Computer Aided Manufacturing 2023/24
CAM Laboratory Final Report

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12 July 2024

Abstract

This report presents the complete CAM (Computer-Aided Manufacturing) project for the production of a mechanical component from a raw stock material. The project encompasses the determination of manufacturing resources, design of machining operations, verification of technical requirements, and implementation of a complete manufacturing process. The workpiece material is P1.1.Z.AN steel (unalloyed steel with carbon content $\leq 0.25\%$ C, forged/rolled, annealed with hardness 125HB). The manufacturing process includes 26 operations across three setups, utilizing various tools for milling, drilling, reaming, tapping, and finishing operations. All operations have been verified for feasibility with respect to the 16kW spindle power constraint, and technical requirements including tolerances and surface roughness specifications have been validated.

Contents

Chapter 1

Introduction of Project Product

1.1 Inputs and Variables

Each group was provided with a 2D sketch of the part to be produced starting from a stock. Some parameters of the sketch and the size of the stock were different for each group, influencing the final choices taken. Our input is provided in 1.1

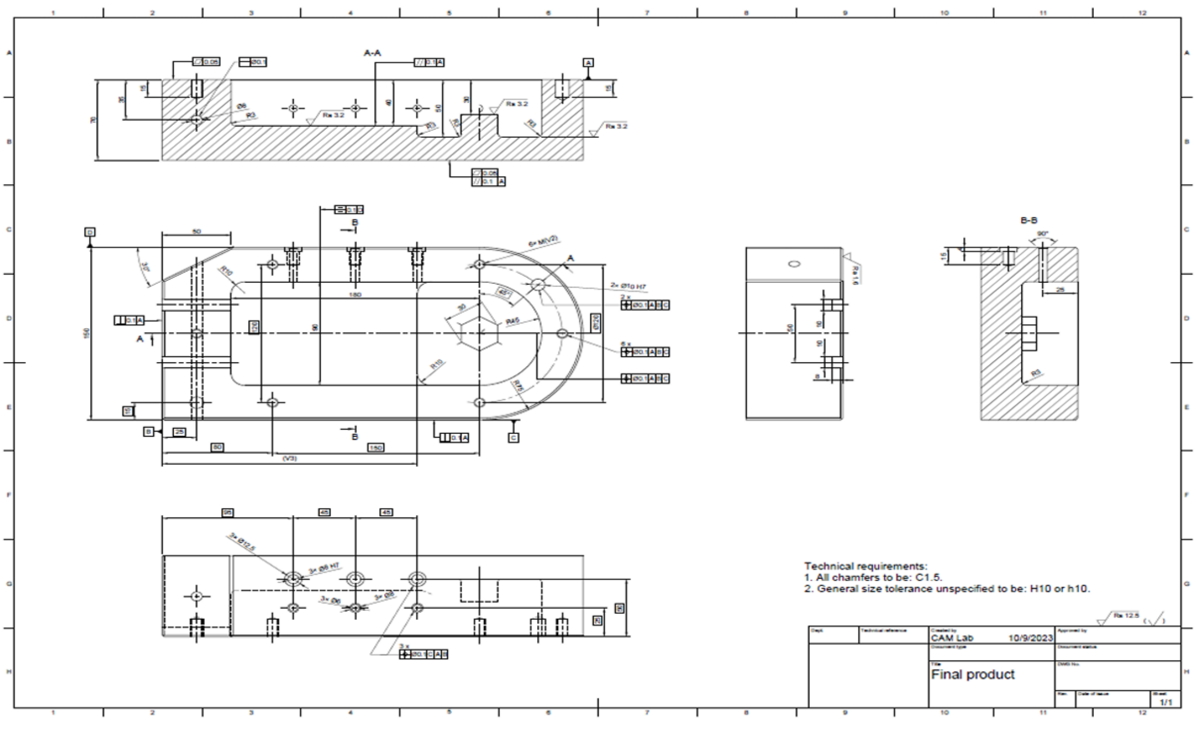

Figure 1.1: Input and variables

1.1.1 Group-Specific Parameters

- **Threaded holes:** According to the metric ISO, our specification for these holes was M7×1.0
- **Design parameter:** Distance between the flat short side of the workpiece and the midline of the main pocket: 154 mm
- **Stock size:** $x = 311$ mm, $y = 156$ mm, $z = 76$ mm

1.1.2 Workpiece Material Specifications

Workpiece material designation: **P1.1.Z.AN**

- **P** → Steel
- **1** → Material group: unalloyed steel
- **1** → Material sub-group: carbon content $\leq 0.25\%$ C
- **Z** → Manufacturing process: forged/rolled/cold drawn
- **AN** → Heat treatment: annealed, supplied with hardness parameter 125HB

Material properties:

- Specific cutting pressure: $K_{c1} = 1500$ N/mm^2
- Kronemberg parameter: $m_c = 0.25$

1.2 Features and Operations

Table 1.1: Features and operations summary

Feature	**Requirement**	**Relation**	**# Op**	**Operation**
Top Surface	R_a 1.6	Datum A ⊥ 0.05	1 2	Rough milling Finish milling
Long lateral surface	Datum C	⊥ 0.1 A	3a 3b	Rough milling Rough milling
Short straight side	Datum B	⊥ 0.1 A	4	Rough milling
Bottom Surface	∥ 0.1 A	⊥ 0.05	5	Rough milling
Thread holes	M7	⌀ 0.1 A B C	6 7	Drilling Threading
Top blind holes	H7	⌀ 0.1 A B C	8 9	Drilling Reaming
Blind holes with counterbore	H7		10 11	Drilling Reaming
Counterbore	H10	⌀ 0.1 C A B	12	Drilling
Through holes with countersink	H10		13	Drilling
Countersink		⌀ 0.1 C A B	14	Drilling
Deep through hole	–	⌀ 0.1	15 16	Pilot drilling Deep drilling
Pocket A	R_a 3.2	⌀ 0.1 A B C	17 18	Rough milling Finish milling

Feature	Requirement	Relation	# Op	Operation
Pocket B	R_a 3.2	$\parallel$ 0.1 A	19 20	Rough milling Finish milling
Pocket C	R_a 3.2		21 22	Rough milling Finish milling
Slot			23	Rough milling
Chamfer A (45°)	C1.5		24a 24b	Rough milling Rough milling
Chamfer B (45°)	C1.5		25	Rough milling
Chamfer C (30°)	C1.5		26	Rough milling
Chamfer D (75°)	C1.5		27	Rough milling
External cylindrical surface			28	Rough milling
Short inclined straight side			29	Rough milling
Fillet			30	Finish milling

1.3 Precedence Graph

We decided the order for the operations according to some rules:

1. First surfaces and then their pockets/holes
2. First roughing and then finishing
3. The operations must follow the order determined by setups to guarantee technical requirements

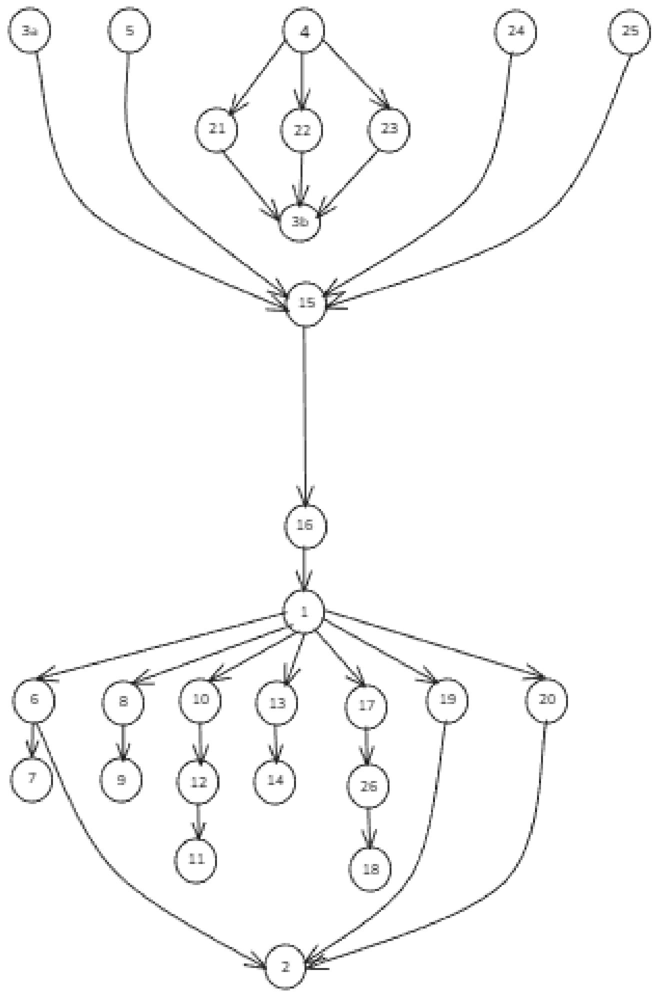

Figure 1.2: Precedence graph showing the sequence of operations

Chapter 2

Detailed Final Solution to Realize the Product

2.1 Throughput of the Product

Fusion 360 provides the machining time required to perform the whole sequence of operations for one setup, already considering tool changing time. To compute the throughput, we need to consider for each setup also the time required to reposition the axis of the spindle and the time to load and unload the part.

Setup 1:

$$T_{s1} = t_{m1} + \text{spindle repositioning} + \text{load} + \text{unload} = 13'42'' + 5'' + 60'' + 60'' = 947 \text{ s} \tag{2.1}$$

Setup 2:

$$T_{s2} = t_{m2} + \text{spindle repositioning} + \text{load} + \text{unload} = 3'43'' + 5'' + 60'' + 60'' = 348 \text{ s} \tag{2.2}$$

Setup 3:

$$T_{s3} = t_{m3} + \text{spindle repositioning} + \text{load} + \text{unload} = 23'09'' + 2 \times 5'' + 60'' + 60'' = 1519 \text{ s} \tag{2.3}$$

Total time:

$$T_{tot} = T_{s1} + T_{s2} + T_{s3} = 2814 \text{ s} \tag{2.4}$$

Throughput:

$$\text{Throughput} = \frac{3600}{2814} = 1.279 \text{ parts/hour} \tag{2.5}$$

2.2 Detailed Information for the Setups

The choices for the setups were made considering the constraints provided. First, the fact that the spindle can change its main axis in one additional direction besides the z-axis (perpendicular to the fixturing), which could be $\pm y$ or $\pm x$. Then, the technical requirements were also relevant to decide the setup configuration.

We ended up with just two fixturing configurations: one clamping the stock from the top (first clamp over the stock) and one from the bottom (now clamping directly the part), both clamping from the lateral straight sides of the part.

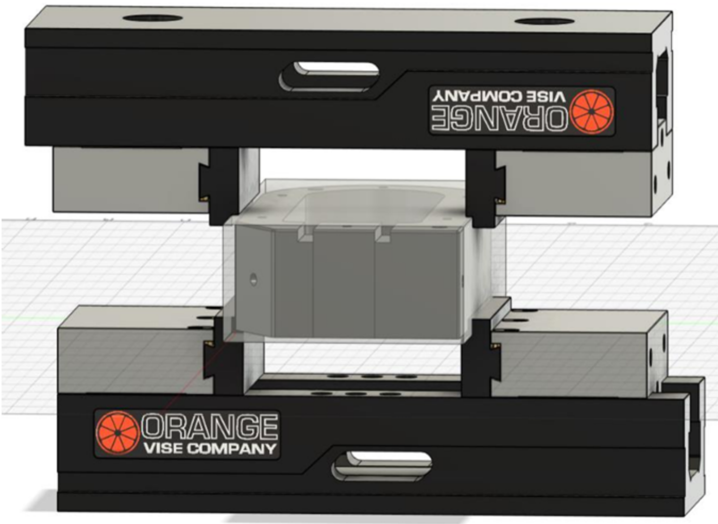

Figure 2.1: Overview of the three setups

2.2.1 Setup 1

We decided to start machining the bottom surface because it has no roughness requirements specified. Therefore, we can clamp it directly in the following setups without the worry of ruining the surface finish, using it as a reference to create the datum reference system, preserving the parallelism and perpendicularity constraints.

In this setup, we machine:

- Bottom surface
- Half of the lateral straight surfaces
- External cylindrical surface
- Inclined short straight side
- Datum B (using spindle axis repositioning)
- Chamfers for these surfaces

2.2.2 Setup 2

We directly clamp the part from the bottom since we have removed the stock and never touch the upper surface with the fixture again, as it has the most restrictive roughness requirements.

In this setup, we:

- Finish the roughing of the lateral surfaces
- Create the deep through hole using spindle axis repositioning

2.2.3 Setup 3

The first operation to perform from this setup is the roughing of the top surface, creating our datum reference system. Note that we left a stock of 0.3 mm to perform finishing of this surface last to preserve it.

Then we machine all remaining features:

- All holes (threaded, blind, through, counterbored, countersunk)
- All pockets
- Slot
- Remaining chamfers
- Fillet
- Finally, finish the pockets and top surface to achieve required roughness

2.3 Manufacturing Resources

2.3.1 Tool 1 – CoroMill 345

Order number: 345-063C5-13M (medium milling conditions)

Tool specifications:

- $DC = 63$ mm
- $AP_{MX} = 6$ mm
- $DC_X = 77.1$ mm (maximum cutting diameter)
- $Z = 5$
- $DC_{ONms} = 50$ mm (diameter at connection, machine side)
- $LF = 60$ mm (functional length)
- $K_r = 45$
- $\gamma_0 = 19$

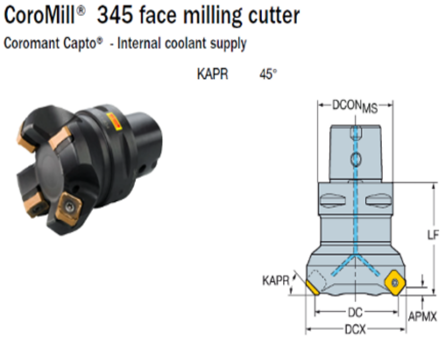

Figure 2.2: CoroMill 345 tool

Insert for roughing operations:
Ordering code: 345R-1305M-PM
First choice for steel: P4330
Specifications: $IC = 13$, $LE = 8.8$, $S = 5.60$, $BS = 2$, $RE = 0.8$ mm

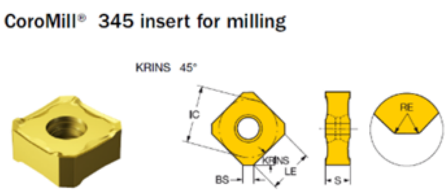

Figure 2.3: CoroMill 345 insert for roughing

Insert for finishing operations:
Ordering code: 345R-1305M-PM
Choice for steel: P4330
Specifications: $IC = 13$, $LE = 8.8$, $S = 5.60$, $BS = 8$, $RE = 1$ mm

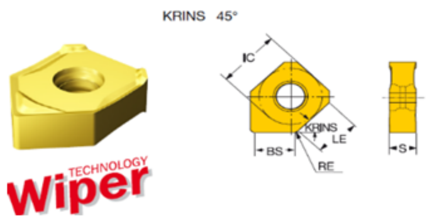

Figure 2.4: CoroMill 345 insert for milling

2.3.2 Tool 2 – CoroMill 390

Order number: R390-020C5D-11L145 (heavy milling)
Tool specifications:

- $DC = 20$ mm
- $AP_{MXffw} = 10$ mm (max radial depth of cut)
- $AP_{MXefw} = 5.5$ mm (max axial depth of cut)
- $Z = 2$
- $DC_{ONms} = 20$ mm
- $LF = 145$ mm (functional length)
- $LU = 120$ mm (usable length)
- $K_r = 90$
- $RM_{PX} = 2$
- $\gamma_0 = 10.27$

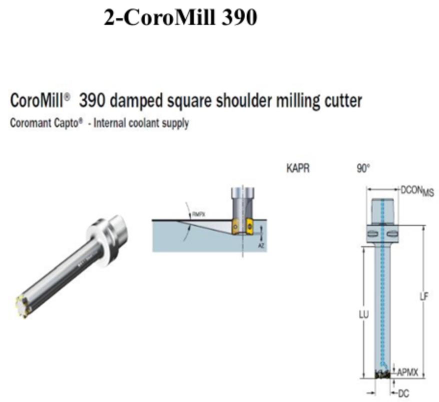

Figure 2.5: CoroMill 390 tool

For rough milling:
Ordering code: R390-11T310M-PH
Choice for steel: P4340
Specifications: $W1 = 6.8$, $LE = 10$, $S = 3.59$, $BS = 1$, $RE = 1$ mm

Figure 2.6: CoroMill 390 insert for rough milling

For finishing (pocket):
Ordering code: R390-180616H-PTW
First choice for steel: P1130
Specifications: $W1 = 11$, $LE = 15.4$, $S = 6.33$, $BS = 8.6$ mm

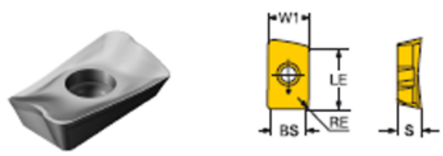

Figure 2.7: CoroMill 390 insert for finishing

2.3.3 Tool 3 – CoroMill 495

These three tools were all introduced to perform chamfer milling along edges to adapt to the desired slope of the chamfer according to the model of the part.

All tools can handle the same type of insert, which determines the feed velocity recommended to use.

- **Tool 3.1:** $K_r = 30$

- **Tool 3.2:** $K_r = 45$
- **Tool 3.3:** $K_r = 75$

Figure 2.8: CoroMill 495 chamfering tool

KAPR1	KAPR2		CZC MS	APMX1	APMX2	CNSC		Ordering code	DCON MS	DC1	DC2	DCX	BD	LF1	LF2	LU	BAR	NM	KG	RPMX	CICT	MID
30°	60°	09	16	3.8	6.5	1	1	495-012A16-3009L	16.0	12.0	18.3	26.0	17.2	100.0	88.7		20	1.4	0.23	14400	1	495-09T3M-XL
45°	45°	09	16	5.4	5.4	1	1	495-012A16-4509L	16.0	12.0	17.7	23.4	11.2	100.0	90.8	51.0	20	1.4	0.23	14400	1	495-09T3M-XL
60°	30°	09	16	6.8	3.9	1	1	495-012A16-6009L	16.0	12.0	13.5	20.1	13.5	100.0	90.3	49.0	20	1.4	0.20	14400	1	495-09T3M-XL
75°		09	16	7.7		1	1	495-012A16-7509L	16.0	12.0		16.2	13.0				20	1.4	0.20	14400	1	495-09T3M-XL

Dimensions, mm

Figure 2.9: CoroMill 495 table

Insert specifications:
Ordering code: 495-09T3M-PM
Choice for steel: P1130
Specifications: $IC = 9$, $LE = 7.4$, $S = 3.51$ mm, $\gamma_0 = 20$

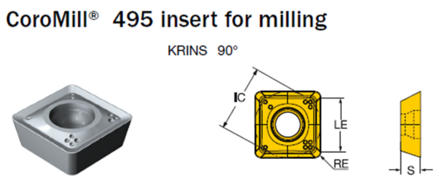

Figure 2.10: CoroMill 495 insert for finishing

2.3.4 Tool 4 – MVS Solid Carbide Twist Drill

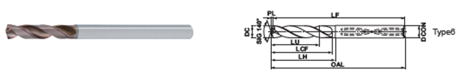

Figure 2.11: MVS solid carbide twist drill overview

Tool 4.1: MVS0780X05S080

- $L/D = 5$; internal coolant
- $DC = 7.8$ mm, $LU = 40.4$ mm, $LCF = 65.4$ mm, $LH = 65.4$ mm
- $OAL = 119.4$ mm, $LF = 118$ mm, $PL = 1.4$ mm, $DCON = 8$ mm

Tool 4.2: MVS0600X08S060

- $L/D = 8$; internal coolant
- $DC = 6$ mm, $LU = 49.1$ mm, $LCF = 67.1$ mm, $LH = 67.1$ mm
- $OAL = 119.1$ mm, $LF = 118$ mm, $PL = 1.1$ mm, $DCON = 6$ mm

Tool 4.3: MVS0980X05S100

- $L/D = 5$; internal coolant
- $DC = 9.8$ mm, $LU = 50.8$ mm, $LCF = 81.8$ mm, $LH = 81.8$ mm
- $OAL = 137.8$ mm, $LF = 136$ mm, $PL = 1.8$ mm, $DCON = 10$ mm

Tool 4.4: MVS0600X05S060

- $L/D = 5$; internal coolant; thread size M7×1.0
- $DC = 6$ mm, $LU = 49.1$ mm, $LCF = 49.1$ mm, $LH = 101.1$ mm
- $OAL = 101.1$ mm, $LF = 100$ mm, $PL = 1.1$ mm, $DCON = 6$ mm

Tool 4.5: MVS0800X02S080PL (for pilot hole)

- $L/D = 2$; internal coolant
- $DC = 8$ mm, $LU = 17.3$ mm, $LCF = 38.3$ mm, $LH = 38.3$ mm
- $OAL = 80.3$ mm, $LF = 79$ mm, $PL = 1.3$ mm, $DCON = 8$ mm

Tool 4.6: MVS0800X20S080 (for deep through hole)

- $L/D = 20$; internal coolant; $Z = 2$
- $DC = 8$ mm, $LU = 161.5$ mm, $LCF = 185.5$ mm, $LH = 188.5$ mm
- $OAL = 242.5$ mm, $LF = 241$ mm, $PL = 1.5$ mm, $DCON = 8$ mm

2.3.5 Tool 5 – MFE Flat Bottom Drill (Counterboring)

Order number: MFE1250X02S140

- $L/D = 2$; TYPE 2; $Z = 2$
- $DC = 8$ mm, $LU = 25$ mm, $LCF = 50$ mm, $LH = 53$ mm
- $OAL = 102$ mm, $DCON = 14$ mm

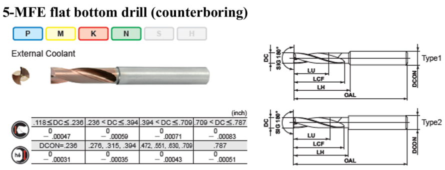

Figure 2.12: MFE flat bottom drill overview

2.3.6 Tool 6 – DLE Solid Carbide Drill (Countersink)

Order number: DLE0800S080P090

- $SIG = 90$; TYPE 2
- $DC = 8$ mm, $LU = 3.2$ mm, $LCF = 20$ mm, $LH = 234.8$ mm
- $OAL = 74$ mm, $LF = 70.6$ mm, $PL = 3.4$ mm, $DCON = 8$ mm

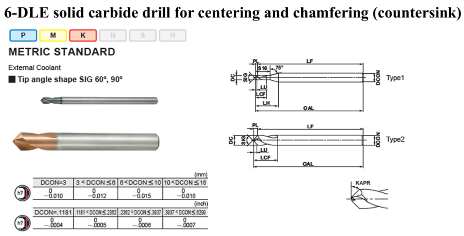

Figure 2.13: DLE solid carbide drill for centering and chamfering

2.3.7 Tool 7 – CoroReamer 835 (Tolerance Class H7)

Tool 7.1: 835.B-1000-A1-PF

- $NOF = 6$
- $DC = 10$ mm, $LU = 80$ mm, $LF = 118.5$ mm, $L = 20$ mm, $DCON = 10$ mm

Tool 7.2: 835.B-0800-A1-PF

- $NOF = 6$
- $DC = 8$ mm, $LU = 64$ mm, $LF = 98.8$ mm, $L = 16$ mm, $DCON = 8$ mm

2.3.8 Tool 8 – CoroTap 835

Order number: T300-XM100DA-M7

- Thread Size: M7
- Grade: PC110
- $LF = 80$ mm, $LU = 31$ mm, $THL = 10$ mm, $DCON = 7$ mm
- $DT = 7$ mm, $TP = 1$ mm
- $NOF = 3$
- GAMF = 10° (radial rake angle)
- Thread profile angle = 60°
- Premachined hole diameter PHD = 6 mm

2.3.9 Tool 9 – VFHVRB (Internal Shoulder/Fillet)

Order number: VFHVRBD1200R30N060

- $DC = 12$ mm, $RE = 3$ mm, $AP_{MAX} = 18$ mm
- $LU = 60$ mm, $DN = 11.7$ mm, $LF = 120$ mm, $DCON = 12$ mm
- $NOF = 4$; TYPE 2; $\gamma_0 = 45$

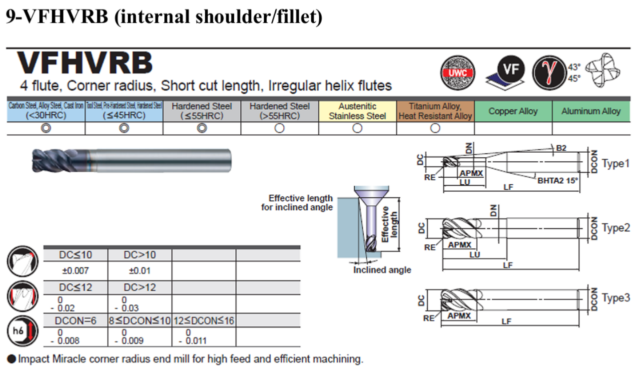

Figure 2.14: Internal shoulder/fillet

2.3.10 Tool 10 – MS2SS (Slotting)

Order number: MS2SSD1000

- $\gamma_0 = 30$; TYPE 3
- $DC = 10$ mm, $AP_{MX} = 15$ mm, $LF = 70$ mm
- $NOF = 2$, $DCON = 10$ mm

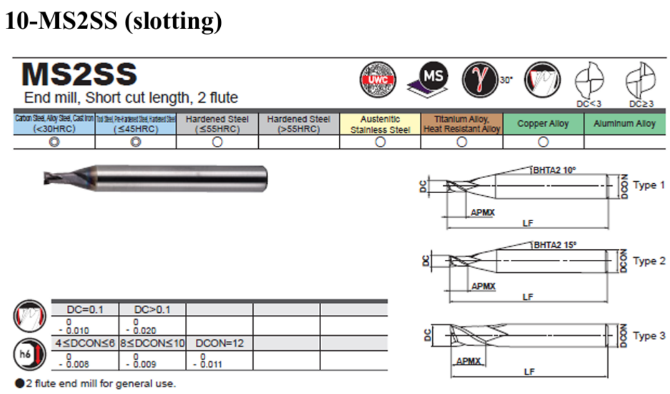

Figure 2.15: Slotting

Chapter 3

Verification of Operations

Operations will be feasible if the power requirement is below 16 kW, which is the spindle power given as input. The retract feed rate will always be set to the rapid feed rate given as input, equal to 42 m/min.

3.1 Bottom Surface Roughing (Op #5) – Tool 1

This is a face milling operation in a single pass where the maximum depth of cut equals the stock left over the model of the part: $a_p = 3$ mm. The radial depth of cut is set to a reasonable value of $a_e = 39.6$ mm.

According to manufacturer recommendations: $v_c = 445$ m/min and $f_z = 0.2$ mm/tooth.

Calculations:

$$\varphi_1 = \arcsin\left(\frac{8.114}{31.5}\right) = 14.926 \tag{3.1}$$

$$\varphi_2 = 90; \quad \varphi = \varphi_1 + \varphi_2 = 104.926 \tag{3.2}$$

$$\varphi_0 = \frac{360}{z} = \frac{360}{5} = 72 \tag{3.3}$$

$$z = \frac{\varphi}{\varphi_0} = 1.457 \rightarrow 1 < z < 2 \tag{3.4}$$

Two cutting teeth symmetric with respect to the direction of motion of the tool.

$$h_d = 0.2 \cdot \cos 36 \cdot \sin 45 = 0.1144 \text{ mm} \tag{3.5}$$

$$k_c = 1500 \cdot 0.1144^{-0.25} \cdot \left(1 - \frac{0.19}{100}\right) = 2574 \text{ N/mm}^2 \tag{3.6}$$

$$A_d = 0.1144 \cdot 3 = 0.3432 \text{ mm}^2 \tag{3.7}$$

$$F_c = k_c \cdot A_d = 2574 \cdot 0.3432 = 883.49 \text{ N} \tag{3.8}$$

$$T_c = 2 \cdot \frac{883.49 \cdot 31.5}{1000} = 55.66 \text{ Nm} \tag{3.9}$$

$$P_c = \frac{55.66 \cdot 1000 \cdot 445}{60 \cdot 31.5} = 13105 \text{ W} \tag{3.10}$$

Result: Feasible ($P_c < 16$ kW)

3.2 Top and Short Side Surfaces Roughing (Op #1, #4) – Tool 1

The feasibility of these operations is ensured by the check on the bottom face milling because the process parameters and cutting data are the same.

A small difference should be considered for the top surface, which has to leave a stock of 0.3 mm to perform a further finishing operation, but this does not change the conclusion about feasibility since we are reducing a_p and therefore the power requirement will be lower.

3.3 Top Surface Finishing – Tool 1, Wiper Insert

For the finishing step, we kept the same cutting data and process parameters used in the face milling but with a much smaller $a_p = 0.3$ mm and a higher feed since we are using wiper inserts. We set the feed to the maximum recommended value: $f_z = 0.3$ mm/tooth.

Results:

$$h_d = 0.27 \text{ mm} \tag{3.11}$$
$$A_d = 0.081 \text{ mm}^2 \tag{3.12}$$
$$K_c = 2076 \text{ N/mm}^2 \tag{3.13}$$
$$F_c = 168.23 \text{ N} \tag{3.14}$$
$$T_c = 10.59 \text{ Nm} \tag{3.15}$$
$$P_c = 2130 \text{ W} \tag{3.16}$$

Result: Feasible

3.4 Chamfers (Op #20, #21, #22, #23)

All tools used to create chamfers along the edges can mount the same type of insert, which determines the feed velocity: $f_z = 0.17$ mm/tooth.

The cutting speed depends on the material properties and selected tool: $v_c = 370$ m/min for all operations.

To check feasibility, we treated them as face milling operations with small engagement, where both a_p and a_e equal 1.5 mm (C1.5 chamfers).

3.4.1 $K_r = 30$ – Tool 3.1

$$\varphi = \arccos\left(\frac{8-1.5}{8}\right) = 35.65 \tag{3.17}$$

$$\varphi_0 = 360 \tag{3.18}$$

$$z = \frac{\varphi}{\varphi_0} = 0.099 \tag{3.19}$$

$$h_d = f_z \cdot \cos\varphi \cdot \sin K_r = 0.15 \cdot \cos 35.65 \cdot \sin 30 = 0.0609 \text{ mm} \tag{3.20}$$

$$k_c = 1500 \cdot 0.0609^{-0.25} \cdot \left(1 + \frac{0.34}{100}\right) = 3008 \text{ N/mm}^2 \tag{3.21}$$

$$A_d = 0.0609 \cdot 5.5 = 0.09 \text{ mm}^2 \tag{3.22}$$

$$F_c = k_c \cdot A_d = 3008 \cdot 0.09 = 274.78 \text{ N} \tag{3.23}$$

$$T_c = \frac{274.78 \cdot 8}{1000} = 2.198 \text{ Nm} \tag{3.24}$$

$$P_c = \frac{2.198 \cdot 1000 \cdot 370}{60 \cdot 8} = 1694.48 \text{ W} \tag{3.25}$$

Result: Feasible

3.4.2 $K_r = 75$ – Tool 3.3

Results: $h_d = 0.0426$ mm, $k_c = 3290$ N/mm^2, $A_d = 0.0639$ mm^2, $F_c = 210.23$ N, $T_c = 1.68$ Nm, $P_c = 1296$ W

Result: Feasible

3.4.3 $K_r = 45$ – Tool 3.2

Results: $h_d = 0.0298$ mm, $k_c = 3598$ N/mm^2, $A_d = 0.0447$ mm^2, $F_c = 160.8$ N, $T_c = 1.286$ Nm, $P_c = 991.6$ W

Result: Feasible

3.5 Pocket Roughing (Op #17) – Tool 2, Standard Insert

The machining of the pocket has many parameters to consider. The tool must be long enough to avoid collisions (usable length > 50 mm) and cannot have a diameter that is too large to machine all corners and navigate around the hexagonal pocket.

Sandvik catalogue provides recommendations for cutting speed depending on engagement and feed per tooth depending on insert type.

The pocket creation involves both larger engagement (during helical ramping) and small engagement along flat paths.

Helical ramping: $v_c = 340$ m/min, $f_z = 0.08$ mm/tooth

Shoulder milling: $v_c = 380$ m/min, $f_z = 0.15$ mm/tooth

3.5.1 Ramping Verification

$$D_{max} = 2 \cdot DC = 40 \text{ mm} \tag{3.26}$$
$$D_{min} = (20 - 2.3) \cdot 2 = 35.4 \text{ mm} \tag{3.27}$$

Reasonable value for machined hole diameter: $D_H = 36$ mm
Helical ramp diameter (center of tool): $D_H - DC = 16$ mm
Ramp leading angle: $\alpha = 2$
Depth of cut per revolution: $P = \pi \cdot 16 \cdot \tan(2) = 1.755$ mm
Calculations:

$$h_d = f_z = 0.08 \text{ mm} \tag{3.28}$$
$$k_c = 1500 \cdot 0.08^{-0.25} \cdot \left(1 - \frac{10.27\pi}{180 \cdot 100}\right) = 2815 \text{ N/mm}^2 \tag{3.29}$$
$$v_f = \frac{0.08 \cdot 2 \cdot 1000 \cdot 340}{\pi \cdot 20} = 865.8 \text{ mm/min} \tag{3.30}$$
$$P_c = \frac{1.755 \cdot 20 \cdot 865.8 \cdot 2815}{60 \cdot 10^6} = 1.42 \text{ kW} \tag{3.31}$$

Result: Feasible

3.5.2 Shoulder Milling Verification

Each pass has maximum roughing stepdown $a_p = 5.5$ mm and maximum stepover $a_e = 10$ mm.
We separate axial and radial contributions and sum them.
Radial (radial rake angle -9.599):

$$\varphi = \arccos\left(\frac{10-9}{10}\right) = 84.26 \tag{3.32}$$
$$\varphi_0 = \frac{360}{z} = \frac{360}{2} = 180 = \pi \tag{3.33}$$
$$z = \frac{\varphi}{\varphi_0} = 0.468 \tag{3.34}$$
$$h_d = f_z \cdot \sin\varphi = 0.15 \cdot \sin 84.26 = 0.149 \text{ mm} \tag{3.35}$$
$$k_c = 1500 \cdot 0.149^{-0.25} \cdot \left(1 + \frac{9.599\pi}{180 \cdot 100}\right) = 2418 \text{ N/mm}^2 \tag{3.36}$$
$$A_d = 0.149 \cdot 5.5 = 0.82 \text{ mm}^2 \tag{3.37}$$
$$F_c = k_c \cdot A_d = 2418 \cdot 0.82 = 1983 \text{ N} \tag{3.38}$$
$$T_c = \frac{1983 \cdot 10}{1000} = 19.83 \text{ Nm} \tag{3.39}$$
$$P_c = \frac{19.83 \cdot 1000 \cdot 380}{60 \cdot 10} = 12559 \text{ W} \tag{3.40}$$

Axial (axial rake angle 10.27):

$$\varphi = 84.26 \tag{3.41}$$
$$z = 0.468 \tag{3.42}$$
$$h_d = f_z \cdot \cos\varphi = 0.15 \cdot \cos 84.26 = 0.015 \text{ mm} \tag{3.43}$$
$$k_c = 1500 \cdot 0.015^{-0.25} \cdot \left(1 + \frac{10.27\pi}{180 \cdot 100}\right) = 4278 \text{ N/mm}^2 \tag{3.44}$$
$$A_d = 0.015 \cdot 5.5 = 0.0825 \text{ mm}^2 \tag{3.45}$$
$$F_c = k_c \cdot A_d = 4278 \cdot 0.0825 = 353 \text{ N} \tag{3.46}$$
$$T_c = \frac{353 \cdot 10}{1000} = 3.53 \text{ Nm} \tag{3.47}$$
$$P_c = \frac{3.53 \cdot 1000 \cdot 380}{60 \cdot 10} = 2235 \text{ W} \tag{3.48}$$

Total power: $P_{tot} = 12559 + 2235 = 14794$ W
Result: Feasible ($P_{tot} < 16$ kW)

3.6 Pocket Finishing (Op #18) – Tool 2, Wiper Insert

For finishing, we kept the same cutting data and process parameters as face milling but with $a_p = 0.3$ mm and higher feed using wiper inserts: $f_z = 0.2$ mm/tooth.

Results:

$$h_d = 0.1989 \text{ mm} \tag{3.49}$$
$$A_d = 0.06 \text{ mm}^2 \tag{3.50}$$
$$K_c = 2242 \text{ N/mm}^2 \tag{3.51}$$
$$F_c = 134.5 \text{ N} \tag{3.52}$$
$$T_c = 1.345 \text{ Nm} \tag{3.53}$$
$$P_c = 908 \text{ W} \tag{3.54}$$

Result: Feasible

3.7 Operations #3a, #3b, #24, #25

All these operations are ensured to be feasible since we use the same tool as for pocketing operations (Tool 2). This tool provides a good compromise between machining time (cutting speed and feed rate) and reachability of deep points, always respecting manufacturer recommendations.

This tool has a main entering angle of 90°, which is ideal for creating straight surfaces through shoulder milling.

Operations 3a and 3b: Contouring milling through multiple depths with maximum stepdown of 5.5 mm, $v_c = 405$ m/min and $f_z = 0.15$ mm/tooth.

Operations 24 and 25: Pocketing operations with maximum stepover of 9 mm and maximum stepdown of 5.5 mm, keeping $v_c = 405$ m/min and $f_z = 0.15$ mm/tooth.

3.8 Fillet (Op #26) – Tool 9

The fillet in the bottom edges of pockets was machined by shoulder milling with multiple depths of $a_p = 8$ mm (maximum roughing stepdown in Fusion 360) and radial depth of 3 mm. We used an end mill with corner radius $RE = 3$ mm so that the fillet was automatically created during the last pass.

The Mitsubishi catalogue provides RPM and feed rate for some values of a_p and a_e related to cutter diameter and usable length. Since we increased the depth of cut, we reduced both recommended values: $n = 2400$ RPM and $v_f = 3600$ mm/min.

Therefore: $v_c = 90.47$ m/min, $f_z = 0.375$ mm/tooth

Feasibility check (face milling approach):

$$\varphi = \arccos\left(\frac{6-3}{6}\right) = 60 \tag{3.55}$$

$$\varphi_0 = \frac{360}{z} = \frac{360}{4} = 90 = \frac{\pi}{2} \tag{3.56}$$

$$z = \frac{\varphi}{\varphi_0} = 0.66 \tag{3.57}$$

$$h_d = f_z \cdot \sin\varphi = 0.375 \cdot \sin 60 = 0.32476 \text{ mm} \tag{3.58}$$

$$k_c = 1500 \cdot 0.32476^{-0.25} \cdot \left(1 - \frac{45\pi}{180 \cdot 100}\right) = 1971.4 \text{ N/mm}^2 \tag{3.59}$$

$$A_d = 0.32476 \cdot 8 = 0.97428 \text{ mm}^2 \tag{3.60}$$

$$F_c = k_c \cdot A_d = 1971.4 \cdot 0.97428 = 1920 \text{ N} \tag{3.61}$$

$$T_c = \frac{1920 \cdot 6}{1000} = 11.52 \text{ Nm} \tag{3.62}$$

$$P_c = \frac{11.52 \cdot 1000 \cdot 90.47}{60 \cdot 6} = 2896 \text{ W} \tag{3.63}$$

Result: Feasible

3.9 Drilling Operations

All drilling tools were selected from the Mitsubishi catalogue following manufacturer recommendations to estimate the L/D parameter, which must consider the actual length of the hole plus an additional length of $1.5 \cdot DC$ to ensure smooth entry.

Cutting parameters are assigned considering the material type (P1.1.Z.AN steel) and hole diameter.

3.9.1 Op #10 – Tool 4.1

According to recommendations, $L/D = 5$ for a blind hole of 7.8 mm diameter (we left 2 mm for reaming) and 15 mm depth.

$v_c = 85$ m/min, $f_r = 0.2311$ mm/rev

Feasibility check:

$$h_d = \frac{f_r}{2} \cdot \sin\left(\frac{\varepsilon}{2}\right) = 0.115 \cdot \sin 70 = 0.108 \text{ mm} \tag{3.64}$$

$$k_c = 1500 \cdot 0.108^{-0.25} \cdot \left(1 - \frac{0.523}{100}\right) = 2602.887 \text{ N/mm}^2 \tag{3.65}$$

$$A_d = f \cdot \frac{D}{4} = 0.45 \text{ mm}^2 \tag{3.66}$$

$$F_c = 1171 \text{ N} \tag{3.67}$$

$$T_c = 4.568 \text{ Nm} \tag{3.68}$$

$$P_c = 1659 \text{ W} \tag{3.69}$$

Result: Feasible

3.9.2 Op #13 – Tool 4.2

$L/D = 8$ for a through hole of 6 mm diameter and 30 mm depth.

$v_c = 80.18$ m/min, $f_r = 0.2$ mm/rev

Results: $h_d = 0.09$ mm, $k_c = 2724$ N/mm^2, $A_d = 0.3$ mm^2, $F_c = 817.28$ N, $T_c = 2.45$ Nm, $P_c = 10.9$ kW

Result: Feasible

3.9.3 Op #6 – Tool 4.4

$L/D = 4$ for a blind hole of 6 mm diameter and 15 mm depth. Final threaded hole size will be M7×1.0, matching the premachined hole diameter required by the tapping tool.

$v_c = 110.03$ m/min, $f_r = 0.2$ mm/rev

Results: $h_d = 0.18$ mm, $k_c = 2270$ N/mm^2, $A_d = 0.3$ mm^2, $F_c = 681$ N, $T_c = 2.04$ Nm, $P_c = 1248$ W

Result: Feasible

3.9.4 Op #15 – Tool 4.5

$L/D = 2$ for a pilot hole of 8 mm diameter and 8 mm depth. This is the first step for creating the deep through hole. We chose the shortest tool as recommended because the initial stage can provide uncertainty due to the huge length of the deep drill.

$v_c = 121.35$ m/min, $f_r = 0.23114$ mm/rev

Results: $h_d = 0.1086$ mm, $k_c = 2604$ N/mm^2, $A_d = 0.4622$ mm^2, $F_c = 1203.49$ N, $T_c = 4.81$ Nm, $P_c = 2424$ W

Result: Feasible

3.9.5 Op #16 – Tool 4.6

$L/D = 20$ for a deep through hole of 8 mm diameter and 138 mm depth.

$v_c = 111.118$ m/min, $f_r = 0.2997$ mm/rev

Results: $h_d = 0.1408$ mm, $k_c = 1958$ N/mm^2, $A_d = 0.46$ mm^2, $F_c = 901$ N, $T_c = 3.6$ Nm, $P_c = 1670$ W

Result: Feasible

3.10 Counterbore (Op #12) – Tool 5

We chose a flat bottom drill to create the counterbore with best possible accuracy. $L/D = 2$ for a hole with depth of 4 mm, starting with an already existing hole to be enlarged from 7.8 to 12.5 mm diameter. This operation was performed before reaming to preserve the final surface finish of the inner hole.

$v_c = 74.676$ m/min, $f_r = 0.2$ mm/rev

Results: $n = 1901.6$ RPM, $a_p = 2.25$ mm, $A_d = 0.225$ mm^2, $h_d = 0.2$ mm, $K_c = 2235$ N/mm^2, $F_c = 502.9$ N, $T_c = 5.1547$ Nm, $P_c = 950.45$ W

Result: Feasible

3.11 Countersink (Op #14) – Tool 6

According to the technical drawing, the countersink should be made with a tool having diameter of 8 mm and point angle of 90°, to enlarge the previously machined hole of 6 mm.

$v_c = 80.08$ m/min, $f_r = 0.07$ mm/rev

Results: $a_p = 1$ mm, $A_d = 0.035$ mm^2, $h_d = 0.0247$ mm, $K_c = 3754$ N/mm^2, $F_c = 131.4$ N, $T_c = 0.919$ Nm, $P_c = 306.88$ W

Result: Feasible

3.12 Reaming Operations

3.12.1 Op #9 – Tool 7.1

The top hole must be enlarged from 9.8 mm to 10 mm diameter to reach H7 tolerance grade, provided by the tool.

$v_c = 180$ m/min, $f_r = 0.8$ mm/rev

Results: $a_p = 0.1$ mm, $A_d = 0.013$ mm^2, $h_d = 0.0646$ mm, $K_c = 2943$ N/mm^2, $F_c = 38.259$ N, $T_c = 1.136$ Nm, $P_c = 681$ W

Result: Feasible

3.12.2 Op #11 – Tool 7.2

The top hole must be enlarged from 7.8 mm to 8 mm diameter to reach H7 tolerance grade, provided by the tool.

$v_c = 180$ m/min, $f_r = 0.8$ mm/rev

Results: $a_p = 0.1$ mm, $A_d = 0.013$ mm^2, $h_d = 0.0646$ mm, $K_c = 2975$ N/mm^2, $F_c = 38.675$ N, $T_c = 0.916$ Nm, $P_c = 687$ W

Result: Feasible

3.13 Tapping (Op #7) – Tool 8

We chose the tool to satisfy the thread requirement M7×1.0 (thread diameter of 7 mm and pitch of 1 mm).

The only tool from Sandvik catalogue available with cutting data recommendations for our steel type (P1.1.Z.AN), matching grade C110 and with ULDR = 2.5 (usable length diameter ratio) had $v_c = 32.5$ m/min.

$$n = \frac{1000 \cdot 32.5}{\pi \cdot 7} = 1477.867 \text{ RPM} \tag{3.70}$$

$$V_f = \text{pitch} \cdot n = 1477.867 \text{ mm/min} \tag{3.71}$$

The premachined hole diameter for this tool is 6 mm and will produce a maximum diameter of 7 mm. In Fusion 360, we set thread pitch and diameter offset both equal to 1 mm.

Calculations:

$$h_d = 1 \cdot \sin\left(\frac{60}{2}\right) = 0.5 \text{ mm} \tag{3.72}$$

$$k_c = 1500 \cdot 0.5^{-0.25} \cdot \left(1 - \frac{45\pi}{180 \cdot 100}\right) = 1769.8 \text{ N/mm}^2 \tag{3.73}$$

$$T_c = \frac{1}{2} \cdot \frac{7 \cdot 1769.8}{8000} = 1.54857 \text{ Nm} \tag{3.74}$$

$$P_c = \frac{1.54857 \cdot 2\pi \cdot 1477.867}{60} = 76.286 \text{ W} \tag{3.75}$$

Result: Feasible

3.14 Slot (Op #19) – Tool 10

The slot was machined in a single pass with radial depth $a_e = 10$ mm and axial depth $a_p = 8$ mm. The Mitsubishi catalogue provided values for RPM and feed rate that we reduced by 70% and 60% respectively as recommended for higher depth of cut: $n = 1920$ RPM, $v_f = 360$ mm/min.

Therefore: $v_c = 60.318$ m/min, $f_z = 0.09375$ mm/tooth

Feasibility verification using face milling formulas (average approach):

$$\varphi_0 = \frac{360}{z} = \frac{360}{2} = 180 = \pi \tag{3.76}$$

$$z = \frac{\varphi}{\varphi_0} = 2 \tag{3.77}$$

$$h_{d,av} = \frac{0.09375 \cdot 2 \cdot 10}{\pi \cdot 10} = 0.05968 \text{ mm} \tag{3.78}$$

$$A_{d,av} = 0.05968 \cdot 8 = 0.47744 \text{ mm}^2 \tag{3.79}$$

$$k_c = 1500 \cdot 0.05968^{-0.25} \cdot \left(1 - \frac{30\pi}{180 \cdot 100}\right) = 3018.898 \text{ N/mm}^2 \tag{3.80}$$

$$F_{c,av} = 3018.898 \cdot 0.47744 = 1441.34 \text{ N} \tag{3.81}$$

$$T_c = \frac{2 \cdot 1441.34 \cdot 10/2}{1000} = 14.41 \text{ Nm} \tag{3.82}$$

$$P_c = \frac{14.41 \cdot 1000 \cdot 60.318}{60 \cdot 10/2} = 2897.96 \text{ W} \tag{3.83}$$

Result: Feasible

Chapter 4

Discussion on Technical Requirements

4.1 Tolerances

4.1.1 Pocket (R_a 3.2)

According to Sandvik guide, to achieve good surface finish in a face milling operation, we must keep feed per tooth $\leq 0.6 \cdot b_s$ (insert feature).

We set feed to the maximum recommended value: $f_z = 0.2$ mm/tooth.

To verify that the roughness limit has not been reached, we use the formulas from theory for face milling:

$$R_{a,max} = \frac{0.2 \cdot 10^3}{\arctan(90)} = 2.238\,\mu\text{m} \tag{4.1}$$

$$R_a = R_{a,max}/4 = 0.559\,\mu\text{m} \tag{4.2}$$

Requirement satisfied ($R_a < 3.2$)

4.1.2 Top Surface (R_a 1.6)

We followed the same recommendations, taking $f_z = 0.3$ mm/tooth:

$$R_{a,max} = \frac{0.3 \cdot 10^3}{\arctan(45)} = 3.38\,\mu\text{m} \tag{4.3}$$

$$R_a = R_{a,max}/4 = 0.845\,\mu\text{m} \tag{4.4}$$

4.1.3 Hole tolerances

The tolerances specified for the holes were guaranteed by the reamers used, since they are made on purpose to perform finishing operation to reach an H7 grade of tolerance, while for the H10 grade it is enough to perform a drilling operation over the hole diameter since it is not a high requirement. The thread size requirement was also guaranteed by the choice of the tapping tool. The geometric specification in the 2d drawing such as location, orientation and forms specifications are all guaranteed by the sequence of operation and clamping modalities(also refer to the 3.2 section of the report). Furthermore, Fusion360 allows to highlight (after all the machining operations) those areas having extra material with respect to the final model we want to obtain, within a tolerance that we can specify, therefore if there are no blue parts highlighted and the tolerance is set for example to 0.1 it means that we should have respected the form tolerances.

Chapter 5

Appendix: Notation and Formulas

5.1 Milling

Parameter	**Symbol**	**Unit**
Feed per tooth	f_z	mm/rev·tooth
Cutting diameter	D	mm
Axial depth of cut	a_p	mm
Radial depth of cut	a_e	mm
Number of teeth	z	-
Tool main entering angle	K_r	degrees

Table 5.1: Milling parameters

Key formulas:

$$n = \frac{1000 \cdot v_c}{\pi \cdot D} \quad \text{[RPM]} \tag{5.1}$$

$$V_f = z \cdot f_z \cdot n \quad \text{[mm/min]} \tag{5.2}$$

Slab milling:

$$h_{d,\theta} = f_z \cdot \sin\theta \quad \text{[mm]} \tag{5.3}$$

$$A_{d,\theta} = h_{d,\theta} \cdot a_p \quad [\text{mm}^2] \tag{5.4}$$

Face milling:

$$h_{d,\theta} = f_z \cdot \cos\theta \cdot \sin K_r \quad \text{[mm]} \tag{5.5}$$

$$A_{d,\theta} = f_z \cdot \cos\theta \cdot a_p \quad [\text{mm}^2] \tag{5.6}$$

Cutting force and power:

$$F_c(\theta) = k_c \cdot A_d \quad \text{[N]} \tag{5.7}$$

$$T_c = \sum_{i=1}^{z} \frac{F_c(\theta_i) \cdot D/2}{1000} \quad \text{[Nm]} \tag{5.8}$$

$$P_c = T_c \cdot \omega \quad \text{[W]}, \quad \omega = \frac{1000 \cdot v_c}{60 \cdot D/2} \tag{5.9}$$

Number of working teeth:

$$z = \frac{\varphi}{\varphi_0}, \quad \varphi_0 = \frac{2\pi}{Z} \tag{5.10}$$

Specific cutting force (Kronemberg):

$$K_c = K_{c1} \cdot h_d^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right) \tag{5.11}$$

Average chip thickness:

$$h_{d,\theta} = \frac{f_z \cdot 2 \cdot a_e}{\varphi \cdot D} \tag{5.12}$$

Average roughness:

$$R_a = \frac{f_z \cdot 10^3}{4 \cdot (\tan^{-1} k_r' + \tan^{-1} k_r)} \quad [] \tag{5.13}$$

5.2 Helical Ramping

$$D_{max} = D \cdot 2 \quad [\text{mm}] \tag{5.14}$$

$$D_{min} = (D - (R_E - b_s)) \cdot 2 \quad [\text{mm}] \tag{5.15}$$

$$P = \pi \cdot D \cdot \tan\alpha \quad [\text{mm}] \tag{5.16}$$

$$P_c = \frac{a_e \cdot a_p \cdot v_f \cdot k_c}{60 \cdot 10^6} \quad [\text{kW}] \tag{5.17}$$

where α is the ramp leading angle, R_E is the corner radius, and b_s is the parallel land of the insert.

5.3 Drilling

$$h_d = f_z \cdot \sin\left(\frac{\varepsilon}{2}\right) \quad [\text{mm}] \tag{5.18}$$

$$A_d = f \cdot \frac{D}{4} \quad [\text{mm}^2] \tag{5.19}$$

$$K_c = K_{c1} \cdot h_d^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right) \quad [\text{N/mm}^2] \tag{5.20}$$

$$F_c = K_c \cdot A_d \quad [\text{N}] \tag{5.21}$$

$$T_c = \frac{F_c \cdot D/2}{1000} \quad [\text{Nm}] \tag{5.22}$$

$$P_c = T_c \cdot \omega \quad [\text{W}] \tag{5.23}$$

where ε is the point angle.

5.4 Tapping

$$h_d = \text{pitch} \cdot \sin(\text{GAMF}) \quad [\text{mm}] \tag{5.24}$$

$$K_c = K_{c1} \cdot h_d^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right) \quad [\text{N/mm}^2] \tag{5.25}$$

$$T_c = \frac{\text{pitch}}{2} \cdot \frac{D \cdot k_c}{8000} \quad [\text{Nm}] \tag{5.26}$$

$$P_c = \frac{T_c \cdot 2\pi \cdot n}{60} \quad [\text{W}] \tag{5.27}$$

$$v_f = \text{pitch} \cdot n \quad [\text{mm/min}] \tag{5.28}$$

where GAMF is the radial rake angle.

5.5 Reaming/Counterboring/Countersinking

$$A_d = f_z \cdot \frac{D_{ext}^2 + D_{int}^2}{2} \quad [\text{mm}^2] \tag{5.29}$$

$$F_c = K_c \cdot A_d \quad [\text{N}] \tag{5.30}$$

$$T_c = Z \cdot F_c \cdot \frac{D_{ext}^2 + D_{int}^2}{2 \cdot 1000} \quad [\text{Nm}] \tag{5.31}$$

$$P_c = T_c \cdot \omega \quad [\text{W}] \tag{5.32}$$