CAM LAB – Final Report – Group 29

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Contents

1. Notation and Formulas

This section outlines the primary equations and notations essential for the calculations and processes involved in the workpiece machining. The following parameters are utilized throughout the analysis:

Variable	Description
D	Tool diameter [mm/min]
n	Spindle speed [rpm]
fz	Feed per tooth [mm/revolution]
ap	Depth of cut [mm]
Zω	Working teeth
γ0	Insert rake angle
kr	Entering angle
Lf	Feed distance
Lr	Rapid distance

The formulas employed for determining cutting speed, spindle speed, feed velocity, and cutting pressure are listed below. The cutting pressure considers a correction factor based on the insert rake angle.

Parameter	Equation
Cutting speed [m/min]	$V_c = \frac{\pi \cdot D \cdot n}{1000}$
Feed velocity [mm/min]	$V_f = f \cdot n$
Angular speed [rad/s]	$\omega = \frac{2 \cdot \pi \cdot n}{60}$
Cutting pressure [MPa]	$k_c = k_{c0,1} \cdot h_D^{-x} \cdot \left(1 - \frac{\gamma_0}{100}\right)$

For specific milling operations, equations differ based on slab or face milling techniques.

Parameter	Equation
Working teeth	$z = \frac{\phi}{\phi_0}$, $\phi_0 = \frac{2 \cdot \pi}{Z}$
Slab Milling – Chip Thickness [mm]	$h_{D,\theta} = f_z \cdot \sin(\theta)$
Slab Milling – Chip Area [mm²]	$A_{D,\theta} = h_{D,\theta} \cdot a_p$
Face Milling – Chip Thickness [mm]	$h_{D,\theta} = f_z \cdot \cos(\theta) \cdot \sin(k_r)$
Face Milling – Chip Area [mm²]	$A_{D,\theta} = f_z \cdot \cos(\theta) \cdot a_p$
Cutting Force [N]	$F_C(\theta) = k_{c,\theta} \cdot A_{D,\theta}$
Cutting Torque [Nm]	$T_C = \sum_{i=1}^{z} F_C(\theta_i) \cdot \frac{D}{2} \cdot \frac{1}{1000}$
Cutting Power [W]	$P_C = T_C \cdot \omega$

For Drilling Operations: Drilling calculations involve determining the chip area, cutting force, feed velocity, torque, and power as outlined below.

Parameter	Equation
Chip Area [mm²]	$A_D = \frac{f \cdot D}{4}$
Cutting Force [N]	$F_C = k_C \cdot A_D$
Feed Velocity [mm/min]	$V_f = n \cdot f_n$
Cutting Torque [Nm]	$T_C = F_C \cdot \frac{D}{2} \cdot \frac{1}{1000}$
Cutting Power [W]	$P_C = T_C \cdot \omega$

For Reaming Operations: Reaming employs similar principles with adjustments for the annular chip area.

Parameter	Equation
Chip Area [mm²]	$A_D = f_z \cdot \frac{(D_{\text{ext}} - D_{\text{int}})}{2}$
Cutting Force [N]	$F_C = k_C \cdot A_D$
Cutting Torque [Nm]	$T_C = Z \cdot F_C \cdot \frac{D_{\text{ext}}}{2} + \frac{D_{\text{int}}}{2} \cdot \frac{1}{1000}$
Cutting Power [W]	$P_C = T_C \cdot \omega$

Surface Roughness: Surface roughness estimations depend on the machining operation. Below are the equations used.

Operation	Equation
Slab Milling [μm]	$R_{\max} = \frac{R}{2 \cdot \pi^2 f_z^2 \cdot 10^3} \cdot \frac{1}{(2\pi R + 60 Z f_z)^2 \cdot \frac{1}{4}}$
Turning Nose Radius [μm]	$R_{\max} = \frac{f^2 \cdot 10^3}{8r}$, if $f \leq 0.8 b_s$

Machining Time: The time required for machining combines feed and rapid distances, calculated using the following formula.

Parameter	Equation
Time of machining [s]	$\frac{L_f}{v_f} + \frac{L_r}{v_r}$

2. Introduction

The present report outlines the selection of tools and the manufacturing process for the required component, employing the third variant for each parameter, in this way, the piece is made from a low-alloy steel with a high carbon content, specifically identified as **P1.3.Z.AN**, according to Sandvik's classification. This material offers enhanced hardness and wear resistance, making it suitable for demanding industrial applications. However, its machining characteristics require careful consideration to ensure compliance with technical requirements and to maintain process efficiency.

The focus of this study is to justify the decisions made regarding tool selection and machining strategies to meet stringent surface roughness and geometrical constraints criteria. These requirements were fulfilled in the Autodesk simulation environment of **Autodesk Fusion 360**, where initially the piece was modelled through its computer-aided design (CAD) environment, while the manufacturing operations were tested within the computer-aided manufacturing (CAM) section of the software, adhering to the capabilities of the 4-axis CNC machine provided with a maximum power output of 16 kW, ensuring an optimal balance between precision and operational limits. Furthermore, productivity improvements were achieved by minimizing the number of setups and tool changes, which reduced machining time and streamlined the overall manufacturing process. By implementing these strategies, the manufacturing approach not only met technical specifications but also contributed to the efficiency of the production system, minimizing potential issues and enhancing the quality of the final product.

2.1 Inputs and Variables

The raw material for the process consists in a rectangular parallelepiped of 126 X 132 X 264 mm, this piece is the stock employed to produce the part that can be seen in the right part of Figure 1.

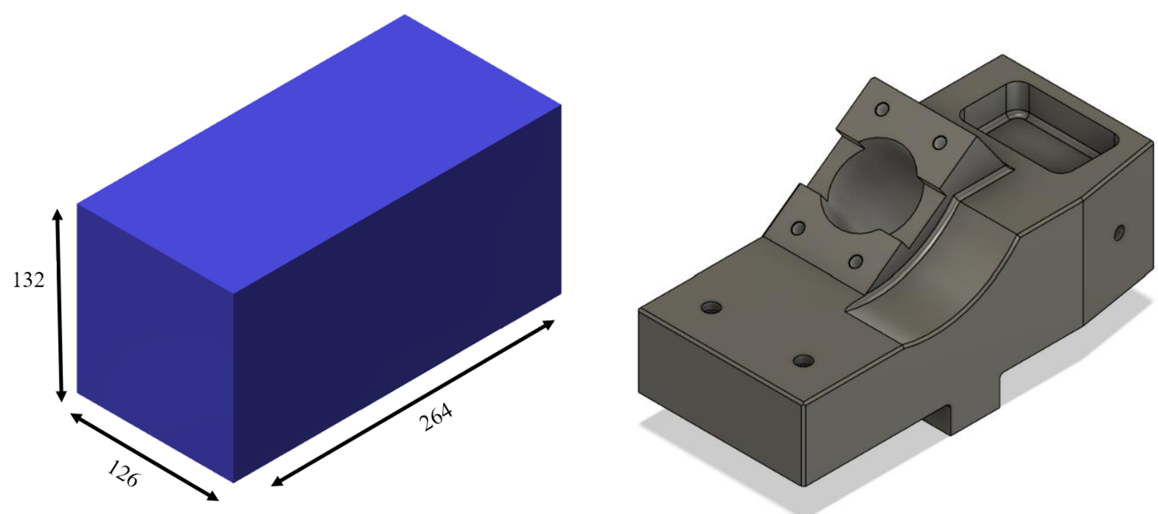

Figure 1. Raw material and final manufactured piece

The material assigned for the piece consists of an unalloyed steel with a high carbon content, it is above 0.55 %. This high-carbon steel has been forged, rolled or cold drawn during its manufacturing process, having an annealing heat treatment to reach a hardness of 190 HB. In this way, the MC code for this material is **P1.3.Z.AN**, from the Sandvick website, the following manufacturing parameters are considered as the inputs for the manufacturing planning.

Material	
MC code	P1.3.Z.AN
HB Hardness	190
Specific Cutting Force (k_{c1}) [N/mm]	1750
Cutting law (m_c)	0.25

Table 1 Workpiece material characteristics provided by Sandvick

A **4-axis CNC machine** will be used for the manufacturing process, offering four axes of movement, the displacement along the three orthogonal axes and the rotation of the tool around the X or Y axes as the Z axis is the primary axis of the spindle rotation. Finally, the **Y-axis** has been selected to allow the rotation of the cutting tool around this axis, providing additional flexibility and capability to perform diverse operations in orthogonal way to the associated surfaces. The following table collect all the information regarding to the machine that is going to be used.

2.2 Features and Operations

The following discussion outlines the three main groups of features relevant to machining the workpiece: large surfaces, the pocket, and the inclined plane. Each group has specific geometric and dimensional requirements to achieve the desired functionality and appearance of the component.

2.2.1 Large Surfaces Section

This group includes the main flat surfaces and contours, such as the top surface, surfaces B, C, D, and E, as well as the bottom surface and circular sections. All chamfers in this group are 1.5 mm, and the fillets have a radius of 3 mm. These surfaces are machined using slab and face milling operations to achieve a surface roughness of 12.5 µm. To ensure proper alignment and flatness, careful setup, precise fixtures, and regular checks are used during machining. These steps are important for the correct assembly and performance of the component. This group also includes the lateral inclined plane and the circular section.

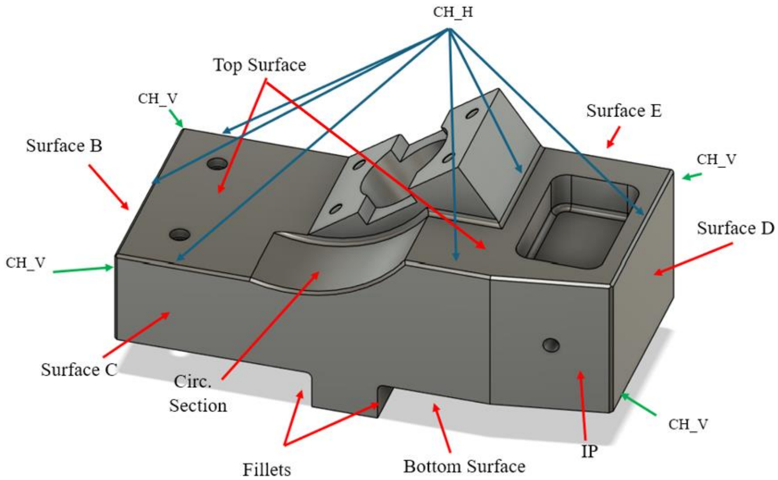

Figure 2 Features of Large Surfaces

2.2.2 Pocket Section

This group focuses on the pocket features, which include the bottom surface, the perimeter fillets, and the vertical walls. The bottom surface requires a surface roughness of 3.2 µm. The perimeter fillets have a larger radius of 8 mm, compared to the 3 mm fillets elsewhere, to meet specific design needs. Machining starts with roughing to remove most of the material, followed by finishing operations using ball-nose and slab milling tools to ensure accuracy and surface quality. Counterbore holes are machined to H7 tolerance, while the others have H10. Additionally, a 9.8 mm diameter access hole is made to allow tools to reach deeper areas for machining.

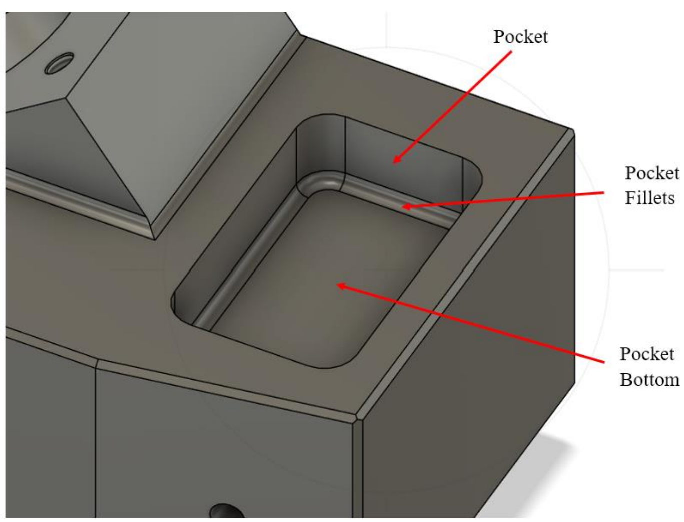

Figure 3 Features of Pocket Section

2.2.3 Inclined Plane Section

This group includes the inclined plane and its related features, such as the main hole, smaller holes, and the rectangular section. The main hole is machined to an H7 tolerance for precise fits, while the inclined face requires a surface roughness of 3.2 µm, achieved with specific milling operations. Smaller holes in this group are finished to an H10 tolerance, suitable for secondary assemblies. As in other groups, the chamfers are 1.5 mm, and the fillets have a 3 mm radius.

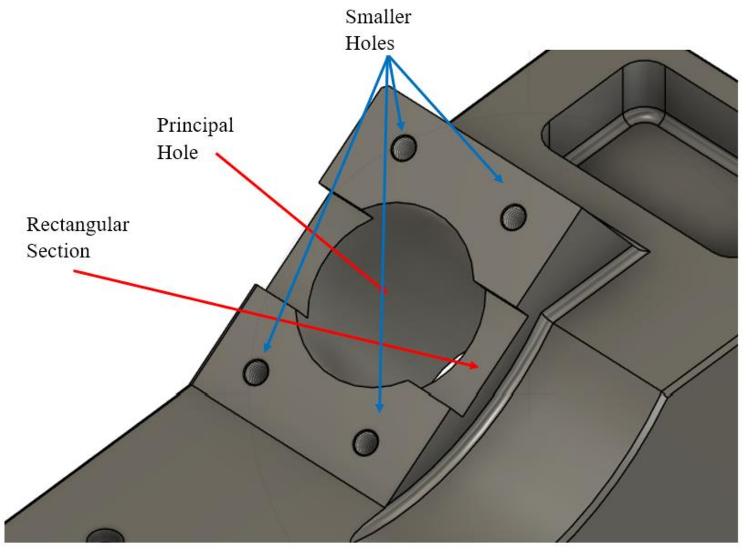

Figure 4 Features of Inclined Plane Section

2.2.4 Table of Operations

The following table summarize all the operations made in chronological order. As observed to obtain the final product we are going to employ a total of 36 manufacturing operations, developed in a set of three setups aiming at meeting all the technical requirements of the workpiece and seeking to maximize final productivity. For that reason, it is planned to further reduce the number of tool changes, in this way, many similar operations are grouped together to achieve this objective. Moreover, the following table collects all the important information regarding the geometrical constraints and the surface requirements, as well as the selected machining operation to carry out each operation by the team.

N°	CODE	FEATURE	SURFACE	GEOMATRICAL RELATION	OPERATION
1	BS	Bottom Surface	Ra 12.5	// 0.1 C	Face Milling
2	SB	Lateral Face B	Ra 12.5		Face Milling
3	SD	Lateral Face D	Ra 12.5		Face Milling
4	SC	Lateral Face C	Ra 12.5		Slab Milling
5	LIP	Lateral Inclined Plane			Slab Milling
6	CH_V	Vertical Chamfers			Slab Milling
7	BFF	Bottom Fillets R3	Ra 12.5		End Milling

8	TS	Top Surface	Ra 12.5	// 0.1 A	Face Milling
9	SE	Lateral Face E	Ra 12.5		Face Milling
10	CS_R	Circular Sec Rough			Face Milling
11	CS_F	Circular Section R76	Ra 12.5		Slab Milling
12	FF_1	Fillets			End Milling
13	S_DR1	Spot Drilling			Spot Drilling
14	PP	Pocket predrill			Drilling
15	PT	Pocket	Ra 12.5	⌯ 0.1 E	Slab Milling
16	PB	Pocket Bottom	Ra 3.2	// 0.1 A	Face Milling Finishing
17	H2_1	Deep through hole Ø6.8 x2			Drilling
18	H2_2	Hole Ø9.8 x2			Drilling
19	H2_3	Hole Ø10 x2	H7		Counter Bore
20	H2_4	Deep through hole Ø8 x2			Tapping
21	S_DR2	Spot Drilling		— Ø0.2	Spot Drilling
22	H1	Deep through hole Ø8		— Ø0.2	Drilling
23	CH_H	Horizontal Chamfers			Chamfer
24	P_IP_1	Principal Inclined Plane 1			Face Milling
25	P_IP_2	Principal Inclined Plane 2		∠ Ø0.1 A	Face Milling
26	P_IP_2F	Principal Inclined Plane 2	Ra 3.2	∠ Ø0.1 A	Face Milling Finishing
27	FF_2	Fillets			End Milling
28	S_DR3	Spot Drilling			Spot Drilling
29	SH_1	Spot Deep through hole			Drilling
30	SH_2	Spot Deep through hole			Reaming
31	IP_H1	Principal Hole Cleaning			Slab Milling
32	IP_H2	Principal IP Hole Ø52	Ra 3.2 / H7	⊥ Ø0.1 D	Boring
33	RS	Rectangular Section	Ra 12.5		End Milling
34	H3_1	Smaller Holes V2x4		⌖ Ø0.1 D F	Drilling
35	H3_2	Smaller Holes V2x4			Tapping
36	CH_H2	Horizontal Chamfers			Chamfer

Table 2 Manufacturing operations with their technical constraints

2.3 Precedence Graph

Figure 5 illustrates the precedence graph of the project, outlining the sequence of operations for each setup to meet the technical requirements of the workpiece. For that purpose, the machining operations are divided into two groups: roughing and finishing. The roughing operations, highlighted in red rectangles in the figure, include all tasks with low surface roughness requirements. Conversely, the finishing operations, highlighted in blue rectangles, encompass tasks requiring high surface finish quality, and final geometric features such as threads, counterbores, fillets and chamfers.

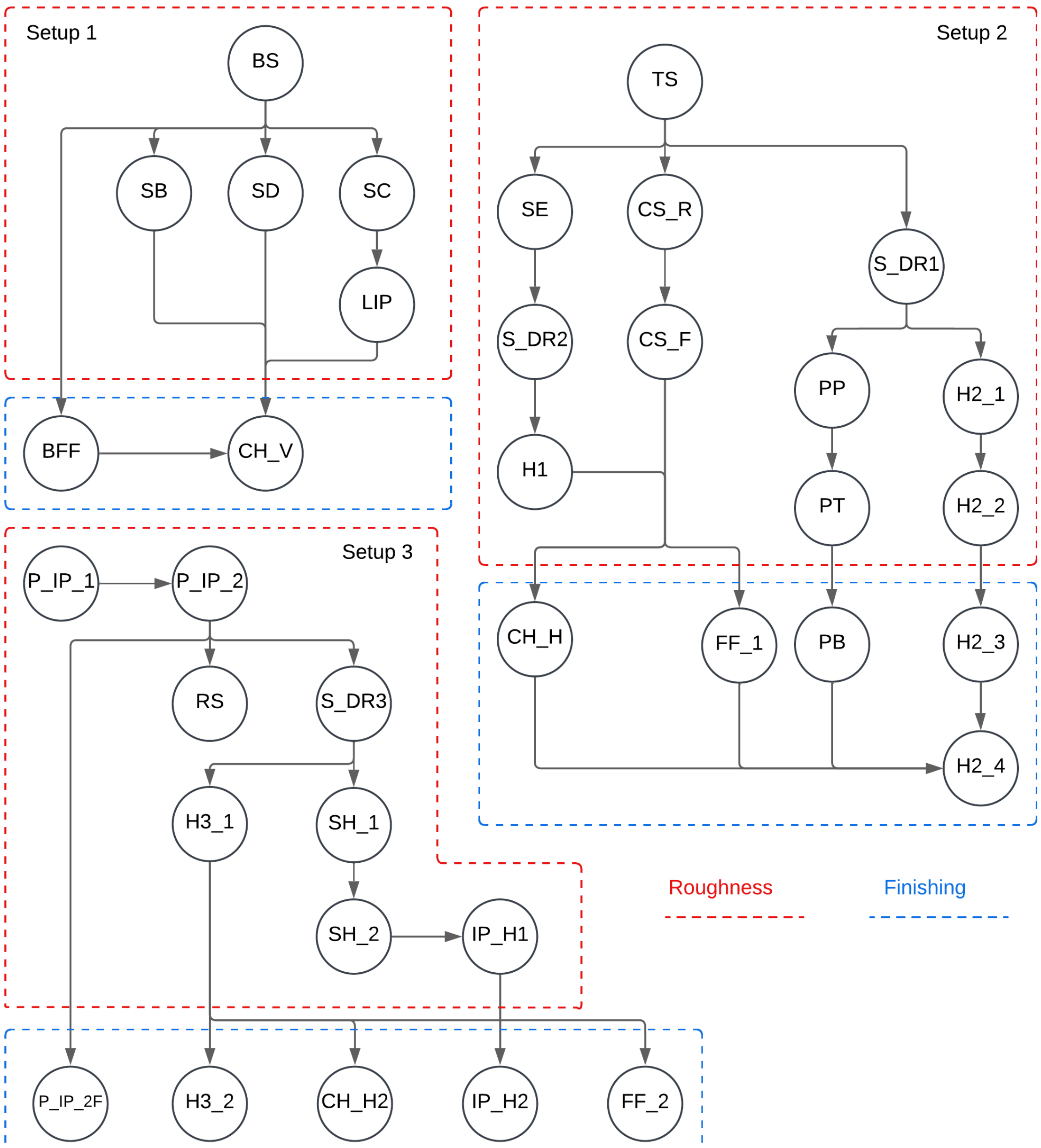

Figure 5 Precedence graph for the manufacturing process

3. Final Solution

3.1 Throughput of the Product

The workpiece manufacturing process is composed by three different setups, it is carried out by 36 manufacturing operations, which includes diverse spindle reorientations and tool changes that are going to be explained in detail below. The machining times formulas employed as they are related above helped us to optimize the machining time, but here we are going to consider the fusion 360 machining times, for that reason it is important to note that the rapid motion of the cutting tool has to be set to 42 m/min as this is the rapid speed of the machine, and including the spindle orientation, setup and tools changes to provide an effective throughput of the final product.

The machining process starts by configuring the first setup, where the bottom face is going to be manufactured as it is going to be explained in detail in the following section, the first tool is mounted onto the spindle and it is oriented in the Z-axis, the first operations are carried out and then the spindle is reoriented, developing a 90-degree rotation about the Y-axis of the tool in order to reach the lateral surface D; then another spindle rotation is required, in this case a 180 degree to manufacture the lateral face B.

When these operations are finished, a reorientation and tool change is required, by having the spindle in the initial orientation (parallel to the Z-axis) this helps us to manufacture the lateral face C, and also to create all the vertical chamfers required in the workpiece, as the selected tool is able to perform the finishing in the neck of the bottom part of the workpiece, the same tool is employed, reducing the number of tool changes. The following table summarizes all the above information for the first setup

Operation	Time [s]
Loading / Unloading Time	60
Tool Changing Time	15
Machining Time (BS)	26
Machining Time (BS1)	319
Spindle Repositioning Time	5
Machining Time (SD)	42
Spindle Repositioning Time	5
Machining Time (SB)	52
Spindle Repositioning Time	5
Tool Changing Time	15
Machining Time (SC)	5
Machining Time (SC_1)	83
Machining Time (LIP)	31
Machining Time (CH_V)	9
Machining Time (CH_V1)	5
Machining Time (BFF)	13
Total Setup 1 Time	**690**

Table 3 First setup throughput

Once the first setup is completed, the workpiece must be repositioned. This is achieved by rotating the piece 180 degrees, using the machined face as the datum and surfaces B and D as clamping surfaces. For further details, refer to the subsequent section of this report. Moreover, the tool is required to be changed in order to rough quickly the large surfaces on top, and maintaining the same tool the face milling operation in the lateral faces, for the last purpose, a spindle reorientation is required, meaning a 90-degrees rotation about the Y-axis to manufacture the lateral face E; and a 180-degree rotation about this axis to develop the roughing operations in the other side of the workpiece. After the roughing operation is done, for the finishing operations, a tool change is required, and finally the fillet is also achieved.

The spindle is located again in its initial configuration, in order to complete the operations in the top surface developing the pocket, and the counterbore holes in the other side of this surface, as threading these holes is required, another tool change is done, and the same process is required for the counterboring of the holes. Finally, the spindle is rotated 90 degrees to develop the lateral deep through hole, for that operation it is required a pre-drill operation and indeed a couple of tool changes. Finally, taking advantage of the orientation of the spindle we develop the horizontal chamfers of the lateral face E, and then we rotate twice the spindle 90 degrees around the Y-axis to generate the chamfer in the top surface, and on the circular section of the workpiece, it is important to remark that all the chamfers are manufactured using the same milling tool, having a point angle of 45 degrees. The following table summarizes the times split for the second setup.

Operation	**Time [s]**
Loading / Unloading Time	60
Tool Changing Time	15
Machining Time (TS)	736
Machining Time (TS1)	349
Spindle Repositioning Time	5
Machining Time (SE)	74
Spindle Repositioning Time	5
Machining Time (CS_R)	105
Tool Changing Time	15
Machining Time (CS_F)	91
Machining Time (FF_1)	4
Spindle Repositioning Time	5
Tool Changing Time	15
Machining Time (S_DR1)	2
Tool Changing Time	15
Machining Time (PP)	1
Tool Changing Time	15
Machining Time (PT/PB)	102
Tool Changing Time	15
Machining Time (H2_1)	11
Tool Changing Time	15
Machining Time (H2_2)	2
Tool Changing Time	15
Machining Time (H2_3)	4
Tool Changing Time	15

Machining Time (H2_4)	17
Spindle Repositioning Time	5
Tool Changing Time	15
Machining Time (S_DR2)	1
Tool Changing Time	15
Machining Time (H1)	20
Tool Changing Time	15
Machining Time (CH_H1)	19
Spindle Repositioning Time	5
Machining Time (CH_H2)	48
Spindle Repositioning Time	5
Machining Time (CH_H)	9
Total Setup 2 Time	**1865**

Table 4 Second setup throughput

The final setup was developed to work perpendicular to the inclined planes of the top surface, this was achieved by rotating the entire workpiece and fixture by 90-degrees. In this setup, the process begins with a tool change to machine the first inclined plane. This requires repositioning the workpiece by rotating it 54 degrees about the Y-axis to work perpendicularly to this plane. Subsequently, a new repositioning is necessary, this time a 36-degree rotation from the original position parallel to the Z-axis. This adjustment allows perpendicular access to the plane where the threaded holes, the open rectangular slot, and the main cavity of the part are machined.

Taking advantage of the spindle's orientation, all required holes are machined using pre-drilling and drilling operations. For the threaded holes, an additional threading operation is necessary. Meanwhile, for the main hole, its diameter must be enlarged, initially achieved using a couple of drills, and slab milling; the final step in order to ensure the required concentricity, the finishing operation is performed using a boring process. It is important to note that, in general, a tool change is required before performing each of the steps mentioned above.

Finally, the rectangular slot is machined using a flat end milling. Lastly, the chamfers on these two planes are created by simply reorienting the spindle axis through a 90-degree rotation around the machine's Y-axis. The following table shows the machining time in each operation.

Operation	Time [s]
Loading / Unloading Time	60
Tool Changing Time	15
Spindle Repositioning Time	5
Machining Time (P_IP_1)	121
Spindle Repositioning Time	5
Machining Time (P_IP_2/F)	419
Tool Changing Time	15
Machining Time (FF_2)	8
Tool Changing Time	15
Machining Time (S_DR3)	4

Tool Changing Time	15
Machining Time (SH_1)	18
Tool Changing Time	15
Machining Time (SH_2)	37
Tool Changing Time	15
Machining Time (IP_H1)	63
Tool Changing Time	15
Machining Time (IP_H2)	44
Tool Changing Time	15
Machining Time (RS)	133
Tool Changing Time	15
Machining Time (H3_1)	7
Tool Changing Time	15
Machining Time (H3_2)	12
Tool Changing Time	15
Machining Time (CH_H2)	3
Spindle Repositioning Time	5
Machining Time (CH_H21)	5
Total Setup 3 Time	**1114**

Table 5 Third setup throughput

The following table, summarizes all the process throughput information, finding a total manufacturing time of 3643 seconds, which means one hour and 69 seconds for producing a piece, it ends up with a production ratio of 0.981 parts per hour.

Setup	Time [s]
Setup 1	690
Setup 2	1865
Setup 3	1114
Total Setup Manufacturing Time	**3669**
Parts per hour	**0.981**

Table 6 Workpiece throughput summary

3.2 Setups Information

To increase the throughput of the product, a basic idea was employed when selecting the number of setups and the way they were used as any change of setup supposed an increase in the manufacturing time by 60 seconds. Initially, the team thought that there were required at least four setups to carry out the manufacturing of the piece and maintaining its geometrical constraints; nevertheless, it was found that the final product was realizable using three setups, in this way a reduction of a minute in the throughput of the product was achieved. The final setups are explained as follows.

3.2.1 First Setup

The first setup was selected to start by machining the bottom surface of the piece, based on its surface roughness requirements, and furthermore, the planar geometry with the same height for both shoulders of the piece, encourages us to use it as clamping surfaces for the following setups, and obviously as datum for other machining operations.

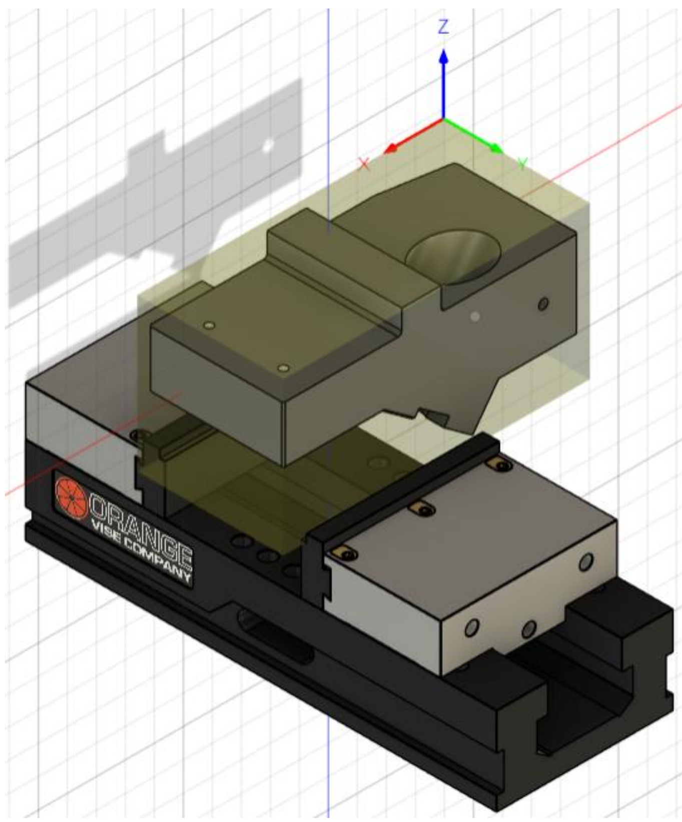

Figure 6 First Setup configuration in Autodesk Fusion 360

The final position of the initial stock for the piece is done by considering that this is going to be not only a suitable setup for achieving the bottom surface of the piece, but also the lateral faces (B, C and D) as well as the inclined plane that connects surfaces C and D, and the vertical chamfers required in the final piece. For this reason, the stock was aligned with an offset of 19.45 mm with respect to the surface B, leaving free the needed space to manufacture the inclined plane without generating collisions between the cutting tool and the fixture.

As the selected fourth axis of the machine was the rotation of the tool around the y-axis, meeting the requirements of parallelism between the lateral faces of the neck of the piece and the surfaces B and D is feasible by developing the required operations of these faces employing this setup.

3.2.2 Second Setup

In the second setup the piece is rotated by 90 degrees on Z axis, in order to reach perpendicularly the lateral faces C and E. The piece was also positioned with surface E beyond the fixture lateral perimeter, achieving the necessary clearance to machine it, leaving an offset of around 8 mm for this purpose. The clamping is executed on the previously manufactured surfaces B and D, moreover, the bottom surface is used as a datum for the parallel operations, on top surface, to this surface required.

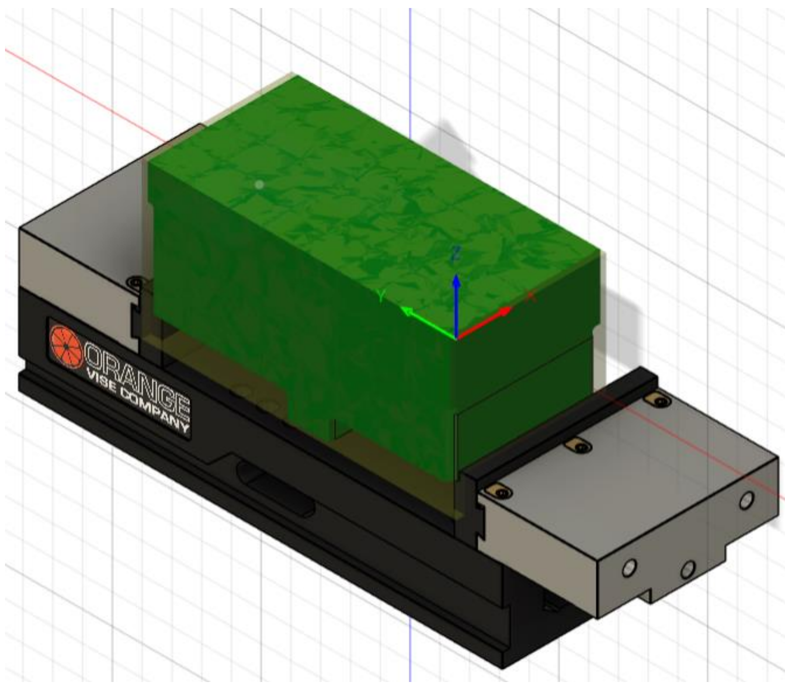

Figure 7 Second Setup configuration in Autodesk Fusion 360

The rotation around the Y-axis is also useful in this setup for manufacturing the circular section employing slab milling. Finally, the top surface is going to be developed leaving a rectangular section for the inclined planes that are going to be manufactured in the final setup; furthermore, as the lateral face E is developed in this setup, and it is the datum for the geometrical restrictions of the pocket, this feature is going to be developed in this setup.

3.2.3 Third Setup

The third setup is similar to the second one as the clamping position remains the same. Instead, a 90-degree rotation is applied to the fixture, having the spindle able to align perpendicularly to the inclined planes on top surface through the 4th axis by developing the rotation around the Y-axis of the CNC machine.

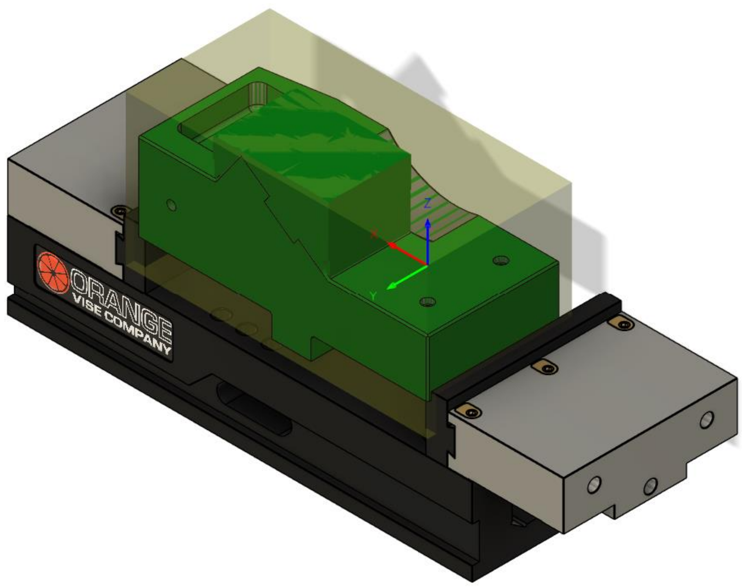

Figure 8 Third Setup configuration in Autodesk Fusion 360

As this setup allows us to work perpendicular to the main inclined plane, the development of the thread holes and the open rectangular slot are carried out with this setup, giving us the opportunity to finalize the manufacturing of the piece meeting all the technical requirements.

3.3 Manufacturing Resources

3.3.1 Fixturing device

The fixturing device consists of a 3 flat clamps, the device was not scaled from its initial configuration, as it was already directly usable. Nevertheless, the Slider of the fixture was modified from its initial 165.25 mm to a final value of 260 mm as it was required to finally clamp the piece employing the largest side of the piece.

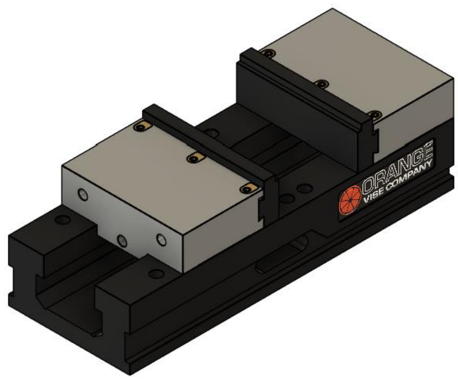

Figure 9 Clamping device in Autodesk Fusion 360

3.3.2 Tools

The table below presents details for each tool used into machining of individual features of the workpiece. This information includes the operation, the corresponding ISO code from the supplier, and the inserts or adapters when they are utilized. Further details of each tool will be discussed in the following sections of this report.

CODE	FEATURE	OPERATION		TOOL TYPE	ISO CODE	INSERT / ADAPTOR
BS	Bottom Surface	Face Milling	Roughness	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
SB	Lateral Face B	Face Milling	Roughness	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
SD	Lateral Face D	Face Milling	Roughness	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
SC	Lateral Face C	Slab Milling	Roughness	Lateral Mill Cutter	316-25SL442-25030P 1730	EH25-A24.7-SS-135
LIP	Lateral Inclined Plane	Slab Milling	Roughness	Lateral Mill Cutter	316-25SL442-25030P 1730	EH25-A24.7-SS-135
CH_V	Vertical Chamfers	Slab Milling	Finishing	Lateral Mill Cutter	316-25SL442-25030P 1730	EH25-A24.7-SS-135
BFF	Bottom Fillets R3	End Milling	Finishing	End Mill Cutter R3	316-25SL442-25030P 1730	EH25-A24.7-SS-135
TS	Top Surface	Face Milling	Roughness	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
SE	Lateral Face E	Face Milling	Roughness	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
CS_R	Circular Sec Rough	Face Milling	Roughness	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
CS_F	Circular Section R76	Slab Milling	Roughness	Lateral Mill Cutter	316-25SL442-25030P 1730	EH25-A24.7-SS-135

FF_1	Fillets	End Milling	Finishing	End Mill Cutter R3 with Extension	316-25SL442-25030P 1730	EH25-A24.7-SS-135
S_DR1	Spot Drilling	Spot Drilling	Roughness	Solid Carbide Drill 147°	860.1-0680-055A1-PM P1BM	
PP	Pocket predrill	Drilling	Roughness	Solid Carbide Drill 147°	860.1-0980-031A1-PM P1BM	
PT	Pocket	Slab Milling	Roughness	End Mill Cutter R3	1K335-1200-300-XD-1730	
PB	Pocket Bottom	Face Milling	Finishing	End Mill Cutter R3	1K335-1200-300-XD-1730	
S_DR2	Spot Drilling	Spot Drilling	Roughness	Solid Carbide Drill 147°	860.1-0680-055A1-PM P1BM	
H1	Deep through hole Ø8	Drilling	Roughness	Solid Carbide Drill 140°	861.1-0800-120A1-GM GC34	
H2_1	Deep through hole Ø6.8 x2	Drilling	Roughness	Solid Carbide Drill 147°	860.1-0680-055A1-PM P1BM	
H2_2	Hole Ø9.8 x2	Drilling	Roughness	Solid Carbide Drill 147°	860.1-0980-031A1-PM P1BM	
H2_3	Hole Ø10 x2	Reaming	Finishing	Reamer	835.B-1000-A1-PF 1024	
H2_4	Deep through hole Ø8 x2	Tapping	Finishing	Deep Through Hole Tapper	T200-XM101DA-M8 C110	
CH_H	Horizontal Chamfers	Chamfer	Roughness	Chamfer Mill Cutter	495-012A16-4509L	495-09T3M-MM 1040
P_IP_1	Principal Inclined Plane 1	Face Milling	Roughness	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
P_IP_2	Principal Inclined Plane 2	Face Milling	Roughness	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
P_IP_2F	Principal Inclined Plane 2	Face Milling Finshing	Finishing	Flat Face Mill Cutter	R390-100Q32-18L	R390-18 06 08M-PM 4330
FF_2	Fillets	End Milling	Finishing	End Mill Cutter R3	1K335-1200-300-XD-1730	
S_DR3	Spot Drilling	Spot Drilling	Roughness	Solid Carbide Drill 147°	860.1-0680-055A1-PM P1BM	
SH_1	Spot Deep through hole	Drilling	Roughness	Solid Carbide Drill 140°	861.1-0800-120A1-GM GC34	
SH_2	Spot Deep through hole	Reaming	Roughness	Indexable insert drill	D DS20-D2600L32-05	DS20-0306-C-L5 1344
IP_H1	Principal Hole Cleaning	Slab Milling	Roughness	Lateral Mill Cutter	316-25SL442-25030P 1730	EH25-A24.7-SS-135
IP_H2	Principal IP Hole Ø52	Boring	Finishing	Boring Bar	825D-56TC09U-C4L	TCGT 09 02 02L-K 1515
RS	Rectangular Section	End Milling	Roughness	Flat End Mill Cutter	2N342-1400-PC 1730	
H3_1	Smaller Holes V2x4	Drilling	Roughness	Solid Carbide Drill 147°	860.1-0680-055A1-PM P1BM	
H3_2	Smaller Holes V2x4	Tapping	Finishing	Blind Hole Tapper	T300-PM104DA-M8 P1PM	
CH_H2	Horizontal Chamfers	Chamfer	Finishing	Chamfer Mill Cutter	495-012A16-4509L	495-09T3M-MM 1040

Table 7 Selected tools codes from supplier

4. Verification of Operations

The team decided to group different operations that can be carried out while maintaining similar cutting parameters based on the use of the same cutting tool, to facilitate the operation verification process by performing the verifications on the most critical operation. Furthermore, in order to maximise productivity, the operation parameters were modified for those operations where the critical conditions were not reached, improving the time required for each of the operation.

4.1 Face Milling Operations

4.1.1 Roughing Face Operations

For the Facing operations that have a high-material removal rate, the team decided to use a large face mill cutter and based on the need to manufacture the neck in the bottom surface of the piece, it was selected a 90-degree shoulder milling cuter, from the CoroMill® 390 Sandvick family. The selected tool was the **R390-100Q32-18L** which is a mill cutter of 100 mm cut diameter employing a course pitch which allows us to obtain lower cutting forces, and indeed these types of tools are highly recommended for limited power CNC machines. The selected tool requires the coupling of 5 cutting inserts, for that purpose, the **R390-18 06 08M-PM 4330** were selected as they are used in general machining operations, and it is reported as a good option for working with unallowed steels.

The most critical operation for this family of operations is going to be carried out in the top surface (TS1 operation) where we are going to rough a final depth of 26 mm, as the finishing operations are not required based on the roughness established for the piece, we are going to develop this surface by realizing 5 passes, each of them having an axial depth of cut (a_p) of 5.2 mm. Finally, Sandvick recommends to use a maximum width of cut of 70% of the total cut diameter of the tool to reduce the vibrations in the operation, so the team follows the suggestion stablishing the maximum radial cutting depth (a_e) as 70 mm which is going to be the maximum engagement of the tool, for this specific part of the top surface machining it is going to be required two steps to obtain the final surface as it has a rectangular shape of 126X91.5 mm. Table 8 collects the cutting parameters as well as the restrictions for them for the selected tool and inserts.

Parameter	**Value**	**Units**
Number of cutting teeth $(\boldsymbol{Z_w})$	5	-
Cutting Diameter $(\boldsymbol{DC})$	100	mm
Rake angle $(\boldsymbol{\gamma_0})$	13.5	°
Cutting angle $(\boldsymbol{\kappa_r})$	90	°
Cutting Speed $(\boldsymbol{V_c})$	300 – 330	m/min
Feed per tooth $(\boldsymbol{f_z})$	0.08 – 0.3	mm/rev
Axial depth of cut $(\boldsymbol{a_p})$	5.2	mm
Radial depth of cut $(\boldsymbol{a_e})$	70	mm

Table 8 Features for R390-100Q32-18L tool employing R390-18 06 08M-PM 4330 inserts

The maximum power is set to 16 kW, in this way we have to find the parameters that maintain us below this power but as near as possible to achieve the best machining times, the cutting parameter selection starts by finding the number of teeth engaged during the cutting operation, for that purpose, we have to find the contact angle through the cutting process, knowing that as we are employing more than the 50% of the cutting diameter of the tool, one of the angles is $\varphi_1 = 90°$

$$\varphi = \varphi_1 + \varphi_2$$

The second angle, can be calculated, with the remaining percentage of the tool that is going to be engaged through the process

$$\varphi_2 = \sin^{-1}\left(\frac{70\% - 50\%}{50\%}\right) = 0.4115\, rad = 23.58°$$

$$\varphi = 90° + 23.58° = 113.58°$$

Furthermore, the angle between inserts, can be found as.

$$\varphi_0 = \frac{360°}{Z_w} = \frac{360°}{5} = 72°$$

Finally, the number of cutting teeth engaged along the manufacturing is found as follows.

$$z = \frac{\varphi}{\varphi_0} = \frac{113.58°}{72°} = 1.5775$$

This result leads the process to the most critical scenario, where two of the teeth are engaged simultaneously, the worst situation, meaning the highest power required, occurs when they are placed having the same angle in magnitude with respect to the feed movement in opposite directions being $\theta_1 = -\theta_2 = \frac{\varphi}{2}$

$$h_{D,\theta} = f_z \cdot \cos(\theta) \cdot \sin(\kappa_r)$$

Considering that the cosine function is an even function, we are going to obtain the same chip thickness for both angles. The feed per tooth was selected as 0.135 mm/rev which is within the admissible ranges for the cutting insert selected.

$$h_{D,\theta_1} = h_{D,\theta_2} = 0.135 \cdot \cos(36°) = 0.1092\, mm$$

The specific cutting pressure can be calculated using the known formulas

$$k_{c,\theta_1} = k_{c,\theta_2} = k_{cs} \cdot {h_{D,\theta_1}}^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right)$$

$$k_{c,\theta_1} = k_{c,\theta_2} = 1750\, MPa \cdot 0.1092^{-0.25} \cdot \left(1 - \frac{13.5}{100}\right) = 2633.18\, MPa$$

The area of the generated chips can be evaluated as follows

$$A_{D,\theta_1} = A_{D,\theta_2} = h_{D,\theta_1} \cdot a_p = 0.1092 \cdot 5.2 = 0.57\, mm^2$$

Finally, the cutting forces can be calculated using the formula

$$F_c = F_{c_1} = F_{c_2} = k_{c,\theta_1} \cdot A_{D,\theta_1} = k_{c,\theta_2} \cdot A_{D,\theta_2}$$

$$F_c = 2633.18\ MPa \cdot 0.57\ mm^2 = 1495.46\ N$$

The torque, can be easily found knowing that the arm of the force is going to be the radius of the cutting tool

$$T_c = T_{c_1} = T_{c_2} = F_c \cdot \frac{D}{2} \cdot \frac{1}{1000} = 74.77\ Nm$$

In order to compute the value of the power required, it is necessary to set a parameter for the cutting speed, in this case, we are going to follow the Sandvick recommendation for this insert of 315 m/min.

$$n = \frac{1000 \cdot v_c}{\pi \cdot DC} = 1002.68\ RPM$$

$$\omega = n \cdot \frac{2\pi}{60} = 105\ rad/s$$

$$P_c = T_{c_{max}} \cdot \omega = 2 \cdot T_c \cdot \omega = 2 \cdot 74.77\ Nm \cdot 105\ rad/s = 15.70\ kW$$

For the final verification regarding the surface finish, several important aspects of the operation performed, and the tool used must be considered. The primary entry angle during the cutting process is 90 degrees. On the other hand, the inserts used do not have cutting edges around its entire surface but only have two cutting edges followed by a set of wipers. These wipers will allow us to achieve very fine finishes, theoretically zero, based on the information from Sandvik condensed in the following equation.

$$f_z < 0.8 \cdot BS = 0.8 \cdot 1.1 = 0.88\ mm/rev$$

As long as the feed per tooth in the operations is within this range, there will be no roughness, although in real life, this will depend on the wear of the cutting edge of the insert cutting edges and wipers. Considering that there are other facing operations that are going to be carried out employing the same milling tool, we are going to maintain the maximum radial depth of cut (a_e) modifying the other parameters based on specific requirements of each operation, the results, for power and roughness are condensed in the following table.

Operation	$a_p\ [mm]$	$a_e\ [mm]$	$h_D\ [mm]$	$f_z\ \left[\frac{mm}{rev}\right]$	$v_c\ \left[\frac{m}{min}\right]$	$P_c\ [kW]$	$R_a\ [\mu m]$
BS	2.765	70	0.22	0.275	315	14.24	-
BS1	5	70	0.11	0.14	315	15.51	-
SD	5	70	0.11	0.14	315	15.51	-
SB	5	50	0.11	0.14	315	15.51	-
TS	4.75	70	0.12	0.15	315	15.52	-
TS1	5.2	70	0.11	0.138	315	15.70	-
SE	5	70	0.11	0.14	315	15.51	-

CS_R	4.9	70	0.12	0.145	315	15.61	-
P_IP_1	5	45	0.11	0.14	315	15.51	-
P_IP_2	4.7	50	0.13	0.155	315	15.74	-

Table 9 Cutting parameters employing R390-100Q32-18L tool with R390-18 06 08M-PM 4330 inserts

4.1.2 Inclined Plane Finishing Face Milling

The inclined plane on the upper face of the figure is one of the surfaces requiring a higher surface finish. Therefore, the parameters listed in the previous table are specified for the roughing process. For the finishing process, which will be performed using the same tool in two passes with a depth of cut of 0.5 mm each, the feed per tooth is set at 0.135 mm/rev, as this feed per tooth falls in the previous specified range, the theoretical roughness is going to be zero, and by guaranteeing the appropriate change of the insert based on the cutting tool life considerations we are going to ensure that the final surface finish requirement is met

$$f_z = 0.135\, mm/rev \ < 0.8 \cdot BS = 0.8 \cdot 1.1 = 0.88\, mm/rev$$

On the other hand, the cutting speed is maximized, and indeed the throughput of the workpiece by using the maximum value allowed for the insert, 330 m/min. The final parameters for this operation can be found using the same process that we have detailed in the previous subsection, and they can be reviewed in the following table.

Operation	$a_p\ [mm]$	$a_e\ [mm]$	$h_D\ [mm]$	$f_z\left[\frac{mm}{rev}\right]$	$v_c\left[\frac{m}{min}\right]$	$P_c\ [kW]$	$R_a\ [\mu m]$
P_IP_2_F	0.5	50	0.109	0.135	330	1.58	-

Table 10 Cutting parameters for finishing operations employing R390-100Q32-18L tool with R390-18 06 08M-PM 4330 inserts

4.1.3 Slot Roughing Face Milling

When realizing a slot operation, the engagement of the tool is required to be the 100 % of the cutting edge of the tool, as all the diameter of the tool is going to be used to produce the final geometry. Taking the above into account, the team decided to use a 14 mm cutting diameter tool. Furthermore, the aim was to use a flat end mill tool with the smallest possible tip rounding, or if needed a chamfer noise tool, selecting the minimum length for the width of the chamfer, being the **2N342-1400-PC 1730** the selected tool, which is a flat end mill cutter of 14 mm cut diameter. The selected tool has five cutting flutes, and the point shape is a 45 degrees chamfer of 0.15 mm length.

Taking into account that we are going to rough a final depth of 8 mm, as the finishing operations are not required based on the roughness established for that part of the piece, we are going to develop this surface by realizing 2 passes, each of them having an axial depth of cut (a_p) of 4 mm. Table 11 collects the cutting parameters as well as the restrictions for them for the selected tool.

Parameter	Value	Units
Number of cutting teeth ($\boldsymbol{Z_w}$)	5	-
Cutting Diameter ($\boldsymbol{DC}$)	14	mm
Rake angle ($\boldsymbol{\gamma_0}$)	10.5	°
Cutting angle ($\boldsymbol{\kappa_r}$)	90	°
Cutting Speed ($\boldsymbol{V_c}$)	150	m/min
Feed per tooth ($\boldsymbol{f_z}$)	0.063	mm/rev
Axial depth of cut $\left(\boldsymbol{a_p}\right)$	4	mm
Radial depth of cut ($\boldsymbol{a_e}$)	14	mm

Table 11 Features for 2N342-1400-PC 1730 tool

The maximum power is set to 16 kW, in this way we have to find the parameters that maintain us below this power but as near as possible to achieve the best machining times, the cutting parameter selection starts by finding the number of teeth engaged during the cutting operation, we know that the angle of attachment is going to be 180 degrees as we are employing the entire cutting diameter

$$\varphi = 180°$$

Furthermore, the angle between inserts, can be found as.

$$\varphi_0 = \frac{360°}{Z_w} = \frac{360°}{5} = 72°$$

Finally, the number of cutting teeth engaged along the manufacturing is found as follows.

$$z = \frac{\varphi}{\varphi_0} = \frac{180°}{72°} = 2.5$$

This result us to consider an approximation for the calculus of the power required, in this way, the average chip thickness can be calculated as follows, using the feed per tooth of 0.063 mm/rev recommended by Sandvick.

$$h_{D,av} = \frac{f_z}{\varphi} \cdot \frac{2 \cdot a_e}{DC} = \frac{2 \cdot 0.0603 \cdot 14}{\pi \cdot 14} = 0.04\, mm$$

The specific cutting pressure can be calculated using the known formulas

$$k_{c,av} = \ k_{cs} \cdot {h_{D,av}}^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right)$$

$$k_{c,av} = \ 1750\, MPa \cdot 0.04^{-0.25} \cdot \left(1 - \frac{10.5}{100}\right) = \ 3499.9\, MPa$$

The area of the generated chips can be evaluated as follows

$$A_{D,av} = h_{D,av} \cdot a_p = 0.04 \cdot 4 = 0.16\, mm^2$$

Finally, the cutting forces can be calculated using the formula

$$F_c = k_{c,av} \cdot A_{D,av} = \ 3499.9 \cdot 0.16 = 561.483\, N$$

The torque, can be easily found knowing that the arm of the force is going to be the radius of the cutting tool, and keeping in mind that we are employing 2.5 effective cutting tooths along all the process

$$T_c = z \cdot F_c \cdot \frac{D}{2} \cdot \frac{1}{1000} = 9.83\ Nm$$

In order to compute the value of the power required, it is necessary to set a parameter for the cutting speed, in this case, we are going to use the parameter given by Sandvick for this tool of 150 m/min.

$$n = \frac{1000 \cdot v_c}{\pi \cdot DC} = 3410.46\ RPM$$

$$\omega = n \cdot \frac{2\pi}{60} = 357.14\ rad/s$$

$$P_c = T_c \cdot \omega = 9.83\ Nm \cdot 357.14\ rad/s = 3.509\ kW$$

The final power employed seems to be low compared to the available cutting power of the machine; nevertheless, we are employing an average model and for that reason we would not like to be extremely close to the limit, and even more important, these cutting parameters are provided by Sandvick to ensure that the tool works well on the workpiece material. Finally, the roughness is verified as follows.

$$R_a = \frac{R_t}{4} = \frac{1000 \cdot f_z}{4 \cdot (\cot \kappa_r + \cot \kappa_r')} = \frac{1000 \cdot 0.063}{4 \cdot (\cot 90° + \cot 10.5°)} = 2.92\ \mu m$$

4.2 Slab Milling Operations

4.2.1 Roughing Slab Milling Operations

To reduce the number of tool changes, the team decided to select a unique slab miller for the large feed operations, moreover we decided to use a tool with a rounded tip, which also allows the fillets to be manufactured on the different surfaces, so a tool with a tip radius of 3 mm is selected. In this way the following calculations stands for the roughing of the lateral surfaces of the piece as well as for the finishing operation on the circular section of the piece and finally for enlarging the principal hole located in the inclined plane of the workpiece.

Based on the above commented we are going to focus the analysis on the most critical operation, which is going to be the finishing on the circular section. By using face milling, the most of the stock material is removed, however for obtaining the final geometry is required a slab milling operation, in this case we are going to use the operation to generate also the final fillet required for that reason we are going to select a tool with 3 mm corner radius, for that purpose we are going to use a head for heavy duty milling, the selected one is from CoroMill® 316 family, **316-25SL442-25030P 1730** was the selected tool as this is the biggest tool from the family in terms of cutting diameter, it has 4 peripheral effective cutting edges and it is required a coupling to assemble the cutting tool to the machine, **EH25-A24.7-SS-135** was selected based on Sandvick recommendations, this coupling item has an effective length of 135 mm useful also for to lengthen the hole to be made in the inclined plane of the upper face of the workpiece.

The total depth of cut is 44 mm as the finishing operations are not required based on the roughness established for the piece, we are going to develop this surface by realizing 4 passes, each of them having an axial depth of cut $\left(a_p\right)$ of 11 mm. Finally, Sandvick recommends using a maximum width of cut of 12% of the total cut diameter of the tool to reduce the vibrations in the operation for machining unalloyed steels, so the team follows the suggestion stablishing the maximum radial cutting depth (a_e) as 3 mm. Table 12 collects the cutting parameters as well as the restrictions for them for the selected tool and inserts.

Parameter	Value	Units
Number of cutting teeth $(\boldsymbol{Z_w})$	4	-
Cutting Diameter $(\boldsymbol{DC})$	25	mm
Rake angle $(\boldsymbol{\gamma_0})$	10.5	°
Cutting angle $(\boldsymbol{\kappa_r})$	90	°
Cutting Speed $(\boldsymbol{V_c})$	250	m/min
Feed per tooth $(\boldsymbol{f_z})$	0.18	mm/rev
Axial depth of cut $\left(\boldsymbol{a_p}\right)$	11	mm
Radial depth of cut $(\boldsymbol{a_e})$	3	mm

Table 12 Features for 316-25SL442-25030P 1730 tool employing EH25-A24.7-SS-135 adapter.

It is important to note, that Sandvick for the carbide tools provides not a range of values but a specific recommended value, in this way, we are going to use the recommended values for the feed per tooth and cutting speed of the process. The process starts with finding the attached angle.

$$\varphi = \cos^{-1}\left(\frac{DC \; - 2 \cdot a_e}{DC}\right) = \cos^{-1}\left(\frac{25 \; - 2 \cdot 3}{25}\right) = 40.54°$$

Furthermore, the angle between inserts can be found as.

$$\varphi_0 = \frac{360°}{Z_w} = \frac{360°}{4} = 90°$$

Finally, the number of cutting teeth engaged along the manufacturing is found as follows.

$$z = \frac{\varphi}{\varphi_0} = \frac{40.54°}{90°} = 0.45$$

This result leads the process to a specific case of study where only one tooth is engaged to the piece during the process, the maximum chip thickness can be estimates as follows.

$$h_{D,max} = f_z \cdot \sin(\varphi) = 0.18 \cdot \sin(40.54°) = 0.12 \, mm$$

The specific cutting pressure can be calculated using the known formulas

$$k_{c,max} = k_{cs} \cdot h_{D,max}{}^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right)$$

$$k_{c,max} = 1750\ MPa \cdot 0.12^{-0.25} \cdot \left(1 - \frac{10.5}{100}\right) = 2678.1\ MPa$$

The area of the generated chips can be evaluated as follows

$$A_{D,max} = h_{D,max} \cdot a_p = 0.12 \cdot 11 = 1.29\ mm^2$$

Finally, the cutting forces can be calculated using the formula

$$F_c = k_{c,max} \cdot A_{D,max} = 3441.31\ N$$

The torque, can be easily found knowing that the arm of the force is going to be the radius of the cutting tool

$$T_c = F_c \cdot \frac{D}{2} \cdot \frac{1}{1000} = 43.0789\ Nm$$

In order to compute the value of the power required, it is necessary to set a parameter for the cutting speed.

$$n = \frac{1000 \cdot v_c}{\pi \cdot DC} = 3183.1\ RPM$$

$$\omega = n \cdot \frac{2\pi}{60} = 333.33\ rad/s$$

$$P_c = T_c \cdot \omega = 43.0789\ Nm \cdot 333.33\ rad/s = 14.36\ kW$$

The final surface roughness of the machined piece can be estimated as follows, considering that a slab milling operation is carried out

$$R_a = \frac{R_t}{4} = \frac{R}{4 \cdot 2} \cdot \frac{\pi^2 \cdot f_z^2}{(2 \cdot \pi \cdot R + 60 \cdot Z \cdot f_z)^2} \cdot 10^3 = \frac{12.5}{4 \cdot 2} \cdot \frac{\pi^2 \cdot 0.18^2}{(2 \cdot \pi \cdot 12.5 + 60 \cdot 4 \cdot 0.18)^2} \cdot 10^3 = 0.034\ \mu m$$

The roughness values in slab milling usually are low, and as expected this value is below the maximum roughness allowed for this operation. The following table collects the cutting parameters and verifications obtained for each of the mentioned operations.

Operation	$a_p\ [mm]$	$a_e\ [mm]$	$h_D\ [mm]$	$f_z\ \left[\frac{mm}{rev}\right]$	$v_c\ \left[\frac{m}{min}\right]$	$P_c\ [kW]$	$R_a\ [\mu m]$
SC	11	3	0.12	0.18	250	14.36	0.034
LIP	11	3	0.12	0.18	250	14.36	0.034
BFF	10	3	0.12	0.18	250	13.05	0.034
CS_F	11	3	0.12	0.18	250	14.36	0.034
FF_1	11	3	0.12	0.18	250	14.36	0.034
IP_H1	11	3	0.12	0.18	250	14.36	0.034

Table 13 Cutting parameters employing 316-25SL442-25030P 1730 tool with EH25-A24.7-SS-135 adapter

4.3 Pocket Manufacturing

The manufacturing of the pocket is going to be carried out employing three operations, we are going to start creating an initial hole called a predrill operation, after that we are going to use a solid carbide tool to create the lateral faces of the slot as well as the roughing operations. Finally, the finishing operation is going to be carried to obtain the surface finish required.

4.3.1 Pre-drill Operation

To perform the pocket predrilling operation on top face the team has decided to use the 9.8mm diameter solid carbide drill **860.1-0980-031A1-PM P1BM**, creating a more suitable spot to facilitate the entering for pocket milling operation. Tool's characteristics are summarized in the following table:

Feature		Value	Units
Diameter of the drill	DC	9,8	mm
Cutting Edge Number	Z	2	-
Max RPM	n_max	8120	RPM
Usable Length	LU	31	mm
Tip Angle	SIG	147	degrees
Tip Length	A	1,4514	mm

The total cutting length was 18mm while fn has been set to 0.12 mm/rev while Rpm to 5000. The following calculations evaluate these choices:

$$k_c = \frac{k_{cs}}{\left(f_z \cdot \sin\left(\frac{\varepsilon}{2}\right)\right)^x} = 3228{,}815\ MPa$$

$$A_D = f \cdot \frac{D}{4} = 0{,}441\ mm^2$$

$$V_c = \frac{n \cdot \pi \cdot D}{1000} = 153{,}938\ \frac{m}{min}$$

$$V_f = f \cdot n = 900\ \frac{mm}{min}$$

$$F_c = k_c \cdot A_D = 1423{,}907\ N$$

$$T_c = F_c \cdot \frac{\frac{D}{2}}{1000} = 6{,}977\ Nm$$

$$P_c = T_c \cdot \omega = 3{,}569\ kW$$

The power required to perform the operation is below the maximum limit, while the cutting time has been calculated as follows

$$t_c = \frac{L + A}{V_f} \cdot 60 = 1{,}297\ s$$

4.3.2 Slab Milling

For the selection of the tool, we have to consider that the pocket have a couple of restrictions regarding to the radius of the bottom fillet, and the radius of the side corners, for that reason, as at the bottom it is required a 3 mm fillet, we are going to search for a tool with 3 mm corner radius, moreover based on the 8 mm radius in the side corners of the rectangular pocket, we have to employ a tool with a maximum cut diameter of 16 mm. The solid carbide **1K335-1200-300-XD 1730** from the CoroMill® Dura family is selected, with a cutting diameter of 12 mm and the specified corner radius of 3 mm, employing 5 cutting edges.

Taking into account that we do not have a specific high requirement in the surface roughness for the pocket lateral faces, we are going to use the parameters for large feed shoulder milling, having a maximum axial depth of cut of 1.5 times the cutting diameter of the tool and a maximum engagement of 0.12 times the cutting diameter. Considering that and based on the fact that the total depth of cut for this slab operation is 19 mm, we are going to do it using two steps of 9.5 mm, the cutting parameters are related in the following table.

Parameter	Value	Units
Number of cutting teeth ($\boldsymbol{Z_w}$)	5	-
Cutting Diameter ($\boldsymbol{DC}$)	12	mm
Rake angle ($\boldsymbol{\gamma_0}$)	10	°
Cutting angle ($\boldsymbol{\kappa_r}$)	90	°
Cutting Speed ($\boldsymbol{V_c}$)	290	m/min
Feed per tooth ($\boldsymbol{f_z}$)	0.093	mm/rev
Axial depth of cut ($\boldsymbol{a_p}$)	9.5	mm
Radial depth of cut ($\boldsymbol{a_e}$)	1.44	mm

Table 14 Features for 1K335-1200-300-XD 1730 tool

The cutting parameters verification process starts with finding the attached angle.

$$\varphi = \cos^{-1}\left(\frac{DC\ - 2 \cdot a_e}{DC}\right) = \ \cos^{-1}\left(\frac{12\ - 2 \cdot 1.2}{12}\right) = 40.54°$$

Furthermore, the angle between inserts can be found as.

$$\varphi_0 = \frac{360°}{Z_w} = \frac{360°}{5} = 72°$$

Finally, the number of cutting teeth engaged along the manufacturing is found as follows.

$$z = \frac{\varphi}{\varphi_0} = \frac{40.54°}{72°} = 0.563$$

This result leads the process to a specific case of study where only one tooth is engaged to the piece during the process, the maximum chip thickness can be estimated as follows.

$$h_{D,max} = f_z \cdot \sin(\varphi) = 0.093 \cdot \sin(40.54°) = 0.06\, mm$$

The specific cutting pressure can be calculated using the known formulas

$$k_{c,max} = k_{cs} \cdot h_{D,max}{}^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right)$$

$$k_{c,max} = 1750\, MPa \cdot 0.06^{-0.25} \cdot \left(1 - \frac{10}{100}\right) = 3176.47\, MPa$$

The area of the generated chips can be evaluated as follows

$$A_{D,max} = h_{D,max} \cdot a_p = 0.06 \cdot 9.5 = 0.57\, mm^2$$

Finally, the cutting forces can be calculated using the formula

$$F_c = k_{c,max} \cdot A_{D,max} = 1823.95\, N$$

The torque, can be easily found knowing that the arm of the force is going to be the radius of the cutting tool

$$T_c = F_c \cdot \frac{D}{2} \cdot \frac{1}{1000} = 10.94\, Nm$$

In order to compute the value of the power required, it is necessary to set a parameter for the cutting speed.

$$n = \frac{1000 \cdot v_c}{\pi \cdot DC} = 7692.49\, RPM$$

$$\omega = n \cdot \frac{2\pi}{60} = 805.56\, rad/s$$

$$P_c = T_c \cdot \omega = 10.94\, Nm \cdot 805.56\, rad/s = 8.816\, kW$$

The final surface roughness of the machined piece can be estimated as follows, considering that a slab milling operation was carried out

$$R_a = \frac{R_t}{4} = \frac{R}{4 \cdot 2} \cdot \frac{\pi^2 \cdot f_z^2}{(2 \cdot \pi \cdot R + 60 \cdot Z \cdot f_z)^2} \cdot 10^3 = \frac{6}{4 \cdot 2} \cdot \frac{\pi^2 \cdot 0.093^2}{(2 \cdot \pi \cdot 6 + 60 \cdot 5 \cdot 0.093)^2} \cdot 10^3 = 0.015\, \mu m$$

The roughness values in slab milling usually are low, and as expected this value is below the maximum roughness allowed for this operation.

4.3.3 Bottom surface Finishing

For developing the finishing operation on the bottom surface of the pocket, the team decided to use the same carbide tool, but modifying the cutting parameters, as we are going to employ an operation that can be seen more similar to a face milling operation. In these terms, Sandvick recommends a maximum axial depth of cut of 0.5 times the cutting diameter of the tool, while the maximum axial depth of cut should be the diameter of the tool. Considering that the remaining stock is 1 mm, we are going to finish the surface employing a final step having an axial depth of cut of 1 mm. The cutting parameters and the related information for the tool are summarized in the following table.

Parameter	**Value**	**Units**
Number of cutting teeth ($\boldsymbol{Z_w}$)	5	-
Cutting Diameter ($\boldsymbol{DC}$)	12	mm
Rake angle ($\boldsymbol{\gamma_0}$)	5	°
Cutting angle ($\boldsymbol{\kappa_r}$)	90	°
Cutting Speed ($\boldsymbol{V_c}$)	175	m/min
Feed per tooth ($\boldsymbol{f_z}$)	0.072	mm/rev
Axial depth of cut ($\boldsymbol{a_p}$)	1	mm
Radial depth of cut ($\boldsymbol{a_e}$)	0.6	mm

Table 15 Features for 1K335-1200-300-XD 1730 tool

The maximum power is set to 16 kW, in this way we have to find the parameters that maintain us below this power but as near as possible to achieve the best machining times, the cutting parameter selection starts by finding the number of teeth engaged during the cutting operation, for that purpose, we know that the engagement angle is going to be 90° as we are going to use the 50% of the cutting diameter

$$\varphi = 90°$$

Furthermore, the angle between inserts can be found as.

$$\varphi_0 = \frac{360°}{Z_w} = \frac{360°}{5} = 72°$$

Finally, the number of cutting teeth engaged along the manufacturing is found as follows.

$$z = \frac{\varphi}{\varphi_0} = \frac{90°}{72°} = 1.25$$

This result leads the process to the most critical scenario, where two of the teeth are engaged simultaneously, the worst situation, meaning the highest power required, occurs when they are placed having the same angle in magnitude with respect to the feed movement in opposite directions being $\theta_1 = -\theta_2 = \frac{\varphi}{2}$

$$h_{D,\theta} = f_z \cdot \cos(\theta) \cdot \sin(\kappa_r)$$

Considering that the cosine function is an even function, we are going to obtain the same chip thickness for both angles.

$$h_{D,\theta_1} = h_{D,\theta_2} = \ 0.072 \cdot \cos(36°) = \ 0.058\, mm$$

The specific cutting pressure can be calculated using the known formulas

$$k_{c,\theta_1} = k_{c,\theta_2} = \ k_{cs} \cdot {h_{D,\theta_1}}^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right)$$

$$k_{c,\theta_1} = k_{c,\theta_2} = 1750\ MPa \cdot 0.058^{-0.25} \cdot \left(1 - \frac{5}{100}\right) = 3384.07\ MPa$$

The area of the generated chips can be evaluated as follows

$$A_{D,\theta_1} = A_{D,\theta_2} = h_{D,\theta_1} \cdot a_p = 0.058 \cdot 1 = 0.58\ mm^2$$

Finally, the cutting forces can be calculated using the formula

$$F_c = F_{c_1} = F_{c_2} = k_{c,\theta_1} \cdot A_{D,\theta_1} = k_{c,\theta_2} \cdot A_{D,\theta_2}$$

$$F_c = 3384.07\ MPa \cdot 0.58\ mm^2 = 197.12\ N$$

The torque, can be easily found knowing that the arm of the force is going to be the radius of the cutting tool

$$T_c = T_{c_1} = T_{c_2} = F_c \cdot \frac{D}{2} \cdot \frac{1}{1000} = 1.182\ Nm$$

In order to compute the value of the power required, we employ the recommendation coming from Sandvik of 175 m/min

$$n = \frac{1000 \cdot v_c}{\pi \cdot DC} = 4642.02\ RPM$$

$$\omega = n \cdot \frac{2\pi}{60} = 486.11\ rad/s$$

$$P_c = T_{c_{max}} \cdot \omega = 2 \cdot T_c \cdot \omega = 2 \cdot 1.182\ Nm \cdot 486.11\ rad/s = 1.15\ kW$$

The final surface roughness of the machined piece can be estimated as follows, based on the corner radius of the insert and its entrance angles.

$$R_a = \frac{1000 \cdot f_z^2}{32 \cdot r} = \frac{1000 \cdot 0.072^2}{32 \cdot 3} = 0.054\ \mu m$$

Having

$$f_z \leq \min(2r \cdot \sin k_r\ ;\ 2r \cdot \sin k_r') \iff 0{,}072 \leq 0.522$$

Obtaining the final requirement of the surface finishing for the pocket bottom surface.

4.4 Drilling Operations

In order to do the drilling operations a spot drill, making a 1mm deep hole, has been used to mark the initial position for the drill head and to increase stability and precision. To ensure the correct spot angle for most operations i.e. 147°, the drill **860.1-0680-055A1-PM P1BM** has been used.

4.4.1 Deep through hole on lateral face E and inclined plane

To perform the drilling operation on lateral face E the team has decided to directly use the 8mm diameter solid carbide drill **861.1-0800-120A1-GM GC34**, since it provides an H9 tolerance hole. Tool's characteristics are summarized in the following table:

Feature		Value	Units
Diameter of the drill	DC	8	mm
Cutting Edge Number	Z	2	-
Max RPM	n_max	12892	RPM
Usable Length	LU	121,3	mm
Point Angle	SIG	140	degrees
Pont Length	A	1,3	mm

The total cutting length was 118mm, considering that the tip had to fully extend over the bottom of the hole. fn has been set to 0.12 mm/rev while Rpm to 5000. The following calculations evaluate these choices:

$$k_c = \frac{k_{cs}}{\left(f_z \cdot \sin\left(\frac{\varepsilon}{2}\right)\right)^x} = 3245{,}122\ MPa$$

$$A_D = f \cdot \frac{D}{4} = 0.36\ mm^2$$

$$V_c = \frac{n \cdot \pi \cdot D}{1000} = 125.664\ \frac{m}{min}$$

$$V_f = f \cdot n = 900\ \frac{mm}{min}$$

$$F_c = k_c \cdot A_D = 1168{,}244\ N$$

$$T_c = F_c \cdot \frac{\frac{D}{2}}{1000} = 4.673\ Nm$$

$$P_c = T_c \cdot \omega = 2.447\ kW$$

The power required to perform the operation is below the maximum limit, while the cutting time has been calculated as follows

$$t_c = \frac{L + A}{V_f} \cdot 60 = 7.953\ s$$

The same operation has also been used to perform the first cut in the Principal Inclined plane.

4.4.2 Deep through hole on Top Face

Initial Hole

The two deep through holes on the top face have been achieved through multiple drilling operations, since they had multiple requirements, The first cut has been performed using the 6.8mm drill **860.1-0680-055A1-PM P1BM** which has the following characteristics:

Feature		Value	Units
Diameter of the drill	DC	6,8	mm
Cutting Edge Number	Z	2	-
Max RPM	n_max	11700	RPM
Usable Length	LU	55	mm
Point Angle	SIG	147	degrees
Pont Length	A	1,1108	mm

As in the previous operation fn has been set to 0.12 mm/rev and Rpm to 5000, while the total cutting length was 52mm. The following calculations evaluate these choices:

$$k_c = \frac{k_{cs}}{\left(f_z \cdot \sin\left(\frac{\varepsilon}{2}\right)\right)^x} = 3573{,}271\ MPa$$

$$A_D = f \cdot \frac{D}{4} = 0.204\ mm^2$$

$$V_c = \frac{n \cdot \pi \cdot D}{1000} = 106{,}814\ \frac{m}{min}$$

$$V_f = f \cdot n = 600\ \frac{mm}{min}$$

$$F_c = k_c\ \cdot A_D = 728{,}947\ N$$

$$T_c = F_c \cdot \frac{\frac{D}{2}}{1000} = 2{,}478\ Nm$$

$$P_c = T_c \cdot \omega = 1{,}298\ kW$$

The power required to perform the operation is below the maximum limit, while the cutting time has been calculated as follows

$$t_c = \frac{L + A}{V_f} \cdot 60 = 5{,}311\ s$$

Counterbore Hole

The counterbore hole has been made using the 9.8mm diameter **860.1-0980-031A1-PM P1BM**, starting from a 6.8 mm diameter. The tool has the following characteristics:

Feature		Value	Units
Diameter of the drill	DC	9,8	mm
Cutting Edge Number	Z	2	-
Max RPM	n_max	8120	RPM
Usable Length	LU	31	mm
Point Angle	SIG	147	degrees
Pont Length	A	1,4514	mm

The cutting length required was 5mm, the chosen parameters remain the same as before. The calculation used to evaluate the operation are presented below:

$$k_c = \frac{k_{cs}}{\left(f_z \cdot \sin\left(\frac{\varepsilon}{2}\right)\right)^x} = 3573{,}271\ MPa$$

$$A_D = fz \cdot \frac{D_{ext} - D_{int}}{2} = 0{,}09\ mm^2$$

$$V_c = \frac{n \cdot \pi \cdot D}{1000} = 153{,}938\ \frac{m}{min}$$

$$V_f = f \cdot n = 600\ \frac{mm}{min}$$

$$F_c = k_c \cdot A_D = 321{,}594\ N$$

$$T_c = F_c \cdot \frac{\frac{D_{ext} + D_{int}}{2}}{1000} = 2{,}669\ Nm$$

$$P_c = T_c \cdot \omega = 1{,}398\ kW$$

The power required to perform the operation is below the maximum limit, while the cutting time has been calculated as follows

$$t_c = \frac{L + A}{V_f} \cdot 60 = 0{,}645\ s$$

Reaming and Tapping operations

To perform the reaming operations the team has used the reamer **835.B-1000-A1-PF 1024** having an H7 tolerance and a 10mm diameter. The tool has the following characteristics:

Feature		Value	Units
Diameter of the drill	DC	10	mm
Cutting Edge Number	Z	6	-
Max RPM	n_max	7066	RPM
Cutting Length	L	20	mm
Usable Length	LU	80	mm
Point Angle	SIG	180	degrees

The reaming operation is machined from a 9.8 mm diameter to a 10mm, with a 5mm depth. The calculations are the same described in the previous point, so fn=0.12 and n=5000. In the end the results are:

$$P_c = 145\ W$$

$$t_c = 0{,}500\ s$$

To perform the tapping operation instead has been used the tapper **T200-XM101DA-M8 C110**. Tool characteristics are summarized as follows

Feature		Value	Units
Diameter of the drill	DC	8	mm
Cutting Edge Number	Z	3	-
Cutting Lenght	L	20	mm
Usable Lenght	LU	67	mm
Feed for Revolution	fn	1.25	mm/rev

With a total cutting depth of 50mm the cutting speed has been set to 15 m/min as suggested by Sandvik, producing the following results:

$$P_c = 443\ W$$

$$t_c = 3{,}429\ s$$

4.4.3 Deep through hole on Inclined Plane

Second Drilling Operation

As said in section 4.3.1 the initial hole for the 52mm wide hole has been performed in the same way as the hole in lateral face E. With a second drilling operation the hole has been enlarged from an 8mm diameter to a 30 mm diameter using the Indexable insert drill **DS20-D2600L32-05**, with 2 inserts **DS20-0306-C-L5 1344.**

The tool has the following characteristics:

Feature		Value	Units
Diameter of the drill	DC	30	mm
Cutting Edge Number	Z	2	-
Max RPM	n_max	8120	RPM
Usable Lenght	LU	130	mm
Point Angle	SIG	162	degrees
Pont Lenght	A	0	mm

The following calculations are made using a fn set to 0.08 mm/rev and 2500 rpm in order to have the cutting velocity arounf 200m/min as sugested by sandvic.

$$k_c = \frac{k_{cs}}{\left(f_z \cdot \sin\left(\frac{\varepsilon}{2}\right)\right)^x} = 3925{,}25\ MPa$$

$$A_D = f_z \cdot \frac{D_{ext} - D_{int}}{2} = 0{,}36\ mm^2$$

$$V_c = \frac{n \cdot \pi \cdot D}{1000} = 204{,}2\ \frac{m}{min}$$

$$V_f = f \cdot n = 200\ \frac{mm}{min}$$

$$F_c = k_c \cdot A_D = 1543{,}601\ N$$

$$T_c = F_c \cdot \frac{\frac{D_{ext} + D_{int}}{2}}{1000} = 24{,}023\ Nm$$

$$P_c = T_c \cdot \omega = 6{,}289\ kW$$

The power required to perform the operation is below the maximum limit, while the cutting time has been calculated as follows

$$t_c = \frac{L + A}{V_f} \cdot 60 = 39\ s$$

4.4.4 Smaller Blind Holes on Inclined Plane

The four smaller holes perpendicular to the inclined plane have been made with two operations, the first being a drill operation with the same 6.8mm carbide drill used for the holes on the Top face and then a tapping operation. With a total depth of cut of 12mm, using the same parameters as before, the team has achieved these results first drilling operation:

$$P_c = 1{,}298\ kW$$

$$t_c = 1{,}311\ s$$

As for the tapping operation the selected tool has been the tapper **T300-PM104DA-M8 P1PM** having the following characteristics:

Feature		Value	Units
Diameter of the drill	DC	8	mm
Cutting Edge Number	Z	3	-
Cutting Lenght	L	20	mm
Usable Lenght	LU	35	mm
Feed for Revolution	fn	1.25	mm/rev

With a total cutting depth of 50mm the cutting speed has been set to 15 m/min as suggested by Sandvik, producing the following results:

$$P_c = 443\ W$$

Boring Operation

The boring operation has been made using the boring bar **825D-56TC09U-C4,** with the insert **TCGT 09 02 02L-K 1515.** This operation is made to finish the internal surface of the 52mm hole, starting from a diameter of 51mm, reached after a SLAB milling operation. The feed and cutting speed have been chosen according to Sandvik suggestion, respectively fn=0,04 and vc=260. The calculations made are the same as in turning operations.

Feature		Value	Units
Main entering angle	kr	92	degrees
Secondary entering angle	kr'	28	degrees
Cutting Lenght	L	130	mm
Cutting velocity	Vc	260	m/min
Feed for Revolution	f	0.1	mm/rev
Depth	a_p	0.5	mm

$$k_c = \frac{k_{cs}}{(f \cdot \sin k_r)^x} = 3112{,}46\ MPa$$

$$A_D = f \cdot a_p = 0{,}05\ mm$$

$$F_c = A_d \cdot k_c = 155{,}62\ N$$

$$T_c = F_c \cdot \frac{D_f}{2} \cdot \frac{1}{1000} = 4{,}05\ Nm$$

$$P_c = F_c \cdot \frac{v_c}{60} = 673{,}66\ W$$

Now as for the final roughness of the internal surface of the hole the calculation is made considering the nose radius of the tool's insert of **r=0,2mm**.

$$R_a = \frac{f^2 \cdot 10^3}{32 \cdot r} = 1{,}56\ \mu m\ \leq\ 3{,}2\ \mu m$$

Having

$$f \leq \min(2r \cdot \sin k_r\ \ ;\ 2r \cdot \sin k_r')\ \Leftrightarrow\ 0{,}1 \leq 0{,}187$$

5. Discussion on technical requirements

To begin the discussion of the technical requirements, we must start by evaluating the number of setups used. The team found that three setups is the minimum number available, considering the constraints, and moreover, that the CNC machine has 4 axes of movement. It is important to note at this point that as we perform a complete rotation of the machining part and the fixture in the final setup, the availability of a fifth axis would make this setup unnecessary, allowing the machine to reposition the spindle through rotations around the second axis of the machine's plane, the X-axis for this report.

The final operations and surfaces required during the manufacturing process can be divided into two main categories. The first set includes those with a high surface roughness requirement (Ra 3.2), where both roughing and finishing steps are necessary. On the other hand, the second set comprises operations where the required roughness is lower (Ra 12.5), making a roughing step sufficient.

Taking the above into account, the machining strategy dictates that the roughing operations (second set) should be completed first. These surfaces can then serve as datums and clamping points for subsequent operations. It is important to note that surfaces with high surface roughness requirements are not available to be used as clamping surfaces. Despite this limitation, while it may not be feasible for the manufacturing of this specific workpiece, it remains an important consideration in the overall manufacturing process.

It is time to focus on explaining each of the decisions made to meet the specified technical constraints, starting with the first setup, where the entire bottom part of the workpiece is machined. The team aimed to reduce the number of tool changes and spindle repositionings, prioritizing this aspect given that tool changes involve longer times. Thus, the process begins by machining the bottom surface of the piece through a face milling operation, removing as much material as possible in a roughing operation. Subsequently, the spindle is repositioned to machine the side faces (surfaces B and D). These operations are performed initially, as the bottom surface is going to be used as a datum (Datum A on the piece's plane) for successive setups, while the side surfaces B and D will serve as clamping surfaces for these setups. To complete this setup, a tool change is made using a solid carbide tool with a 3 mm tip radius. Using the parameters specified in previous sections of this report, the side surface C, as well as the inclined plane and the vertical chamfers of the final piece are machined. Lastly, the finishing of the neck on the bottom part of the workpiece must be carried out. It is important to note that the fillet radius is achieved using the selected tool, and the geometric constraint of parallelism with respect to the lateral face B (Datum C on the piece's plane) is met by machining both surfaces in the initial setup.

The setup change is then carried out using the bottom surface of the piece as the datum and the side faces B and D as clamping surfaces, as previously explained. In this setup, large roughing operations are also performed through face milling, which allows us to obtain the horizontal surfaces of the top face of the piece, while meeting the geometric parallelism constraints with respect to the bottom surface of the piece (Datum A in the piece's plane). Subsequently, roughing operations are performed on the side faces, which allows us to finally obtain the side face E, leaving only a small section to be removed in the circular section of the piece through a finishing operation, where a tool change is required, again using the solid carbide tool, which directly achieves the required fillet with a 3 mm radius.

At this point, only the operations related to the holes in the top surface and lateral face E, the horizontal chamfers, as well as the rectangular pocket, remain. Initially, pre-drilling operations will be carried out on the top face to ensure the stability of the cutting operation and reduce the vibrations generated in this case. Following the required operations for the development of the pocket are carried out, a drill is used to create an initial hole from which the pocket is manufactured. A solid carbide tool with a 3 mm tip radius and a cutting diameter of 12 mm is employed. It is important to note that this operation belongs to the first group specified, where there is a high roughness requirement on the bottom surface of the pocket. As observed in the previous section of this report, this operation is divided into an initial roughing operation, verified as a slab milling operation, which forms the pocket walls, where there is a geometric symmetry constraint with respect to the side face E (Datum E in the plane of the figure), this requirement is met as the datum surface was obtained using this setup. The finishing operation follows, this manufacturing operation can be seen as a face milling operation, resulting in a final roughness of 1.57 µm, which falls within the specified parameters for this surface, it also has a parallelism geometrical requirement with respect to the bottom surface (Datum A in the plane of the piece) which is addressed as this is the datum for the setup clamping used for manufacturing the pocket.

Every drill operation is preceded by spot drilling operation of 1mm depth of cut, in order to ensure better stability in the initial contact of the drill. The correct initial positioning and the perpendicularity of the cuts are ensured through the setup geometry, having as datum the surfaces where the holes are made out; the tip entering angle of every drill operation is always 90°. The through hole on lateral face is made using directly a single drill operation with an 8mm drill that provides the requested tolerance of H10. As for the other 2 deep through holes on the top face the operation is carried out in multiple steps, using a 6.8mm drill at first, a 9.8mm drill for the initial cut of the counterboring hole, then the reamer that has a tolerance of H7 to finish the 10mm counterbore and finally the tapper with the M8 specified threads. Finally, for the development of the chamfers, a tool with inserts recommended by Sandvik for chamfer manufacturing is used, employing a 45° cutting angle insert to achieve the specified requirement. The cutting parameters provided by Sandvik were used, allowing for low power parameters, making it feasible for the machine employed.

The final setup involves rotating the previous setup, that is, rotating the fixture and the workpiece together, while maintaining the datum and clamping surfaces. Initially, the inclined surface is machined, on which no further manufacturing operations should be performed, using a face milling tool. Subsequently, using the same tool, the tilted surface is machined, which has an angular requirement relative to the bottom surface (Datum A in the plane of the piece), fulfilled by using it as the datum for the setup. Additionally, this operation belongs to the first group of operations, requiring initial roughing operations, followed by a finishing operation that achieves a roughness of 2.95 µm, staying within the specified parameters for this surface.

The setup choice has mainly been made to be able to precisely align perpendicularly the tool to the inclined plane, as to have the previously machined flat surface as a datum to the principal drilling operation of 52mm. This operation is made in 4 steps: after the spot drilling the first through guide hole is made using the 8mm drill; then the second drilling operation enlarges the hole to a 26mm diameter to facilitate the third operation; using an end miller the diameter of the hole is enlarged to 51mm, the leaving position of the tool is the same as the entering one leaving the datum for the last operation; the final boring operation bring the diameter to 52mm and finish the surface with the required roughness.

At this point, the piece is almost complete. The open rectangular pocket is machined using a flat end tool with a 14 mm diameter, allowing us to achieve the desired geometry while following Sandvik's recommendations for this solid carbide tool, staying within the power levels allowed for the machine. Additionally, the threaded holes are machined with two operations, a first cut using the same 6.8mm drill used for the other holes on the top face and then the tapping operation, suing a tapper with M8 specified threads suitable for blind holes. Finally, using the same tool and the considerations previously mentioned, the remaining chamfers are completed to finalize the piece.

In this way, all the operations previously outlined were carried out, which, based on the comments throughout this discussion section, allows us to establish that the geometric tolerance parameters were successfully achieved employing the 36 proposed operations, divided into 3 different setups, with a total time of 3669 seconds, resulting in a productivity rate of 0.981 pieces per hour.

6. References

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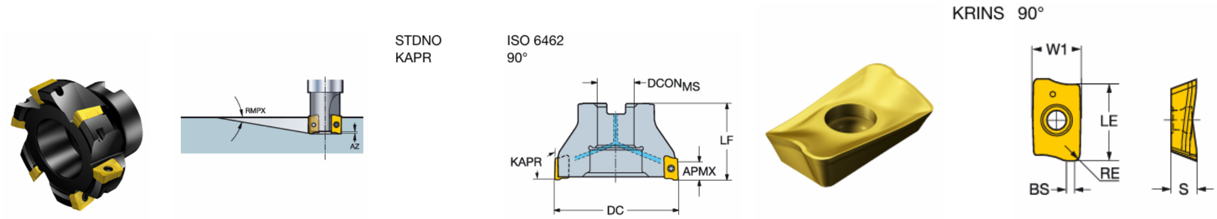
7. Tools Appendix

7.1 Face Milling

7.1.1 CoroMill® 390 square shoulder milling cutter

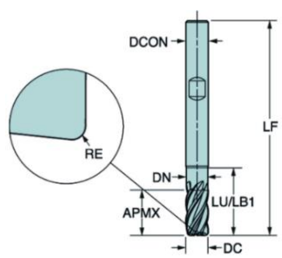


DC	DCCON	APMX	LF	Z	CODE
100	32	18	50	5	R390-100Q32-18L

W1	LS	S	BS	CODE
11.0	15.4	6.33	1.1	R390-18 06 08M-PM 4330

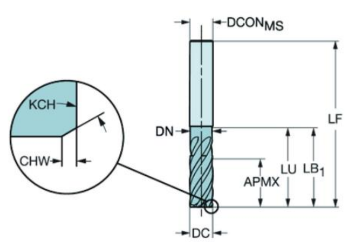
7.2 End Milling

7.2.1 CoroMill® Dura End milling cutter



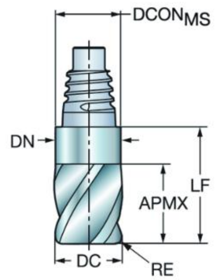
KAPR	DC	DCCON	APMX	LF	Z	LU	RE	CODE
90°	12	12	24	83	5	36	3	1K335-1200-300-XD-1730

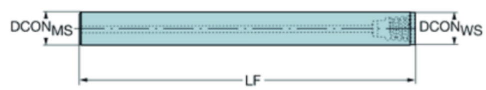
7.2.2 CoroMill® Plura solid carbide End milling cutter



KAPR	DC	DCCON	APMX	LF	Z	KCH	CHW	CODE
90°	14	14	30	83	5	45°	0.15	2N342-1400-PC 1730

7.2.3 CoroMill® 316 Head for End milling and Extention



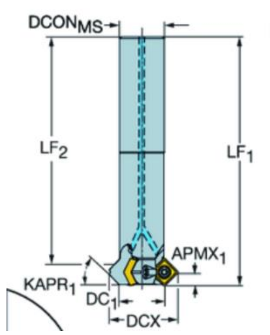


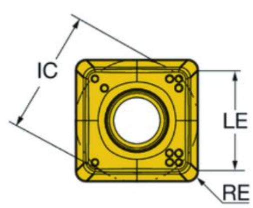
KAPR	DC	DCCON	APMX	LF	Z	RE	CODE
90°	25	24.2	30	41,9	4	3	316-25SL442-25030P 1730

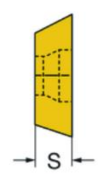
DC	DCCON	LF	CODE
24.7	24.7	135	EH25-A24.7-SS-135

7.3 Chamfer Milling

7.3.1 CoroMill® 495 Chamfer milling cutter





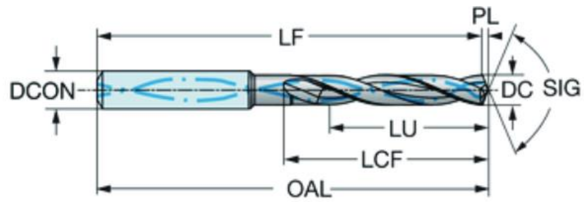


KAPR	DCX	DCCON	APMX	LF	Z	CODE
45°	23.4	18	5.5	100	1	495-012A16-4509L

IC	LE	S	RE	CODE
9	7.4	3.51	0.8	495-09T3M-MM 1040

7.4 Carbide Drills

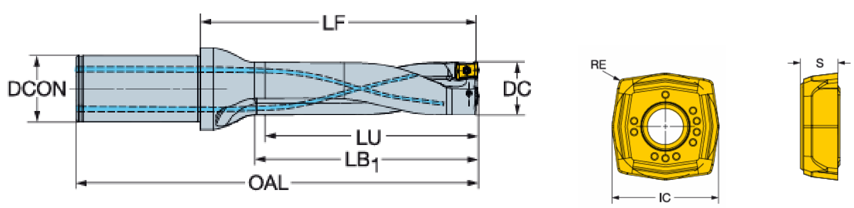
7.4.1 CoroDrill® 860 Solid Carbide Drills



SIG	DC	Tolerance	LU	f_{min} - f_{max}	Z	CODE
140°	8	H9	121	0.12 - 0.22	2	861.1-0800-120A1-GM GC34
147°	6.8	H8	55	0.12 - 0.28	2	860.1-0680-055A1-PM P1BM
147°	9.8	H8	31	0.12 - 0.28	2	860.1-0980-031A1-PM P1BM

7.5 Indexable Drills

7.5.1 CoroDrill® DS20 Indexable Drill

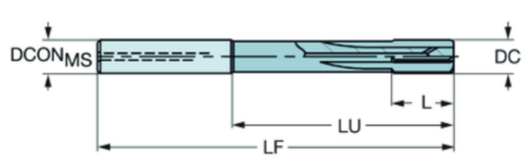


KAPR	DC	LU	f_{min} - f_{max}	Z	CODE
81°	26	130	0.05 - 0.12	2	DS20-D2600L32-05

IC	S	RE	CODE
8.88	3	0.35	DS20-0306-C-L5 1344

7.6 Reamers

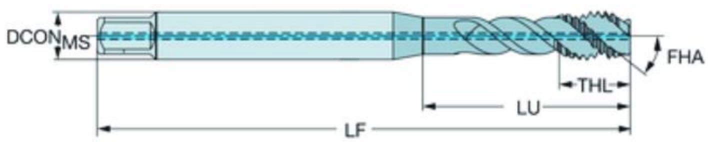
7.6.1 CoroReamer® 835 Solid Carbide Reamer



KAPR	DC	Tolerance	LF	Z	LU	L	CODE
180°	10	H7	118	6	80	20	835.B-1000-A1-PF 1024

7.7 Tappers

7.7.1 CoroTap® 300 Cutting tap with Spiral flute



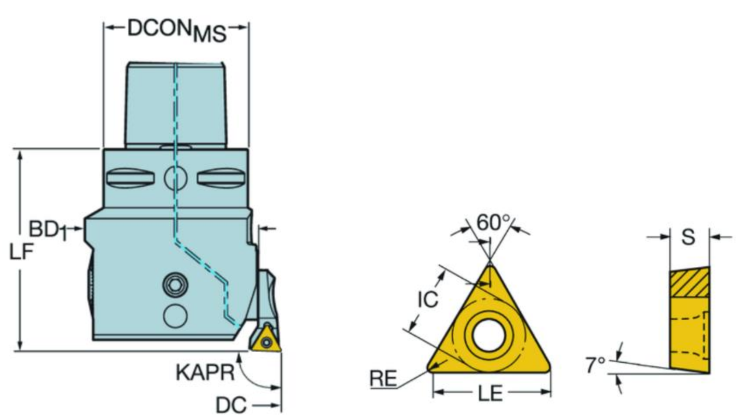
FHA	DC	LU	LF	THL	TP	CODE
48°	M8	35	90	12	1.25	T300 XM100DA M7 C150

7.7.2 CoroTap® 200 Cutting tap

DC	LU	LF	THL	TP	CODE
M8	67	90	18	1.25	T200-XM101DA-M8 C110

7.8 Boring Bars

7.8.1 CoroBore® 825 Boring Bar



KAPR	DCN	DCX	DCCON	LF	Z	CODE
92°	44	56	40	56	1	825-56TC09-C4

IC	LE	S	RE	CODE
5.56	9.17	2.38	0.2	TCGT 09 02 02L-K 1515