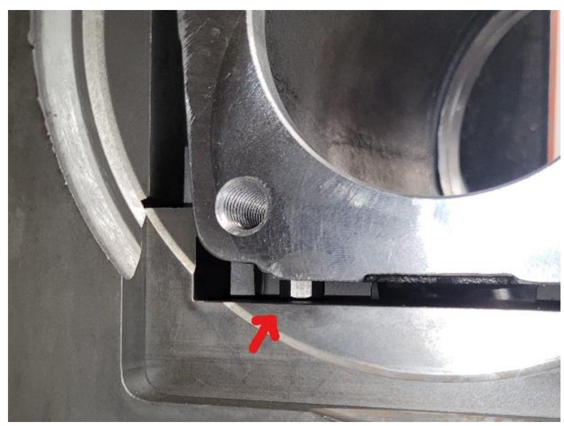


Figure 32 - Locator Pins for Supporting BIM Middle Housing

However, the fixture developed for this reference fails to fulfill its function due to several reasons, resulting in significant losses for the company:

1. Deformation of the housing: The clamping pressure exerted on the housing can lead to elastic and sometimes plastic deformation of the workpiece. As a result, the position of the piece varies when it is clamped, and the machined features do not align with the intended design. This deformation occurs because the clamping forces are not directed towards the

locators but rather perpendicular to the surface of the middle housing creating stresses on the body because of the lack of part rigidity in relation to the loading implied.

2. Tolerance issues: As a consequence of the previous point, measurements conducted in the CMM measuring subchapter will reveal that the important dimensional and cylindricity tolerances required for future assembly are not met, conflicting with the design specifications of the reference technical drawing. Consequently, many parts machined using this fixture end up being scrapped, resulting in significant financial losses for the company.

3. Inadequate support and location principle: The fixture's support and location principle are poorly developed, as it fails to ensure that the workpiece remains stationary during machining. The four locating pins beneath the workpiece are insufficient to fully locate and support the piece, allowing for undesired movement in the remaining degrees of freedom. According to the 3-2-1 Locating Principle, it is necessary to have locators in three mutually perpendicular planes. In this case, only one plane is located, allowing the workpiece to move freely in other directions. Even if the locating pins are replaced with grippers, it is challenging to guarantee that the workpiece will not move under the high forces generated by the cutting tools, especially without additional locating planes.

4. Dimensional variation: Due to the sand-casting process, the dimensions of the workpieces can vary significantly. For example, considering the dimension represented in Figure 33, applying Aber's geometric tolerance DCTG11, the variation can reach up to 5mm [25]. Consequently, when machining the workpiece, since it is located and supported from the bottom, the machining hole locations are not centered on the workpiece's front and rear face but instead at a fixed distance from this bottom located plane according to the machining operations code instructions.

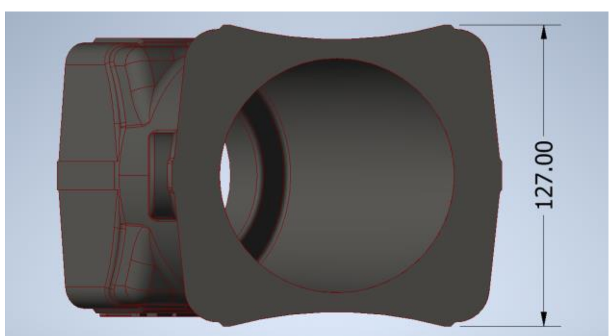


Figure 33 - Vertical Dimension for BIP Middle Housing

The machining code is not instructed to perform precision probes measurements on each part individually, resulting in a strict machining location and a lack of adaptability to correspond to the dimensional variation. Instead, the method utilized is to measure a finite number of parts before scaling up production aiming to determine an average location for each machining operation. By doing this, is possible to minimize the machining time for each workpiece.

5. Pressure Drop: The hydraulic press system within the fixture was poorly designed, leading to a loss of pressure in a much shorter time frame than desired. When the fixtures are used in conjunction with Palletech, they serve as a storage system for workpieces. The workpiece may wait for machining for an extended period, depending on the urgency of other products and the availability of the three CNC machines. Therefore, if the pressure is lost during the waiting period, the consequences can be severe. The slightest oil leakage can spoil the entire system, as it not only affects the workpiece being machined but also creates a threat to the CNC machines themselves, which can be damaged when a workpiece loses fixation and is accelerated by the cutting forces.

3.3.1.1 Cutting Operations

As previously mentioned, the middle housing is machined in a single setup. This means that the workpiece is clamped in its casting form and unclamped with the final shape, ready for assembly with the rest of the pump components. Due to this, all areas where operations will take place need to be clear so that the cutting tool and the machine's spindle can approach without contacting the developed fixture.

The approach of the tools for each housing is performed in one of the three axis that need to be machined (front face, rear face, or side hole). The workpiece operations are sequenced so that all necessary machining in each axis is completed before moving to the next one. This is due to the extra time required for the indexing of the table that allows for workpiece rotation and minimization of cutting forces direction changes.

The required operations have some differences among BIP and BIM housings, but for exemplification Table 4 presents the operation sequence, the part axis in which they are performed, cutting tool type, and cutting parameters used for BIP Middle Housing.

Table 4 - Tools and Cutting Parameters for BIP housing machining

	Operation Sequence	**Tool Type**	**Tool Ø** (mm)	V_c (m/min)	F_n (mm/rev)
Axis 1	Front Face Roughing	Face Mill	50	200	0,6
	Front Face Finishing	Face Mill	63	300	0,3
	Front Hole Ø83,5	End Mill	50	260	0,8
	Front Hole Ø84	Boring Bar	84	200	0,1
	Drill Bit 10,2 for M12	Drill	10,2	85	0,12
	Chamfer 15 for M12	Chamfer	15	200	0,2
	Tap M12	Tap	12	12	1,75
	Chamfer Ø84 Hole	Chamfer	15	200	0,2
	Open Hole Ø94	End Mill	50	240	0,05
	Open Hole Ø107,5	End Mill	77	600	0,05
Axis 2	Back Face Roughing	Face Mill	50	200	0,6
	Back Face Finishing	Face Mill	63	300	0,3
	Back Hole Ø104,8	Drill	104,8	110	0,05
	Back Hole Ø105	Boring Bar	105	200	0,1
	End Mill Ø107,5	End Mill	77	600	0,05
	Drill 10,2 for M12	Drill	10,2	85	0,12
	Chamfer 15 for M12	Chamfer	15	100	0,12
	Tap M12	Tap	12	12	1,75
	Chamfer Ø107,5 Hole	Chamfer	77	600	0,05
Axis 3	Lateral Hole Ø20	Drill	20,5	160	0,06
	Lateral Roughing/Finishing	Face Mill	50	180	0,1
	Chamfer Ø22 Hole	Chamfer	15	200	0,2
	Tap M22	Tap	22	Manual	Manual

3.3.1.2 Deformation due to Clamping force

In order to demonstrate the origin of the problem with the old fixture, this finite element simulation shows the deformation resulting from the clamping forces applied to the pump body. The calibrated pressure in the hydraulic system, which can be seen on the pressure gauge when pressure is applied to the system, is 180 bar. This value was determined previously through a series of attempts to ensure that the workpiece would not move during clamping and would not deform too much.

The cylinder into which this pressure is inserted has an internal diameter of 22 mm, as shown in Figure 34. With a simple calculation, it is possible to determine a vertical force on the cylinder of 6842.3N, indicated in black in Figure 35. Based on the lever distances at the contact moment with the workpiece surface, the force indicated in orange can be calculated as 2715.23 N.

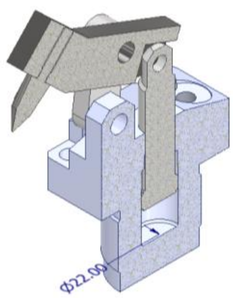


Figure 34 - Clamping Tool

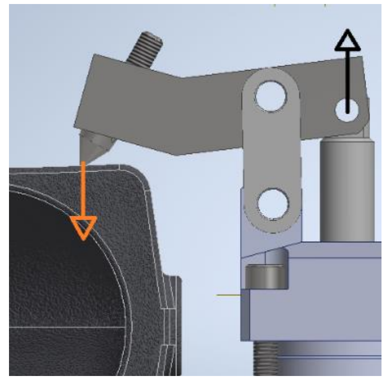


Figure 35 - Forces and lever dimensions

By using the finite element method, it is possible to conduct a stress analysis in the extension from inventor software provided by the company. This allows for the study of deformation and stresses present in the pump housing. A model was created using the existing CAD file of the housing in question, which was already developed in Inventor. A new material was added to the material list in the program to make the mechanical characteristics of the cast iron EN-GJS-400-15 as realistic as possible. The inserted mechanical properties can be seen in Table 5.

Table 5 - EN-GJS-400-15 mechanical properties [40]

Mechanical Properties	
Young's Modulus $(\mathbf{GPa})$	169
Poisson's Ratio $(-)$	0,26
Density $(\mathbf{Kg/m^3})$	7200
Yield Strenght $(\mathbf{MPa})$	250
Tensile Strenght $(\mathbf{MPa})$	400

The forces exerted by the two clamps were applied to the pump body in the locations and directions designed for them. The CAD design of the housing includes two surfaces indicating where the clamps will exert force. This information is important to be marked at the CAD and technical drawing, so it is possible to communicate to the supplier of the cast part, as it specifies the region of clamping or locating, ensuring that this surface is well defined. If there is any casting defect on this surface, the part cannot be used and should not be sent to ABER.

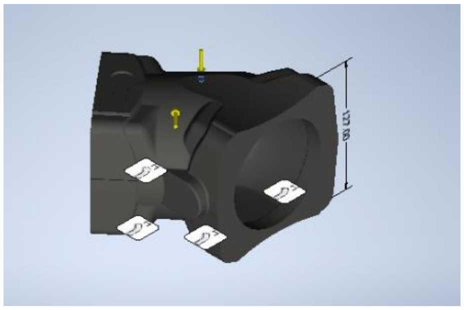


Figure 36 - Forces directions and positions

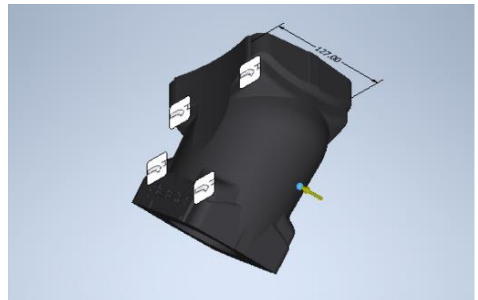


Figure 37 - Fixed constraints positions

The report provided by the study allows for the analysis of two factors:

Firstly, the stresses present during clamping are concentrated mainly in the support and force application regions, reaching a maximum local value of 446,7 MPa on the Von Mises scale. The rest of the body doesn't present high stress values, as shown in Figure 38.

However, when examining the displacements, it becomes apparent that there are some areas where displacements are significant. Therefore, during machining, there is a misalignment of the workpiece due to the elastic deformation previously described, resulting in incorrect machining. In the front face, there is a large area with a deformation of up to 0,048 mm, as shown in Figure 39. The same issue occurs in the region where the forces are applied, leading to the same problem as the internal part is also machined.

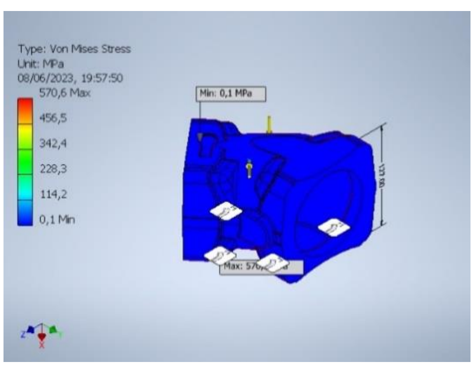


Figure 38 - Von Mises Stresses

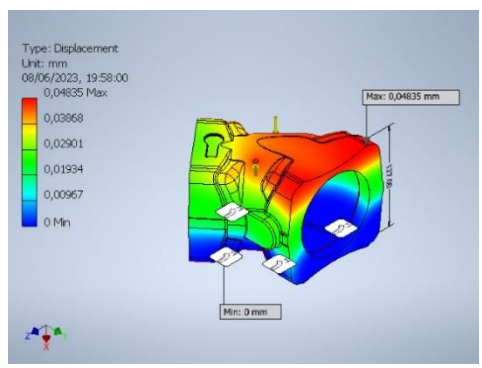


Figure 39 - Displacement

It can be predicted that the problem is exacerbated during machining, as the force applied to the workpiece remains the same, but the structural resistance of the part decreases as material is removed and the thicknesses decrease. To analyze the critical case, a study with the same forces and fixtures was conducted for the machined part model.

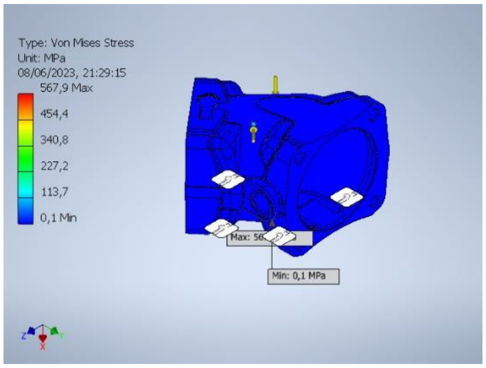


Figure 40 - Von Mises Stresses of Machined Part

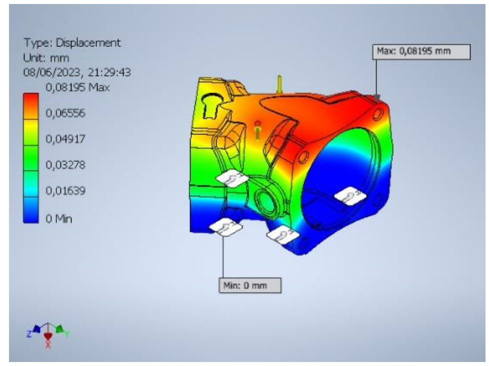


Figure 41 – Displacements of Machined Part

The results confirm the established hypothesis. Figure 40 and Figure 41 shows the regions most affected after material loss, indicating the locations of maximum stress and deformation.

Table 6 summarizes the important information from both reports, including the maximum deformations and stresses for each case and in each location of importance, making it more practical to visualize the influence of material loss on these factors.

Table 6 – Stresses and Displacements for Casted and Machined BIP Middle Housing

	Casted	**Machined**
Max displacment Front Face [mm]	0,048	0,082
Max stress Front Face [MPa]	17,8	33,2
Max displacement Forces locations [mm]	0,046	0,075
Max stress forces locations [MPa]	210,3	216,5
Max displacements Locating Pins [mm]	-	-
Max Stresses locating Pins [MPa]	570,6	567,9

Regarding the front face displacements, this was the parameter that changed the most after machining, demonstrating the importance of the material in maintaining the original shape of the face. The stresses on the front face and the displacements in the force areas also increased considerably with the weakening of the structure. The locating pins and force location stresses did not have a significant variation after machining since the force continues to be applied and propagated to the same location, even if it does not follow a straight line, but rather contours the middle housing body.

Through this analysis, the main problem with using this clamping tool becomes clearer. The workpiece location is not ideal, as it cannot accurately locate the workpiece due to its deformations. The upper part of the front face has a maximum variation of 0.082mm, which is much larger than the tolerances allowed in the following subchapters. The application of forces is done in an area where the material thickness is minimal and goes towards the empty part of the workpiece. As a result, the deformations are aggravated again, as the clamping force is not directed to the part locators, which should directly absorb all the clamping force.

The deformation that occurs in the workpiece leads to poor machining quality that does not adhere to the required dimensions and tolerances. As a result, during the assembly process, other parts will have difficulty fitting on the created surfaces.

3.3.1.3 Technical Drawings

To specify the geometry of the machined part, the technical drawings of the project are created in such a way that all dimensions and tolerances are well specified. This allows the geometry to be implemented accordingly in the CNC machine programming code.

In the case of BIP, exhibited in Figure 42, certain tolerances are project requirements to ensure proper functioning and good fit with other assembled parts. Failure to meet these tolerances can result in difficulties or prevent the assembly of other parts, as well as causing malfunctions in the hydraulic pump, such as misalignment of surfaces.

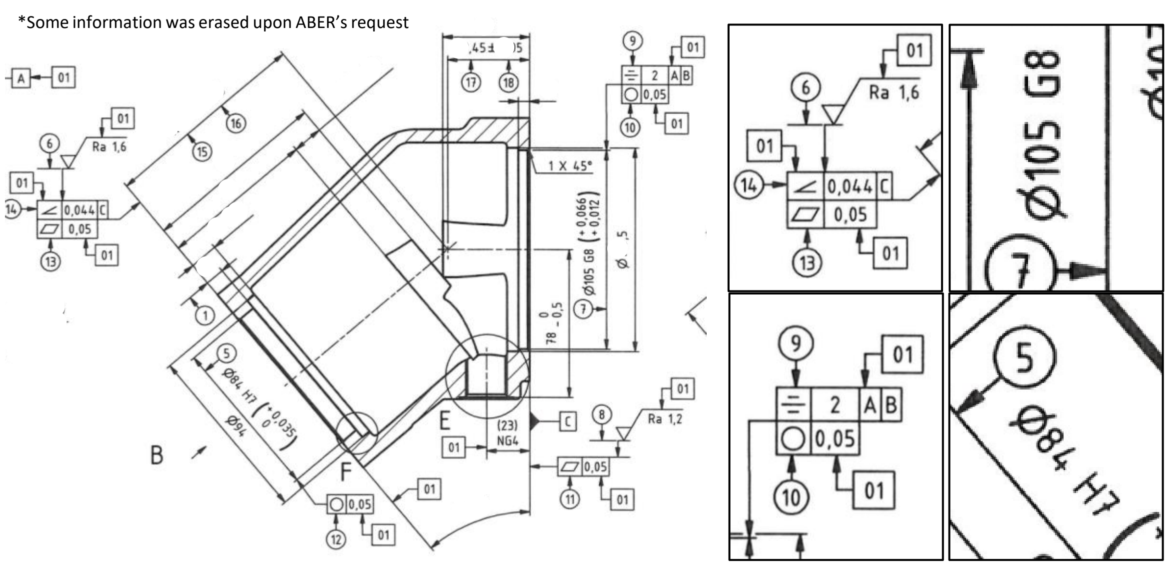


Figure 42 - Technical Drawing, BIP Middle Housing Pump

H7 and G8 are dimensional tolerances applied to the Ø84 and Ø105 holes, respectively. The H7 tolerance indicates that the actual dimension has a tolerance grade of 7, i.e., IT7. For an 84 mm dimension, this corresponds to a tolerance range of 35 µm, and the lower deviation of the hole is defined as 0mm. Therefore, the maximum allowed diameter, D_{max}, is calculated using equation (8), resulting in a value of 84,035 mm. For the second case, D_{max} is equal to 105,066 mm.

$$D_{max} = D_n + ES \tag{8}$$

In addition to the existing dimensional tolerances, these are the geometric tolerances also present in the technical drawing [41]:

○ Circularity is a geometric tolerance where a straight section should always be between two theoretically exact, coplanar, and concentric circles, with a specified distance between them, in this case, 0.05mm.

⏥ Flatness refers to a surface and requires that all points on that surface be limited by two parallel planes with a specified distance between them, as shown in Figure 8, which is 0,05mm.

∠ Angularity, similar to flatness, requires that all points on a surface be between two planes that are parallel at a specified distance. However, in this case, the inclination of both planes is related to another surface in the project.

3.3.1.4 CMM Measurements

CMM stands for Coordinate Measuring Machine. It is a device used in manufacturing and quality control processes to measure the dimensions and geometric properties of objects. The company acquired one of these machines in 2018, from the brand Global, model 07-07-05, Figure 43. The machine has the capability to perform point measurements on the studied object with a precision of $\pm 2\ \mu m$ in a fast and repetitive manner. This process is called probing. The data points obtained can be used to create a digital representation of the object's surface, which can be analyzed and compared to the desired specifications.

Global 07-07-05 can measure various parameters, including dimensions, distances, angles, geometrical tolerances. The measurements obtained from the CMM are used to verify the accuracy and quality of the machined parts and ensure compliance with the design specifications.

The data collected by the CMM can be analyzed using a specialized software that provides graphical representations, statistical analysis, and comparison against the intended specifications. This allows to identify any deviations or errors in the manufacturing process and make necessary adjustments to ensure product quality.

Figure 43 - ABER CMM, Global model 07-07-05

Regarding the BIP Middle Housing machining, two samples from four different orders, totaling eight middle housings, were randomly selected from the production line for measurements and comparison against the specified tolerances. This process totalized eight reports, which were compiled to analyze the results obtained from CMM measurements.

For each part, the same procedure was done. The machined part was mounted on the table shown in Figure 44, following the standard procedure for using the Global 07-07-05. It is worth noting that even the ambient temperature is controlled to ensure that it does not have any influence on material expansion, which could be detected by the contact probe. The machine's software was then configured to measure the location and circularity of the 84 mm diameter hole, and the same was done for the hole on the opposite side with a 105 mm diameter. Additionally, the flatness of the machined surface was measured for both cases, and finally, the angularity tolerance was measured between the rear face and the theoretically exact front face.

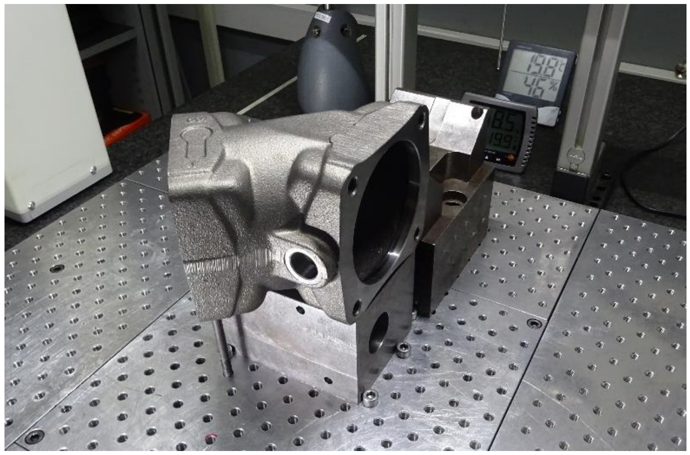


Figure 44 - BIP housing mounted at Global 07-07-05

Analyzing the results, is evident that there is a problem in the machining of this part. The measurement performed is able to detect issues within certain tolerances. Firstly, regarding angularity tolerance, the CMM did not consistently show indications of form error for all references. Almost all of them obtained an intermediate value that did not exceed the maximum tolerance, as shown in Figure 45, with only one exception that reached a value close to the tolerance limit. Overall, this indicates that the rear face is at the correct angle compared to the front face.

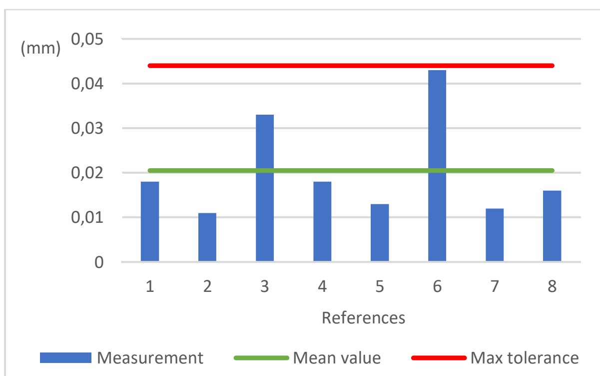


Figure 45 - Angularity Tolerance Measurements

When it comes to the flatness of both faces, is possible to see the best results of the CMM measuring, as shown in Figure 46 and Figure 47.

For all 8 references, the results were well below the imposed tolerance. However, it is noticeable that the front face exhibited slightly more irregularity compared to the rear face, with maximum values of 0.013 vs 0.005 mm. This already is an indicator that maybe the front face is having a deformation problem, since the cutting tools and cutting parameters utilized for both surfaces are the same, and the results indicate flatness differences between both.

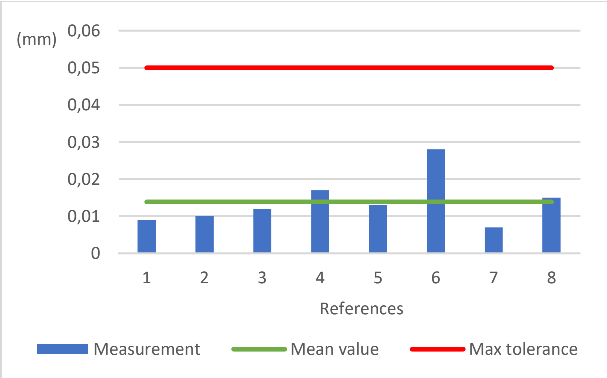


Figure 46 - Flatness Tolerance Measurements Front Face

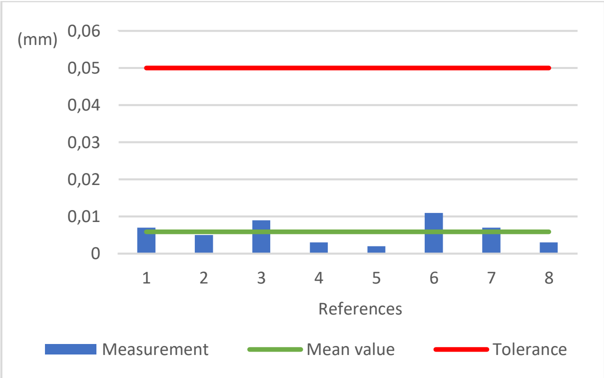


Figure 47 - Flatness Tolerance Measurements Rear Face

The main problem starts to appear during the analysis of results related to circularity and dimensional tolerance of the holes. Regarding the Ø84 hole H7 dimensional tolerance, Figure 48, it is noticeable that the Mean Line is between the maximum and minimal tolerance. However, half of the analyzed references presented dimensions outside the desired tolerance, making them to be considered scrap parts. Depending on the error, they can be reworked, but this constantly happening would disrupt the straight-line production flow and cause logistical issues with the machine centers.

The circularity of the same hole shows highly irregular values, as shown in Figure 49. Some of them do not comply with the tolerance and may not be able to assemble the rear cover of the BIP. It is also possible to observe a relationship between the H7 tolerance and the circularity tolerance for each reference. Often, when one presents higher values, the other also tends to do so.

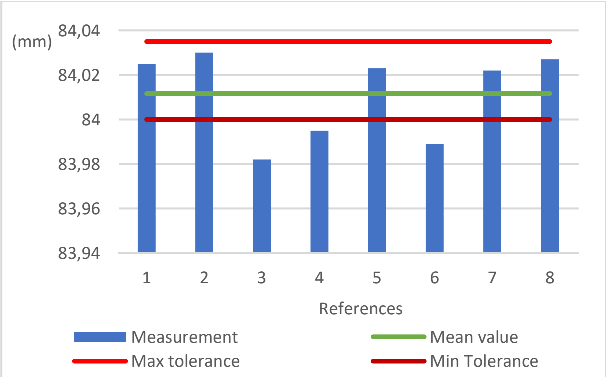


Figure 48 - H7 Tolerance Measurements for Ø84 Hole

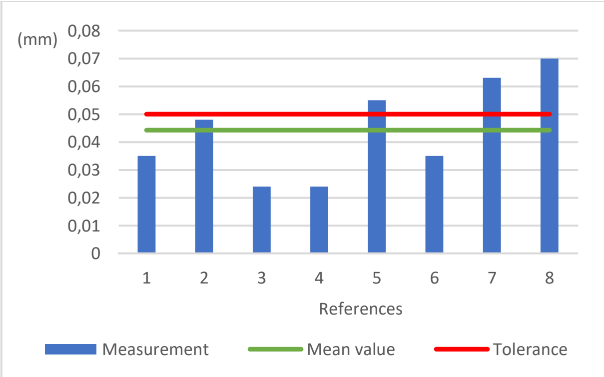


Figure 49 - Circularity Tolerance Measurements for Ø84 Hole

Regarding the Ø105 hole, the obtained data shows that it is in this location where the problem related to clamping forces is intensified. The G8 tolerance shows the Mean Line in Figure 50, outside the desired tolerance, with 6 references having values exceeding the maximum limit for G8. The circularity also exhibits the same observation, as the Mean Value, along with 5 references, shows measurements above the tolerance, Figure 51.

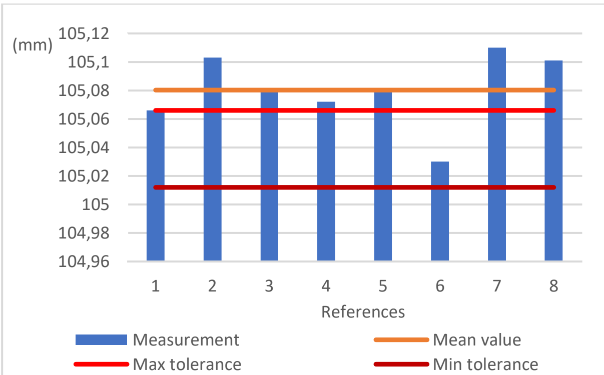


Figure 50 - G8 Tolerance Measurements for Ø105 Hole

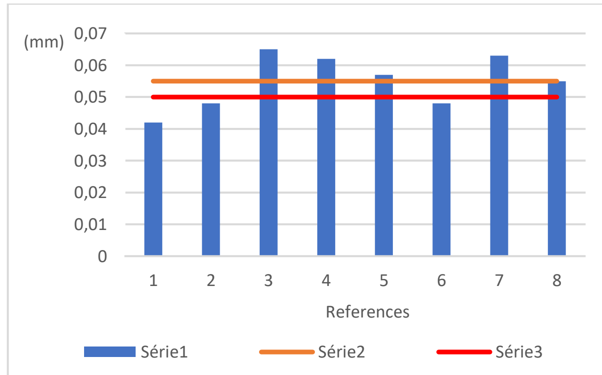


Figure 51 - Circularity Tolerance Measurements for Ø105 Hole

Therefore, based on the data visualized above, it is possible to attempt to understand the origin of the problem that causes the holes not to meet their tolerances. Combining the information from the results with those obtained during the FEM study for clamp force deformation, it is observed that the worst results for both approaches occur in the same location, confirming the issue with the fixing model.

The established theory is that machining while the part is deformed, makes the hole momentarily acquire the supposed shape of the holes. However, when unclamping the part, it returns to its original shape due to elastic deformation, resulting in ovalization in both holes, with greater intensity in the 105-diameter hole due to higher deformation in that location.

Regarding the rest of the tolerances, the established hypothesis does not have much influence on those measurements, which is why they do not vary. The deformation during tightening primarily has a vertical direction, so the elastic deformation would not affect the plane on which the face is situated. However, the slight deformation in the normal direction of the front face likely explains the worse flatness quality compared to the rear face.

The same measurements were carried out for the BIM middle housing, and in this case, the problem was also observed, but on a smaller scale. Fewer references in the measured sample exceeded the maximum tolerances, and for those that did, the deviations were significantly smaller compared to the BIP measurements.

3.4 New Middle Housing Fixture Design

The next step is to develop a machining solution for the inclined pump bodies made of cast iron, BIF. To ensure that the changes are implemented, various areas of production need to be addressed.

Based on the previous chapter, the problems with the old fixture can be summarized in a few points:

- Deformation of the housing due to clamping.
- Lack of locating planes (3-2-1 locating principle not followed).
- Forces applied to regions without structural resistance.
- Lack of repeatability.
- Influence of dimensional variation from casting on machining location.

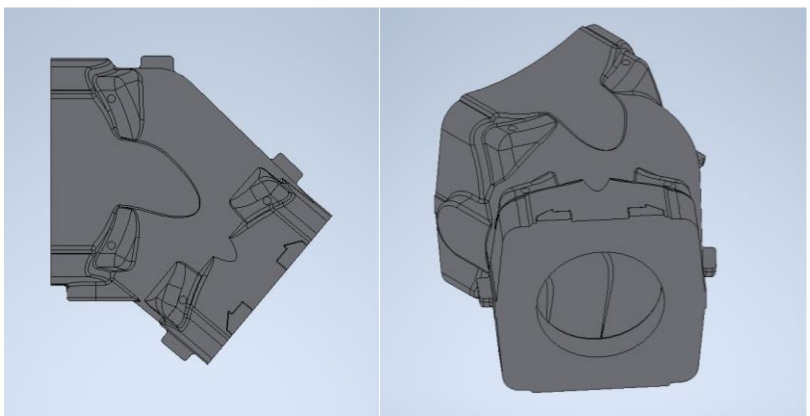


Figure 52 - BIP housing solution with Protrusions

Therefore, the new fixture needs to change the location of the force application so that the housing does not deform in critical regions. It is also necessary for new surfaces of the part to contact the fixture in order to improve the accuracy of locating the middle housing during machining. This will result in better repeatability and more direct force transfer to the support devices. Dimensional variation is an unavoidable consequence of the casting process, as sand casting is the most suitable method for this product. However, if the part is located by its middle height plane and not by its bottom face, the dimensional variation becomes less problematic as it is equally distributed in all directions, minimizing the deviation between the theoretical and practical part centers.

Due to the limited number of surfaces on the pump housing that can be used for location and support, the solution found to address this problem was to implement new surfaces on the cast part. These surfaces will only assist in part fixation and can be deformed during clamping or removed afterwards if necessary. These surfaces, referred to as **Protrusions** from now on, are small, raised features located in the mid-height plane of the part. By utilizing these protrusions, most of the problems should be solved.

When clamping forces are applied to these protrusions, they are directly transferred to the supports, ensuring that the deformation caused by clamping no longer affects the front and back faces of the housing. Since the protrusions are located in the central plane of the part, the dimensional variation is equally distributed without altering the location of the part's center. This theory is better understood with the diagram in Figure 53. The gray circle represents a casting with dimensions smaller than the theoretical black circle dimension, but the left image is located using the base while the right-hand image is located using the part's intermediate plane. Additionally, with the new protrusions, multiple planes can be used for locating the part, as there are now surfaces perpendicular to the base that are not machined and can be utilized for locating the part. The new cast part model developed from the casting process is shown in Figure 52, where three protrusions are present, solely designed to facilitate the part fixation compatible with the new fixture.

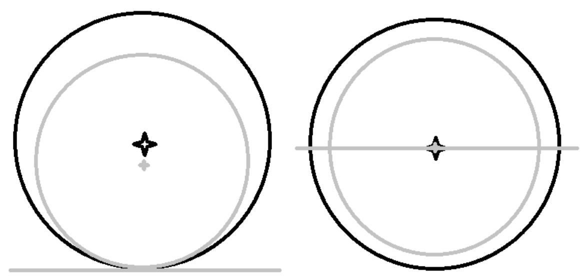


Figure 53 - Scheme of base locating vs axial locating.

To implement these changes, a series of steps must be taken to bring the project to reality:

- The casting mold needs to be redesigned to incorporate the desired three protrusions.
- A study on the fixation using these protrusions is necessary to ensure that the part is securely fixed during the clamping process. Otherwise, issues related to repeatability in machining the fixed housing may happen.
- An analysis of the cutting parameters should be conducted for the more aggressive machining operations, with the purpose of calculating the clamping forces required by the newly developed clamps to withstand the cutting forces generated by these operations. The cutting forces will be calculated based on an optimization of the cutting parameters since these can possibly present some disparity with the previous utilized parameters.
- The fixture parts will need to be developed from scratch. They will be engineered, designed, prototyped, tested, optimized, and manufactured. Structural calculations and finite element analysis will be performed to ensure they are not close to the material yield stress for those subjected to demanding forces.

- A study will be conducted for a future implementation of hydraulic systems in the developed fixture. However, it is important to note that this research will not be implemented in the current system, as ABER has opted to switch to a mechanical clamping system. This choice adds setup time but expedites the implementation of the project, allowing the references to be produced as fast as possible, to deliver orders. The increased setup time will not be significant since a pneumatic screwdriver with torque control will be used by the operator of the Mazak HCN-4000. This tool can be easily adjusted to apply the desired force to the fixture during the tightening and loosening of each part, ensuring repeatability in a fast way.
- For the testing, the new fixture will be calibrated and used to machine samples of housings and then measured into the CMM machine to compare the results with the previous fixture.

3.4.1 Casting Mold Protrusions design

The implementation of the three lateral protrusions serves the purpose of providing surfaces for support, locating the part, and applying force during clamping for machining. All three protrusions have the same geometry, as shown in Figure 54, with a flat upper face and a curved lower surface. It is important that the geometry of each protrusion is as close as possible to the design, as failure to properly shape these protrusions during casting would make the part unfixable for machining.

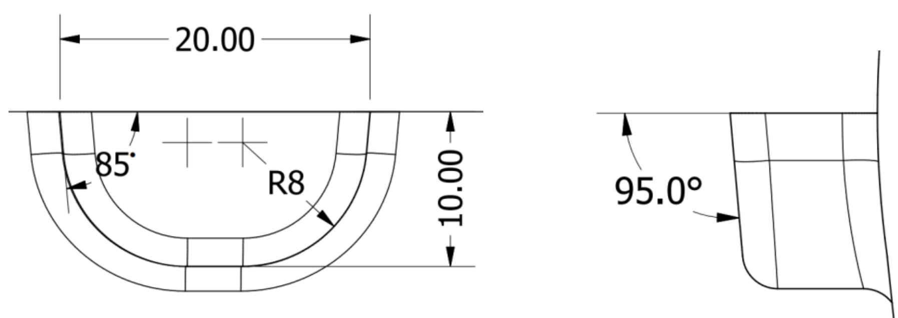


Figure 54 - Protrusions dimensions

The flat upper faces of the protrusions were created to align with the central plane of the part. This ensures that during casting, the entire protrusion will be situated on the same side of the sand-casting mold. By having the protrusions located on the same side of the mold, the protrusions are protected against defects such as the mismatch defect, where the part appears divided in the middle and not aligned. This defect can occur due to improper placement of the cope and drag, loose box pins, or inaccurate pattern dowel pins between them [42]. By ensuring that the protrusions are situated on the same side of the mold, we mitigate the risk of such defects in this critical part where the surface must be as perfect as possible.

Another important detail is the 5-degree draft angle on the side and front surfaces of each protrusion. Similar to the rest of the carter, the side walls have an angle to aid in the removal of the mold from the cope and drag.

To implement the protrusions, changes needed to be implemented to ABER's mold so a new wooden mold was manufactured with the shapes of the protrusions implemented accounting for the 1% shrinkage that will occur during the solidification of the metal in all three dimensions.

3.4.2 Fixtures

With the change made to the casting model, it is now possible to fix the housing in a way that it does not deform during clamping and remains stable throughout the machining process. The new surfaces created ensure, unlike the previous fixation, a much smaller distance between the clamping mechanism and the part support. Therefore, even if there is deformation during clamping, it can be neglected for being proportional to this distance. Furthermore, the area being used for clamping is not a machining area, so any deformation present in that area is of little importance.

To apply the concept of location and restrict the movement of the part, the bottom and side surfaces of the protrusions will be used. Each protrusion will be located in two perpendicular planes. To partially apply the 3-2-1 principle, a third plane perpendicular to the two previous planes must be located to suppress the remaining degrees of freedom. Therefore, locating pins positioned against spring-loaded devices will be used. These prevent movement in the directions of the protrusions before clamping.

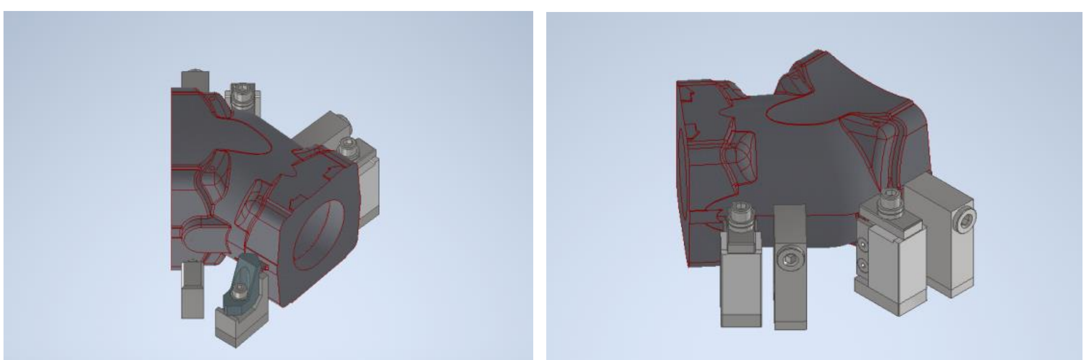


Figure 55 - CAD project fixture Assembly

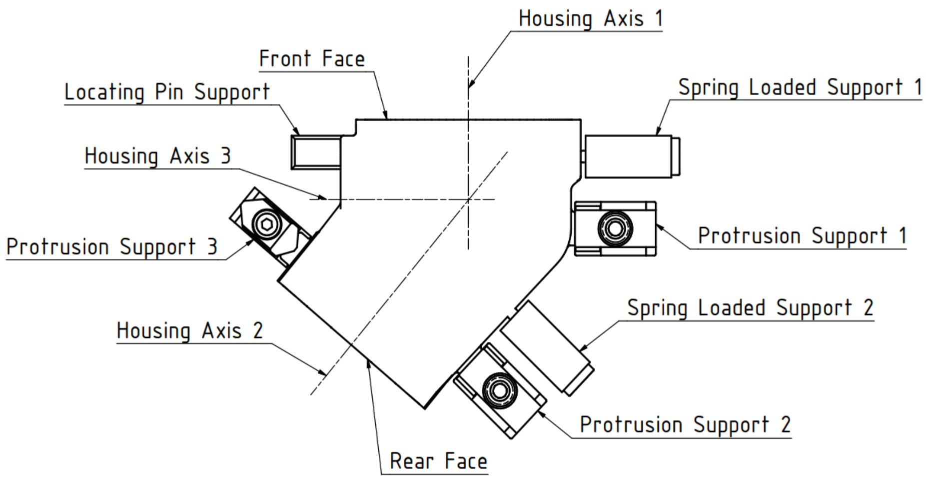


Figure 56 - Fixture sub-assemblies layout

To assist the explanation, Figure 55 and Figure 56 presents the fixture developed for BIP middle housing with the indication of each developed fixture sub-assemblies for the project. The same fixture was designed for the middle housings of the BIM, where the same components are used, only with different base plates and shim heights. BIP and BIM housings have different sizes so the layout of the screw holes and dowels for the fixture plate are in different places and because of height difference BIP needs higher shims.

3.4.2.1 Protrusions Supports

To achieve the fixation, protrusions supports were designed to ensure that the part is securely fixed. These assemblies consist of several components that work together to create a lever system for clamping the housing against the support on the same assembly.

3.4.2.1.1 Protrusion Support 1 and 2 (PS1 and PS2)

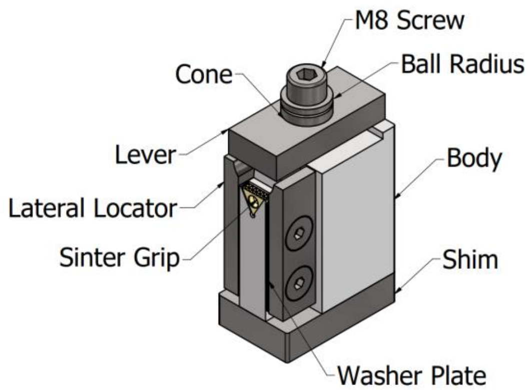


Figure 57 - PS1/PS2 Sub Assembly

The Protrusion Supports 1 and 2 (PS1 and PS2) are located on the same side of the part and ensure the positioning of the bottom and side faces of the protrusions. They are also capable of clamping the top surface of the protrusion against the Sinter Grips, which act as locators.

The lateral locating is achieved with the help of 4 screws that, when tightened, adjust the position of the Lateral Locators. This is important due to the variation in geometry of the cast middle housing. By inserting more or fewer washer plates between the body and lateral locators, the position can be adjusted to accommodate variations in dimensions resulting from the casting process. This allows for compatibility with occasional larger or mislocated protrusions.

The clamping force is applied using a single vertical screw that passes through the lever and tightens into the body. The lever transfers the axial force from the screw to the tip of the lever where the protrusion is located. This clamping force applies pressure to the protrusions, securing them against the Sinter Grips, that localizes and supports the housing.

The Sinter Grips are prefabricated gripper components that concentrate the clamping force on a smaller area, resulting in higher localized pressure indenting the protrusion surface. The indentation helps prevent movement of the protrusions. Using a smooth surface instead of the Sinter Grips would result in a lower coefficient of friction between the surfaces, increasing the likelihood of relative movement under cutting forces. Additionally, the force would be distributed across the rough surface of the cast part, which may not be structurally strong due to micro porosity defects commonly found in medium-scale castings [42].

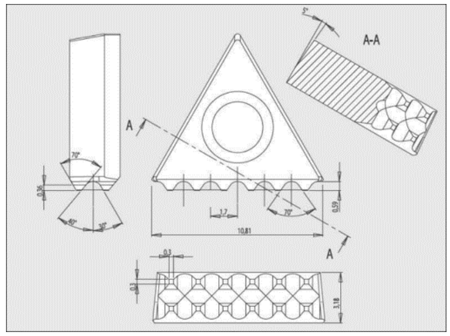


Figure 58 - Sinter Grip Technical Drawing

The gripper is positioned in PS1 and PS2 using a tapered head M3 screw, with its two smooth surfaces accurately located by machining the custom-made supports. The specific gripper used is model 58450129 from the company SMW Autoblok. It is designed to fix a part utilizing a small surface area and features a rectangular face that contacts the middle housing, unlike other grippers that typically have a circular face. This rectangular shape makes better use of the available area for fixing the protrusion. The gripper is capable of fixing parts made of hardened steel and titanium with a hardness of up to 545 BHN and is wear resistant. It offers a long service life under the applied conditions, when used against the Brinell Hardness of 130-180 of EN-GJS-400-15 material.

The shim is the only part that differs in the BIP and BIM middle housing fixtures. Different sizes of shim were manufactured to maintain the distance from the base plate, accommodating the varying heights of the middle housings.

Regarding the cone and ball radius, this composition protects the contact between the bolt and the lever, similar to a washer. Furthermore, it creates a joint that allows the lever not to be parallel to the bolt head surface without creating any stresses.

3.4.2.1.2 Protrusion Support 3 (PS3)

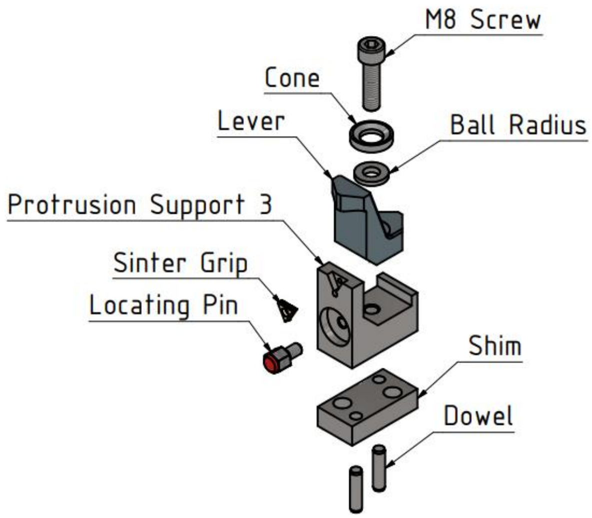


Figure 59 - PS3 Sub Assembly

The PS3, located on the opposite side of the carter to secure the remaining protrusion, functions in the same way as the other supports. It uses the same gripper, but this time the lever created has an alternative shape. In order to provide space for the cutting tools to machine the lateral hole, which requires three operations, this component had to be redesigned.

The PS3 does not have lateral locators since those present in PS1 and PS2 already locate the part in that direction. However, a Locating Pin is housed on its front face, similar to the one described in the following fixture, to ensure that the part is always located in the third plane where PS2 is unable to locate it.

3.4.2.1.3 Locating Pin Support (LPS)

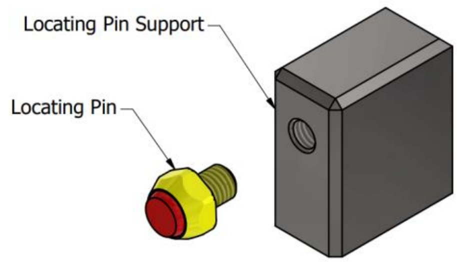


Figure 60 - Locating Pin Sub-Assembly

The Locating Pin Support (LPS) assembly is responsible for properly locating the third direction that PS1 is not able to locate, before the tool clamps. It acts as a limit for the movement that the part is imposed by the spring plungers (tools located on the other side of the housing, which will be described next).

Since the face of the housing where the locating pin will make contact is inclined, the locator used in the LPS has rotational capability, joint of a sectioned sphere shape. This type of locating pin is known as swivel contact bolt. Its design allows them to adjust to the inclination of the surface they contact with. It is important because it ensures that regardless of the inclination resulting from the casting of the middle housing, there will be perfect contact between the surfaces.

3.4.2.1.4 Spring Loaded Supports (SLS)

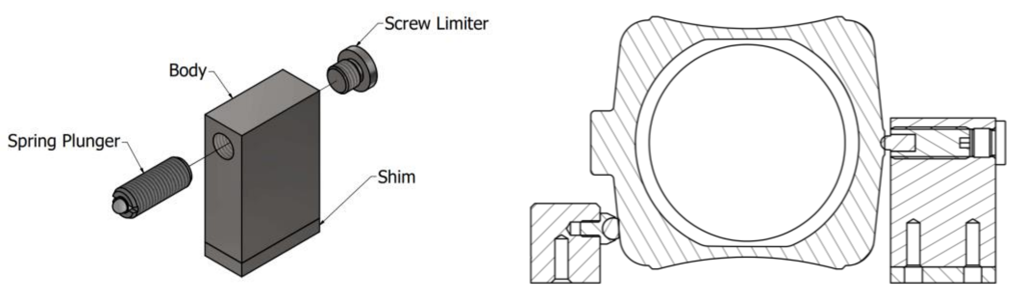


Figure 61 - Spring Loaded Support Sub-Assembly and Sectioned View drawing

The two Spring Loaded Supports (SLS) are fixtures that house a purchased component from Halder, the Spring Plunger, model 22060.0016. The component is inserted into the fixture through its external thread, and its position is axially adjusted using a rear screw limiter to regulate the force imposed by the spring on the middle housing when assembled.

The function of SLP is to push the carter against the locating pins on the other side of the housing pump before applying the clamping force. This allows the piece to be located and clamped always at the same place even with dimensions variations resulting from casting, applying the repeatability concept. Each plunger pushes perpendicular to one of the carter's axes.

3.4.2.1.5 Base Plates and Intermediate Aluminum Plate

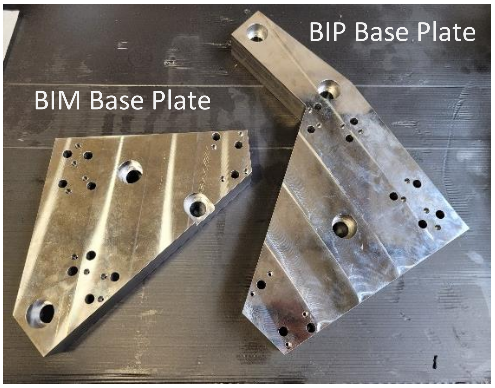


Figure 62 - Intermediate Aluminum Plate

Figure 63 - BIM Base Plate, BIP Base Plate

All the previously described components need to be attached to one of Palletech's pallet tooling plates in order to be machined. However, the Palletech has standard hole patterns on its pallets, making it impossible to secure the components directly onto it. Therefore, an adapter base plate with the corresponding hole pattern needs to be created for each side.

For each of the developed fixtures sub-assemblies, screws and dowel pins are required to connect them to the base plate. The screws are used to fasten the two components together, while the dowel pins serve as positioning guides, as they have well-defined position and diameter dimensions. For the fixture holes for the dowel pins, a dimensional tolerance of G6 was used, which is the recommended tolerance for guiding purposes [41]. Additionally, the distance between the holes for the two dowel pins connecting the same components had a dimensional tolerance of L±0.002 mm. If the hole distances are not as designed, the fixtures would not fit together properly.

To ensure greater production versatility, both base plates can be simultaneously mounted on a pallet tooling plate. This allows for machining both the BIP and BIM middle housings at the same time, which was one of the company's requirements during the fixture redesign.

Furthermore, another component is inserted between the tooling plate and the base plate, which is the intermediate aluminum plate. This plate has the same hole layout for screws as the base plate and also has dowel pin holes to maintain proper positioning with its two neighboring pieces with a G6 tolerance. Its main function is to absorb vibrations caused by machining and isolate the fixture from the factory floor that is susceptible for vibrations. Machining vibrations can occur due to various reasons, such as material inhomogeneity in the middle housing, variations in hardness in the machining regions, or tool imbalance [43]. By inserting a layer between the pallet and the base plate made of a less rigid and more ductile material, it acts as a damping body, allowing occasional vibrations to dissipate more quickly before entering in resonance.

3.4.3 Cutting parameters optimization and Clamping Forces Calculation

Even with the changes in the BIP and BIM Middle housing fixation, its machining process remains essentially the same. Therefore, the cutting tools used for the process can be maintained. However, to ensure proper fixation of the carter, the cutting forces generated during machining must be calculated so it can be determined the forces required in the developed clamps. For this calculation, an optimization of cutting tool parameters with more aggressive machining characteristics were taken into consideration. This optimization is based on the use of parameters reccomended by the tool manufacturer's catalog.

By analyzing the cutting parameters presented in Table 4, it can be noted that there are two tools that can exert a higher force on the workpiece compared to the others. The first tool is a face mill for roughing the main surfaces, identified in the factory as Face Mill 50 A. It has a high material removal rate (Q) with the intention of removing the maximum volume of material in the shortest time. It possesses aggressive cutting parameters and results in a high-intensity force perpendicular to the direction of the cutting tool rotation axis.

On the other hand, there are tools that have a lower material removal rate but exert force in the direction of the CNC spindle, such as the drills used for opening the M12 holes. Since these forces act in a different direction, they will also be analyzed to observe the reaction of the fixture.

The optimized cutting parameters will provide sufficient information for calculating the clamping force, referred to as F_A from now on, required for the clamps in the developed fixture. The three vertical screws must be precisely tightened using an adjustable torque screwdriver so that the levers exert the appropriate clamping forces on the carter, ensuring its complete fixation while the cutting forces are applied to the workpiece. It is the responsibility of the operator in charge to constantly calibrate the torque applied to the screws every time a part is placed, to ensure that the value remains within the specified range and that neither the workpiece nor the tool is damaged.

3.4.3.1 Face Mill 50A

The tool identified as Face Mill 50A is a purchased component from the company SANDVIK. The model 490-050Q22-08M, shown in Figure 64, is a square shoulder milling cutter that is used in this case to face the front and rear surfaces of the pump housing. For this model, there are many different options of insert that can be chosen depending on the application. For this operation the insert utilized by ABER is the model 490R-08T308M-KM 3330 from SANDVIK as well.

This insert is suitable for cast iron material, group K, made with a tungsten carbide (WC) substrate and coated with CVD ($\mathrm{TiCN/Al_2O_3/\ TiN}$). The coating ensures excellent wear adhesion resistance when subjected to high temperatures, allowing productivity to be increased with higher cutting speeds. It also provides reduced friction, increased tool life and better performance [44] [45] [46].

Using the SANDVIK online catalog [47], it was possible to determine the cutting parameters that best suit the existing conditions based on the class of material, type of operation, depth of cut and width of cut.

Table 7 – Face Mill 50A Parameters

Parameter	Old	Optimized
V_c $[m/min]$	200	264
f_z $[mm/tooth]$	0,12	0,26
D_c $[mm]$	50	50
a_p $[mm]$	1,25	5
$Z_n - number\ of\ teeth$	5	5

By using the newly defined parameters, it is possible to calculate the cutting force that will be imposed in the middle housing in this operation, as presented in the Palbit catalog, [48]:

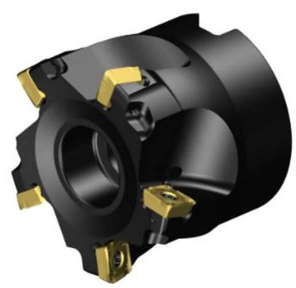


Figure 64 - Sandvik square shoulder milling cutter, model 490-050Q22-08M [48]

Based on Equation (9), the cutting power can be related to the cutting force.

$$F_c = \frac{P_c}{V_c} \tag{9}$$

On the other hand, the cutting power can be defined based on the specific cutting force, K_c, equation (10). This indicator is a pseudo-property of the material to be machined since it does not depend solely on the material and can vary with the material, tool wear, and also the chip thickness.

$$P_c = \frac{a_p * a_e * V_f}{60 * 10^6 * \eta} * K_c \quad (10)$$

Where:

P_c, is the Cutting Power, [kW],

a_e, is the Width of cut, [mm],

a_p, is the Depth of cut, [mm],

V_f, is the Feed Speed, [mm/min],

η, is the Machine Efficiency, [%],

K_c, is the Specific Cutting Force, $[N/mm^2]$.

To account for the variation in chip thickness and its effect on the specific cutting pressure, K_c, it is necessary to calculate the average chip thickness, h_m, in order to correct the value of $k_c x$, specific cutting pressure, for a chip with a 1mm average thickness. This can be done using the equation (11):

$$K_c = \frac{1}{{h_m}^{m_c}} * k_c x \quad (11)$$

Based on the optimized parameters of the face milling tool, Table 7, the first step is to calculate the spindle speed, $n\ [RPM]$, using equation (12).

$$n = \frac{V_c * 1000}{\pi * D_c} = \frac{264 * 1000}{\pi * 50} = 1680{,}7\ [RPM] \quad (12)$$

After this, is possible to calculate the feed speed, V_f.

$$V_f = n * Z_n * f_z = 1680{,}7 * 5 * 0{,}26 = 2184{,}9\ [mm/min] \quad (13)$$

To determine a_e, as shown in Figure 65, an analysis of the front and rear face pointed that in the worst case scenario this distance would be of 40 mm, Figure 67. By applying Equation (14), is possible to calculate the engagement angle, ω_e, which defined in Figure 66.

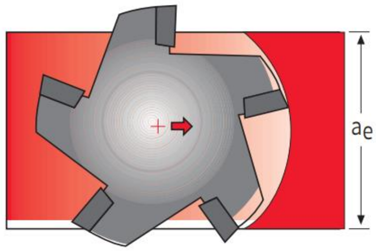


Figure 65 - Width of cut definition [48]

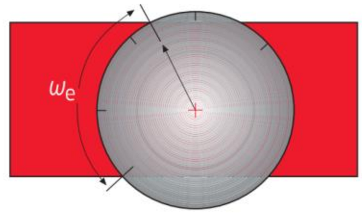


Figure 66 - Engagement angle definitions [48]

$$\sin\left(\frac{\omega_e}{2}\right) = \frac{a_e}{D_c} \tag{14}$$

Substituting the values in the equation:

$$\omega_e = 2 * \sin^{-1}\left(\frac{a_e}{D_c}\right) = 2 * \sin^{-1}\left(\frac{40}{50}\right) = 106{,}26°$$

Given this, it is already possible to calculate the average chip thickness, h_m:

$$h_m = \frac{360 * f_z * a_e}{\pi * D_c * \omega_e} * \sin k_r \tag{15}$$

Where:

h_m, is the Average Chip Thickness,

f_z, is the Feed per Tooth,

ω_e, is the engagement angle,

D_c, is the tool diameter,

k_r, is the Lead angle, i.e., angle of the surface with the side cutting edge of the tool.

Substituting the values:

$$h_m = \frac{360 * 0{,}26 * 40}{\pi * 50 * 106{,}26} * \sin 90° = 0{,}224\ [mm]$$

Therefore, by obtaining the values of m_c e $k_c x$ for grey cast irons from Table 8 and inserting them into equations (9), (10) and (11), is possible to obtain the desired cutting force:

Table 8 - m_c and $k_c x$ values for ISO K, Cast Iron [28]

ISO	Material Group	Description	$k_c x$	m_c
K	7	Medium / hard cast iron; Grey cast iron.	1150	0,22
	8	Low-alloy cast iron; Malleable cast iron; Nodular cast iron.	1225	0,25
	9	Difficult high-alloy cast iron; Difficult malleable cast iron; Nodular cast iron	1470	0,30

$$K_c = \frac{1}{0{,}224^{0{,}22}} * 1150 = 1597{,}76 \; [N/mm^2]$$

$$P_c = \frac{40 * 5 * 2184{,}879}{60 * 10^6 * 1} * 1597{,}76 = 11{,}64 \; [kW]$$

$$F_c = \frac{11{,}636}{264 * 60 * 10^3} = 2644{,}63 \; [N]$$

One of the limitations is that P_c (cutting power) should be lower than the power allowed by the HCN 4000 machine, where the housing will be machined. This information can be obtained from the Mazak catalog [11], which states that the power is 18,5 kW for periods shorter than 30 minutes, or 15 kW for continuous use. Therefore, P_c is below the allowed value.

Machine efficiency has not been considered, so a value of η=1 was used, as the cutting force should not have a direct relationship with machine efficiency. However, to calculate the input power required in the CNC electric motor for this operation, a value of η=0.9 could be utilized.

$$P_c = \frac{40 * 5 * 2184{,}879}{60 * 10^6 * 0{,}9} * 1597{,}76 = 12{,}94 \; [kW] < 15 \; [kW]$$

The same knowledge transposed by Palbit catalog can be adapted to be more intuitively understood. To do so, it is necessary to calculate the number of teeth in action during the operation, denoted as z_e. This represents the mean number of teeth in contact with the workpiece at a given moment, based on equation (16).

$$z_e = \frac{\omega_e * z}{360°} = \frac{106{,}26° * 5}{360°} = 1{,}48\ edges \tag{16}$$

With this parameter, it is possible to determine the chip cross-sectional area, A, using equation (17). Therefore, since the cutting pressure, K_c, has already been calculated, it is sufficient to use equation (18) to define the cutting force according to the second method, F_{c2}.

$$A = a_p * h_m * z_e = 5 * 0{,}224 * 1{,}476 = 1{,}66\ [mm^2] \tag{17}$$

$$F_{c2}[N] = K_c\ \left[\frac{N}{mm^2}\right] * A\ [mm^2] = 1597{,}76 * 1{,}66 = 2644{,}63\ [N] = F_c[N] \tag{18}$$

As seen in equation (18), F_{c2} and F_c have the same values since they represent the same indicator but calculated algebraically in different ways.

In order to keep the workpiece static during this operation, the clamping force, F_A, should be greater than the cutting force, F_c. To ensure this, a safety factor of $\mu = 1{,}5$ was applied to F_A, considering potential approximations in the calculations.

Therefore, the value of the clamping force with the safety factor, $F_{A\ cs}$, is given by equation 19.

$$F_{A\ cs} = F_c * 1{,}5 = 2644{,}63 * 1{,}5 = 3967\ [N] \tag{19}$$

3.4.3.1.1.1 Distribution of F_c into PS's

To approximate the force that each of the three clamps would need to withstand in the worst-case scenario, the following analysis was conducted.

When facing the rear face is where the maximum a_e is located. Intuitively, it is possible to determine that this is the machining location for the worst-case scenario that will result in the biggest reaction forces at the protrusions. Based on Figure 67, it is possible to guess bigger reaction forces on PS2 and PS3 since they are closer to the cutting force.

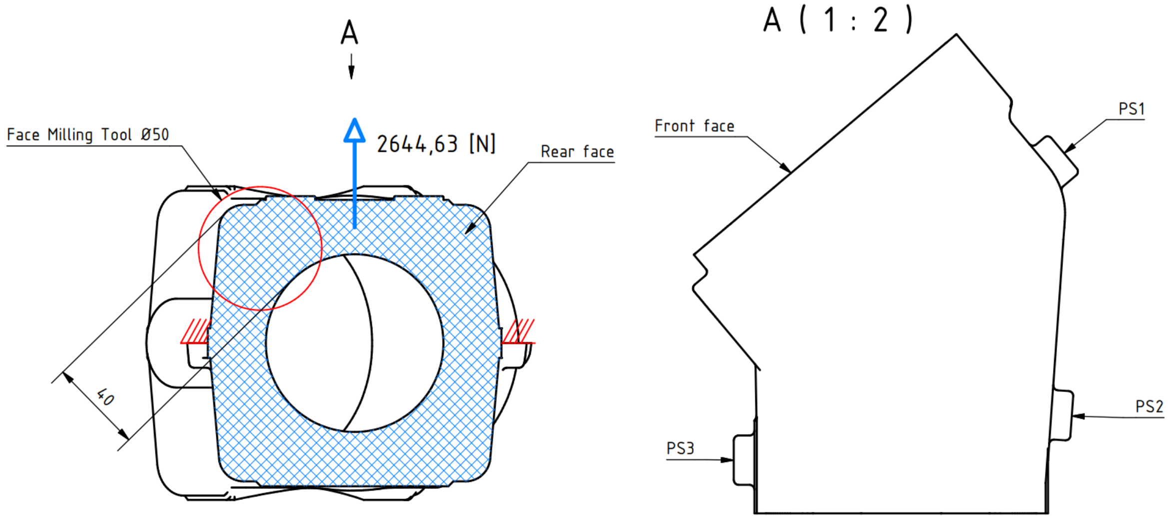


Figure 67 – Reaction forces PS's FEM analysis

To determine the distribution of the cutting force among the three clamps, a finite element analysis study was conducted on the fixture. In this analysis, a vertical force corresponding to $F_c[N] = 2644{,}63\ [N]$ was applied tangentially to the rear face, while the upper faces of the three supports were fixed as illustrated in Figure 67. The purpose of this analysis was to calculate the reaction forces on each of the clamps.

Table 9 - Reaction Forces Rear Face Roughing

Constraint	Reaction Force			Reaction Moment	
	Magnitude [N]	Magnitude * Safety Factor [N]	Component (X,Y,Z) [N]	Magnitude [N×m]	Component (X,Y,Z) [N×m]
PS3	1358,86	2038,29	-1358,32	7,08318	0
			-29,67		1,200
			-23,20		-6,980
PS2	1975,22	2962,83	-1974,44	8,71094	0,246
			28,93		-8,570
			47,18		1,539
PS1	688,523	1032,785	688,11	3,65267	-0,048
			0,733		2,450
			-23,84		-2,708

As predicted, the forces were not evenly distributed. Both clamps located closer to the force application, PS3, and PS2, obtained a higher reaction force compared to the clamp located at Support 1, as exhibit in Table 9, based on the information provided by the study report. The same safety factor was applied to each of the reaction forces to determine the final clamping force.

On the other hand, during the roughing operation at the front face, only PS1 (Primary Support 1) is in close proximity to cutting forces. Therefore, it becomes important to calculate the force that PS1 will be subjected to during the roughing operation on the front face, similar to the previous analysis, as the reaction force on PS1 may exceed the current maximum reaction force. It is worth noting that in this case, the parameter $a_e = 34\ [mm]$ in the worst-case scenario for this face, so $F_c[N]$ was recalculated, 2222,04 [N].

Table 10 - Reaction Forces Front Face Roughing

Constraint Name	Reaction Force			Reaction Moment	
	Magnitude [N]	**Magnitude * Safety Factor [N]**	**Component (X,Y,Z) [N]**	**Magnitude [N×m]**	**Component (X,Y,Z) [N×m]**
PS3	1588,87	2383,30	-1588,2	8,226	-0,115
			22,658		8,021
			-39,878		1,825
PS2	1881,16	2821,74	1880,78	8,098	-0,467
			-20,537		8,079
			-32,053		-0,292
PS1	2515,64	3773,46	-2514,61	14,725	0,172
			-2,075		-9,957
			71,944		10,846

As predicted, the value indicated in Table 10 becomes the largest value among the two tables. Therefore, it becomes the new value for $F_{A\ cs}$.

Finally, this value determines the required clamping force on PS1 to be machined during the rear face operation. However, for the purpose of simplifying the setup and minimizing operator errors, it is of logistical interest to standardize the clamping force for all three supports, considering their similar constructions and capabilities.

3.4.3.2 Drill Bit 10.2

In the case of the 10.2 drill bit manufactured by Kennametal, model B977F10200 KC7315, the cutting forces can be calculated using the optimal cutting parameters provided in Table 11, along with the material properties as specified by the manufacturer Sandvik [28] and Suhner [29].

This drill bit has a solid carbide body material with coolant entry and exit. The tool has a multi-layer coating based on TiAlN, which provides high heat hardness and allows for 30% higher cutting speeds while maintaining a constant tool life. This drill bit is designed for applications in both steel and cast iron.

Table 11 - Drill Bit 10.2 Parameters

Parameter	Old	Optmized
V_c [m/min]	85	140
f_n [mm/rev]	0,12	0,35
D_c [mm]	10,2	10,2
Z_n	2	2
k_r	140°	140°

The Feed force, F_f, in the direction of the tool axis, is the biggest share of all the forces involved in the drilling operation and has the direction that has not been analyzed yet to the fixture system. The Equation (20) is utilized in this case:

$$F_f = 0,5 * K_c * \frac{D_c}{2} * f_n * \sin k_r \tag{20}$$

Where:

D_c, is the Tool Ø $[mm]$

f_n, is the feed per revolution, $[mm/rev\ ]$

K_c, is the specific cutting force, $[N/mm^2\ ]$.

k_r, is the Lead angle.

The value of K_c can be determined by utilizing Equation (11), but in this case, the chip thickness is determined using Equation (21).

$$h_m = f_z * \sin k_r \tag{21}$$

By referring to the required information in Table 5, considering that f_z represents the feed per tooth and the drill bit has two cutting edges, it is possible to calculate the axial force exerted by the tool during machining.

$$K_c = \frac{1150}{(\frac{0,35}{2} * \sin 140°)^{0,25}} = 1985,7 \; [N/mm^2]$$

$$F_f = 0,5 * 1985,736 * \frac{10,2}{2} * f_n * \sin(140°) = 1139 \; [N]$$

Since F_f occurs on the face, its direction is not against the clamping force but perpendicular to it. The component is subject to movement in the plane it is placed on if the Lateral Locators are not properly adjusted, and the lateral face of the protrusions is not in contact with them due to cast dimensional variation. To prevent this movement, the clamping force needs to be capable of generating a frictional force, $F_s = F_A * \mu$, greater than F_f, where μ represents the friction coefficient between the surface of the protrusions and the supporting surfaces (PS's), as shown in the force diagram in Figure 68. Therefore, to prevent movement, F_A needs to be greater than F_f and can be calculated by substituting the corresponding values into Equation (22). The value of μ for the contact between cast iron and unlubricated mild steel is 0.4 [49].

$$\frac{F_s}{\mu} = F_A \rightarrow \frac{1139}{0,4} = 2848 \; [N] \qquad (22)$$

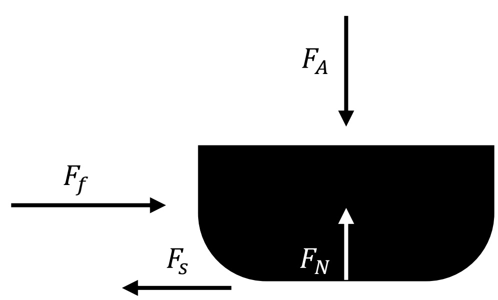


Figure 68 - Forces diagram for protrusion section

However, the use of the Sinter Grip tool changes the relationship between forces. Due to the geometry of its teeth, the tool has a clamping depth of up to 3.5 mm [30]. Therefore, the required frictional force is partially replaced by a normal force perpendicular to the face of each Sinter Grip tooth.

This means that the frictional force from the contact between the Sinter Grip and the protrusion, combined with the normal forces resulting from the deformation of the middle housing due to the penetration of the Sinter Grip teeth, must exceed the axial force caused by the drill bit.

In the schematic diagram in Figure 69, which represents a cut parallel to the face of one of the protrusions, a better understanding of the necessary force balance can be achieved. F_f, due to the inclination of the Sinter Grip teeth, will be divided and resisted by two forces. For this purpose, a projection of F_f in the direction normal to the inclined face of the teeth and in the direction of F_A has been made. These are denoted as F_{fn} and F_{fA}, respectively.

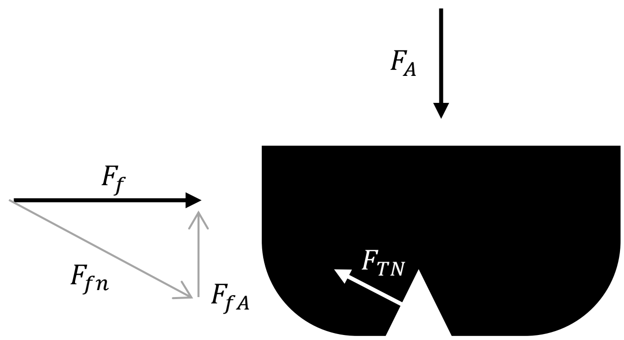


Figure 69 - Force Diagram for Sinter Grip and Protrusion relation

Following the reasoning, it is possible to state that F_{fn} will be counteracted by a normal force present on the inclined face of each of the teeth that penetrate into all the lugs, denoted as F_{TN}. Therefore, this force will be dispersed by the fixture structure. The remaining force, projected as F_{fA}, will be resisted by F_A. Therefore, in order to calculate the forces, the angle of the inclined faces mentioned in the Figure 58 was used. Since the force exerted has the same direction as the larger dimension of the Sinter Grips, the face that will exert the normal force is the one with an angle of 70° between teeth, or 35° with respect to the vertical axis.

Table 12 - Force distribution values

Sinter Grip Tooth Angle	**35°**
F_f [N]	1139,2
F_{fn} [N]	1390,7
F_{fA} [N]	797,7

Finally, for this operation, F_A needs to be greater than 797.671 [N] as shown in Table 12. This value is nearly four times lower than what would be required if the Sinter Grips were not used. Comparing it with the value found based on the face milling operation, it can be observed that the drilling operation is not relevant for determining $F_{A\,sc}$, as the calculated value is 4.7 times lower than the previously defined $F_{A\,sc}$. Therefore, the clamping force can be defined as 3773.46 N for each lever.

3.4.4 Fixture Mechanical Resistance

On the other hand, if the clamping force used exceeds the required amount, it can lead to damaging the developed fixtures or even the protrusions. Several factors need to be taken into consideration that limit the allowable clamping force on the screws. The threaded holes have a stress limit that should not be exceeded; otherwise, the threads will be damaged, resulting in the need to manufacture the PS part again. The screws themselves also have a stress limit that must be respected for their proper functioning. Additionally, the levers, which experience a bending moment caused by the tightening of the screw, can also reach their material's resistance limit if the “beam” section, distances, clamp location are not properly dimensioned, resulting in part failure.

3.4.4.1 PS1 and PS2 Levers

In the case of PS1 and PS2, the Lever has a constant cross-section, with only a variation at L/2 due to the through-hole where the screw passes in order to exert clamping force when tightened. The analysis of the Lever part can be adapted to a rectangular cross-section beam with simple support at one end, double support at L/2, and a vertical force at the other end caused by the part being tightened, with this force already determined beforehand as $F_{A\,sc}$.

To begin the analysis, it is necessary to calculate the reactions at each support to determine the set of forces applied to the beam. Therefore, it is necessary to create a free body diagram with the forces and supports involved in the part, as shown in Figure 70. In the project, the forces will not be applied at the ends of the Lever; however, in order to simplify the study, it was decided to analyze the case in this manner, as it represents the critical scenario in which the moment created by the forces is maximized.

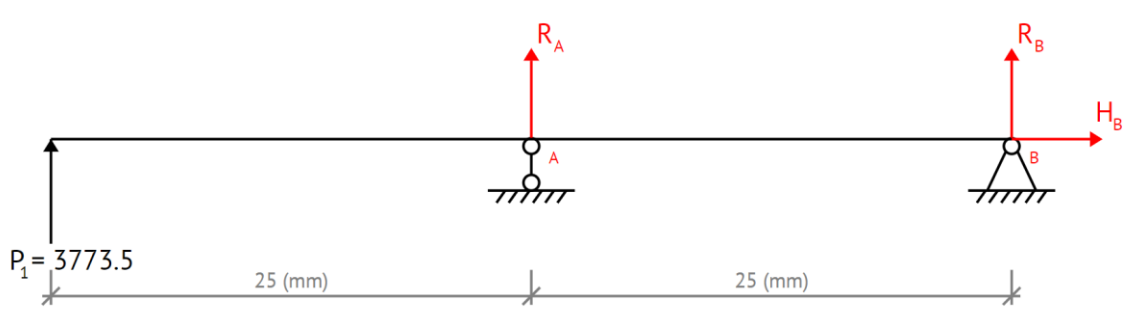


Figure 70 - Free Body Diagram for Lever component

By applying a simple balance of forces and moments, as visualized in Equation (22) and Equation (23), a system of equations with two unknowns can be developed, allowing the determination of the reactions at each support.

$\Sigma F_y = 0$

$$R_A + R_B + 3773{,}5 = 0 \tag{22}$$

$\Sigma M_B = 0$

$$R_A * 0{,}025 + 3773{,}5 * 0{,}05 = 0 \tag{23}$$

By solving the system of equations, the results are as follow: $R_A = -7547\ [N]$ e $R_B = 3773{,}5\ [N]$.

3.4.4.2 Screw Dimensioning

Before continuing with the lever dimensioning calculation, it is important to define the bolt that will be used, as this choice affects the critical section of the lever.

To ensure consistent tightening, it is necessary to determine the torque that should be applied to the bolt. Calculating this information requires specifying the size of the bolt to be used. This choice needs to take into account the space available between the supports and the stresses to which it will be subjected.

The reaction force, R_A, calculated earlier, represents the tensile force that the bolt will experience. To dimension the bolt, it is necessary to calculate the minimum cross-sectional area required to withstand this tension.

For a bolt with a material grade of 8.8, this means that the material used has a tensile strength of 800 N/mm², indicated by the first 8. The second 8 indicates that its yield strength is 80% of the tensile strength, resulting in a yield strength, σ_y, of 640 N/mm² [41]. This type of bolt is commonly used in factory environments and, therefore, is a suitable option for implementation in the fixture.

With Equation (24), it is possible to determine the value of the cross-sectional area that the bolt must have to prevent it from breaking under tension.

$$\sigma_y = \frac{R_A}{A} \rightarrow A > \frac{R_A}{\sigma_c} \tag{24}$$

Substituting the values into the equation (24), it is determined that the cross-sectional area of the bolt should be greater than 11.792 mm². To calculate the corresponding bolt diameter, Equation (25) and Equation (26) can be applied, which are applicable to ISO metric threads, in order to determine the diameter of the cross-sectional area and, ultimately, the external diameter of the bolt thread.

$$A = \frac{\pi * d^2}{4} \tag{25}$$

$$d = D - 1{,}23 * P \tag{26}$$

Where:

D, is the screw diameter.

d, is the screw small diameter.

P, is the thread pitch.

Therefore, it can be stated that the bolt diameter (D) should be greater than 5.719 mm. Hence, for now, it has been decided to use an M8 bolt.

The torque required to generate an axial load of 7547 N in this bolt is calculated to be 12.075 N·m, as shown in Equation (27). The K factor, also known as the torque coefficient, is a value that determines the interaction between the threads. This coefficient can vary for different reasons, such as material, lubrication, humidity, surface heat treatment, among others. For this calculation, a torque coefficient of 0.2 was used, considering the lack of lubrication.

$$T = K * L * D \tag{27}$$

Where:

T, is the torque [N·m]

K, is the torque coefficient [-]

L, is the axial load [kN]

D, is the screw diameter [mm]

Regarding the thread strength of the PS bodies, it is important to consider two fundamental aspects when designing the thread connection. The first is to ensure proper thread engagement by using fasteners manufactured to a known standard, such as ASTM, ANSI, DIN, or ISO. The second is to design the bolt to break before the female or male thread strips. This is because when a bolt breaks, the problem is quickly identified and can be replaced.

3.4.4.3 PS1 and PS2 Levers - Sequel

With the information about the reaction forces, it is possible to develop a force diagram to analyze the critical point of the structure, as shown in Figure 71.

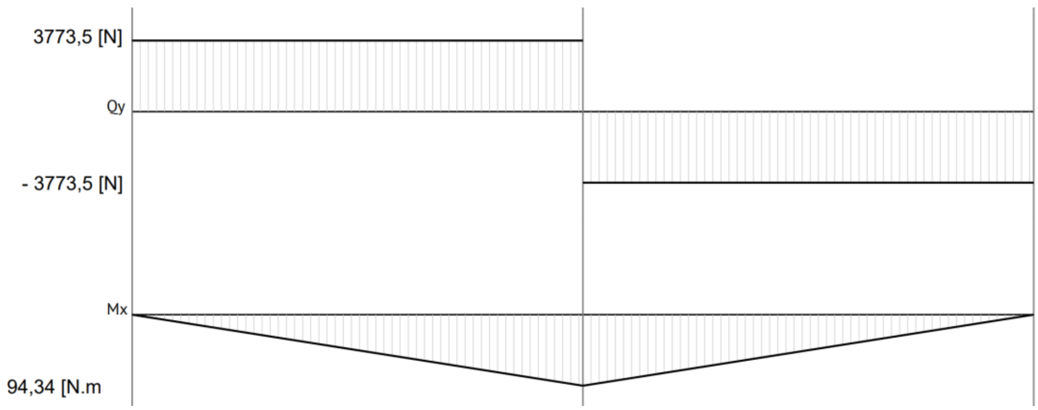


Figure 71 - Shear (Q_y) and Bend Moment (M_x) Diagrams

Observing the diagrams above, it is noticeable that the critical section located at L=25 mm has the highest bending moment and also experiences the maximum shear force. By using the values of the shear force and bending moment at this section, it is possible to determine the maximum stresses present in the part. To do so, the normal stresses and shear stresses were calculated based on Equation (28) and Equation (29), respectively.

$$\sigma_{xx} = -\frac{M_f * y}{I_z} \tag{28}$$

$$\tau_{xy} = -\frac{3 * Q}{2bh} * \left[1 - \left(\frac{2y}{h}\right)^2\right] \tag{29}$$

Where:

M_f, is the bending moment.

y, is the distance to the the neutral axis.

I_z, is the moment of inertia in respect to the z axis.

Q, is the shear force.

b, is the width of the section.

h, is the height of the section.

It is important to highlight that the critical section coincidentally coincides with the path of the bolt, making it substantially weaker. According to Figure 72, these are the dimensions that should be considered for the calculation. It is noted that dimension b is influenced entirely by the bolt diameter. The through-hole required for an M8 bolt, according to ISO 273 standard, can have three possible dimensions: fine, medium, and coarse, which are 8.4 mm, 9 mm, and 10 mm, respectively, [41]. For the calculation, a through-hole of 8.4 mm was considered, as the critical section requires maximum resistance. Only half of M_f and Q are used for the calculation since they are equally distributed on both sides of the section.

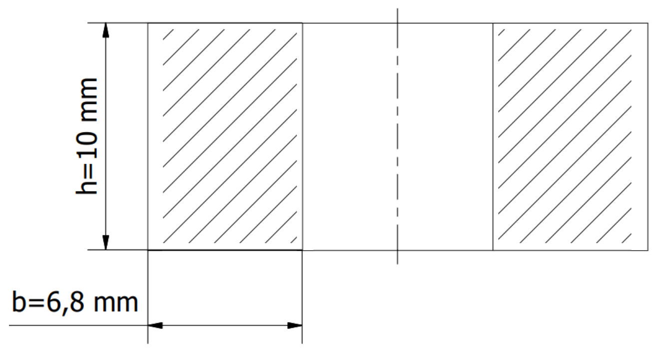


Figure 72 - Lever screw hole cross-section

$$I_z = \frac{b * h^3}{12} \tag{30}$$

The moment of inertia for a rectangular section can be calculated using Equation (30), resulting in a value of $566{,}67\ [\mathrm{mm}^4]$. Then, by using Equation (28), the maximum value of σ_{xx} can be calculated, resulting in a value of 416.2 $[\mathrm{MPa}]$, which occurs at the furthest axis from the neutral axis of the part, h = 0 or 10 [mm]. Therefore, this information was taken into consideration for the choice of material for the construction of the levers.

The chosen material is steel grade 16MnCr5. This material ensures good machinability, along with good mechanical properties. It has high surface hardness, wear resistance, and can be heat-treated to achieve a variety of mechanical properties. The material is commonly used in gears, worms, levers, and other machine components. The main reason for choosing this material is its mechanical strength, with a yield stress, σ_y, ranging from 440 to 735 $[\mathrm{MPa}]$, and a tensile strength ranging from 640 to 1375 $[\mathrm{MPa}]$, thus providing the necessary mechanical strength for the stresses present in the lever design [36].

For the maximum shear stress τ_{xy}, by substituting the values into Equation (29), a value of 41.62 $[\mathrm{N/mm^2}]$ is obtained, which occurs at the neutral axis of the part, y = 0. Therefore, an analysis based on the Tresca criterion for the stress imposed by tightening is performed, as shown in Equation (31).

$$\sigma_1 - \sigma_3 \leq \frac{\sigma_y}{N} \tag{31}$$

With the knowledge that there are no normal stresses at the neutral axis, by analyzing the Mohr's circle, Figure 73, it can be deduced that: $\sigma_1 - \sigma_3 = 2 * \tau_{xy}$. Using an exaggerated safety factor of 2, the criterion is still fulfilled.

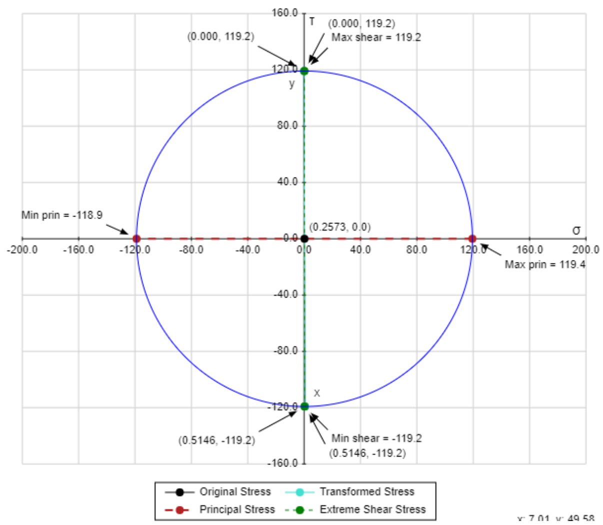


Figure 73 - Mohr's Circle for Neutral Axis

Thus, it can be concluded that the stresses imposed on the levers belonging to PS1 and PS2 are perfectly acceptable and ensure that the clamp forces reach the appropriate value to enable machining.

3.4.4.4 PS3 Lever

For the study of stresses in the PS3 Lever, a different approach was taken due to its more complex geometry. In order to ensure that the stresses are below the yield strength of the material, a finite element analysis of the body in question was performed. Similar to PS2 and PS3 clamps, the area where the bolt applies force and the end supported against the PS1 body ledge were constrained in all directions, and a force of $\mathrm{F}_{\mathrm{A\ sc}}$ = 3773.5 [N] was applied to the face in contact with the protrusion. The material properties of 16MnCr15 were applied.

For the first version of this tool, the designed structure was not sufficient to withstand the desired clamping force, as can be seen in Figure 74. The body experienced stresses reaching 1000 MPa at the force application location, which is unsuitable for any economically viable material. Additionally, the moment generated by the force on the tool also resulted in stresses of around 500 MPa in the lateral ribs of the part.

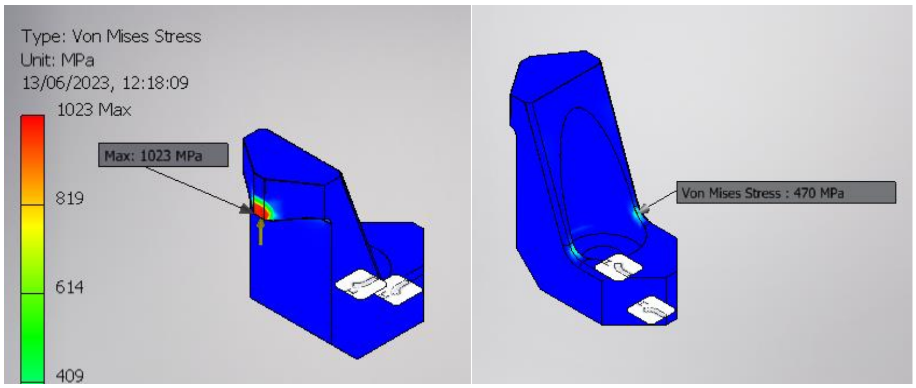


Figure 74 - FEM analysis for PS3 Lever V1

To solve the problem without changing the clamping force, any other component, or the material of the part, the approach was to redesign the lever in order to ensure greater structural strength by simply changing its shape. The first step taken was to increase the contact area with the protrusion, distributing the force over a larger area to better distribute the local stress. Regarding the Lateral ribs, the right rib, which is located further away from the space used by the cutting tools, was upsized to reduce the stress caused by bending moments. So, a custom cutout was made to maximize the material in the rib, as can be seen in Figure 76.

Based on the results obtained from the finite element analysis of the second version of the lever, it can be affirmed that it has the necessary strength to withstand the required clamping force, with a maximum stress of 333.3 MPa, as shown in Figure 75.

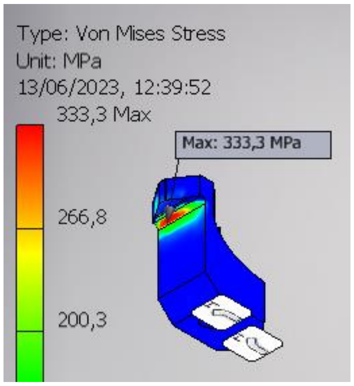


Figure 75 - FEM analysis for PS3 Lever V2

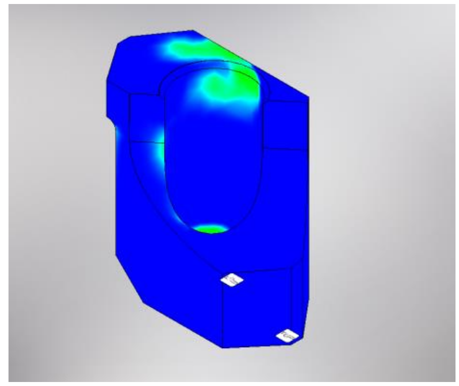


Figure 76 - Rib detail, FEM analysis Lever V2

3.5 Finite Element Method Analysis for Middle Housing Clamp Forces

Based on the information provided in the previous chapter, this chapter aims to perform a finite element analysis of the newly developed fixture system. In this way, it is possible to visualize whether the previously identified issues have been successfully resolved. It is expected that the results obtained will allow the identification of possible design errors before the fixture is manufactured. Conversely, with a positive analysis of the results, credibility will be established to the project, enabling the investment in fixture production.

For the formulation of the finite element study of the new fixture, the updated version of the CAD model of the middle housing for the BIP pump was used, incorporating the protrusions. Similar to the finite element study of the previous part, the same material properties as presented in Table 5 of the previous chapter were assigned. Fixed constraints were implemented for each part: on the bottom face due to the Sinter Grip support and on the side faces due to the location done by the Lateral Locators. Regarding the clamping forces, $F_{A\,cs}$ was applied to each of the protrusion's top surfaces as designed.

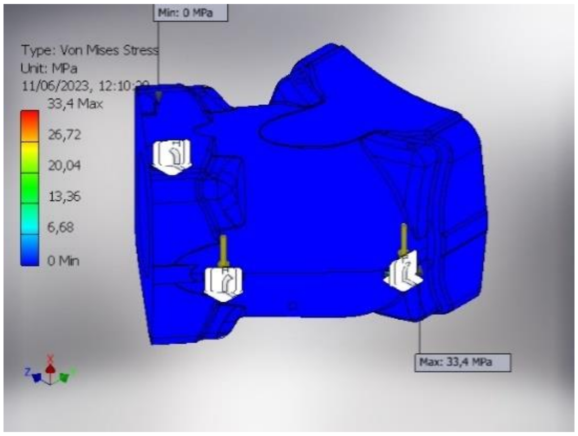


Figure 77 - Von Mises Stresses

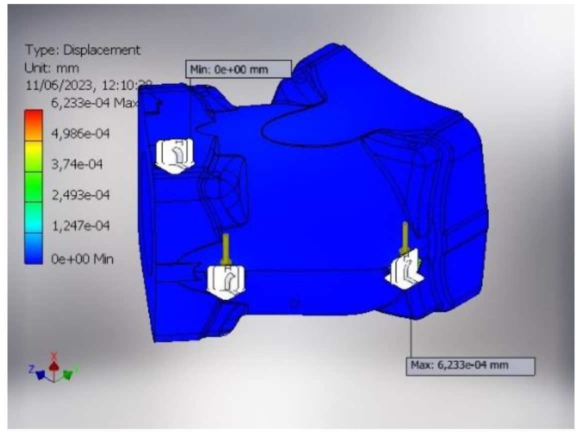


Figure 78 - Displacement

Based on the report provided by the study, it was possible to analyze the maximum stresses involved in the housing, as shown in Figure 77, as well as the maximum deformations, exhibited in Figure 78. Regarding the stresses, they are only concentrated in each of the protrusions, as the forces are quickly transferred to the supports, as expected in a well-designed fixture. Furthermore, these stresses have values well below the yield strength of the material, ensuring that the protrusions will not fracture or deform excessively during tightening. Similarly, the deformations practically disappear in the rest of the body, as planned, eliminating any tolerance issues caused by undesired deformations during machining, solving theoretically the main problem of the previous fixture.

Table 13 presents the results obtained during the analysis of the old clamping system, along with the new values found for easier visualization of the disparity between them. The current values are significantly lower, allowing for successful machining with deformations in the range of micrometers due to stresses almost 20 times lower than in the previous case on the front and rear faces. Based on this, the production of fixtures using the new manufacturing method can be approved.

Table 13 – Old x New displacements and stresses comparison

	Old	**New**
Max displacement Front Face	0,048 mm	0,00015 mm
Max stress Front Face	17,8 MPa	0,02 MPa
Max displacement Forces locations	0,045 mm	0,00059 mm
Max stress forces locations	210,3 MPa	13,3 MPa
Max displacements Locating Devices	-	-
Max Stresses locating Pins	570,6 MPa	33,4 MPa

3.6 Heat treatment

The materials used for fixtures already guarantee good resistance. However, like any other material, constant contact, and friction between them eventually wears down the surface, resulting in clearances and/or possible surface defects that can develop into larger cracks over time. To ensure that the produced fixtures do not easily wear out, some parts were selected based on their applications and interactions to undergo surface heat treatments before their utilization.

The contact between the levers and the surface of the middle housing and the PS's ledges can eventually damage each other over time due to abrasive wear. Furthermore, repeated tightening and loosening intentionally contribute to this wear and may also propagate surface defects. Therefore, to prevent microcracks and surface fractures that could propagate during repetitive loading cycles, a surface carburizing treatment was performed to the levers and lateral locators.

Carburizing is a heat treatment process utilized in mechanical components to enhance their surface properties and improve their wear resistance and fatigue strength. It involves the diffusion of carbon into the surface layer of a steel component by heating it in a carbon-rich environment, typically using a gas or solid medium. The carbon atoms diffuse into the steel, forming a hardened layer with increased surface hardness and improved resistance to abrasion and friction. This process is particularly useful for components that experience high contact pressures or sliding contact, as it significantly increases their durability and extends their operational lifespan without compromising their ductile core, which is better at absorbing stresses without fracturing [50].

3.7 Assembly and fixture testing

Each part was properly inspected to verify if the dimensions and tolerances specified in the production technical drawings were respected during manufacturing. This step was carried out with great caution, as any unnoticed error in the future will appear during CMM tolerance measurements of the housing. This would lead to an investment of time to trace back the source of the problem.

Each of the base plates, for BIP and BIM, was assembled separately to later be joined with the intermediate plate and mounted on the Palletech's pallet tooling plate as shown in Figure 79.

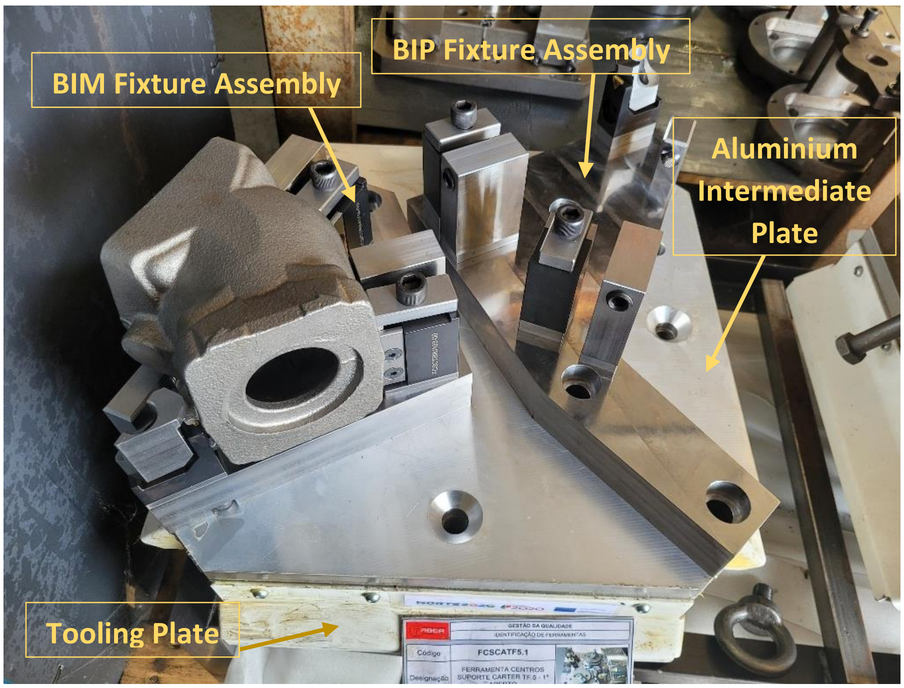


Figure 79 - Final Fixture Assembly

3.7.1 Sinter Grips heights

To ensure proper functioning of the fixture, it is necessary to make some adjustments to ensure it operates appropriately. Firstly, using the CMM, a measurement process was carried out on each of the two bases with their respective fixtures mounted to check if all the Sinter Grips are situated on the same plane parallel to the base in question. By having them on the same plane, this means that the Middle Housing when mounted will be horizontal, resulting in the front and rear face perpendicular to the spindle axis. The measurement results can be seen in Table 14.

Table 14 - CMM measurements and calculations for Shim Rectification, BIP fixture

BIP	Fixture	Body Height (mm)	Shim Height (mm)	Sum (mm)	Correction (mm)	Shim Final Height (mm)
Projected	PS1	48,75	11,75	60,5	-	-
	PS2	48,75	11,75		-	-
	PS3	49	11,5		-	-
Measured	PS1	48,75	11,65	60,4	0	11,65
	PS2	48,8	11,75	60,55	-0,15	11,6
	PS3	49,05	11,5	60,55	-0,15	11,35

As observed from the results, the heights dimension of the 3 sinter grips are not equal (Sum column). There was a maximum variation of 0.1 mm among the measured components. Therefore, in order to achieve equal height between the 3 sinter grips, a correction must be made to the shims where the sum of the values resulted in a higher height.

To achieve the same height a grinding process was established aiming for the Shim Final Height Column presented at Table 14. A correction of 0.15 mm was made for the shims belonging to PS2 and PS3 to align them at the same height. This ensures that machining errors are minimized in the future and parallelism between the locating faces is achieved. The same approach was applied to the Protrusion Supports of the BIM, as shown in Table 15, where a correction of 0.05 mm was made to the shim belonging to PS3.

Table 15 - CMM measurements and calculations for Shim Rectification, BIM fixture

BIM	Fixture	Body Height (mm)	Shim Height (mm)	Sum (mm)	Correction (mm)	Shim Final Height (mm)
Projected	PS1	48,75	6,5	55,25	-	-
	PS2	48,75	6,5		-	-
	PS3	49	6,25		-	-
Measured	PS1	48,8	6,4	55,2	0	6,4
	PS2	48,8	6,4	55,2	0	6,4
	PS3	49	6,25	55,25	-0,05	6,2

3.7.2 CMM Final Measurements

With the fixture properly set up, the next step was to identify errors in relation to the geometric tolerances present after machining for a finite sample of middle housings, BIP, and BIM, before starting mass production using the fixture, for the purpose of identifying if the problem was solved. The CMM measurements carried out at this stage aimed to compare the results with the old fixture and the permitted tolerances in the technical drawing. Therefore, the exact same procedure was followed to avoid measurement errors.

To enable machining in the new fixture, since the part is not in the same geometric space compared to the middle housing in the old fixture, it was necessary to adapt the machining code. To do this, the process carried out in the Palletech was to use the machine's probe to measure the location of the centers of the front and rear faces for 20 different middle housings. Based on the obtained information, an average of the coordinates was determined and Part Zero (Datum corresponding to (0,0,0) coordinate) could be computed into the machining code.

After the code adaptation performed by the machining operations manager, the first machining of the middle housing using the developed fixture was carried out. Since it was the first one, it had to be carefully controlled to inspect the created machining code and the calculation of cutting tool dimensions in comparison with the developed fixtures, ensuring that there was no undesired contact between the cutting tool and the fixture.

Thereafter completing 8 workpieces, the same procedure carried out in the CMM for the old middle housings was performed. From this new study, the results for each tolerance analyzed side-by-side with the previous charts data created on the analysis in the CMM Measurements Sub-chapter.

3.7.2.1 Flatness and Angularity

When analyzing the results of the Flatness geometric tolerance, for the front face and the rear face, no abnormal variations were observed. For the rear face, Figure 81, the average flatness value remained below the tolerance at 0.0095 mm, slightly higher than the previous analysis. The variance obtained was $8{,}2 * 10^{-6}\ \mathrm{mm}^2$, meaning that the values were not spread out, they remained close compared to the previous machining sample, which had a variance of $8{,}8 * 10^{-6}\ \mathrm{mm}^2$.

For the front face, Figure 80, the average flatness was slightly below the previous average, at 0.009375 mm. It is interesting to note that the difference between the averages of the rear and front faces is almost non-existent, at $1{,}25 * 10^{-4}\ \mathrm{mm}$. For the old middle housing, this difference was $8 * 10^{-4}\ \mathrm{mm}$, approximately 7 times higher. This is expected since both surfaces were machined in a very similar manner and should not exhibit different flatness results. However, it's important to note that the values may be influenced due to the low number of samples in this case, as we are dealing with differences on the milli scale.

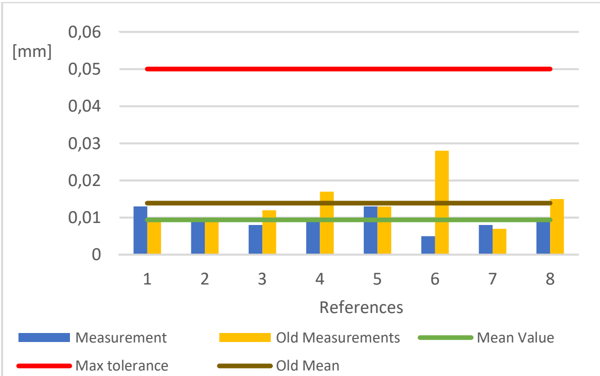


Figure 80 - Old vs New Flatness Tolerance Measurements Front Face

Figure 81 - Old vs New Flatness Tolerance Measurements Rear Face

Regarding the angularity tolerance, the results show a very similar average in relation to the previous one, Figure 82. Through data analysis, it can be observed that the sample presents less scattered values, with a variance of $2{,}03 * 10^{-5}\ \mathrm{mm}^2$ compared to the $11{,}4 * 10^{-5}\ \mathrm{mm}^2$ of the old sample, which showed in reference 6 a value very near the 0,045 mm limit. Therefore, the new angularity test was approved.

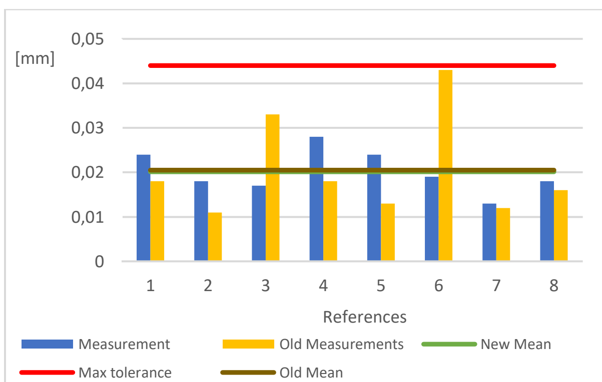


Figure 82 - Old vs New Angularity Tolerance Measurements

3.7.2.2 Circularity and H7 for Ø84 Hole

Regarding the Ø84 hole tolerances, the results already show more concrete improvement. For the dimensional tolerance, as shown in Figure 83, it is noticeable that the values are much more consistent, with a variance of $1{,}22 * 10^{-5}\ mm^2$ *compared to* $33 * 10^{-5}\ mm^2$ in the previous measurements. These values are well centered within the tolerance range, which is the target of the machining code, meaning that the IT rating could be even smaller without having the measurements out of tolerance. All references remained within the tolerance, resulting in a rejection rate of 0 based on this small sample, which should be expanded in the future.

For circularity, the same trend was observed in Figure 84. The results are closer to each other and further away from the 0.05 mm tolerance, demonstrating the effectiveness of changing the clamping force application location to avoid possible ovalization during machining.

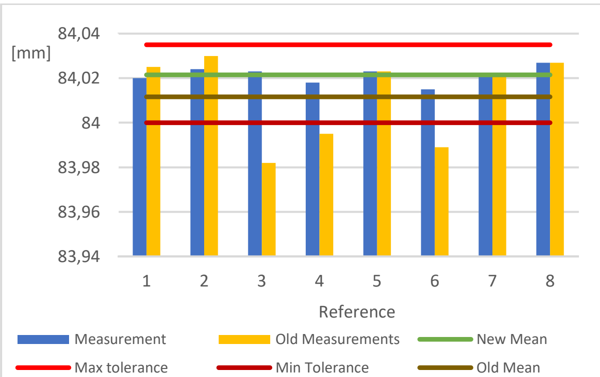


Figure 83 - Old vs New H7 tolerance Measurements for Ø84 Hole

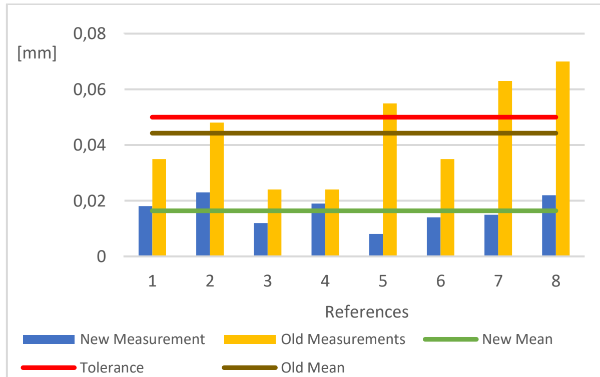


Figure 84 - Old vs New Circularity tolerance Measurements for Ø84 Hole

3.7.2.3 Circularity and H7 for Ø105 Hole

Regarding the Ø105 hole, the improvement was even more drastic. Since this was the area with the highest deformation according to the FEM analysis in the previous case, it makes sense that if the problem has been resolved on the Ø105 measurements, it would show the greatest improvement. For the G8 tolerance, once again, all samples showed measurements well centered within the tolerance range, with an average of 105.042 mm, and the intermediate value of the tolerances being 105.039 mm, as shown in Figure 85.

The circularity results for the 8 references are further away from the maximum tolerance and show significant differences from the previous measurements, as shown in Figure 86. These data points are similar to the circularity measurements for the Ø84 hole. This indicates stability of deformations present throughout the part when clamped by the newly developed fixture, with an average circularity of $1{,}5 * 10^{-2}$ *mm for Ø105 and* $1{,}6 * 10^{-2}$ *mm* for Ø84.

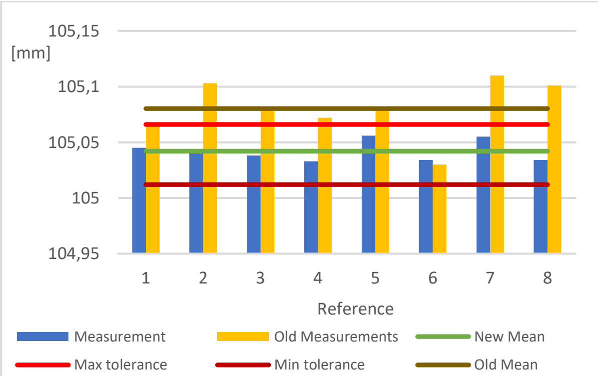


Figure 85 - Old vs New G8 Tolerance Measurements for Ø105 Hole

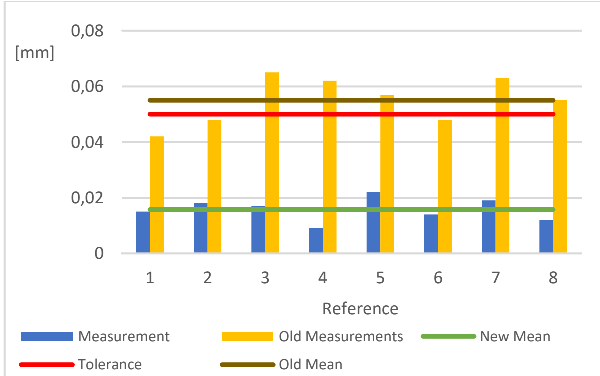


Figure 86 - Old vs New Circularity tolerance Measurements for Ø105 Hole

3.7.2.4 Final analysis

Based on the obtained results, it can be stated that the fixture was successful. For all measurements, the values obtained were within the imposed tolerances with greater precision than before. This was possible due to the application of fixturing technology principles and knowledge in the development of the new fixture system. Directing the clamping force directly to the locators was a solution that allowed for consistent shape of the entire body during machining, no deformation. As a result, when the part was unclamped, it maintained the shape achieved during machining. This was not the case with the old data, where each sample deformed differently depending on the material resistance of the cast part, resulting in spread data points, less precise values, and a higher percentage of scrapped parts.

Furthermore, locating the part using its central plane, with the implementation of protrusions at a middle height plane of the Middle Housing, ensured the positioning and alignment of the machining features with the outer faces of the part, regardless of dimensional variations from the casting process. The protrusions application resulted in a well-located part with appropriate support, allowing the fixture to precisely accommodate the parts with casting variations, preserving the concept of repeatability.

4 Conclusion and Future works

4.1 Conclusion

In conclusion, this thesis addressed the challenges faced in machining the bent axis piston pump Middle Housing manufactured by ABER by developing an efficient and effective fixturing system. The previous fixture used for manufacturing this component had limitations and required a new approach to improve the machining process.

The study began with a detailed analysis of the existing machining fixtures and their limitations. Industry standards for fixturing principles were considered, leading to the realization that a new fixturing approach was necessary. The design phase focused on developing a fixturing system that would address the identified challenges and meet the specific tolerance requirements of the pump housing machining process.

To improve the fixturing system, it was recognized that the middle housing needed additional surfaces to facilitate its fixation. Therefore, a new casting mold was developed to implement the 3 lateral protrusions, considering the precise location and clamping principles of fixturing to address the issue of elastic deformation caused by clamping forces.

The project also considered the cutting forces exerted by the main cutting tools after optimizing their cutting parameters. The distribution of forces and the stress analysis of the fixture components were taken into account. Special attention was given to the flexibility and adaptability of the system to accommodate variations in pump housing designs and sizes.

After the design phase, a prototype of the fixturing system was manufactured and tested. The testing phase involved evaluating the system's performance in real-world machining scenarios. Tests were conducted using a Coordinate Measuring Machine (CMM) to assess tolerances and repeatability, comparing the new fixture with the old fixture used for the BIP and BIM middle housing machining. The obtained results demonstrated significant improvements in machining precision, validating the effectiveness of the new fixturing system.

Based on the reasoning presented, it can be concluded that this dissertation has resulted in a methodology for the development of new fixturing systems that can be applied to optimize or develop the production of other parts with machining limitations. This methodology provides a framework for designing and implementing effective fixturing solutions, taking into account the specific constraints and requirements of the parts being machined. By offering a systematic approach, this methodology contributes improving overall manufacturing efficiency. It provides a valuable tool for practitioners in the field to address the challenges associated with machining parts, ultimately leading to more efficient and effective production processes.

In summary, this thesis successfully developed a fixturing system for the middle housing of ABER's BIP and BIM pumps. The research and development efforts encompassed comprehensive analysis, meticulous design, manufacturing, and testing. The results confirmed that the fixturing system significantly improved machining accuracy, ensuring the product meets the required tolerances and reducing the rejection rates for both Middle Housings.

4.2 Future works

This thesis has successfully addressed the challenges of fixture design and machining for Middle Housings, but there are still areas that can be explored and improved for the created fixture.

Firstly, it would be interesting to implement the hydraulic system into the fixture, combining the benefits provided by hydraulic clamping with the fixture knowledge gained and applied in the development of the new fixture. These benefits would be essential for increasing system productivity, ensuring greater precision and repeatability in clamping forces, and reducing the manual effort required by the operator.

Furthermore, as the number of parts produced by the new fixture increases during large-scale production, it would be valuable to conduct an economic analysis of the implementation and benefits generated by the fixture. This analysis would consider all implementation and development costs of the fixture, as well as the rejection rate data for each Middle Housing in comparison to the old fixture data.

Optimization of cutting parameters for the remaining tools could be studied to increase tool life and ensure the best surface finish for the housing.

Lastly, the studied and implemented concepts could be applied to the development of fixtures for other components manufactured by ABER that present some tolerance problems even if these references do not have a high rejection rate like the BIP and BIM Middle Housings.

By exploring these areas and further enhancing the fixture, future work can continue to improve productivity, accuracy, and cost-effectiveness in the machining process for Middle Housings in ABER company and potentially expand its application to other components as well.

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6 Annex

Annex 1

*Some information has been erased upon ABER's request