# FINAL REPORT - CAM LAB GROUP #77

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## 1. Notation and Formulas

### *Machining – Roughness*

| | |
|---|---|
| *Slab Milling* $[\mu m]$ | $R_{max} = \frac{R}{2}\frac{\pi^2 {f_z}^2}{(2\pi R+60Zf_z)^2}10^3;\ R_a = \frac{R_{max}}{4}$ |
| *Face Milling* $[\mu m]$ | $R_{max}= \frac{f_z}{(tan^{-1}k_r+tan^{-1}k'_r)}10^3;\ R_a = \frac{R_{max}}{4};$<br>$R_a= \frac{f_z}{32r}\ 10^3$ |

### *Machining – Milling*

| | |
|---|---|
| *Feed per tooth* $[mm/rev.\cdot tooth]$ | $f_z$ |
| *Specific Cutting Force* $[N/ mm^2]$ | $k_C = k_{C1}h_D^{-m_c}\left(1-{\gamma_0}/{100}\right);\gamma_0$ *is the rake angle*;<br>$k_{C1} = 1500\ N/mm^2\ ;\ m_c = 0.25$ |
| *Slab milling – Chip Thickness* $[mm]$ | $h_{D,\theta} = h_D(\theta) = f_z\ sin\theta$ |
| *Slab milling – Chip Area* $[mm^2]$ | $A_{D,\theta} = h_{D,\theta}\ a_p$ |
| *Face milling – Chip Thickness* $[mm]$ | $h_{D,\theta} = f_z\ cos\theta\ sink_r$ |
| *Face milling – Chip Area* $[mm^2]$ | $A_{D,\theta} = f_z\ cos\theta\ a_p$ |
| *Cutting Force* $[N]$ | $F_C(\theta) = k_{C,\theta}\ A_{D,\theta}$ |
| *Cutting Torque* $[Nm]$ | $T_C = \sum_{i=1}^{z} F_c(\theta_i)\frac{D/2}{1000}$ |
| *Number of working teeth* | $z = \varphi/\varphi_0\ ;\ \varphi_0 = 2\pi/z$ |
| *Cutting Power* $[W]$ | $P_C = T_C\ \omega\ ;\ \ \omega = \frac{1000*vc}{60*D/2}$ |
| *Average Chip Thickness* $[mm]$ | $h_{D,av} = \frac{f_z 2a_e}{\varphi D}$ |

### *Machining – Drilling (twist drill)*

| | |
|---|---|
| *Chip Thickness* $[mm]$ | $h_D = f_z \sin(\varepsilon/2),$ |
| *Specific Cutting Force* $[N/ mm^2]$ | $k_C = k_{C1}\ h_D^{-m_c}\left(1-{\gamma_0}/{100}\right);\ \gamma_0$ *is the rake angle*<br>$k_{C1} = 1500\ N/mm^2\ ;\ m_c = 0.25$ |
| *Chip Area* $[mm^2]$ | $A_D = f\ D/4$ |
| *Cutting Force* $[N]$ | $F_C = k_C\ A_D$ |
| *Cutting Torque* $[Nm]$ | $T_C = F_C\ \frac{D/2}{1000}$ |
| *Cutting Power* $[W]$ | $P_C = T_C\ \omega\ ;\ \omega = \frac{1000*vc}{60*D/2}$ |

***Machining – Reaming / Counterboring***

| | |
|---|---|
| *Chip Thickness* $[mm]$ | $h_D = f_z \sin(\varepsilon/2)$ |
| *Specific Cutting Force* $[N/mm^2]$ | $k_C = k_{C1}\, h_D^{-m_c} \left(1 - {}^{\gamma_0}/_{100}\right); \gamma_0$ *is the rake angle*<br>$k_{C1} = 1500\ N/mm^2\ ;\ m_c = 0.25$ |
| *Chip Area* $[mm^2]$ | $A_D = f_z \frac{Dext-Dint}{2}$ |
| *Cutting Force* $[N]$ | $F_C = k_C\, A_D$ |
| *Cutting Torque* $[Nm]$ | $T_C = Z\, F_C \frac{\frac{Dext+Dint}{4}}{1000}$ |
| *Cutting Power* $[W]$ | $P_C = T_C\, \omega\ ;\ \omega = \frac{1000*vc}{60*D/2}$ |

# 2. Introduction of Project Product

## 2.1 Inputs and variables

In this section, we illustrate the parametric variables assigned to our group.

- Workpiece Materials:

| MC code | Material group | | Material sub-group | | Manufacturing process | | Heat treatment | | nom | Specific cutting force, $k_{c1}$ (N/mm$^2$) | $m_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P1.1.Z.AN | 1 | | 1 | <=0.25% C | Z | forged/rolled/ cold drawn | AN | annealed | 125 HB | 1500 | 0.25 |

- Threaded Holes: M8 x 1.0 (mm)
- Distance to the midline: 170 mm
- Stock size: 311 mm x 156 mm x 76 mm (X, Y, Z)

## 2.2 Features and operations

In this section, we list all the operations required to manufacture our product. For each operation, we specify the corresponding feature, the order of execution, the setup, the surface requirements, and the relationship with the Datums.

| Setup | Feature | Requirement | Relation | Num | Operation |
|---|---|---|---|---|---|
| 1 | Bottom Surface | Ra 12.5 | ⏥ 0.05<br>// 0.1 A | 1 | Face Milling |
| 2 | Top Surface | Ra 1.6 | ⏥ 0.05<br>Datum A | 2 | Rough Milling |
| | | | | 3 | Finish Milling |
| | Curved Surface | Ra 12.5 | ⊥ 0.1 A | 4 | Contouring |
| | Back Surface | Ra 12.5 | ⊥ 0.1 A<br>Datum B | 5 | Contouring |
| | Pocket | Ra 3.2 | // 0.1 A | 6 | Rough Pocketing |
| | | | | 7 | Finish Pocketing |
| | High Fillet | Ra 3.2 | | 8 | Finish Pocketing |
| | Low Fillet | Ra 3.2 | | 9 | Finish Pocketing |
| | Top Slots | Ra 12.5 | | 10 | End Milling |
| 3 | Right-Side Surface | Ra 12.5 | ⊥ 0.1 A<br>Datum C | 11 | Rough Milling |
| | | | | 12 | Finish Milling |
| | Hole A | H10 | — Ø0.1 | 13 | Pilot Drilling |
| | | | | 14 | Deep Drilling |
| 4 | Left-Side Surface | Ra 12.5 | ⊥ 0.1 A<br>Datum D | 15 | Rough Milling |
| | | | | 16 | Finish Milling |

| | | | | | |
|---|---|---|---|---|---|
| | 3 Holes B | H10 | ⌖ Ø0.1 C A B | 17 | Drilling |
| | | | | 18 | Countersinking |
| | 3 Holes C | H7 | | 19 | Drilling |
| | | | | 20 | Reaming |
| | | | | 21 | Counterboring |
| 5 | Chamfers | Ra 12.5 | | 22 | Chamfer Milling |
| | 2 Holes D | H7 | ⌖ Ø0.1 A B C | 23 | Drilling |
| | | | | 24 | Reaming |
| | 6 Holes E | M8 | | 25 | Drilling |
| | | | | 26 | Thread Milling |

## 2.3 Precedence Graph

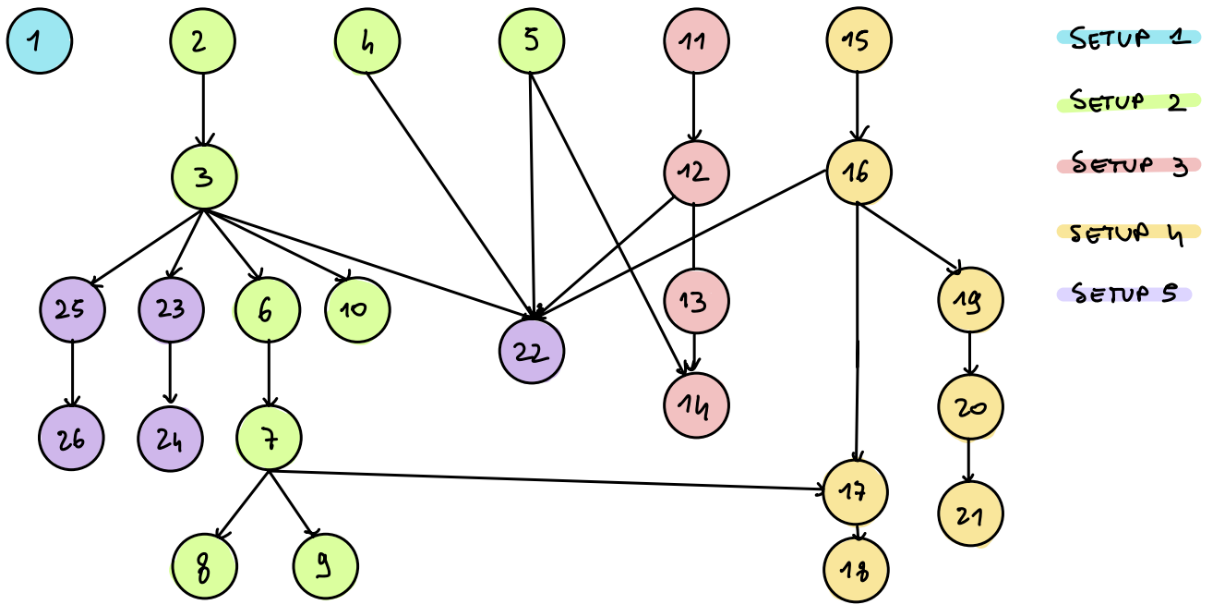
In the last section of the introduction chapter, we present the precedence graph. We consider the following rules:

1. First roughing, then finishing;
2. First surface, then holes/pockets.

Additionally, we consider the special requirements:

3. First drilling, then reaming (for holes with high requirements such as H7);
4. First drilling, then threading (for thread holes such as M8x1.0);
5. First pilot drilling, then deep drilling (for deep holes).

Considering that all the datums and the tolerances are verified in the design procedure, we obtained the following graph:




**Setup 1:** In the first setup, we only perform a roughing face milling operation **1**.

**Setup 2:** In the second setup, we perform first the roughing **2** and then the finishing operation **3** for the top surface (RULE #1). These operations allow us to manufacture pockets **6**&**7** (RULE #2), the holes, and the chamfers of the upper surface. Furthermore, the contouring of the curved **4** and back surface **5** lays the foundations for the chamfers and the deep hole operations. The end milling operation **10** is performed. The finishing pocketing operation allows us to manufacture high **8** and low **9** fillets.

**Setup 3:** In the third setup, we rough **11** and finish **12** the right-side surface. Once we manufactured the right surface, we can perform pilot **13** and deep **14** drilling operations for Hole A.

**Setup 4:** In the fourth setup, we rough **15** and finish **16** the left-side surface. The left-side surface finishing, together with the back surface, curved surface and the right surface manufacturing, finally allow us to operate the chamfers. Once we finish the left surface, we can perform drilling **17** and countersinking

**18** for Holes B. The left surface finishing allows us to manufacture the Holes C, throughout drilling **19**, reaming **20**, and counterboring **21** operations.

**Setup 5:** In the fifth setup, we perform chamfer milling operation **22**. After that, we perform drilling **23** and reaming **24** for Holes D, then drilling **25** and thread milling **26** for Holes E.

# 3. Detailed Final Solution to Realize Our Product

## 3.1 Throughput of the Product

In order to compute the throughput of the product, we simulated the 26 operations in Fusion360 using the parameters of the catalogs. From the software, we obtained the resulting machining time.

We first considered a tool changing time of 15 s and a setup changing time of 60 s. In our calculations, we omitted the spindle reposition time, since we always kept the spindle axis along the z direction (as it may be noticed in the Fusion360 file). We also rounded every machining time to the first decimal digit. In addition, for every tool we considered a tool life sufficient for its related operation in the process.

It is important to point out that Fusion360 is merely simulative software: the machining time for each operation is independent of the cutting speed and other process parameters, but it only depends on the tool path (editable from "setup"-> "edit" -> "passes"). Therefore, the total machining time is just an indicative value, just like the throughput of the product we derived.

For each operation, we obtained the following machining time:

| Setup | Num | Operation | Machining Time | Tool Changing Time | Tot Machining Time |
|---|---|---|---|---|---|
| Change to Setup 1 | / | Loading | 60 s | / | 88 s |
| Setup 1 | 1 | Face Milling | 28 s | / | |
| Change to Setup 2 | / | Loading and Unloading | 60 s | / | 2906 s |
| Setup 2 | 2 | Rough Milling | 28 s | 15 s | |
| | 3 | Finish Milling | 27 s | 15 s | |
| | 4 | Contouring | 235 s | 15 s | |
| | 5 | Contouring | 194 s | / | |
| | 6 | Rough Pocketing | 1092 s | 15 s | |
| | 7 | Finish Pocketing | 1149 s | / | |
| | 8 | Finish Pocketing | 7 s | 15 s | |
| | 9 | Finish Pocketing | 7 s | / | |
| | 10 | End Milling | 17 s | 15 s | |
| Change to Setup 3 | / | Loading and Unloading | 60 s | / | 138 s |
| Setup 3 | 11 | Rough Milling | 11 s | 15 s | |
| | 12 | Finish Milling | 11 s | / | |
| | 13 | Pilot Drilling | 1 s | 15 s | |
| | 14 | Deep Drilling | 10 s | 15 s | |
| Change to Setup 4 | / | Loading and Unloading | 60 s | / | 186 s |
| Setup 4 | 15 | Rough Milling | 11 s | 15 s | |
| | 16 | Finish Milling | 11 s | / | |
| | 17 | Drilling | 4 s | 15 s | |
| | 18 | Countersinking | 5 s | 15 s | |
| | 19 | Drilling | 2 s | 15 s | |
| | 20 | Reaming | 1 s | 15 s | |
| | 21 | Counterboring | 2 s | 15 s | |
| Change to Setup 5 | / | Loading and Unloading | 60 s | / | 161 s |

| | | | | | |
|---|---|---|---|---|---|
| Setup 5 | 22 | Chamfer Milling | 11 s | 15 s | |
| | 23 | Drilling | 3 s | 15 s | |
| | 24 | Reaming | 1 s | 15 s | |
| | 25 | Drilling | 7 s | 15 s | |
| | 26 | Thread Milling | 4 s | 15 s | |

The total machining time we obtain is

$$t_m = 3479\, s = 57{,}98\, min.$$

Therefore, the throughput of the product in terms of parts per hour is

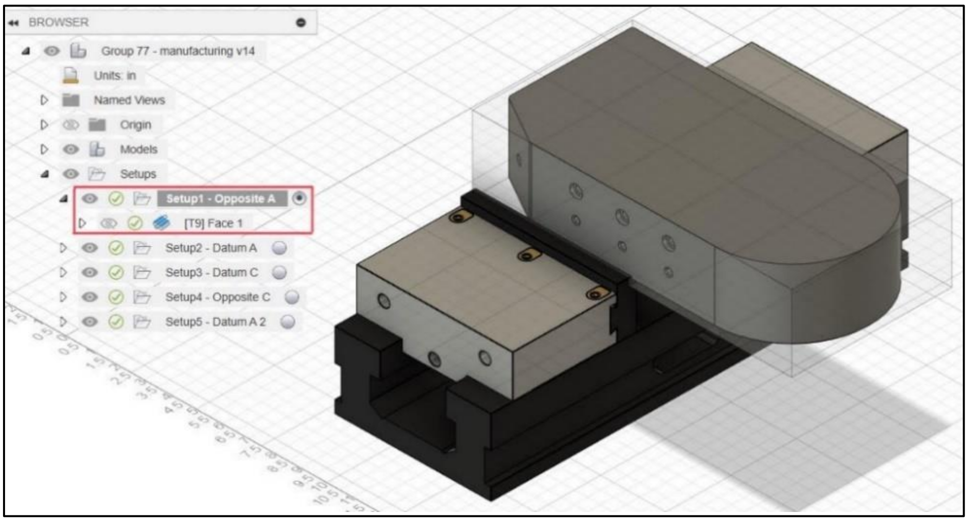
$$\mathrm{n_{parts}} = \frac{3600\, s}{3479\, s} \approx 1.03.$$

## 3.2 Detailed Information for Your Setups

The setups we used to machine the final product are described below. For each setup, we carried out the clamping in order to obtain the minimum bending possible. It is important to understand whether we are clamping the stock or the product in any configuration.

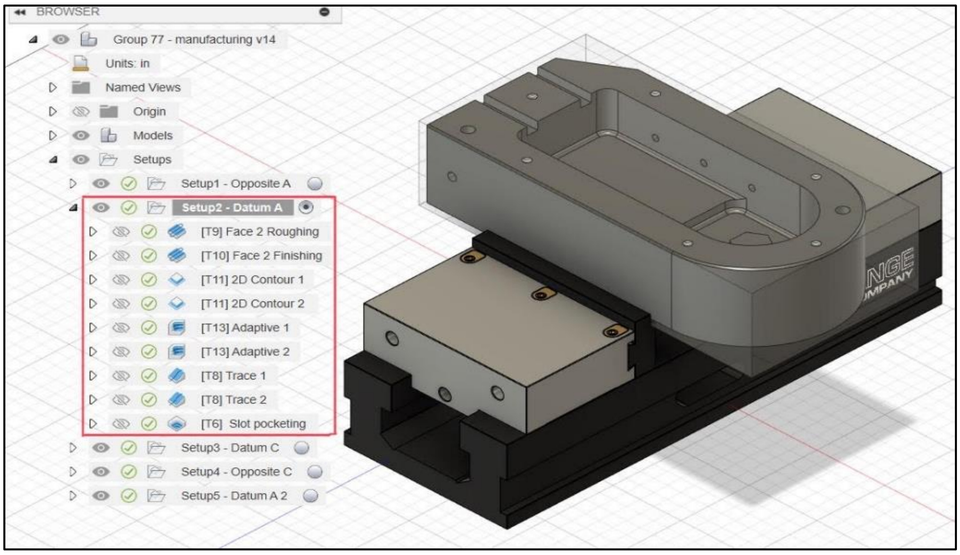
For every setup, we selected the product as the model and the z-axis as the one perpendicular to the face we wanted to machine. In the first setup, the stock model is the actual stock, while in the other setups we use the stock machined from the previous setup as the stock model.

**Setup 1**



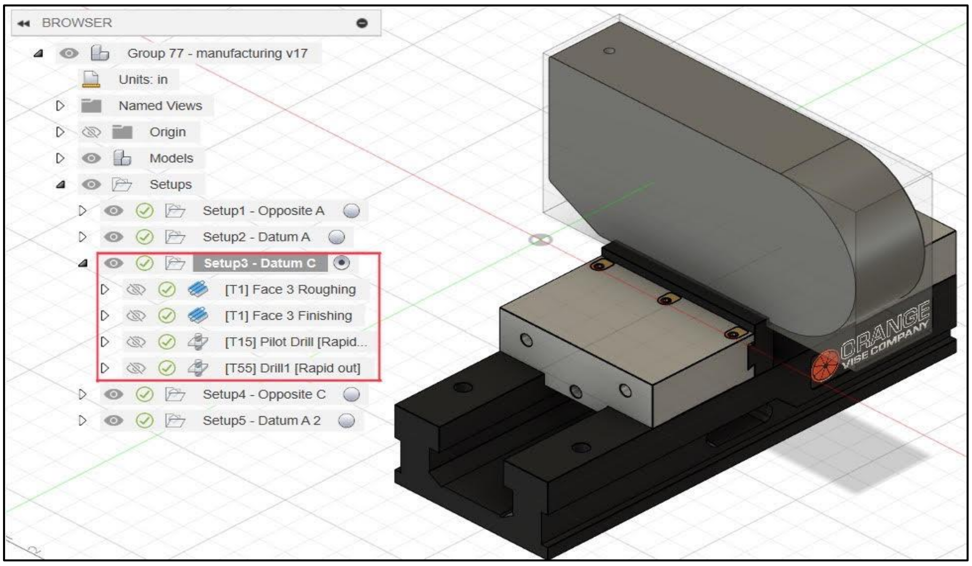

In the first setup, we fix the stock from the top surface, in order to machine the bottom surface. So that we can perform the face milling operation.

**Setup 2**



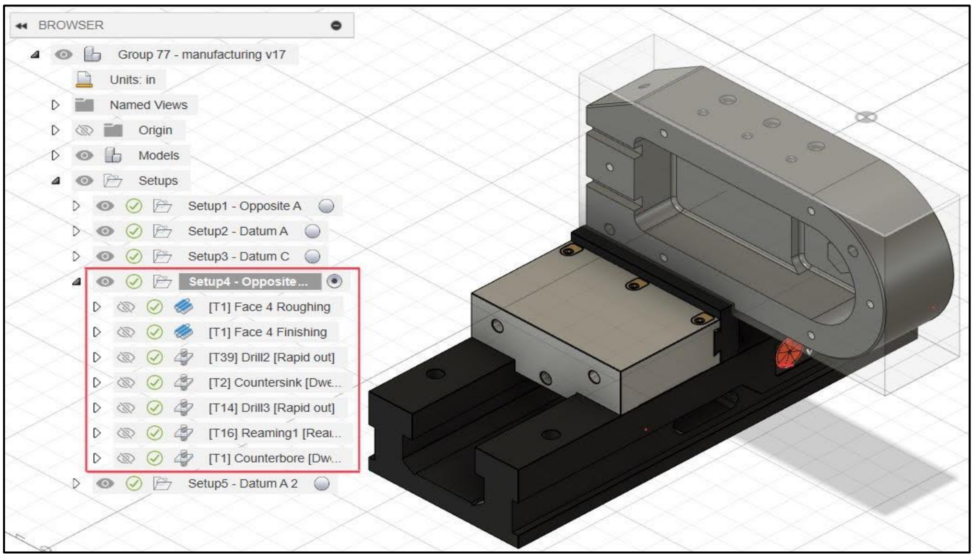

In the second setup, we fix the stock from the bottom surface, in order to machine the top surface. We perform face milling, contouring, pocketing and end milling operations. The top surface operations we avoid are drilling and chamfer milling: chamfer milling requires manufacturing on the side surfaces.

## Setup 3



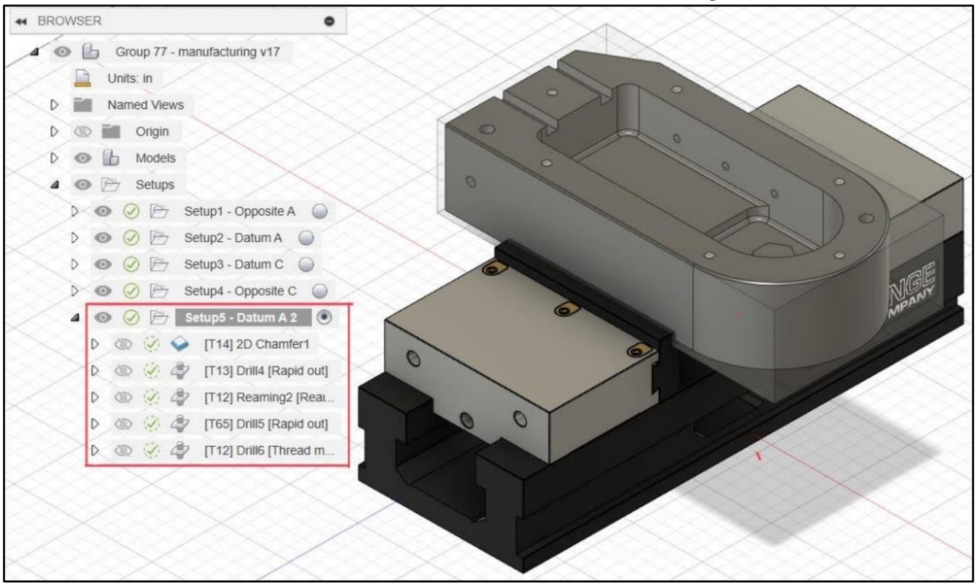

In the third setup, we fix the product sideways, in order to machine the right-side surface. We perform face milling and pilot/deep drilling in this setup.

## Setup 4




In the fourth setup, we fix the product sideways again, but this time we machine the left-side surface. We perform face milling, drilling, countersinking, reaming and counterboring operations.

## Setup 5




In the fifth setup, we fix the product from the bottom surface, in order to complete the manufacturing of the top surface. The setup is similar to the second one, but this time we are holding the product rather than the stock. We perform chamfer milling, drilling, and reaming operations.

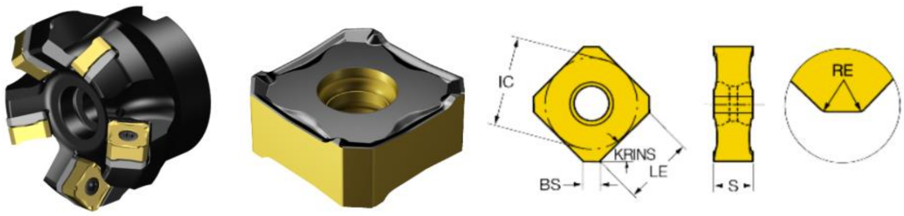
## 3.3 Manufacturing resources

In verifying operations, we considered the nominal power as $16\,kW$, with an efficiency of $100\%$. Therefore, the cutting power for each operation is required to be smaller than $16\,kW$. In addition, the maximum spindle rotational speed is equal to $14000\,rpm$, so we have to respect also this limit. The maximum roughness is different for every surface.

### SETUP 1 - OPPOSITE wrt DATUM A

- **Face Milling #1**

***SANDVIK 345-063Q22-13H, 345R-1305M-PH***




CoroMill® 345

| Ordering code | Feed per tooth, $f_z$ mm/tooth Starting value | (min.- max.) | Max chip thickness, $h_{ex}$ mm Starting value | (min.- max.) |
|---|---|---|---|---|
| 345L-1305M-PM | 0.3 | (0.16-0.4) | 0.21 | (0.11-0.28) |
| 345R-1305E-KL | 0.11 | (0.07-0.2) | 0.08 | (0.05-0.14) |
| 345R-1305E-KM | 0.3 | (0.16-0.4) | 0.21 | (0.11-0.28) |
| 345R-1305E-PL | 0.11 | (0.07-0.2) | 0.08 | (0.05-0.14) |
| 345R-1305M-KH | 0.35 | (0.3-0.49) | 0.25 | (0.21-0.35) |
| 345R-1305M-KL | 0.16 | (0.07-0.23) | 0.11 | (0.05-0.16) |
| 345R-1305M-KM | 0.3 | (0.16-0.4) | 0.21 | (0.11-0.28) |
| 345R-1305M-PH | 0.45 | (0.35-0.55) | 0.32 | (0.25-0.39) |
| 345R-1305M-PL | 0.17 | (0.07-0.21) | 0.12 | (0.05-0.15) |
| 345R-1305M-PM | 0.3 | (0.16-0.4) | 0.21 | (0.11-0.28) |
| 345R-13T5E-ML | 0.11 | (0.07-0.2) | 0.08 | (0.05-0.14) |
| 345R-13T5E-MM | 0.11 | (0.07-0.2) | 0.08 | (0.05-0.14) |
| 345R-13T5M-MM | 0.25 | (0.16-0.34) | 0.18 | (0.11-0.24) |

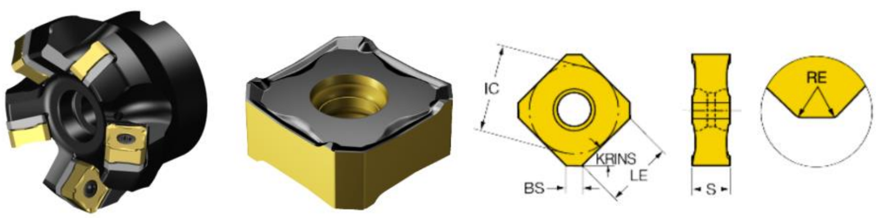
| ISO P | | | Specific cutting force $k_{c1}$ | Hardness Brinell | | CT530 | GC1010 | GC1025 | GC1130 | GC4220 | GC4330 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Max chip thickness, $h_{ex}$ mm | | | Max chip thickness, $h_{ex}$ mm | | |
| | | | | | | 0.1 – 0.15 – 0.2 | 0.05 – 0.1 – 0.2 | 0.05 – 0.1 – 0.2 | 0.05-0.1-0.2 | 0.1– 0.2–0.3 | 0.1– 0.2–0.3 |
| MC No. | CMC No. | Material | N/mm² | HB | mc | Cutting speed $v_c$, m/min | | | Cutting speed $v_c$, m/min | | |
| P1.1.Z.AN | 01.1 | Steel Unalloyed C = 0.1–0.25% | 1500 | 125 | 0.25 | 430–390–350 | - | 340-310-255 | 375–340–280 | 490–405–330 | 400–330–270 |

For the face milling operation, we deduct that $r = 0{,}8\,mm$ and $\gamma_0 = 11.17°$ by means of the technical illustrations. From the Sandvik *Rotating Tools* catalog we obtain the parameters we need: $f_z = 0{,}45\,mm/tooth$, $v_c = 270\,m/min$, $D = 63\,mm$, $k_r = k_r' = 45°$. We arbitrarily set $f_z = 0{,}40\,mm/tooth$, in order to have better performance in roughness and cutting power at the expense of the machining time. We determine $a_e \simeq 5\,mm + D/2 = 36.5\,mm$ from the software representation (see figure in section 4).

### SETUP 2 – DATUM A

- **Face Milling #2 Roughing**

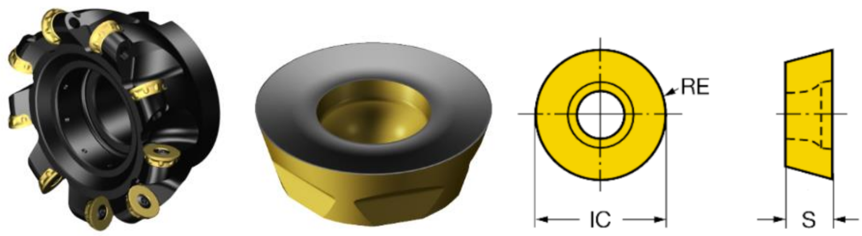
***SANDVIK 345-063Q22-13H, 345R-1305M-PH***




The insert is the same one used for the previous face milling operation, so we utilize the same parameters.

- **Face Milling #2 Finishing**

***SANDVIK R300-125Q40-20H, R300-2060M-PH 4330***




CoroMill® 300

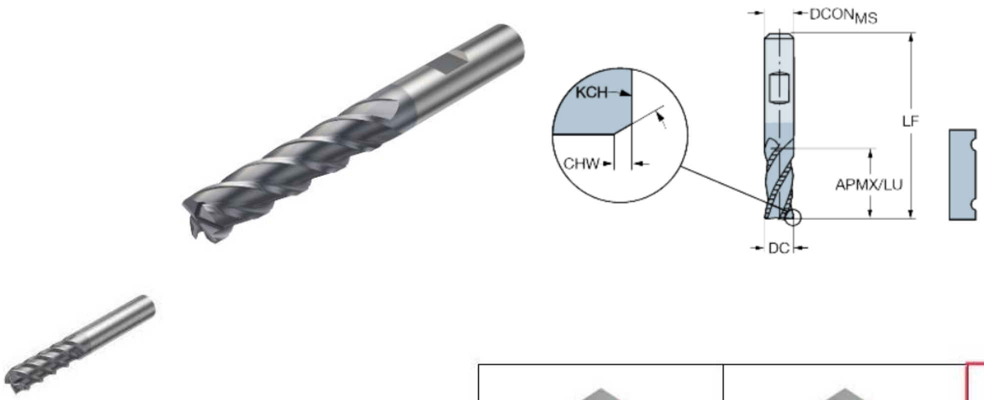
| Ordering code | Feed per tooth, $f_z$ mm/tooth Starting value | (min.- max.) | Max chip thickness, $h_{ex}$ mm Starting value | (min.- max.) |
|---|---|---|---|---|
| R300-2060M-MH | 0.49 | (0.07-0.78) | 0.35 | (0.05-0.55) |
| R300-2060M-MM | 0.28 | (0.07-0.42) | 0.2 | (0.05-0.3) |
| R300-2060M-PH | 0.49 | (0.07-0.78) | 0.35 | (0.05-0.55) |
| R300-2060M-PM | 0.28 | (0.07-0.42) | 0.2 | (0.05-0.3) |
| R300-2570E-ML | 0.31 | (0.06-0.4) | 0.22 | (0.04-0.28) |

| ISO P | | | Specific cutting force $k_{c1}$ | Hardness Brinell | | CT530 | GC1010 | GC1025 | GC1130 | GC4220 | GC4330 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Max chip thickness, $h_{ex}$ mm | | | Max chip thickness, $h_{ex}$ mm | | |
| | | | | | | 0.1 – 0.15 – 0.2 | 0.05 – 0.1 – 0.2 | 0.05 – 0.1 – 0.2 | 0.05–0.1–0.2 | 0.1–0.2–0.3 | 0.1–0.2–0.3 |
| MC No. | CMC No. | Material | N/mm² | HB | mc | Cutting speed $v_c$, m/min | | | Cutting speed $v_c$, m/min | | |
| P1.1.Z.AN | 01.1 | Steel Unalloyed C = 0.1–0.25% | 1500 | 125 | 0.25 | 430–390–350 | - | 340-310-255 | 375–340–280 | 490–405–330 | 400–330–270 |

For the face milling finishing operation, we deduct that $r = 10\ mm$ by means of the technical illustrations. From the Sandvik *Rotating Tools* catalog we obtain the parameters $f_z = 0.49\ mm/tooth$, $v_c = 270\ m/min$, $D = 125\ mm$, $Z = 8$, $a_p = 0.5\ mm$. We determine $a_e = 19\ mm + D/2 = 81.5\ mm$ from the software representation (see figure in section 4).

- **Contouring #1**

***SANDIVK 2P370-2000-PB 1740***



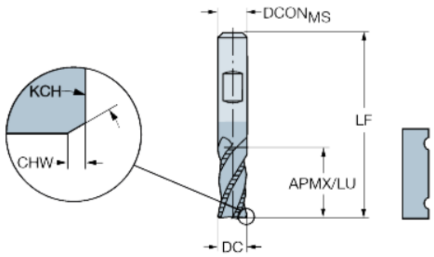

| ISO | MC No. | CMC | Material | HB | $a_e$ | $f_z$ | $v_c$ m/min | $v_c$ feet/min | $a_e$ | $f_z$ | $v_c$ m/min | $v_c$ feet/min | $a_e$ | $f_z$ | $v_c$ m/min | $v_c$ feet/min |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $a_e$ = according to material | | | | $a_e$ = according to material | | | | $a_e$ = according to material | | | |
| | | | | | $a_p$ = 2.0 x DC | | | | $a_p$ = 3.0 x DC | | | | $a_p$ = 4.0 x DC | | | |
| | P1.2.Z.AN | 01.2 | Unalloyed steel | 190 | 0.12 x DC | F01 | 250 | 820 | 0.10 x DC | F04 | 250 | 820 | 0.10 x DC | F07 | 230 | 755 |

| DC | 2.000 | 3.000 | 4.000 | 6.000 | 6.350 | 7.938 | 8.000 | 9.525 | 10.000 | 12.000 | 12.700 | 14.000 | 15.875 | 16.000 | 18.000 | 19.050 | 20.000 | 25.000 | 25.400 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_z$ | *0.079* | *0.118* | *0.157* | *0.236* | *0.250* | *0.313* | *0.315* | *0.375* | *0.394* | *0.472* | *0.500* | *0.551* | *0.625* | *0.630* | *0.709* | *0.750* | *0.787* | *0.984* | *1.000* |
| F07 | - | - | - | 0.070 | 0.070 | 0.080 | 0.080 | 0.080 | 0.080 | 0.090 | 0.090 | 0.100 | 0.100 | 0.100 | 0.150 | 0.150 | 0.160 | 0.190 | 0.190 |
| | - | - | - | *0.0028* | *0.0028* | *0.0031* | *0.0031* | *0.0031* | *0.0031* | *0.0035* | *0.0035* | *0.0039* | *0.0039* | *0.0039* | *0.0059* | *0.0059* | *0.0063* | *0.0075* | *0.0075* |

For the first contouring operation, we deduct that $R = 10\ mm, \gamma_0 = 7.5°$ by means of the technical illustrations. From the Sandvik *Solid Round Tools* catalog we obtain the parameters $Z = 4,\ D = 20\ mm, f_z = 0.16\ mm/tooth,\ v_c = 230\ m/min$,. We know from the software representation that the maximum $a_e \simeq 14\ mm$ (see figure in section 4). We divide the operation into multiple depths of $a_p = 7\ mm$, in order to make the operation feasible with respect to the cutting power constraint.

- **Contouring #2**

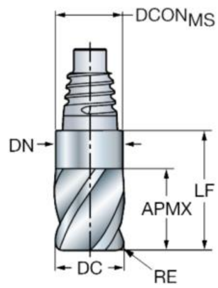
***SANDIVK 2P370-2000-PB 1740***




For the second contouring operation, the tool is the same. We know from the software representation that the maximum $a_e \simeq 15.75\ \ mm$ (see figure in section 4). We divide the operation into multiple depths of $a_p = 7\ mm$, in order to make the operation feasible with respect to the cutting power constraint.

- **Pocket Roughing: Adaptive 1 and Pocket Finishing: Adaptive 2**

***SANDVIK 316-16SL442-16030P 1730***



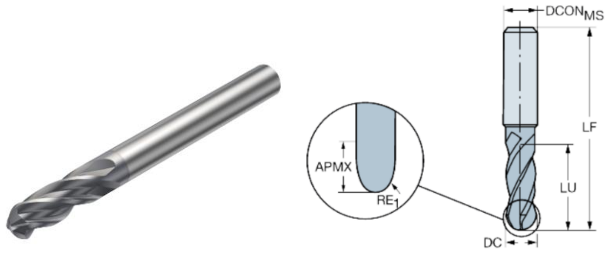

| | | | | |  | | |  | | |  | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $a_e = 1.0 \times DC$ | | | $a_e = 0.5 \times DC$ | | | $a_e = 0.1 \times DC$ | | |
| | | | | | $a_p = 0.5 \times DC$ | | | $a_p = 0.5 \times DC$ | | | $a_p = 1.0 \times DC$ | | |
| ISO | MC No. | CMC | Material | HB | $f_z$ | $v_c$ m/min | $v_c$ feet/min | $f_z$ | $v_c$ m/min | $v_c$ feet/min | $f_z$ | $v_c$ m/min | $v_c$ feet/min |
| | P1.2.Z.AN | 01.2 | Unalloyed steel | 190 | E01 | 150 | 476 | E02 | 180 | 640 | E03 | 250 | 951 |

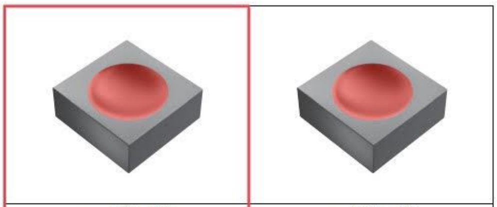
| DC | 9.525 | 10.000 | 12.000 | 12.700 | 15.875 | 16.000 | 19.050 | 20.000 | 25.000 | 25.400 |
|---|---|---|---|---|---|---|---|---|---|---|
| $f_z$ | *0.375* | *0.394* | *0.472* | *0.500* | *0.625* | *0.630* | *0.750* | *0.787* | *0.984* | *1.000* |
| E01 | 0.048 | 0.050 | 0.057 | 0.059 | 0.070 | 0.070 | 0.080 | 0.083 | 0.100 | 0.100 |
| | *0.0019* | *0.0020* | *0.0022* | *0.0023* | *0.0027* | *0.0028* | *0.0032* | *0.0033* | *0.0039* | *0.0039* |

For these operations, we deduct that $r = 3\ mm, \gamma_0 = 10.5°$ by means of the technical illustrations. From the Sandvik *Solid Round Tools* catalog we obtain the parameters $f_z = 0.07\ mm/tooth,\ v_c = 150\ m/min,\ Z = 4,\ D = 16\ mm$. Also, $a_e = 16\ mm,\ k_r = 90°,\ a_p = 8\ mm$.

- **Pocket Finishing: Traces #1 and #2**

***SANDVIK 1B240-0600-XA 1630***



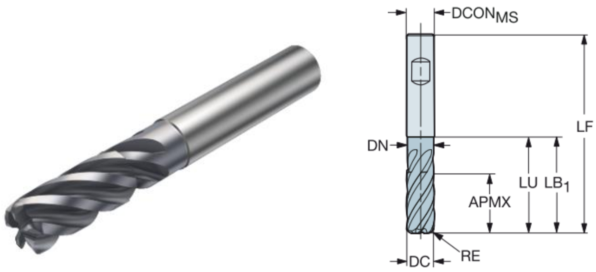
| ISO | MC No. | CMC | Material | HB | $a_p$ = 0.05 x DC | | | $a_p$ = 0.01 x DC | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $f_z$ | $v_c$ m/min | $v_c$ feet/min | $f_z$ | $v_c$ m/min | $v_c$ feet/min |
| | P1.2.Z.AN | 01.2 | Unalloyed steel | 190 | B01 | 245 | 804 | B03 | 295 | 968 |

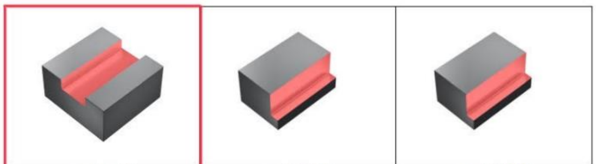
| DC | 1.000 | 2.000 | 3.000 | 4.000 | 6.000 | 6.350 | 7.938 | 8.000 | 9.525 | 10.000 | 12.000 | 12.700 | 14.000 | 15.875 | 16.000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_z$ | *0.039* | *0.079* | *0.118* | *0.157* | *0.236* | *0.250* | *0.313* | *0.315* | *0.375* | *0.394* | *0.472* | *0.500* | *0.551* | *0.625* | *0.630* |
| B01 | 0.020 | 0.030 | 0.050 | 0.060 | 0.080 | 0.080 | 0.120 | 0.120 | 0.150 | 0.150 | 0.150 | 0.150 | 0.150 | 0.160 | 0.160 |
| | *0.0008* | *0.0012* | *0.0020* | *0.0024* | *0.0031* | *0.0031* | *0.0047* | *0.0047* | *0.0059* | *0.0059* | *0.0059* | *0.0059* | *0.0059* | *0.0063* | *0.0063* |

For these operations, we deduct that $r = 3\,mm,\ \gamma_0 = 1.5°$ by means of the technical illustrations. From the Sandvik *Solid Round Tools* catalog we obtain the parameters $f_z = 0.08\,mm/tooth$, $v_c = 245\,m/min$, $Z = 4$, $D = 6\,mm$. Also, $a_p = 0.3\,mm$.

- **Slot Pocketing**

***SANDVIK 2F342-0800-050-PC 1730***



| ISO | MC No. | CMC | Material | HB | $a_e$ = 1.0 x DC, $a_p$ = 1.0 x DC | | | $a_e$ = 0.5 x DC, $a_p$ = 1.0 x DC | | | $a_e$ = 0.25 x DC, $a_p$ = 1.0 x DC | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $f_z$ | $v_c$ m/min | $v_c$ feet/min | $f_z$ | $v_c$ m/min | $v_c$ feet/min | $f_z$ | $v_c$ m/min | $v_c$ feet/min |
| | P1.2.Z.AN | 01.2 | Unalloyed steel | 190 | D01 | 150 | 492 | D02 | 180 | 590 | D03 | 250 | 820 |

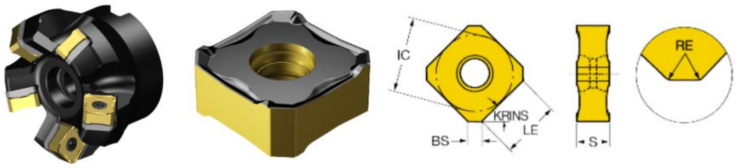
| DC | 2.000 | 3.000 | 4.000 | 6.000 | 6.350 | 7.938 | 8.000 | 9.525 | 10.000 | 12.000 | 12.700 | 14.000 | 15.875 | 16.000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_z$ | *0.079* | *0.118* | *0.157* | *0.236* | *0.250* | *0.313* | *0.315* | *0.375* | *0.394* | *0.472* | *0.500* | *0.551* | *0.625* | *0.630* |
| D01 | 0.020 | 0.024 | 0.028 | 0.035 | 0.036 | 0.042 | 0.043 | 0.048 | 0.050 | 0.057 | 0.059 | 0.063 | 0.070 | 0.070 |
| | *0.0008* | *0.0009* | *0.0011* | *0.0014* | *0.0014* | *0.0017* | *0.0017* | *0.0019* | *0.0020* | *0.0022* | *0.0023* | *0.0025* | *0.0027* | *0.0028* |

For pocketing, we deduct that $r = 0.5\,mm,\ \gamma_0 = 10.5°$ by means of the technical illustrations. From the Sandvik *Solid Round Tools* catalog, we obtain the parameters $f_z = 0.05\,mm/tooth$, $v_c = 150\,m/min$, $Z = 5$, $D = 8\,mm$. Also, $a_e = 8\,mm$, $k_r = 90°$, $a_p = 8\,mm$.

## SETUP 3 – DATUM C

- **Face Milling #3 Roughing**

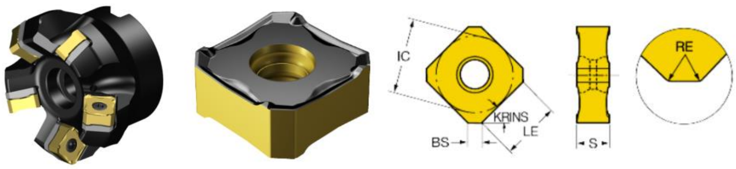
***SANDVIK 345-050Q22-13H, 345R-1305M-PH***




The insert is the same one used for the previous face milling operation, so we utilize the same parameters. We arbitrarily set $f_z = 0{,}40\ mm/tooth$, in order to have better performance in roughness and cutting power at the expense of the machining time. We know that $a_e \simeq 12.5\ mm + D/2 = 37.5\ mm$ from the software representation (see figure in section 4).

- **Face Milling #3 Finishing**

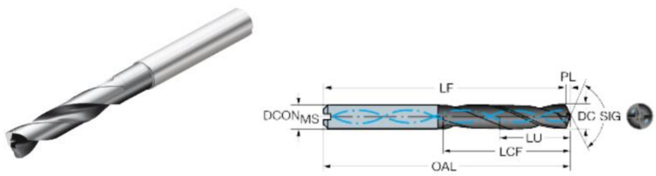
***SANDVIK 345-050Q22-13H, 345R-1305M-PH***




For the finishing operation, we use the same tool, changing $a_p = 0.5\ mm$.

- **Pilot Drilling #1**

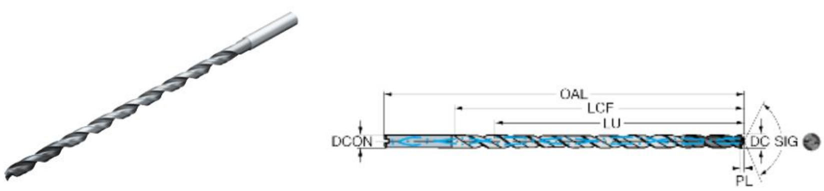
***SANDVIK 861.1-0600-018A1-GP GC34***




Unfortunately, the Sandvik *Solid Round Tools* catalog doesn't include any cutting data related to pilot drilling cutting tools (CoroDrill 861-GP). Therefore, we utilize the same data provided for the following deep drilling: $v_c = 118\ m/min$, $f = 0{,}2\ mm/rev$, $D = 6\ mm$.

- **Deep Drilling #1**

***SANDVIK 861.1-0800-160A1-GM GC34***



| CoroDrill® 861 -GM<br>12 - 15 x DC<br>Metric values | | | | | |
|---|---|---|---|---|---|
| | | | Hardness Brinell | Cutting speed ($V_c$) m/min | |
| ISO | MC No. | Material | HB | Min. | Max. |
| P | P1.1.Z.AN | Unalloyed steel<br>C=0.10-0.25% | 125 | 80 | 156 |

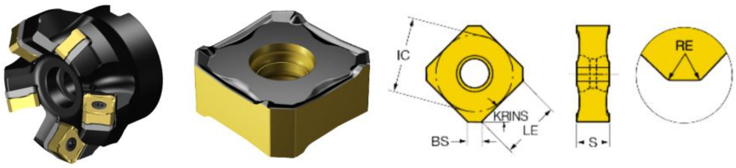
| Drill diameter, mm<br>$f_n$ mm/rev. | | | | | |
|---|---|---|---|---|---|
| 6.00-7.99 | | 8.00-9.99 | | 10.00-11.99 | |
| Min. | Max. | Min. | Max. | Min. | Max. |
| 0.15 | 0.20 | 0.20 | 0.26 | 0.25 | 0.33 |
| 0.15 | 0.20 | 0.20 | 0.26 | 0.25 | 0.33 |

From the Sandvik *Solid Round Tools* catalog, we obtain the parameters for this operation: $v_c = 118\ m/min$, $f = 0{,}2\ mm/rev$, $D = 8\ mm$.

## SETUP 4 – OPPOSITE wrt DATUM C

- **Face Milling #4: Roughing and Finishing**

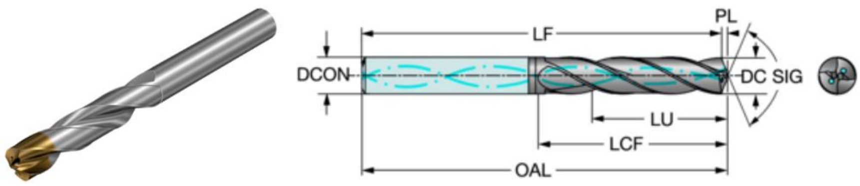
***SANDVIK 345-050Q22-13H, 345R-1305M-PH***




For this face milling operation, we use the same tool as "Face Milling #3", with the same parameters for both the roughing and the finishing operation.

- **Drilling #2**

***SANDVIK 860.1-0600-049A1-GM X1BM***



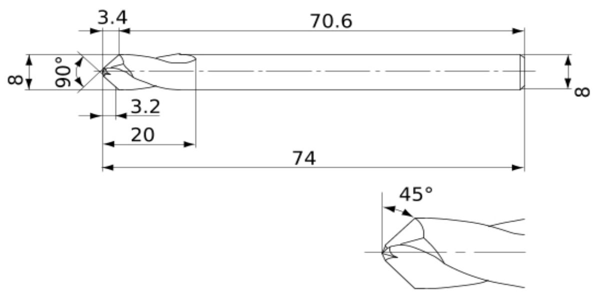

| CoroDrill® 860-GM<br>Metric values | | | | |
|---|---|---|---|---|
| | | | Hardness Brinell | Cutting speed, vc (m/min) |
| ISO | Mc No. | Material | HB | |
| P | P1.1.Z.AN | Unalloyed steel<br>C = 0.05-0.10% | 125 | (min-start-max)<br>120-145-170 |

| Drill diameter, mm | | |
|---|---|---|
| 6 | 8 | 10 |
| Feed ($f_n$) mm/r<br>(min-start-max) | | |
| 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 |
| 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 |

From the Sandvik *Solid Round Tools* catalog, we obtain the parameters $v_c = 145\ m/min$, $f = 0{,}2\ mm/rev$, $D = 6\ mm$.

- **Countersinking**

***MITSUBISHI DLE0800S080P090***




**DLE**
LEADING DRILL SERIES

**Point Angle SIG 90°, 120° and 145°**

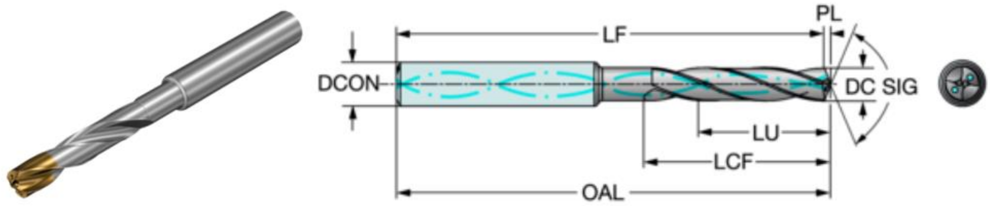
**RECOMMENDED CUTTING CONDITIO**

| Workpiece Material | | Mild Steels (≤180HB)<br>AISI 1010 etc. | |
|---|---|---|---|
| DC | | Cutting Speed (SFM) | Feed (Min.—Max.) (IPR) |
| (mm) | (inch) | | |
| 1.0 | .0394 | 100 | .0008 (.0004—.0012) |
| 1.5 | .0591 | 150 | .0008 (.0004—.0012) |
| 2.0 | .0787 | 195 | .0016 (.0012—.0020) |
| 2.5 | .0984 | 245 | .0016 (.0012—.0020) |
| 3.0 | .1181 | 245 | .0024 (.0016—.0031) |
| 4.0 | .1575 | 245 | .0024 (.0016—.0031) |
| 5.0 | .1969 | 260 | .0028 (.0020—.0035) |
| 6.0 | .2362 | 260 | .0028 (.0020—.0035) |
| 7.0 | .2756 | 260 | .0031 (.0020—.0039) |
| 8.0 | .3150 | 260 | .0031 (.0020—.0039) |
| 10.0 | .3937 | 280 | .0035 (.0020—.0043) |
| 12.0 | .4724 | 280 | .0035 (.0020—.0043) |
| 16.0 | .6299 | 295 | .0047 (.0039—.0055) |

From the Mitsubishi catalog, we get the parameters $v_c = 260\ m/min$, $f = 0.0031\ mm/rev$, $D = 8\ mm$.

- **Drilling #3**

***SANDVIK 860.1-0780-024A1-GM X1BM***




CoroDrill® 860-GM

Metric values

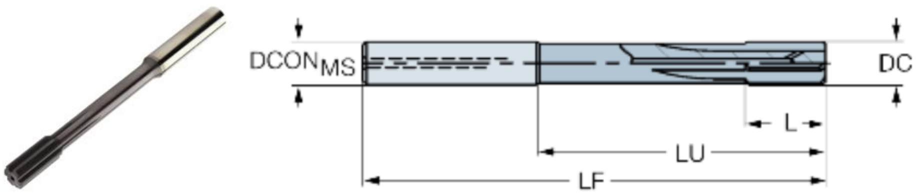
| ISO | Mc No. | Material | Hardness Brinell HB | Cutting speed, vc (m/min) |
|---|---|---|---|---|
| P | | Unalloyed steel | | (min-start-max) |
| | P1.1.Z.AN | C = 0.05-0.10% | 125 | 120-145-170 |
| | P1.1.Z.AN | C = 0.1-0.25% | 125 | 120-145-170 |

| Drill diameter, mm | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 | 4 | 6 | 8 | 10 | 12 | 16 | 20 |
| Feed ($f_n$) mm/r (min-start-max) | | | | | | | |
| 0.06-0.10-0.14 | 0.10-0.16-0.22 | 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 | 0.20-0.26-0.34 | 0.24-0.30-0.38 | 0.26-0.34-0.40 |
| 0.06-0.10-0.14 | 0.10-0.16-0.22 | 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 | 0.20-0.26-0.34 | 0.24-0.30-0.38 | 0.26-0.34-0.40 |
| 0.06-0.10-0.14 | 0.10-0.16-0.22 | 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 | 0.20-0.26-0.34 | 0.24-0.30-0.38 | 0.26-0.34-0.40 |
| 0.06-0.10-0.14 | 0.10-0.16-0.22 | 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 | 0.20-0.26-0.34 | 0.24-0.30-0.38 | 0.26-0.34-0.40 |

From the Sandvik *Solid Round Tools* catalog, we get the parameters $v_c = 145\ m/min$, $f = 0.22\ mm/rev$, $D = 7.8\ mm$.

- **Reaming #1**

***SANDVIK 835.B-0800-A1-PF 1024***




## Cutting data for CoroReamer™ 835

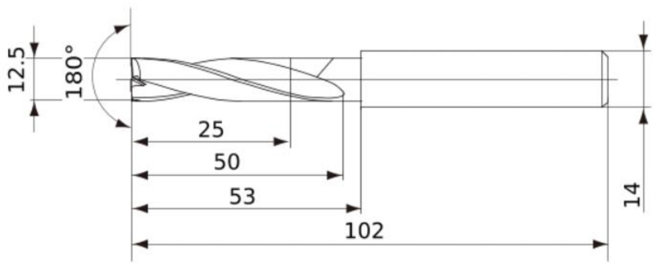
Metric values

| CoroReamer™ 835 - PF | | | | | Ø mm | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ISO | MC No. | Material | N/mm² | Application data | < 5.00 | 5.00 - 6.20 | 6.20 - 8.00 | 8.00 - 12.00 | 12.00 - 16.00 | 16.00 - 20.00 |
| P | | Unalloyed steel | | | | | | | | |
| | | | | $v_c$ m/min | | | 180 | | | |
| | P1.1.Z.AN | C=0.10-0.25% | 428 | $f_n$ mm/rev | 0.20 | 0.30 | 0.50 | 0.80 | 1.10 | 1.50 |

From the Sandvik *Solid Round Tools* catalog, we get the parameters $v_c = 180\ m/min$, $f = 0.5\ mm/rev$, $D = 8\ mm$, $Z = 6$.

- **Counterboring**

***MITSUBISHI MFE1250X02S140***



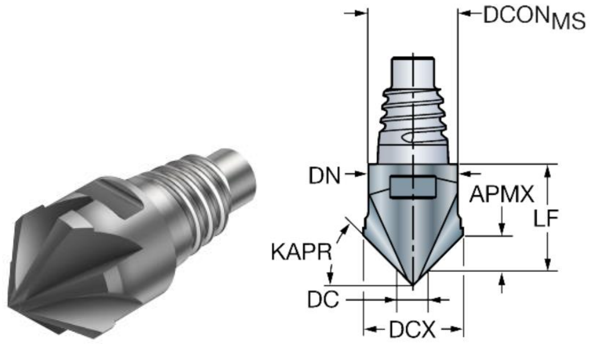

| Workpiece Material | | Mild Steel (≤180HB) AISI 1010 etc. | |
|---|---|---|---|
| DC | | Cutting Speed vc (SFM) | Feed fr (Min.—Max.) (IPR) |
| inch | mm | | |
| .0295 | 0.75 | 180 | .0012 (.0004—.0020) |
| .0394 | 1.0 | 180 | .0012 (.0004—.0020) |
| .0591 | 1.5 | 190 | .0014 (.0006—.0022) |
| .0787 | 2.0 | 195 | .0016 (.0008—.0024) |
| .0984 | 2.5 | 205 | .0020 (.0012—.0028) |
| .1181 | 3.0 | 245 | .0024 (.0016—.0031) |
| .1575 | 4.0 | 245 | .0031 (.0024—.0039) |
| .1969 | 5.0 | 245 | .0039 (.0031—.0051) |
| .2362 | 6.0 | 245 | .0051 (.0039—.0059) |
| .3150 | 8.0 | 245 | .0059 (.0051—.0067) |
| .3937 | 10.0 | 245 | .0067 (.0059—.0079) |
| .4724 | 12.0 | 245 | .0079 (.0067—.0098) |
| .6299 | 16.0 | 245 | .0098 (.0079—.0118) |
| .7874 | 20.0 | 245 | .0118 (.0098—.0138) |

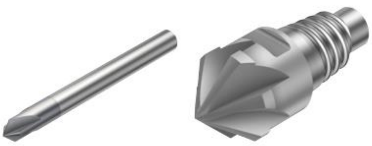
From the Mitsubishi catalog, we get the parameters $v_c = 245\, m/min$, $f = 0.0079\, mm/rev$, $D = 12.5\, mm$, $Z = 2$ (determining $f$ and $v_c$ considering $DC = 12$).

## SETUP 5 – DATUM A-2

- **Chamfer Milling**

***SANDVIK 316-10CM400-10045G 1730***



| | |
|---|---|
| $a_e$ = 0.1 x DC | |
| $a_p$ = 0.1 x DC | |

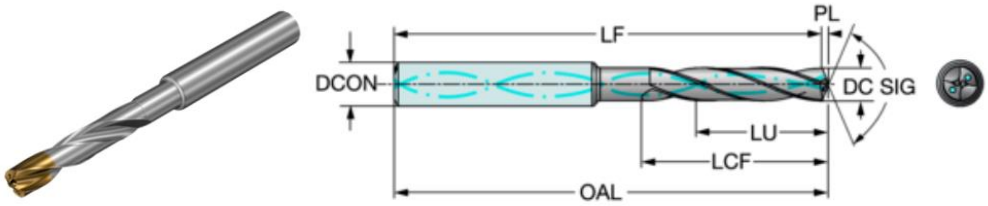
| ISO | MC No. | CMC | Material | HB | $f_z$ | $v_c$ m/min | $v_c$ feet/min |
|---|---|---|---|---|---|---|---|
| | P1.2.Z.AN | 01.2 | Unalloyed steel | 190 | C01 | 320 | 1050 |

| DC | 1 | 2 | 3 | 4 | 6 | 6.35 | 8 | 9.525 | 10 | 12 | 12.7 | 14 | 15.875 | 16 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_z$ | *0.039* | *0.079* | *0.118* | *0.157* | *0.236* | *0.250* | *0.315* | *0.375* | *0.394* | *0.472* | *0.500* | *0.551* | *0.625* | *0.630* | *0.787* |
| C01 | 0.020<br>*0.0008* | 0.030<br>*0.0012* | 0.040<br>*0.0016* | 0.050<br>*0.0020* | 0.070<br>*0.0028* | 0.070<br>*0.0028* | 0.100<br>*0.0039* | 0.120<br>*0.0047* | 0.120<br>*0.0047* | 0.120<br>*0.0047* | 0.120<br>*0.0047* | 0.120<br>*0.0047* | 0.120<br>*0.0047* | 0.120<br>*0.0047* | 0.200<br>*0.0079* |

For the first chamfers, we deduct that $R = 0{,}75\, mm$ by means of the technical illustrations. From the Sandvik *Solid Round Tools* catalog, we obtain the parameters $f_z = 0.025\, mm/tooth$, $v_c = 320\, m/min$, $Z = 4$, $DCX = 10\, mm$. Also, $a_p = 0.15\, mm$, $a_e = 0.15\, mm$.

- **Drilling #4**

***SANDVIK 860.1-0980-030°1-GM X1BM***




**CoroDrill® 860-GM**

**Metric values**

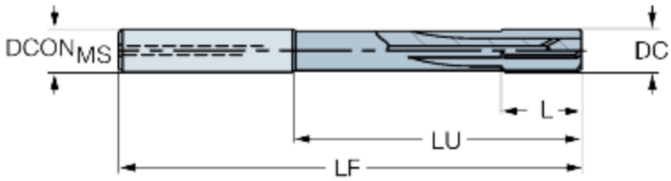
| ISO | Mc No. | Material | Hardness Brinell HB | Cutting speed, vc (m/min) |
|---|---|---|---|---|
| P | | **Unalloyed steel** | | (min-start-max) |
| | P1.1.Z.AN | C = 0.05-0.10% | 125 | 120-145-170 |
| | P1.1.Z.AN | C = 0.1-0.25% | 125 | 120-145-170 |

| Drill diameter, mm | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 | 4 | 6 | 8 | 10 | 12 | 16 | 20 |
| Feed ($f_n$) mm/r (min-start-max) | | | | | | | |
| 0.06-0.10-0.14 | 0.10-0.16-0.22 | 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 | 0.20-0.26-0.34 | 0.24-0.30-0.38 | 0.26-0.34-0.40 |
| 0.06-0.10-0.14 | 0.10-0.16-0.22 | 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 | 0.20-0.26-0.34 | 0.24-0.30-0.38 | 0.26-0.34-0.40 |
| 0.06-0.10-0.14 | 0.10-0.16-0.22 | 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 | 0.20-0.26-0.34 | 0.24-0.30-0.38 | 0.26-0.34-0.40 |
| 0.06-0.10-0.14 | 0.10-0.16-0.22 | 0.15-0.20-0.25 | 0.16-0.22-0.28 | 0.20-0.25-0.30 | 0.20-0.26-0.34 | 0.24-0.30-0.38 | 0.26-0.34-0.40 |

From the Sandvik *Solid Round Tools* catalog, we get the parameters $v_c = 145\ m/min$, $f = 0.25\ mm/rev$, $D = 9.8\ mm$.

- **Reaming #2**

***SANDVIK 835.B-1000-A1-PF 1024***




## Cutting data for CoroReamer™ 835

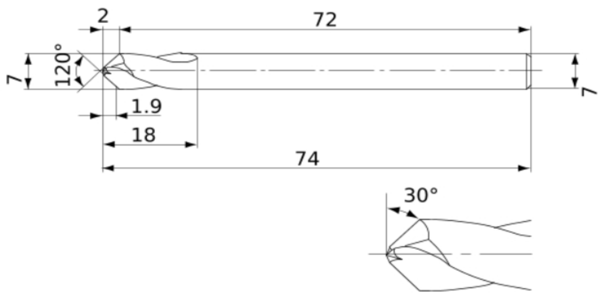
**Metric values**

| CoroReamer™ 835 - PF | | | | | Ø mm | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ISO | MC No. | Material | N/mm² | Application data | < 5.00 | 5.00 - 6.20 | 6.20 - 8.00 | 8.00 - 12.00 | 12.00 - 16.00 | 16.00 - 20.00 |
| P | | Unalloyed steel | | | | | | | | |
| | | | | $v_c$ m/min | | | 180 | | | |
| | P1.1.Z.AN | C=0.10-0.25% | 428 | $f_n$ mm/rev | 0.20 | 0.30 | 0.50 | 0.80 | 1.10 | 1.50 |

From the Sandvik *Solid Round Tools* catalog, we get the parameters $v_c = 180\ m/min$, $f = 0.8\ mm/rev$, $D = 10\ mm$, $Z = 6$.

- **Drilling #5**

***MITSUBISHI DLE0700S070P120***




**DLE**
LEADING DRILL SERIES

**Point Angle SIG 90°, 120° and 145°**

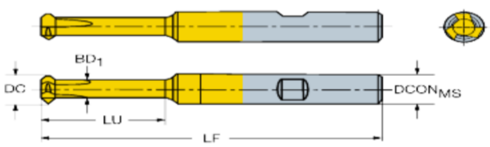
**RECOMMENDED CUTTING CONDITIO**

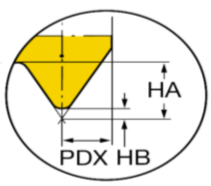
| Workpiece Material | | Mild Steels (≤180HB) AISI 1010 etc. | |
|---|---|---|---|
| DC | | Cutting Speed (SFM) | Feed (Min.—Max.) (IPR) |
| (mm) | (inch) | | |
| **1.0** | **.0394** | 100 | .0008 (.0004—.0012) |
| **1.5** | **.0591** | 150 | .0008 (.0004—.0012) |
| **2.0** | **.0787** | 195 | .0016 (.0012—.0020) |
| **2.5** | **.0984** | 245 | .0016 (.0012—.0020) |
| **3.0** | **.1181** | 245 | .0024 (.0016—.0031) |
| **4.0** | **.1575** | 245 | .0024 (.0016—.0031) |
| **5.0** | **.1969** | 260 | .0028 (.0020—.0035) |
| **6.0** | **.2362** | 260 | .0028 (.0020—.0035) |
| **7.0** | **.2756** | 260 | .0031 (.0020—.0039) |
| **8.0** | **.3150** | 260 | .0031 (.0020—.0039) |
| **10.0** | **.3937** | 280 | .0035 (.0020—.0043) |
| **12.0** | **.4724** | 280 | .0035 (.0020—.0043) |
| **16.0** | **.6299** | 295 | .0047 (.0039—.0055) |

From the Mitsubishi catalog, we get the parameters $v_c = 260\ m/min$, $f = 0.0031\ mm/rev$, $D = 7\ mm$.

- **Drilling #6 (Threading)**

***SANDVIK 326R06-B15050VM-TH 1025***



## CoroMill® Plura thread milling cutting data

Speed and feed recommendations

| ISO | Material MC | Hardness HB | Hardness HRC | Thread mill Thread | Dimensions, mm, inch DC | DC" | ZEFP | $l_{Th} = 0.5 \times a_p$ Cutting speed $v_c$ m/min | ft/min | Feed per tooth, $f_z$ mm | inch | $l_{Th} = a_p$ Cutting speed $v_c$ m/min | ft/min | Feed per tooth, $f_z$ mm | inch |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P | **Unalloyed steel** P1.1.Z.AN | 125 | | M2 | 1.55 | .061 | 3 | 127 | 417 | 0.027 | .0011 | 120 | 396 | 0.020 | .0008 |
| | | | | M4 | 3.2 | .126 | 3 | 152 | 500 | 0.030 | .0012 | 141 | 465 | 0.018 | .0007 |
| | | | | M10 | 8.2 | .323 | 4 | 132 | 435 | 0.052 | .0020 | 124 | 410 | 0.029 | .0012 |
| | | | | M20 | 16 | .630 | 5 | 141 | 465 | 0.130 | .0051 | 131 | 430 | 0.069 | .0028 |

From the Sandvik *Solid Round Tools* catalog, we obtain thread M8 – $DC = 5.8\, mm$ through an interpolation, $v_c = 130\, m/min$, $Z = 3$, $\gamma_0 = 1.5°$. We set $f_z = 0.025\, mm/tooth$ since it's a threading operation. Also, $a_p = 0.91\, mm$, $a_e = 0.91\, mm$.

# 4. Verification of operations

## SETUP 1 – OPPOSITE wrt DATUM A

- **Face Milling #1**

The parameters for this operation are:

$$v_c = 270 \frac{m}{min}, f_z = 0{,}40 \frac{mm}{tooth}, r = 0{,}8\, mm, \gamma_0 = 11.17°, D = 63\, mm, Z = 8, a_p = 3\, mm, a_e = 36.5\, mm, k_r = k_r' = 45°.$$

Fusion360 automatically gives us a spindle speed of $1364\, rpm$, which is less than $14000\, rpm$ (the maximum spindle speed allowed). The surface roughness

$$R_a = \frac{1}{4} \frac{f_z}{(tan^{-1}k_r + tan^{-1}k'_r)} 10^3 = 0.564\ \mu m$$

is far less than $12{,}5\ \mu m$ (the maximum roughness allowed).

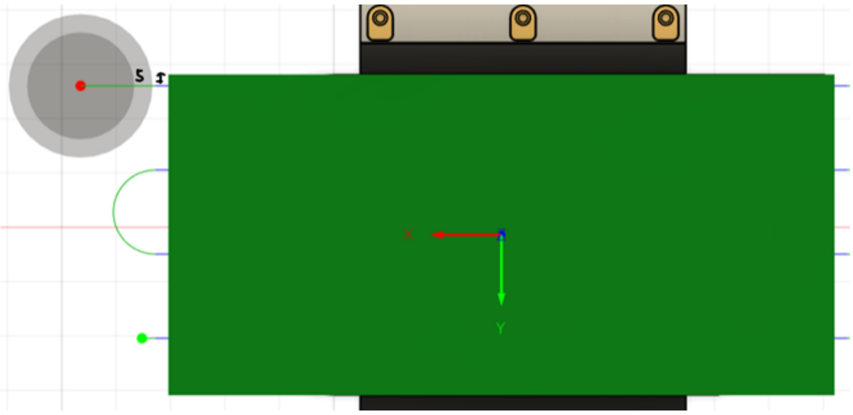


*Fig: Draw of the Setup 1 – face milling #1 on software*

In order to determine the cutting power, it is necessary to understand what the actual situation in this face milling operation is. First, we need to compute the engagement angle and then the number of simultaneously working teeth. Referring to the figure, the overall engagement angle is the sum of the following two angles:

$$\varphi_1 = 90° \text{ (given by the software)}$$

$$\varphi_2 = \arcsin\left(\frac{5}{D/2}\right) = 9.13°$$

$$\varphi = \varphi_1 + \varphi_2 = 99.13° = 1.73\, rad$$

$$\varphi_0 = \frac{2\pi}{Z} = 45°$$

$$z = \frac{\varphi}{\varphi_0} = 2{,}2 > 2$$

Therefore, we have to use the average approach:

$$h_{D,AV} = f_z\, a_e\, \frac{2}{\varphi\, D} = 0.268\ mm$$

$$k_{C,AV} = k_{c1}\, h_D^{-mc}\left(1 - \frac{\gamma_0}{100}\right) = 1851.9\ N/mm^2$$

$$A_{D,AV} = h_{D,AV}\, a_p = 0.804\ mm^2$$

$$F_{C,AV} = k_{c,AV}\, A_{D,AV} = 1488.93\ N$$

$$T_C = z\, F_{C,AV}\, \frac{D/2}{1000} = 103.2\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 142.86\ rad/s$$

$$P_C = T_C\, \omega = 14.740\ kW$$

The cutting power is less than 16 kW, the operation is feasible.

- **Face Milling #2 Roughing**

The parameters for this operation are:

$$v_c = 270\ m/min, f_z = 0{,}40\ mm/tooth, r = 0{,}8\ mm, \gamma_0 = 11.17°, D = 63\ mm, Z = 8, a_p = 2.5\ mm, a_e = 36.5\ mm.$$

The spindle speed is equal to $1364\ rpm$ (smaller than $14000\ rpm$). We don't need to compute the surface roughness, since this is a roughing operation. This operation has the same parameters as the "Face Milling #1" but an $a_p$ equal to $2.5\ mm$, so it will surely respect the limit on the cutting power. In fact

$$P_C = 12.283\ kW.$$

The cutting power is less than $16\ kW$, the operation is feasible.

- **Face Milling #2 Finishing**

The parameters for this operation are:

$$v_c = 270\ m/min, f_z = 0.49\ mm/tooth, r = 10\ mm, D = 125\ mm, Z = 8, a_p = 0.5\ mm, a_e = 81.5\ mm.$$

The spindle speed is $668\ rpm$ (again smaller than $14000\ rpm$). We must verify the surface roughness

$$R_a = \frac{1000}{32r}\, f_z^2 = 0.75\ \mu m$$

that is far less than $1{,}6\ \mu m$ (the maximum roughness for this surface).

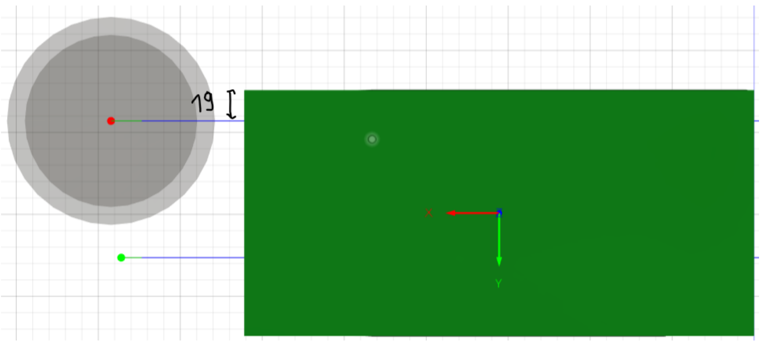



*Fig: Draw of the Setup 2 – finish milling #2 on software*

In order to determine the cutting power, we compute the engagement angle and then the number of simultaneously working teeth. Referring to the figure, the overall engagement angle is the sum of the following two angles:

$$\varphi_1 = 90° \ \text{(given by the software)}$$

$$\varphi_2 = \arcsin\left(\frac{19}{D/2}\right) = 17.7°$$

$$\varphi = \varphi_1 + \varphi_2 = 107.7° = 1.88\ rad$$

$$\varphi_0 = \frac{2\pi}{Z} = 45°$$

$$z = \frac{\varphi}{\varphi_0} = 2{,}39 > 2$$

Therefore, we must use the average approach:

$$h_{D,AV} = f_z\, a_e\, \frac{2}{\varphi\, D} = 0.34\ \text{mm}$$

For computing $k_{C,AV}$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_{C,AV} = k_{c1}\, h_D^{-mc}\left(1 - \frac{\gamma_0}{100}\right) = 1964.36\ \text{N/mm2}$$

$$A_{D,AV} = h_{D,AV}\, a_p = 0.17\ \text{mm}^2$$

$$F_{C,AV} = k_{c,AV}\, A_{D,AV} = 333.94\ \text{N}$$

$$T_C = z\, F_{C,AV}\, \frac{D/2}{1000} = 49.88\ \text{Nm}$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 72\ \text{rad/s}$$

$$P_C = T_C\, \omega = 3.591\ \text{kW}$$

The cutting power is less than $16\ kW$, the operation is feasible.

- **Contouring #1**

The parameters for this operation are:

$$v_c = 230\ m/min, f_z = 0.16\ mm/tooth, R = 10\ mm, \gamma_0 = 7.5°, D = 20\ mm, Z = 4, a_p = 7\ mm, a_e = 14\ mm.$$

The spindle speed is $3661\ rpm$ (again smaller than $14000\ rpm$). We must verify the surface roughness using the slab milling formula. We verify the surface roughness

$$R_a = \frac{1}{4}\frac{R}{2}\frac{\pi^2 {f_z}^2}{(2\pi R + 60 Z f_z)^2} 10^3 = 0.031\ \mu m$$

that is far less than $12.5\ \mu m$ (the maximum roughness for this surface).

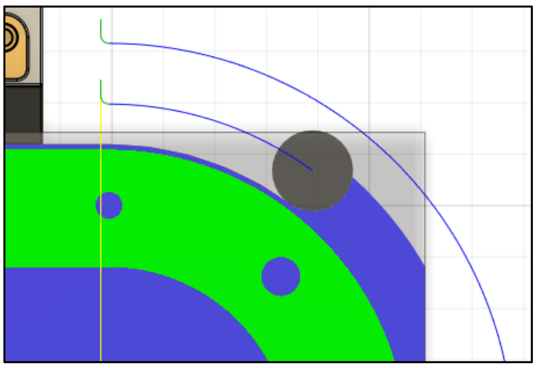


*Fig: Draw of the Setup 2 – Contour #1 on software*

In order to determine the cutting power, it is necessary to understand what the actual situation in this operation is. First of all, we need to compute the engagement angle and then the number of simultaneously working teeth:

$$\varphi = arccos\left(\frac{R - a_e}{R}\right) = 114°$$

$$\varphi_0 = \frac{2\pi}{Z} = 90°$$

$$z = \frac{\varphi}{\varphi_0} = 1.26$$

Therefore, we have to consider the worst-case scenario when two cutting edges are simultaneously cutting, that we have when the angular position of the two cutting edge is symmetric with respect to the feed direction. Thus:

- Cutting tooth 1, angular position: $\theta_1 = \varphi_0 = 90°$
- Cutting tooth 2, angular position: $\theta_2 = \varphi - \varphi_0 = 24°$

The two angular positions are coherent with respect to the engagement angles. We notice that:

$$h_{D1}(\theta_1) = f_z \, sin(\theta_1) = 0.16 \; mm$$

$$h_{D2}(\theta_2) = f_z \, sin(\theta_2) = 0.065 \; mm$$

Therefore:

$$h_{D1}(\theta_1) = h_{DMAX}$$

It follows that for the first angular position:

$$k_{C1} = k_{c1} \, h_{DMAX}^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 2193.8 \; N/mm^2$$

$$A_{DMAX} = h_{DMAX} \, a_p = 1.12 \; mm^2$$

$$F_{C1} = k_{C1} \, A_{DMAX} = 2457.01 \; N$$

And for the second one:

$$k_{C2} = k_{c1} \, h_{D2}^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 2747.92 \; N/mm^2$$

$$A_{D2} = h_{D2} \, a_p = 0.455 \; mm^2$$

$$F_{C2} = k_{C2} \, A_{D2} = 1250.31 \; N$$

So:

$$T_C = F_{C1} \frac{D/2}{1000} + F_{C2} \frac{D/2}{1000} = 23.91 + 12.16 = 37.07 \; Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 383.33 \; rad/s$$

$$P_C = T_C \, \omega = 14.211 \; kW$$

The cutting power is less than $16 \; kW$, the operation is feasible.

- **Contouring #2**

The parameters for this operation are:

$$v_c = 230 \; m/min, f_z = 0.16 \; mm/tooth, R = 10 \; mm, \gamma_0 = 7.5°, D = 20 \; mm, Z = 4, a_p = 7 \; mm, a_e = 15.17 \; mm.$$

The spindle speed and surface roughness are the same as in the previous operation, and so are the constraints.

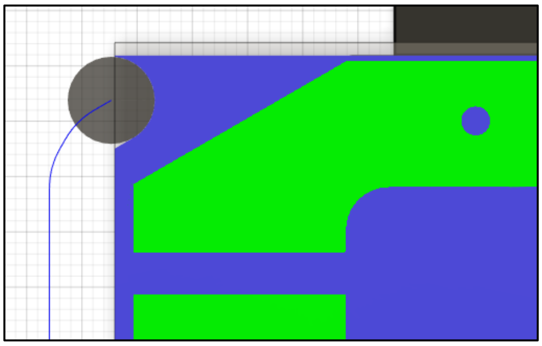


*Fig: Draw of the Setup 2 – Contour #2 on software*

In order to determine the cutting power, it is necessary to understand what the actual situation in this operation is. First of all, we need to compute the engagement angle and then the number of simultaneously working teeth:

$$\varphi = arccos\left(\frac{R - a_e}{R}\right) = 125°$$

$$\varphi_0 = \frac{2\pi}{Z} = 90°$$

$$z = \frac{\varphi}{\varphi_0} = 1.39$$

Just like in the previous operation, we have to consider the worst-case scenario when two cutting edges are simultaneously cutting, that we have when the angular position of the two cutting edge is symmetric with respect to the feed direction, so:

- Cutting tooth 1, angular position: $\theta_1 = \varphi_0 = 90°$
- Cutting tooth 2, angular position: $\theta_2 = \varphi - \varphi_0 = 35°$

The two angular positions are coherent with respect to the engagement angles. We notice that:

$$h_{D1}(\theta_1) = f_z\, sin(\theta_1) = 0.16\, mm$$

$$h_{D2}(\theta_2) = f_z\, sin(\theta_2) = 0.092\, mm$$

Again:

$$h_{D1}(\theta_1) = h_{DMAX}$$

It follows that for the first angular position:

$$k_{C1} = k_{c1}\, h_{DMAX}^{-mc}\left(1 - \frac{\gamma_0}{100}\right) = 2193.83\, N/mm^2$$

$$A_{DMAX} = h_{DMAX}\, a_p = 1.12\, mm^2$$

$$F_{C1} = k_{C1}\, A_{DMAX} = 2457.01\, N$$

And for the second one:

$$k_{C2} = k_{c1}\, h_{D2}^{-mc}\left(1 - \frac{\gamma_0}{100}\right) = 2519.34\ \mathrm{N/mm^2}$$

$$A_{D2} = h_{D2}\, a_p = 0.644\ \mathrm{mm^2}$$

$$F_{C2} = k_{C2}\, A_{D2} = 1622.45\ \mathrm{N}$$

So:

$$T_C = F_{C1}\frac{D/2}{1000} + F_{C2}\frac{D/2}{1000} = 40.79\ \mathrm{Nm}$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 383.33\, rad/s$$

$$P_C = T_C\ \omega\ = 15.638\ \mathrm{kW}$$

The cutting power is less than $16\ kW$, the operation is feasible.

- **Pocket Roughing: Adaptive 1 / Pocket Finishing: Adaptive 2**

The parameters for the operations are:

$$v_c = 150\ m/min, f_z = 0.07\ mm/tooth, r = 3\ mm, \gamma_0\ = 10.5°, D = 16\ mm, Z = 4, a_p = 8\ mm, a_e = 16\ mm, k_r = 90°.$$

The spindle speed is $2984\ rpm$ (again smaller than $14000\ rpm$). We must verify the surface roughness

$$R_a = \frac{1000}{32r}\ f_z^2 = 0.051\mu m$$

that is far less than $3.2\ \mu m$ (the maximum roughness for this surface).

Before performing a face milling operation, the cutting tool executes a drilling operation into the stock. For the drilling operation we have:

$$h_D = f_z\ si\,n\left(\frac{180°}{2}\right) = 0.07\ mm$$

$$k_C = k_{c1}\ h_D^{-mc}\ \left(1 - \frac{\gamma 0}{100}\right) = 2610\ N/mm^2$$

$$A_D = f\ \frac{D}{4} = 1.12\ mm^2$$

$$F_C = k_C\ A_D = 2923.2\ N$$

$$T_C = F_C\ \frac{D/2}{1000} = 23.38\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 619.66\ rad/s$$

$$P_C = T_C\ \omega = 14.475\ kW$$

The cutting power is less than $16\ kW$, the first operation is feasible.

After the drilling operation, the tool executes a face milling operation. Considering the geometry of the cutting, the engagement angle $\varphi$ is equal to $180°$ and the angular step between two consecutive cutting teeth is equal to $\varphi_0\ = \frac{2\pi}{Z}\ = 90°$, then the number of simultaneously working teeth is equal to:

$$z = \frac{\varphi}{\varphi_0} = \frac{180\,^o}{90\,^o} = 2$$

In this configuration:

- Cutting tooth 1, angular position: $\theta_1\ = \frac{\varphi_0}{2} = 45°$
- Cutting tooth 2, angular position: $\theta_2\ = -\frac{\varphi_0}{2} = -45°$

We notice that:

$$h_D(\theta_1) = f_z\ cos\ (\theta_1)$$

$$h_D(\theta_2) = f_z\ cos\ (\theta_2)$$

So:

$$h_D(\theta_1) = h_D(\theta_2) = h_D\ = 0.0495\ mm$$

Therefore:

$$k_C = k_{c_1} h_D^{-mc}\ \left(1 - \frac{\gamma_0}{100}\right) = 2846.22\ N/mm^2$$

$$A_D = h_D \frac{a_p}{sin(k_r)} = 0.396\, mm^2$$

$$F_C = k_C\, A_D = 1127.1\, N$$

$$T_C = F_C(\theta_1)\frac{D/2}{1000} + F_C(\theta_2)\frac{\frac{D}{2}}{1000} = 2\, F_C \frac{D/2}{1000} = 18.03\, Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 312.5\, rad/s$$

$$P_C = T_C\, \omega \; = 5.634\, kW$$

The cutting power is less than 16 kW, the entire operation is feasible.

- **Pocket Finishing: Traces #1 and #2**

The parameters for the operations are:

$$v_c = 245\, m/min, f_z = 0.08\, mm/tooth, r = 3\, mm, \gamma_0 \; = 1.5°, D = 6\, mm, Z = 4, a_p = 0.3\, mm.$$

The spindle speed is $12998\, rpm$ (smaller than $14000\, rpm$). We must verify the surface roughness

$$R_a = \frac{1000}{32r}\, f_z^2 = 0.067\, \mu m$$

that is by far less than $3.2\, \mu m$ (the maximum roughness for this surface). This is again an end milling. Considering the geometry of the cutting: $\varphi = 180°$, $\varphi_0 = \frac{2\pi}{Z} = 90°$. The number of simultaneously working teeth is equal to:

$$z = \frac{\varphi}{\varphi_0} = \frac{180\,^o}{90\,^o} = 2$$

In this configuration:

- Cutting tooth 1, angular position: $\theta_1 = \varphi_0 = 90°$
- Cutting tooth 2, angular position: $\theta_2 = \varphi_0 = 90°$

So:

$$h_D(\theta_1) = h_D(\theta_2) = h_{DMAX}$$

Therefore:

$$h_{DMAX} = f_z\, sin(90°) = 0.08\, mm$$

$$k_C = k_{c1}\, h_D^{-mc}\, \left(1 - \frac{\gamma_0}{100}\right) = 2778.15\, N/mm^2$$

$$A_{DMAX} = h_{DMAX}\, a_p = 0.024\, mm^2$$

$$F_{C1} = F_{C2} = k_C\, A_{DMAX} = 66.68\, N$$

$$T_C = F_{C1}\frac{D/2}{1000} + F_{C2}\frac{D/2}{1000} = 0.40\, Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 1361.1\, rad/s$$

$$P_C = T_C\, \omega = 544.51\, W$$

The cutting power is less than $16\, kW$, the operation is feasible.

- **Slot Pocketing**

The parameters for the operations are:

$$v_c = 150\ m/min, f_z = 0.05\ mm/tooth, r = 0.5\ mm, \gamma_0\ = 10.5°, D = 8\ mm, Z = 5, a_p = 8\ mm, a_e = 8\ mm, k_r = 90°.$$

The spindle speed is $5968\ rpm$ (smaller than $14000\ rpm$). We must verify the surface roughness

$$R_a = \frac{1000}{32r} f_z^2 = 0.156\ \mu m$$

that is far less than $12.5\ \mu m$ (the maximum roughness for this surface). This is again an end milling. Considering the geometry of the cutting: $\varphi = 180°$, $\varphi_0 = \frac{2\pi}{Z} = 72°$. The number of simultaneously working teeth is equal to:

$$z = \frac{\varphi}{\varphi_0} = \frac{180\,^o}{72\,^o} = 2.5$$

So, we may apply the average approach:

$$h_{D,AV} = f_z\ a_e\ \frac{2}{\varphi\ D} = 0.0318\ mm$$

$$k_{c,AV} = k_{c1}\ h_D^{-mc}\ \left(1 - \frac{\gamma_0}{100}\right) = 3179.12\ N/mm^2$$

$$A_{D,AV} = h_{D,AV}\ a_p = 0.2544\ mm^2$$

$$F_{C,AV} = k_{c,AV}\ A_{D,AV} = 808.77\ N$$

$$T_C = z\ F_{C,AV}\ \frac{D/2}{1000} = 8.088\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 625\ rad/s$$

$$P_C = T_C\ \omega = 5.055\ kW$$

The cutting power is less than $16\ kW$, the operation is feasible.

## SETUP 3 – DATUM C

- **Face Milling #3 Roughing**

The parameters for this operation are:

$$v_c = 270\ m/min, f_z = 0.40\ mm/tooth, r = 0.8\ mm, \gamma_0\ = 11.17°, D = 50\ mm, Z = 8, a_p = 2.5\ mm, a_e = 37.5\ mm.$$

The spindle speed is equal to $1719\ rpm$ (far less than the limit). We don't need to compute the surface roughness, since this is a roughing operation.

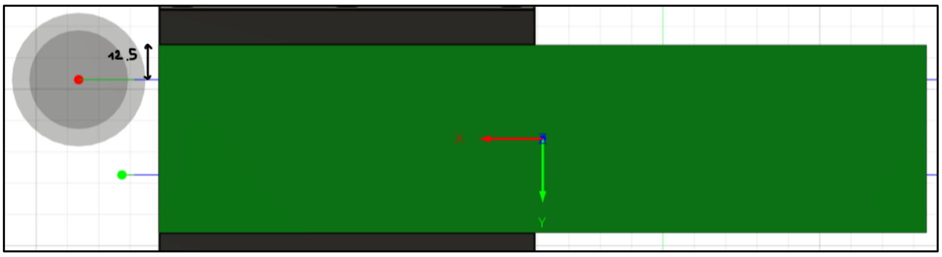



*Fig: Draw of the Setup 3 - face milling #3 on software*

It is necessary to understand what the actual situation in this face milling operation is. First, we need to compute the engagement angle and then the number of simultaneously working teeth. The overall engagement angle is the sum of the following two angles:

$$\varphi_1 = 90°$$

$$\varphi_2 = arcsin(\frac{12.5}{D/2})\ = 30\,°$$

$$\varphi = \varphi_1 + \varphi_2 = 120° = 2.1\ rad$$

$$\varphi_0 = \frac{2\pi}{Z} = 45°$$

$$z = \frac{\varphi}{\varphi_0} = 2{,}67$$

Therefore, we must consider the average approach:

$$h_{D,AV} = f_z\, a_e\, \frac{2}{\varphi\, D} = 0.286\ mm$$

$$k_{c,AV} = k_{c1}\, h_D^{-mc}\left(1 - \frac{\gamma_0}{100}\right) = 1822.05\ N/mm^2$$

$$A_{D,AV} = h_{D,AV}\, a_p = 0.715\ mm^2$$

$$F_{C,AV} = k_{c,AV}\, A_{D,AV} = 1302.76\ N$$

$$T_C = z\, F_{C,AV}\, \frac{D/2}{1000} = 86.96\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 180\ rad/s$$

$$P_C = T_C\, \omega = 15.652\ kW$$

The cutting power is less than $16\ kW$, the operation is feasible.

- **Face Milling #3 Finishing**

The parameters are:

$$v_c = 270\frac{m}{min}, f_z = 0.40\frac{mm}{tooth}, r = 0.8\ mm, \gamma_0 = 19°, D = 50\ mm, Z = 8, a_p = 0.5\ mm, a_e = 37.5\ mm, k_r = k_r' = 45°.$$

The spindle speed is $1719\ rpm$, far less than $14000\ rpm$. The surface roughness

$$R_a = \frac{1}{4}\frac{f_z}{(tan^{-1}k_r + tan^{-1}k'_r)}10^3 = 0.564\ \mu m$$

is far less than $12.5\ \mu m$ (the maximum roughness for this surface). This operation has the same parameters as the previous one except for having an $a_p$ smaller than the previous one. So, the operation will surely respect the cutting power constraint (in fact, $P_C = 2.238\ kW$).

- **Pilot Drilling #1**

The parameters are:

$$V_c = 118\ m/min, f = 0.2\ mm/rev, D = 6\ mm.$$

The spindle speed is equal to $6260\ rpm$ (less than $14000\ rpm$). Pilot drilling is generally used as a basis for the following deep drilling. In this scenario, the hole has usually a diameter equal to the 75% of the next screw diameter. We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} sin\left(\frac{140°}{2}\right) = 0{,}09397\ mm$$

For computing $k_c$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C = k_{c1}\, h_D^{-mc}\left(1 - \frac{\gamma_0}{100}\right) = 2709.22\ N/mm^2$$

$$A_D = f\,\frac{D}{4} = 0.3\ mm^2$$

$$F_C = k_C\, A_D = 812.77\ N$$

$$T_C = F_C \frac{D/2}{1000} = 2.438\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 655.56\ rad/s$$

$$P_C = T_C\ \omega = 1.598\ kW$$

The cutting power is less than $16\ kW$, the operation is feasible.

- **Deep Drilling #1**

The parameters are:

$$V_c = 118\ m/min, f = 0.2\ mm/rev, D = 8\ mm.$$

The spindle speed is equal to $4695\ rpm$ (less than $14000\ rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} si\,n\left(\frac{140°}{2}\right) = 0{,}09397\ mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C\ = \ k_{c1}\ h_D^{-mc}\ \left(1 - \frac{\gamma_0}{100}\right) = 830.49\ N/mm^2$$

$$A_D = f\ \frac{D}{4} = 0.4\ mm^2$$

$$F_C = k_C\ A_D = 332.19\ N$$

$$T_C = F_C\ \frac{D/2}{1000} = 1.32Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 491.67\ rad/s$$

$$P_C = T_C\ \omega = 649\ \mathrm{W}$$

The cutting power is less than $16\ kW$, the operation is feasible.

## SETUP 4 – OPPOSITE wrt DATUM C

- **Face Milling #4: Roughing and Finishing**

The parameters for the roughing operation are:

$$v_c = 270\frac{m}{min}, f_z = 0.40\frac{mm}{tooth}, r = 0.8\ mm, \gamma_0\ = 11.17°, D = 50\ mm, Z = 8, a_p = 2.5\ mm, a_e = 37.5\ mm, k_r\ =\ k_r'\ =\ 45°.$$

The parameters for the finishing operation are:

$$v_c = 270\frac{m}{min}, f_z = 0.40\frac{mm}{tooth}, r = 0.8\ mm, \gamma_0\ = 11.17°, D = 50\ mm, Z = 8, a_p = 0.5\ mm, a_e = 37.5\ mm, k_r\ =\ k_r'\ =\ 45°.$$

The computations are the same as Face Milling #3 (same tool and same parameters). The spindle speed is $1719\ rpm$ for both the roughing and the finishing operation. The cutting power is $15.652\ kW$ for the roughing operation and $2.238\ kW$ for the finishing operation. Since the maximum roughness for this surface is again $12.5\ \mu m$ for the finishing operation, the constraint is respected. Therefore, every constraint is respected.

- **Drilling #2**

The parameters are:

$$V_c = 145\ m/min, f = 0{,}2\ mm/rev, D = 6\ mm.$$

The spindle speed is equal to $7692\ rpm$ (less than $14000\ rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} si\,n\left(\frac{140°}{2}\right) = 0{,}09397\ mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C = k_{c1}\, h_D^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 830.49\ N/mm^2$$

$$A_D = f\ \frac{D}{4} = 0.3\ mm^2$$

$$F_C = k_C\, A_D = 249.15\ N$$

$$T_C = F_C\ \frac{D/2}{1000} = 0.7474\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 805.56\ rad/s$$

$$P_C = T_C\, \omega = 602.08\ \mathrm{W}$$

The cutting power is less than $16\ kW$, the operation is feasible.

- **Countersinking**

The parameters are:

$$V_c = 260\ m/min, f = 0.0031\ mm/rev, D = 8\ mm.$$

The spindle speed is equal to $10345\ rpm$ (less than $14000\ rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} si\,n\left(\frac{140°}{2}\right) = 0.001096\ mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C = k_{c1}\, h_D^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 8243.98\ N/mm^2$$

$$A_D = f\ \frac{D}{4} = 0.0062\ mm^2$$

$$F_C = k_C\, A_D = 51.11\ N$$

$$T_C = F_C\ \frac{D/2}{1000} = 0.204\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 1083.33\ rad/s$$

$$P_C = T_C\, \omega = 221.49\ \mathrm{W}$$

The cutting power is far less than $16\ kW$, the operation is feasible.

- **Drilling #3**

The parameters are:

$$V_c = 145\ m/min, f = 0.22\ mm/rev, D = 7.8\ mm.$$

The spindle speed is equal to $5917\ rpm$ (less than $14000\ rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} si\,n\left(\frac{140°}{2}\right) = 0{,}1034\; mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C \;=\; k_{c1}\, h_D^{-mc}\, \left(1 - \frac{\gamma_0}{100}\right) = 2645.43\; N/mm^2$$

$$A_D = f\, \frac{D}{4} = 0.429\; mm^2$$

$$F_C = k_C\, A_D = 1134.89\; N$$

$$T_C = F_C\, \frac{D/2}{1000} = 4.426\; Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 619.66\; rad/s$$

$$P_C = T_C\, \omega = 2.743\; \mathrm{kW}$$

The cutting power is less than 16 kW, the operation is feasible.

- **Reaming #1**

The parameters are:

$$V_c = 180\; m/min, f = 0.5\; mm/rev, D = 8\; mm, Z = 6.$$

The spindle speed is equal to $7162\; rpm$ (less than $14000\; rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} si\,n\left(\frac{140°}{2}\right) = 0.083\; mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C \;=\; k_{c1}\, h_D^{-mc}\, \left(1 - \frac{\gamma_0}{100}\right) = 2791.81\; N/mm^2$$

Setting $D_{ext} = 8\; mm$, $D_{int} = 7.8\; mm$ we obtain:

$$A_D = \frac{f}{Z}\, \frac{D_{ext} - D_{int}}{2} = 0.0083\; mm^2$$

$$F_C = k_C\, A_D = 23.265\; N$$

$$T_C = Z\, F_C \frac{D_{ext} + D_{int}}{4}\, \frac{1}{1000} = 0.551\; Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 750\; rad/s$$

$$P_C = T_C\, \omega = 413.54\; \mathrm{W}$$

The cutting power is less than $16\; kW$, the operation is feasible.

- **Counterboring**

The parameters are:

$$V_c = 245\; m/min, f = 0.0079\; mm/rev, D = 12.5\; mm, Z = 2.$$

The spindle speed is equal to $6239\; rpm$ (less than $14000\; rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} si\,n\left(\frac{140°}{2}\right) = 0.00395\;\; mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C = k_{c1}\, h_D^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 5983.32\ N/mm^2$$

Setting $D_{ext} = 12.5\ mm$, $D_{int} = 8\ mm$ we obtain:

$$A_D = \frac{f}{Z} \frac{D_{ext} - D_{int}}{2} = 0.008875 mm^2$$

$$F_C = k_C\, A_D = 53.18\ N$$

$$T_C = Z\, F_C \frac{D_{ext} + D_{int}}{4} \frac{1}{1000} = 0.545\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 653.33\ rad/s$$

$$P_C = T_C\ \omega = 356.07\ \mathrm{W}$$

The cutting power is far less than $16\ kW$, the operation is feasible.

## SETUP 5 – DATUM A-2

- **Chamfer Milling:**

The parameters are:

$$v_c = 320\ m/min, f_z = 0.025\ mm/tooth, R = 0.75\ mm, DCX = 10\ mm, Z = 4, a_p = 0.15\ mm, a_e = 0.15\ mm.$$

The spindle speed is $10186\ rpm$ (smaller than $14000\ rpm$). Through the face milling formulas, we verify the surface roughness:

$$R_a = \frac{1}{4} \frac{f_z}{(tan^{-1}k_r + tan^{-1}k'_r)} 10^3 = 0.035\ \mu m$$

That is far less than $12.5\ \mu m$ (the maximum roughness allowed for this surface). Considering the geometry of the cutting, the engagement angle $\varphi$ is equal to $90°$ and the angular step between two consecutive cutting teeth is equal to $\varphi_0 = \frac{2\pi}{Z} = 90°$, then the number of simultaneously working teeth is equal to:

$$z = \frac{\varphi}{\varphi_0} = \frac{180^o}{90^o} = 1$$

Being $z \leq 1$:

$$h_{DMAX} = f_z = 0.025\ mm$$

Therefore, we compute $k_C$ in the worst-case scenario when $\gamma_0 = 0°$:

$$k_C = k_{c1}\, h_{DMAX}^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 3772.3\ N/mm^2$$

$$A_{DMAX} = h_{DMAX}\ a_p = 0.00375\ mm^2$$

$$F_C = k_C\ A_{DMAX} = 14.15\ N$$

$$T_C = F_C \frac{D/2}{1000} = 0.011\ Nm$$

Considering the DCX of the entire shaft rotating with the cutting diameter:

$$\omega = \frac{1000 * vc}{60 * D/2} = 1066.67\ rad/s$$

$$P_C = T_C\ \omega = 11.32\ W$$

Being the cutting power far less than $16\ kW$, the operation is feasible.

- **Drilling #4**

The parameters are:

$$V_c = 145\ m/min, f = 0.25\ mm/rev, D = 9.8\ mm.$$

We utilized a tool with an angle of $140°$ since there is no tool with an angle of $120°$ for the pre-hole making. The spindle speed is equal to $4710\ rpm$ (less than $14000\ rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} sin\left(\frac{140°}{2}\right) = 0.1174\ mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C = k_{c1}\ h_D^{-mc}\ \left(1 - \frac{\gamma_0}{100}\right) = 2562.23\ N/mm^2$$

$$A_D = f\ \frac{D}{4} = 0.6125\ mm^2$$

$$F_C = k_C\ A_D = 1569.37\ N$$

$$T_C = F_C\ \frac{D/2}{1000} = 7.69\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 493.2\ rad/s$$

$$P_C = T_C\ \omega = 3.793\ \text{kW}$$

The cutting power is less than $16\ kW$, the operation is feasible.

- **Reaming #2**

The parameters are:

$$V_c = 180\ m/min, f = 0.8\ mm/rev, D = 10\ mm, Z = 6.$$

The spindle speed is equal to $5730\ rpm$ (less than $14000\ rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} sin\left(\frac{120°}{2}\right) = 0.4\ mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C = k_{c1}\ h_D^{-mc}\ \left(1 - \frac{\gamma_0}{100}\right) = 1886.15\ N/mm^2$$

Setting $D_{ext} = 10\ mm$, $D_{int} = 9.8\ mm$ we obtain:

$$A_D = \frac{f}{Z}\frac{D_{ext} - D_{int}}{2} = 0.04\ mm^2$$

$$F_C = k_C\ A_D = 75.45\ N$$

$$T_C = Z\ F_C \frac{D_{ext} + D_{int}}{4}\ \frac{1}{1000} = 0.747\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 600\ rad/s$$

$$P_C = T_C\ \omega = 448.15\ \text{W}$$

The cutting power is less than $16\ kW$, the operation is feasible.

- **Drilling #5**

The parameters are:

$$V_c = 260\, m/min, f = 0.0031\, mm/rev, D = 7\, mm.$$

The spindle speed is equal to $11823\, rpm$ (less than $14000\, rpm$). We can determine the cutting force, torque, and power:

$$h_D = \frac{f}{2} sin\left(\frac{120°}{2}\right) = 0.00134\, mm$$

For computing $k_C$ we consider the worst case scenario $\gamma_0 = 0$:

$$k_C = k_{c1}\, h_D^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 7839.98\, N/mm^2$$

$$A_D = f\, \frac{D}{4} = 0.005425\, mm^2$$

$$F_C = k_C\, A_D = 42.53\, N$$

$$T_C = F_C\, \frac{D/2}{1000} = 0.149\, Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 1238.09\, rad/s$$

$$P_C = T_C\, \omega = 184.30\text{ W}$$

The cutting power is far less than 16 kW, the operation is feasible.

- **Drilling #6 (Threading)**

The parameters for this operation are the following:

$$v_c = 130\, m/min, f_z = 0.025\, mm/tooth, \gamma_0 = 1.5°, D = 5.8\, mm, Z = 3, a_p = 0.91\, mm, a_e = 0.91\, mm.$$

The spindle speed is equal to $7135\, rpm$ (less than $14000\, rpm$). Considering the geometry of the cutting, the engagement angle $\varphi$ is equal to $180°$ and the angular step between two consecutive cutting teeth is equal to $\varphi_0 = \frac{2\pi}{Z} = 120°$, then the number of simultaneously working teeth is equal to:

$$z = \frac{\varphi}{\varphi_0} = \frac{180°}{120°} = 1.5$$

Therefore, we must consider the worst-case scenario when two cutting edges are simultaneously cutting, that we have when the angular position of the two cutting edge is symmetric with respect to the feed direction, so:

- Cutting tooth 1, angular position: $\theta_1 = \varphi_0 = 120°$
- Cutting tooth 2, angular position: $\theta_2 = \varphi - \varphi_0 = 60°$

The two angular positions are coherent with respect to the engagement angles. We notice that:

$$h_{D1}(\theta_1) = f_z\, sin(\theta_1) = 0.02165\, mm$$

$$h_{D2}(\theta_2) = f_z\, sin(\theta_2) = 0.02165\, mm$$

So, it follows that:

$$h_{D1}(\theta_1) = h_{D2}(\theta_2) = h_{DMAX}$$

It follows that for the first angular position:

$$k_{C1} = k_{c1}\, h_{DMAX}^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 3851.79\, N/mm^2$$

$$A_{D1} = h_{DMAX}\, a_p = 0.0197\, mm^2$$

$$F_{C1} = k_{C1}\, A_{D1} = 75.88\, N$$

For the second angular position:

$$k_{C2} = k_{c1}\, h_{DMAX}^{-mc} \left(1 - \frac{\gamma_0}{100}\right) = 3851.79\, N/mm^2$$

$$A_{D2} = h_{DMAX}\, a_p = 0.0197\ mm^2$$

$$F_{C2} = k_{C1}\, A_{D1} = 75.88\ N$$

Therefore:

$$T_C = F_{C1}\,\frac{D/2}{1000} + F_{C2}\,\frac{D/2}{1000} = 0.440\ Nm$$

$$\omega = \frac{1000 * vc}{60 * D/2} = 747.13\ rad/s$$

$$P_C = T_C\ \omega = 328.81\ W$$

The cutting power is far less than $16\ kW$, the last operation is completely feasible.

# 5. Discussion on technical requirements

Since our product respects all the requirements outlined in the table of section 2.2, the constraints on the spindle rotational speed, the roughness, and the cutting power, we can conclude that our final solution is feasible.

About the choosing of the Sandvik tools, we chose them from the "Sandvik ToolGuide" wherever it was possible in order to have the best tool that fit our needs.

Regarding the tool life, for every tool we considered a tool life sufficient for its related operation in the process. We made this decision because the only operations that may require a tool change due to the large machining time are the pocketing ones: if we consider two additional tool changing times for the pocketing operations, the total machining time will increase by 30 s, so the final throughput wouldn't change significantly.

About the optimality of the product, it is important to specify that most operations are still feasible if we consider a realistic efficiency of 90% ($P_{C,LIMIT} = 14.4\ kW$: the operations that exceed this limit are the face milling #1, rough milling #3 and #4 and contouring #2, in which we could reduce the cutting power by decreasing $a_p$, and adaptive #1 and #2, in which we could reduce the cutting power by decreasing $f_z$). We chose the order of the setups and the setups themselves in order to respect the machining precedence rules and optimize the machining time. The machining time on Fusion360 is influenced only by the toolpath: with more specific goals apart from feasibility, we could have tried to modify some process parameters in order to lower the machining time (e.g. increasing the cutting speed). The roughness obtained is always at least twice smaller than the limit (frequently significantly smaller).

In conclusion, considering the hypothesis previously stated and the simulations on Fusion360, we believe we achieved a correct and satisfying result.