UNIVERSITY OF BIRMINGHAM

Machining Support System

Coursework Report

Submitted to:

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Section 1: CAM Design of SD-6 front bulkhead

1. Introduction

The SD-6, which is a prototype of a component of Jennings Aerospace, is manufactured by using advanced machining techniques in the simulation software Autodesk PowerMill. The customer, Jennings Aerospace, specified the software and the manufacturing machine during the agreement. MAZAK Variaxis i-600 [1], a multiple-surface 5-axis machining centre CNC machine will be used for the manufacturing process of the final product. Furthermore, SECO Tools Ltd [2] was used as the tool supplier for machining the product as in agreement. But few tools which were not available within the SECO Tools Ltd catalogue were selected from other tooling companies which will be discussed in later sections.

In this report, a brief review of the CNC machine MAZAK Variaxis i-600; material of the block; a detail description and appraisal of the strategies used and detailed information of the tooling used is presented.

2. MAZAK Variaxis i-600 review

MAZAK Variaxis i-600, shown in Figure 1, is an advanced 5-axis CNC machine with centre design. A ‘SIEMENS SINUMERIK 840D sl’ operating system is used by the machine with a 19’’ touch screen panel. In addition, the machine can operate on 12,000 rpm spindle speed, which can be upgraded to 18,000 rpm and 30,000 rpm. Furthermore, the machine is having rapid transverse feed rate of 60,000/60,000/56,000 mm/min in X/Y/Z direction [1].

Figure 1. MAZAK Variaxis i-600 Siemens (courtesy of www.mazakeu.co.uk [1])

3. Material of the block

The block of the workpiece, shown in Figure 2 and Figure 3, exceeds by 2 mm in Z direction from the model because every component needs to be machined on the surface to make it finish fine. The 315×280×34mm block is made up of aluminium (grade 7075), which is an aluminium alloy. This material is classified as N1 (Non-ferrous metal) by ISO standard of classification. The N1 is having less than 9% of Silicon (Si) content. It is graded as a softer type of metal [3]. The Aluminium (grade 7075) is a widely used in manufacturing of aerospace components. It was introduced in the aerospace industry since 1940 [4].

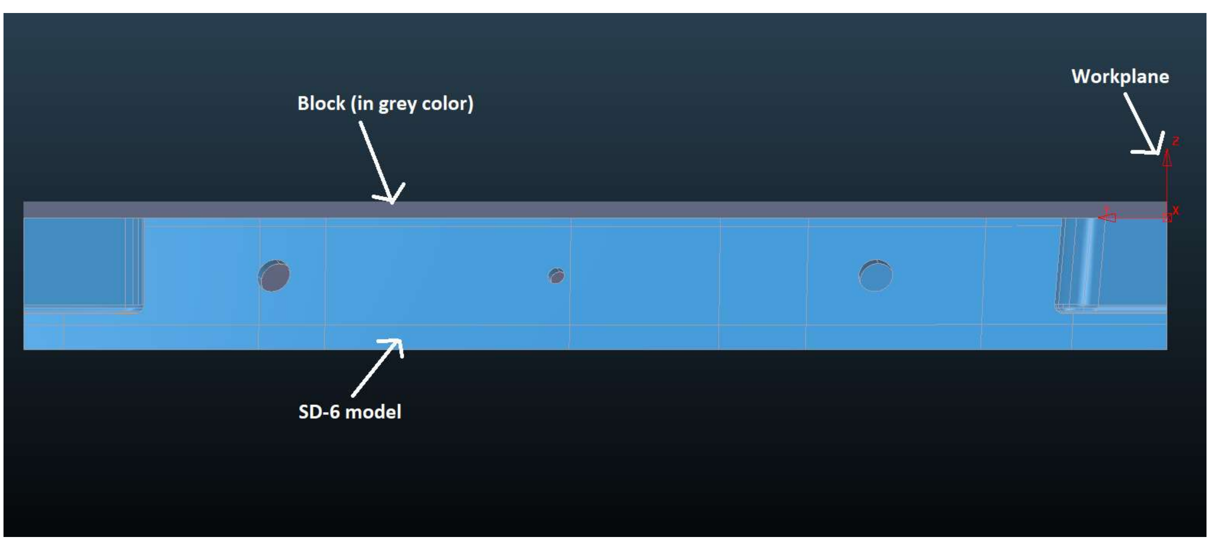


Figure 2. Left Side view of Block

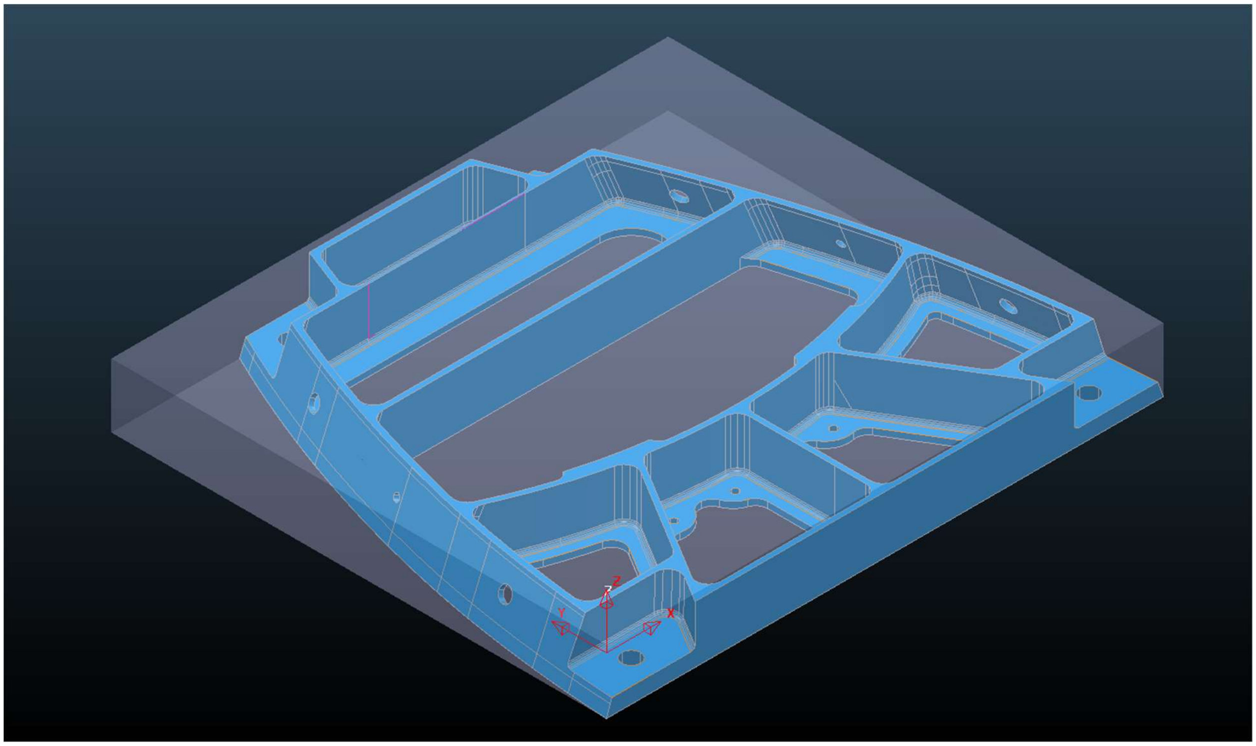


Figure 3. Isometric view of Block

Before selecting tools, it is required to find out what material is going to be machined. Because there are different tools used for different materials. The selection of tool depends on the material type, chip forming, material hardness and alloy elements [3].

Furthermore, before tool selection the machining operation should also be selected. Therefore, for the manufacturing of SD-6, only two types of machining operations are required:

a) milling
b) drilling

4. Toolpaths

There are total of 26 toolpaths used for the manufacturing of the component. All these toolpaths are divided into Roughing, Drilling, Semi Finishing and Finishing. The toolpaths are categorised in Table 1 below.

Table 1. Toolpaths categorization

Types	Toolpaths name
Roughing	Roughing
	Rest Roughing
	Inner Roughing
Drilling	Drilling 1
	Drilling 2
Semi Finishing	Undercut clearance
	Pocketing 1
	Pocketing 1 2
	Pocketing 6
	Pocketing 6 1
	Pocketing 5 1
Finishing	Outer finishing
	Nonhidden Area Finishing
	Hidden Area 1 Finishing
	Hidden Area 2 Finishing
	Hidden Area 3 Finishing
	Hidden Area 4 Finishing
	Hidden Area 5 Finishing
	Hidden Area 6 Finishing
	Leftover radius 1 Finishing
	Leftover radius 2 Finishing
	Leftover Corner 1 Finishing
	Leftover Corner 2 Finishing
	Leftover Corner 3 Finishing
	Leftover Corner 4 Finishing
	Bottom Clearance

Table 2. Toolpaths with designated tools

Process	Tool Name	Diameter (mm)	Type
Roughing	JHP490 (490V200R050Z3A-MEGA-T)	20	Tip Radius
Rest Roughing	JHP490 (490100R100Z2A-MEGA-T)	10	Tip Radius
Inner Roughing	JS520 (JS520100D3C.3Z6-NXT)	10	End Mill
Under cut	R331.35 D38.1 Tip Disc	38.1	Tip Disc
Drilling 1	JS553 (553080SZ3.0-SIRON-AW)	8	End Mill
Drilling 2	JS553 (553040SZ3.0-SIRON-AW)	4	End Mill
Pocketing (ALL)	JS534 (JS534060D1B.3Z4-NXT)	6	Ball Nose
Outer Finish	JS520 (JS520100D3C.3Z6-NXT)	10	End Mill
Finishing	JS534 (JS534040F1B.3Z4-NXT)	4	Ball Nose

Table 2 represent the toolpaths and tools used for these toolpaths with its diameters and types. Every toolpath is explained in detail below.

4.1. Roughing

For excess of material removal, the very first strategy to be used for the milling the workpiece is roughing. Roughing requires a strengthened large tool with a big step over and step down. The spindle speed and feed rate for roughing tool path are calculated with formulae mentioned in Appendix C. For all other toolpaths the cutting speed is kept constant at 11,000 mm/min because by calculating it was going above the maximum speed of the machine, which is 12,000 mm/min.

4.1.1. Roughing Toolpath

Table 3. Roughing details

Toolpath Type	3D Model Area Clearance (offset model style)
Tool (diameter and style)	20mm Tip radius
Tolerance	0.1mm
Thickness (sides and bottom)	0.5mm and 0.0mm
Stepover	20.0mm
Stepdown	20.0mm
Spindle speed	10,345 rpm
Cutting feed rate	10552 mm/min

Table 3 shows all the facts of the roughing toolpath. The roughing toolpath on the SD-6, which is called model area clearance in PowerMill, shown in Figure 5. The model area clearance generates a toolpath by carving the model at stated Z height. Figure 6 shows when the strategy is performed on the component. The leftover material from this toolpath is 0.5mm. In addition, the roughing tool path uses stepdown and stepover values of 20mm, because roughing is a High Performance Machining (HPM) strategy, in which a very high material removal can be achieved [2]. Furthermore, the tool used is also a HPM tool and it is from the SECO Tools Ltd JHP (JABRO HPM) series named, JHP 490, which is having a tool diameter of 20mm with a tip radius, shown in Figure 4.

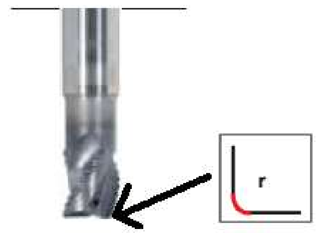


Figure 4. JHP490 D20 Tip Radius

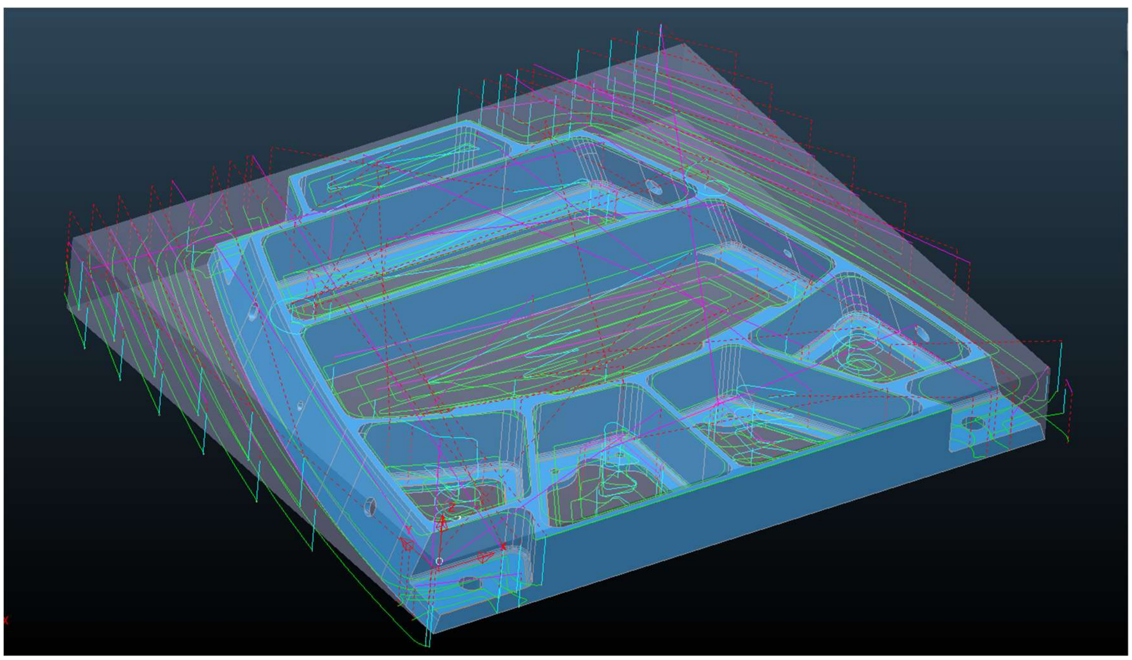


Figure 5. Roughing Toolpath

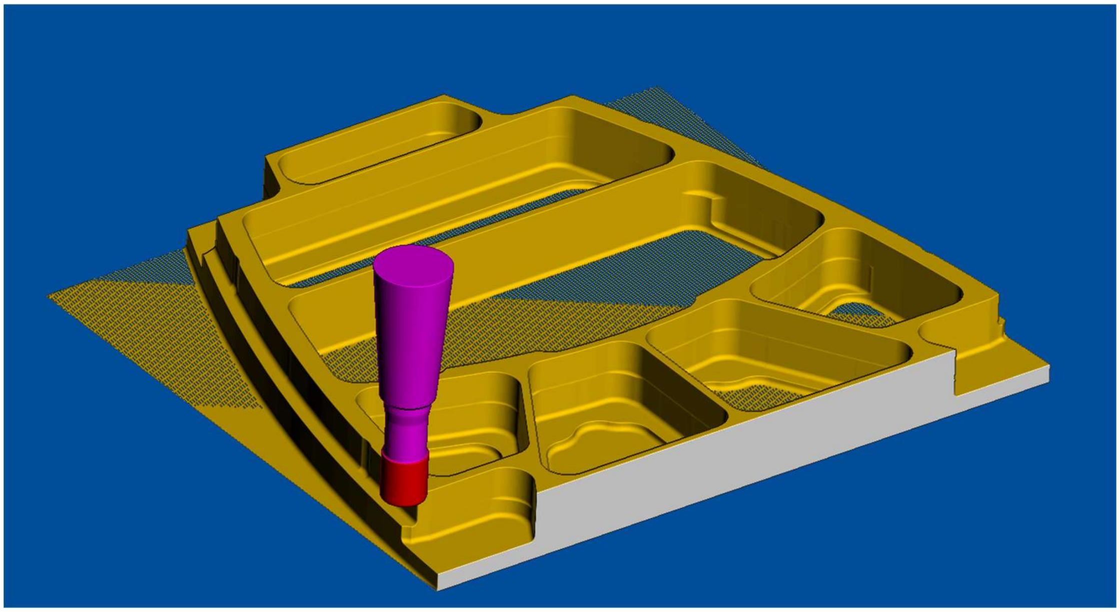


Figure 6. Roughing result

4.1.2. Rest Roughing

The rest roughing toolpath is based on the roughing toolpath and it is called Rest Area Clearance toolpath in PowerMill. The facts of the rest roughing are shown in Table 4 and the results of the toolpath is shown in Figure 7. The left-over material from this toolpath is 0.3mm.

Table 4. Rest Roughing Toolpath details

Toolpath Type	3D Model Area Clearance (offset model style)
Tool (diameter and style)	10mm Tip radius
Tolerance	0.1mm
Thickness (sides and bottom)	0.3mm and 0.0mm
Stepover	5.0mm
Stepdown	5.0mm
Spindle speed	11,000 rpm
Cutting feed rate	4,400 mm/min

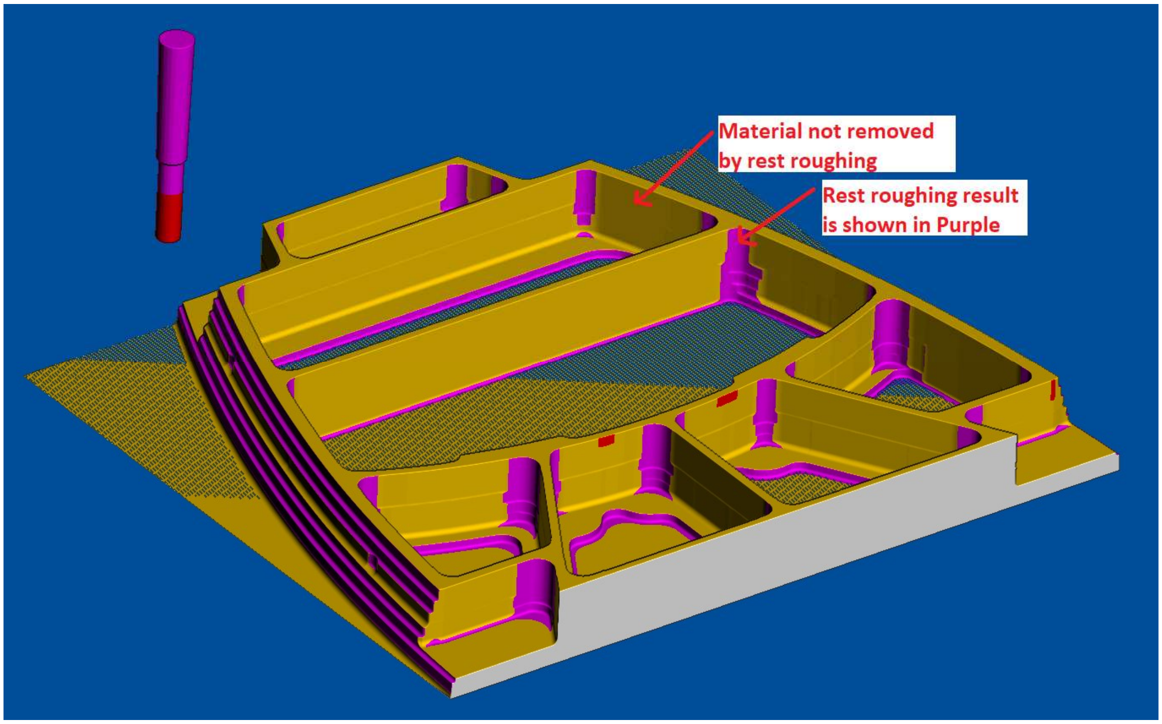


Figure 7. Rest roughing result

In addition, the stepover and stepdown are 5mm. The tool has also been changed for this toolpath. And this time the tool used is of the JHP 490 tool with the diameter of 10mm. The diameter is reduced to clear more material from the corners of the workpiece.

Despite removing the excess material from the component, the rest toolpath was not able to remove the material from the side walls of SD-6, shown in the Figure 7. Therefore, to remove the material from the side walls, Inner Roughing toolpath is used.

4.1.3. Inner Roughing

The inner roughing toolpath can reach to the side walls, which are at an angle and cannot be reached by a vertical tool. Therefore, the 'Swarf finishing' toolpath is used. It is basically a finishing toolpath but, in this case, it is used for material clearance. And the material leftover from this toolpath is 0.05mm, this is left on purpose for the final finishing. The rest of the facts are mentioned in Table 5. Figure 8 shows the result of the inner roughing and how it reached the side walls of the SD-6.

Table 5. Inner roughing details

Toolpath Type	Swarf finishing
Tool (diameter and style)	10mm Endmill
Tolerance	0.05mm
Thickness (sides and bottom)	0.05mm and 0.0mm
Stepover	Not applicable
Stepdown	Not applicable
Spindle speed	11,000 rpm
Cutting feed rate	14,520 mm/min

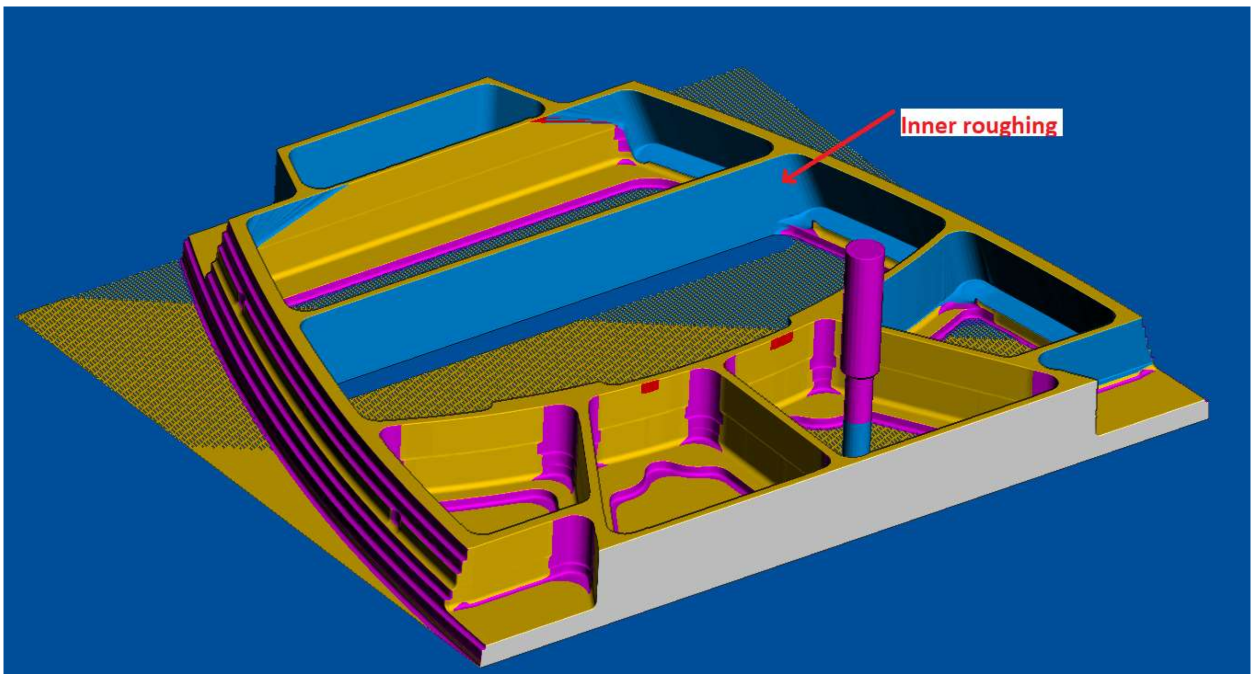


Figure 8. Inner roughing result

The tool used for this toolpath is JS520, which is an end-mill tool with a diameter of 10mm.

With this toolpath the roughing of the component came to an end, as shown in Table 1.

4.2. Drilling

There are 18 number of holes with three different diameters (4.2mm, 8.4mm and 10.5mm diameter) in the SD-6. And there are two toolpaths used for the drilling of these holes in the

SD-6. The first one is named, drilling_1, whereas the second one named, drilling_2. For both the facts are shown in Table 6 and Table 7.

Table 6. Drilling 1 details

Toolpath Type	Drilling (Helical type)
Tool (diameter and style)	8.0mm Endmill
Tolerance	0.1mm
Thickness	0.0mm
Stepover	Not applicable
Stepdown	Not applicable
Spindle speed	11,000 rpm
Cutting feed rate	1,815 mm/min

Table 7. Drilling 2 details

Toolpath Type	Drilling (Helical type)
Tool (diameter and style)	4.0mm Endmill
Tolerance	0.1mm
Thickness	0.0mm
Stepover	Not applicable
Stepdown	Not applicable
Spindle speed	11,000 rpm
Cutting feed rate	924 mm/min

Drilling_1 is basically for the large holes, those diameters are bigger than 8mm, whereas, drilling_2 is used for all the holes.

Drilling_1 uses the tool named, JS553, which is having a diameter of 8mm Endmill. The JS (Jabro Solid) is new series of tools in SECO Tools Ltd. And they are general purpose tools, which offer flexibility, speed and cost efficiency [2].

For drilling in a helical style, the diameter for the tool is supposed to be bigger than the half of the diameter of the hole. Otherwise, it can may break. However, is the hole is already drilled then a small diameter tool can be used to make it fine. Therefore, drilling_2 uses a small diameter tool of 4mm, which is of small type as drilling_1 (JS553), for the small holes and as well the large holes. The results of the drilling_1 and drilling_2 are shown in Figures 9 and 10 respectively.

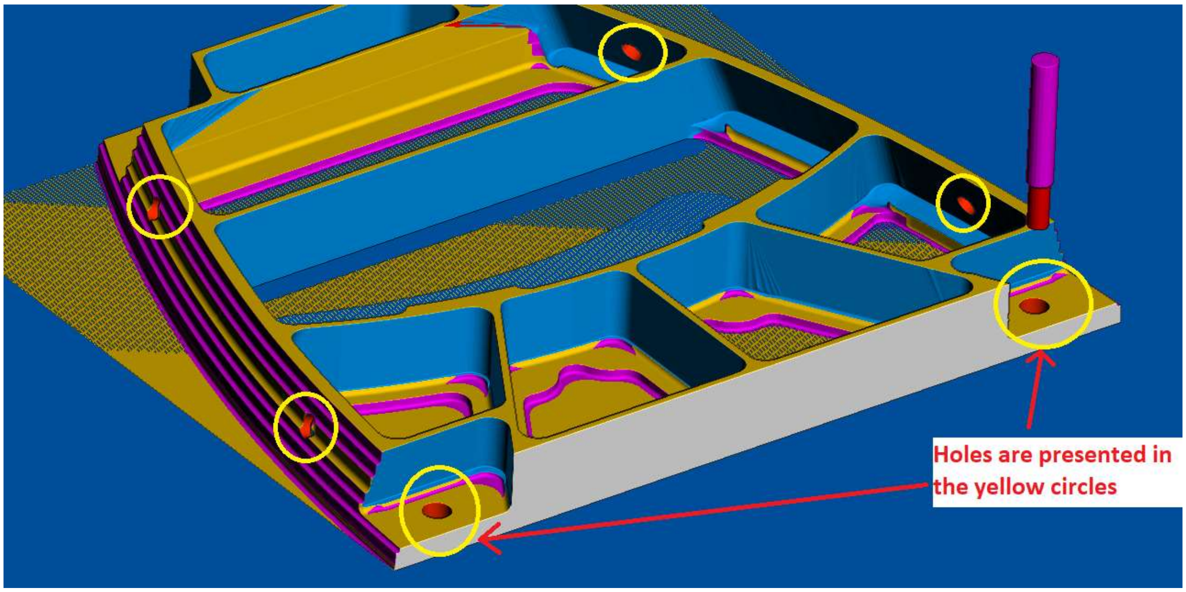


Figure 9. Drilling 1 result

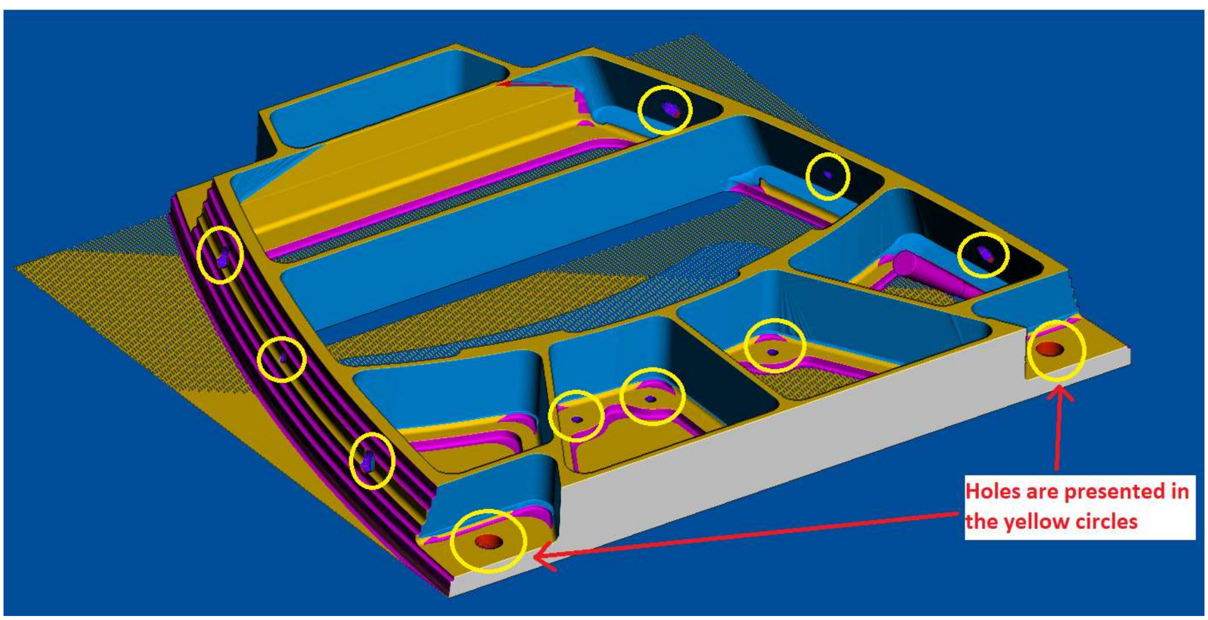


Figure 10. Drilling 2 result

4.3. Semi Finishing

4.3.1. Undercut Clearance

There is a portion of wall in the SD-6, which was supposed to be milled by an undercut strategy with an end-disc tool, show in Figure 11. Area need to be machined by Tip Disc tool Figure 11.

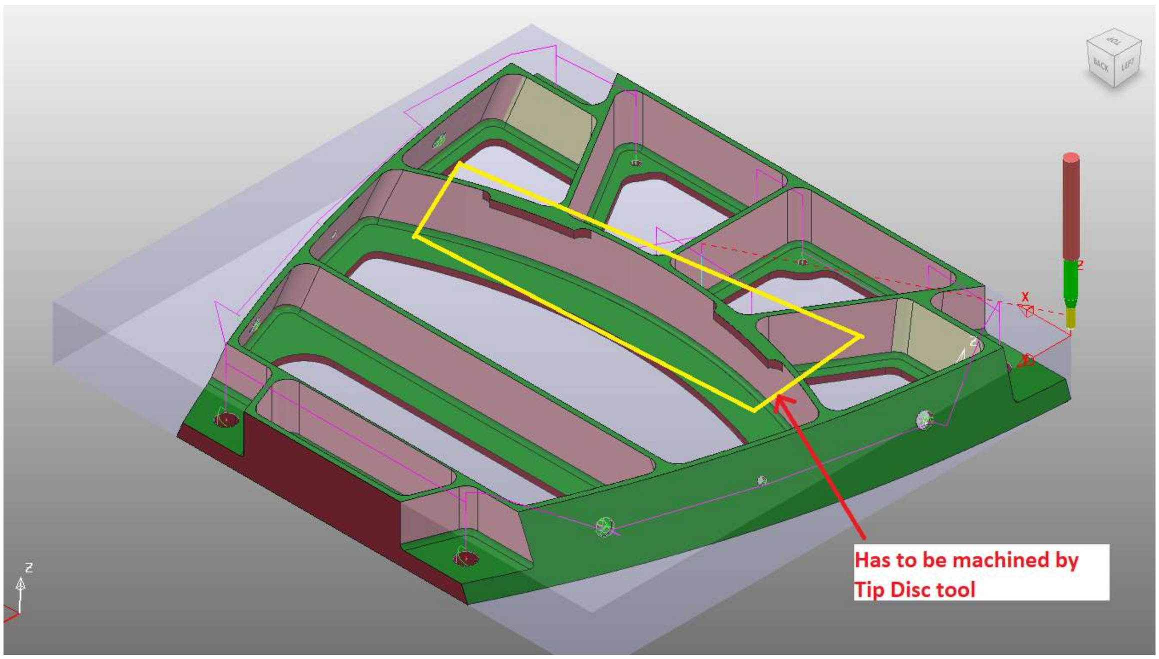


Figure 11. Area need to be machined by Tip Disc tool

Table 8. Undercut clearance details

Toolpath Type	Constant Z-Finishing
Tool (diameter and style)	38.1mm Tip Disc
Tolerance	0.05mm
Thickness	0.0mm
Stepover	Not applicable
Stepdown	0.3mm
Spindle speed	11,000 rpm
Cutting feed rate	6,600 mm/min

However, the end-disc tool was not available in the SECO Tools Ltd catalogue, therefore, a tool has been selected from a Sandvik Coromant UK catalogue. The tool is 38.1mm in diameter and the insert selected is 4mm in length and 0.5mm in radius edge [5], shown in Figure 12.

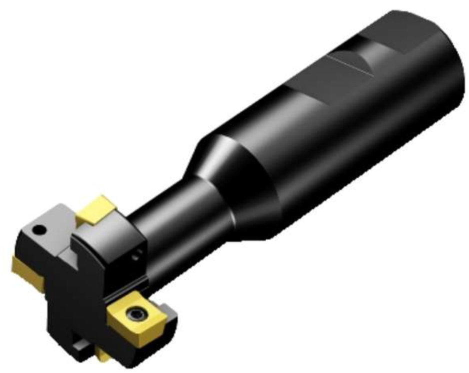


Figure 12. Tip Disc tool with 38.1mm Diameter

This toolpath is the only one toolpath for undercut, therefore, the leftover material from this toolpath is zero. In addition, the detail facts are given in Table 8. Furthermore, the tool path result is shown in Figure 13.

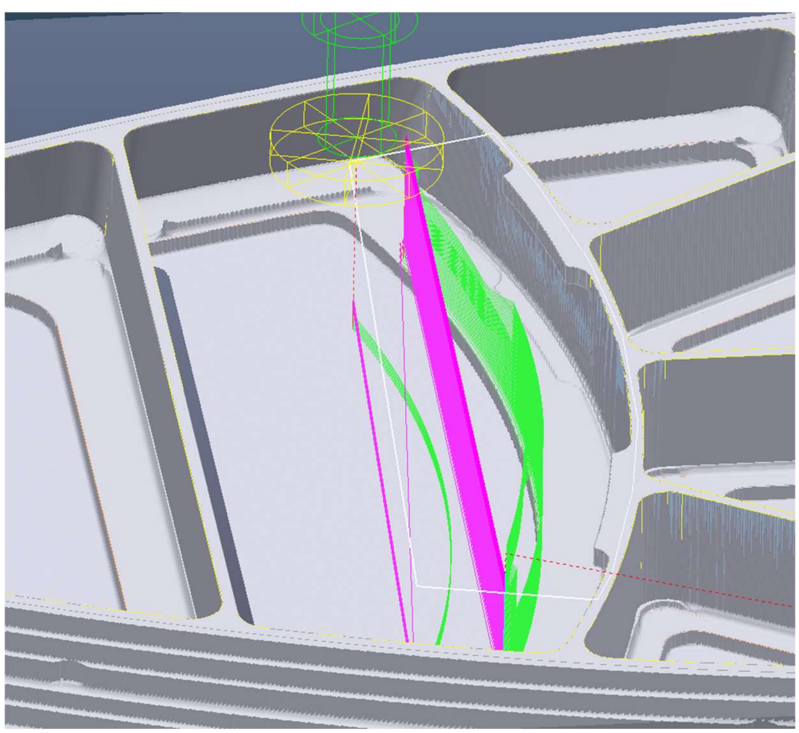


Figure 13. Undercut clearance result

4.3.2. Pocketing

There are in total of 5 toolpaths (Z-constant finishing with zero leftover) used on 5 pockets, shown in Figure 14, Figure 15, Figure 16, Figure 17 and Figure 18.

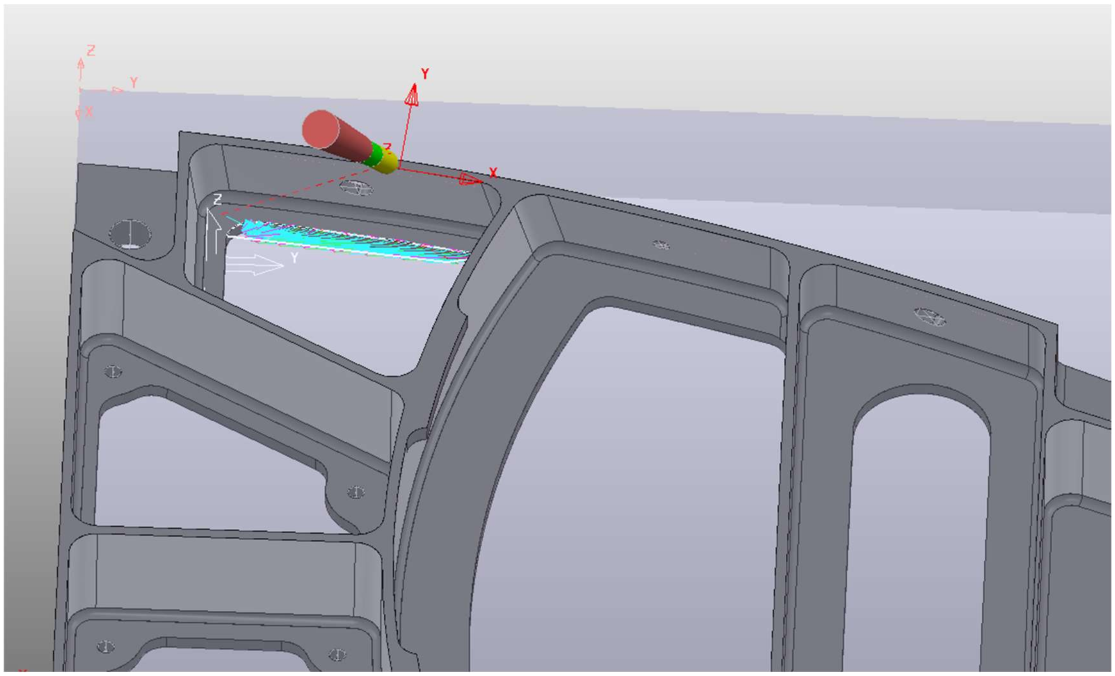


Figure 14. Pocket 1

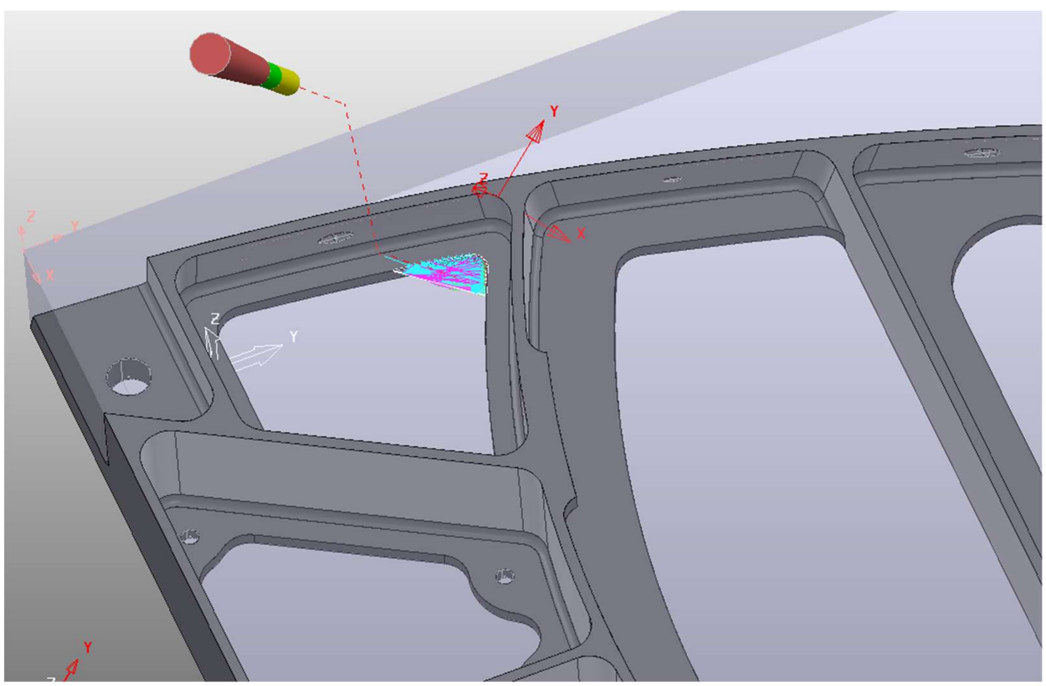


Figure 15. Pocket 2

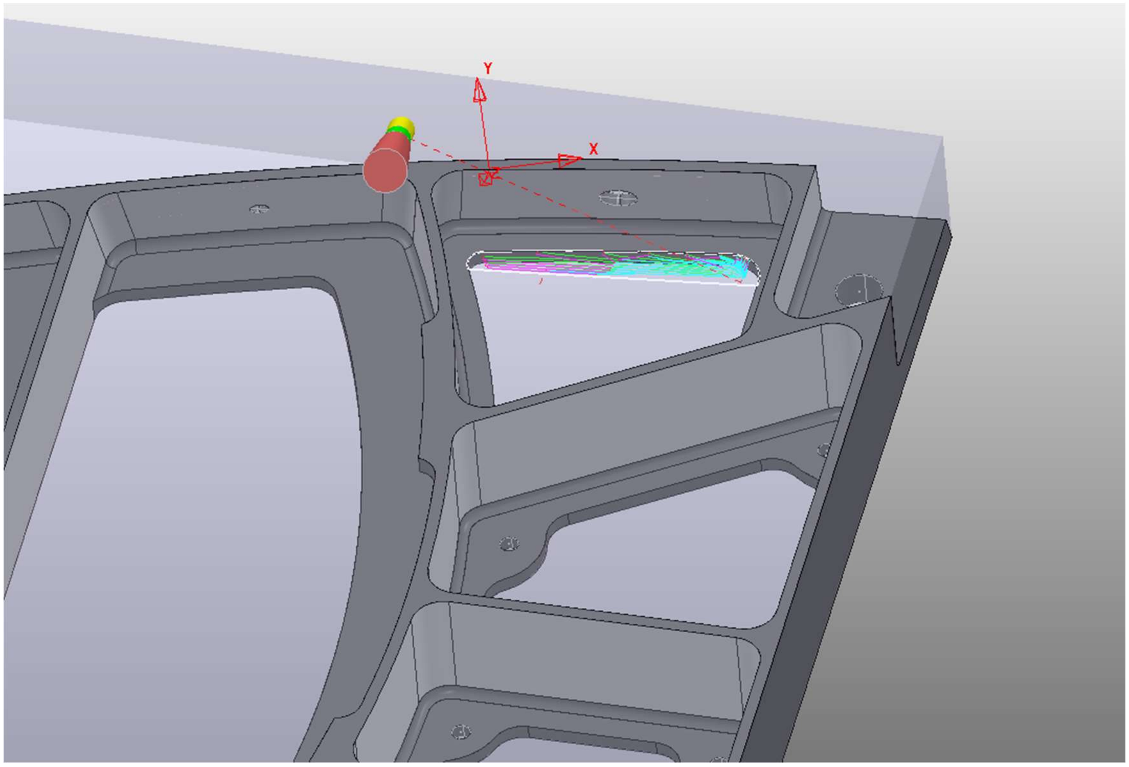


Figure 16. Pocket 3

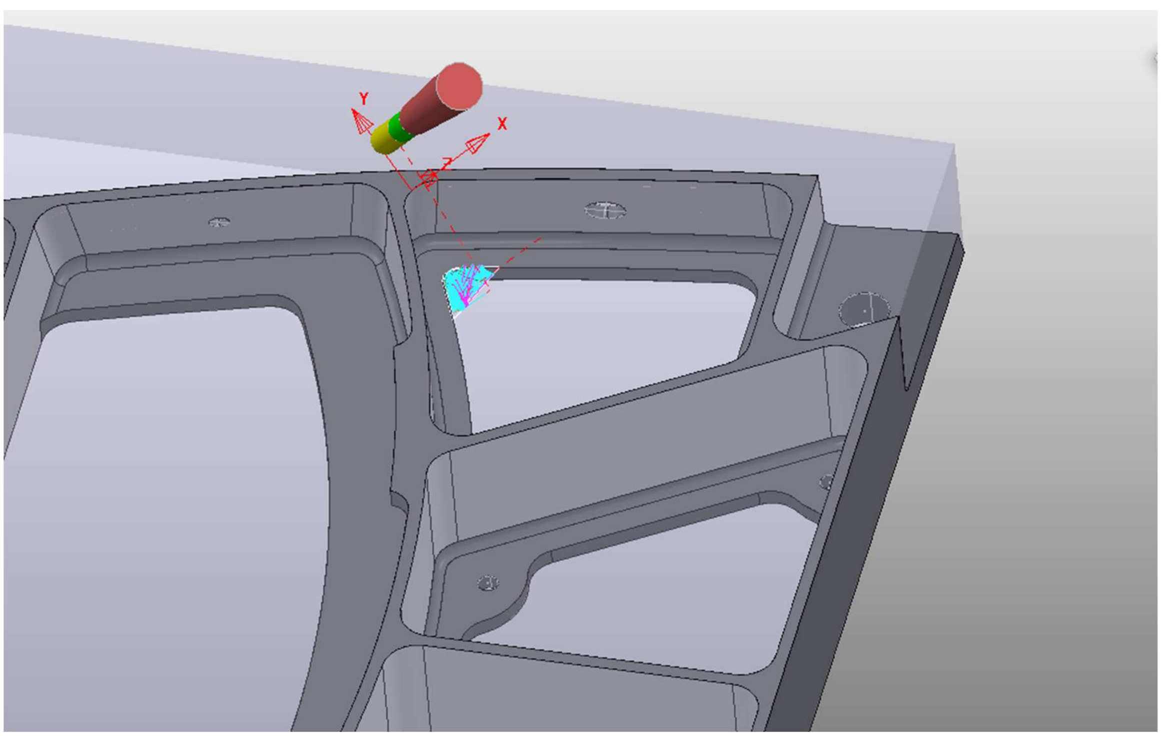


Figure 17. Pocket 4

These pockets are not properly touched/finished by the toolpaths before, therefore, the material on these pockets are less and can be properly removed with a Z-constant finishing.

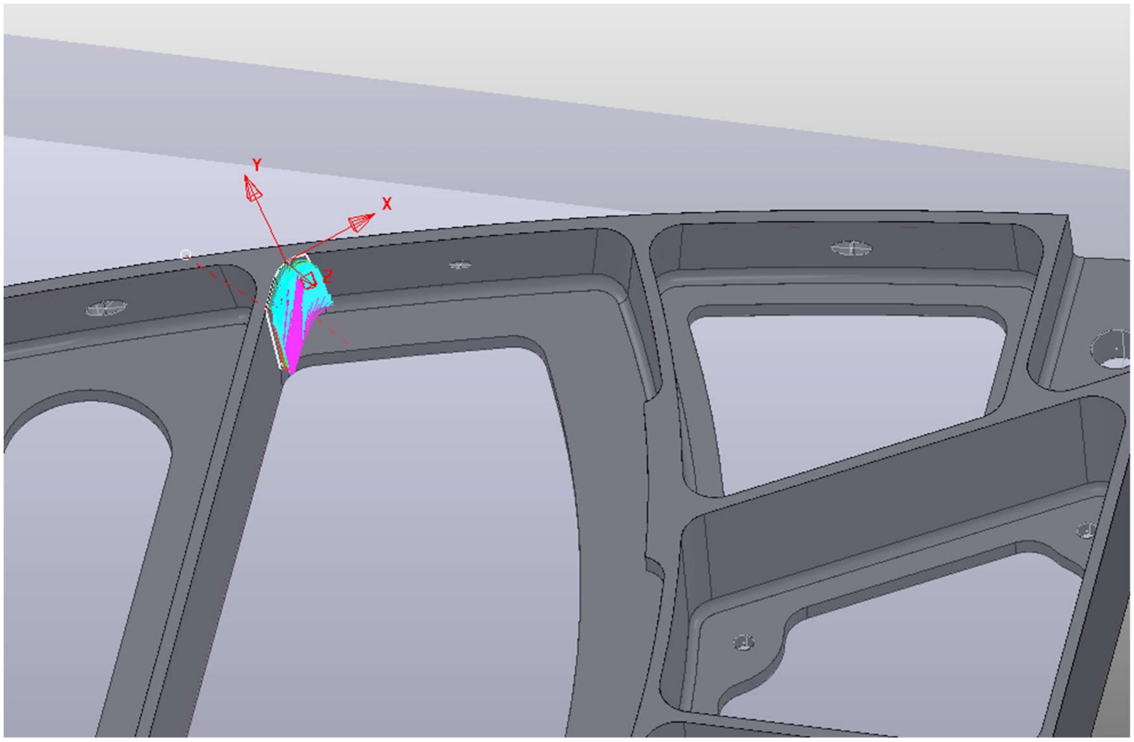


Figure 18. Pocket 5

In addition, the tool used for these pocketing is a Ball-nose 6mm diameter, selected from the SECO Tools Ltd catalogue. The facts of pocketing are given in Table 9.

Table 9. Pocketing details

Toolpath Type	Constant Z-Finishing
Tool (diameter and style)	6.0mm Ball nose
Tolerance	0.1mm
Thickness	0.0mm
Stepover	Not applicable
Stepdown	0.5mm
Spindle speed	11,000 rpm
Cutting feed rate	1,408 mm/min

4.4. Finishing

4.4.1. Outer finishing

This is the first toolpath of finishing. It only finishes the outer walls of the component. The facts of this toolpath are given in Table 10. The toolpath used is the swarf finishing with a JS520 10mm diameter end-mill tool used. The result of the outer finishing toolpath is shown in Figure 19.

Table 10. Outer finishing details

Toolpath Type	Swarf finishing
Tool (diameter and style)	10.0mm End mill
Tolerance	0.01mm
Thickness	0.0mm
Stepover	Not applicable
Stepdown	Not applicable
Spindle speed	11,000 rpm
Cutting feed rate	14,520 mm/min

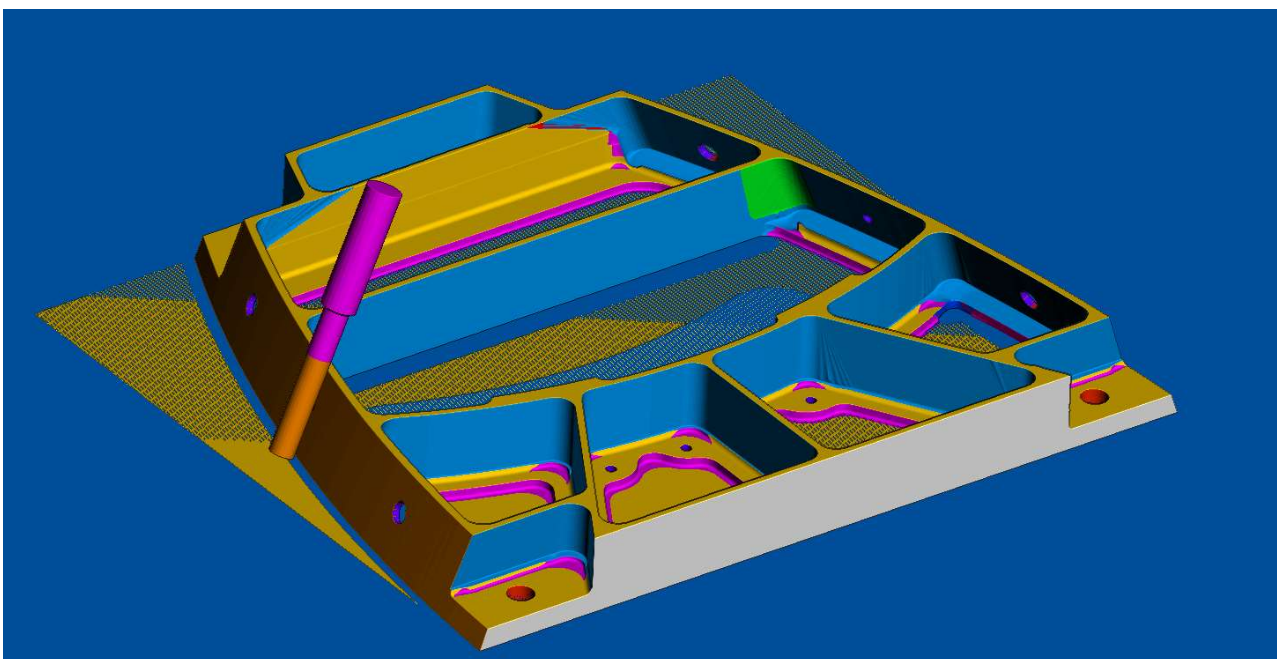


Figure 19. Outer finishing result

4.4.2. Nonhidden Area Finishing

The nonhidden area finishing is ‘Steep and Shallow Finishing’ by nature. Steep and shallow finishing is a very common finishing strategy used in the PowerMill software. It works on steep and shallow regions of a workpiece. In the steep region it uses the method of Z-constant toolpath and in shallow region it uses the method of 3D offset or raster toolpath. In this case, 20 degrees of value has been set to make an overlap between steep and shallow region. By applying the overlap option both the toolpaths of steep and shallow are made in the region of the pre-set value in degree. Furthermore, this toolpath finishes the top of the component as well. Those places where the tool cannot be reached will be milled in the ‘Hidden Area Clearance’ and ‘Leftover Area Clearance’ toolpaths.

Furthermore, the tool selected, for this finishing and the rest of all finishing afterwards, is a ball-nose 4mm diameter by company named Associated Production Tools (APT). This tool does not belong to SECO Tools Ltd. Because there is no tool such type (cylindrical) and long, which can be reached to the bottom of the component without colliding with the walls. The tool is shown in Figure 20 and its details are given in the Table 11. Furthermore, the 4mm diameter tool is selected because of the radius, shown in Figure 21, which is around 2mm. The result is shown in Figure 22 and the facts, which are same for all the rest finishing toolpaths, are shown in Table 12.

Figure 20. APT 4mm diameter Ball nose tool

Table 11. Details of APT 4mm Ball nose tool

Dimensions for 2AABN-04040050 (mm)				
Cutting Diameter	Radius	Flute Length	Overall Length	Shank Diameter
4.0	2.0	8.0	50	4

Speeds and Feeds for Side Milling for Slot Milling reduce the Feed Rate by 70% Water Soluble Cutting Fluid and Clockwise Side Milling is recommended using the shortest overhang possible.

Aluminium Alloy	Silicon Aluminium Alloy ≤10% Si
RPM 20000 Feed 1950 mm/min	RPM 16000 Feed 1550 mm/min

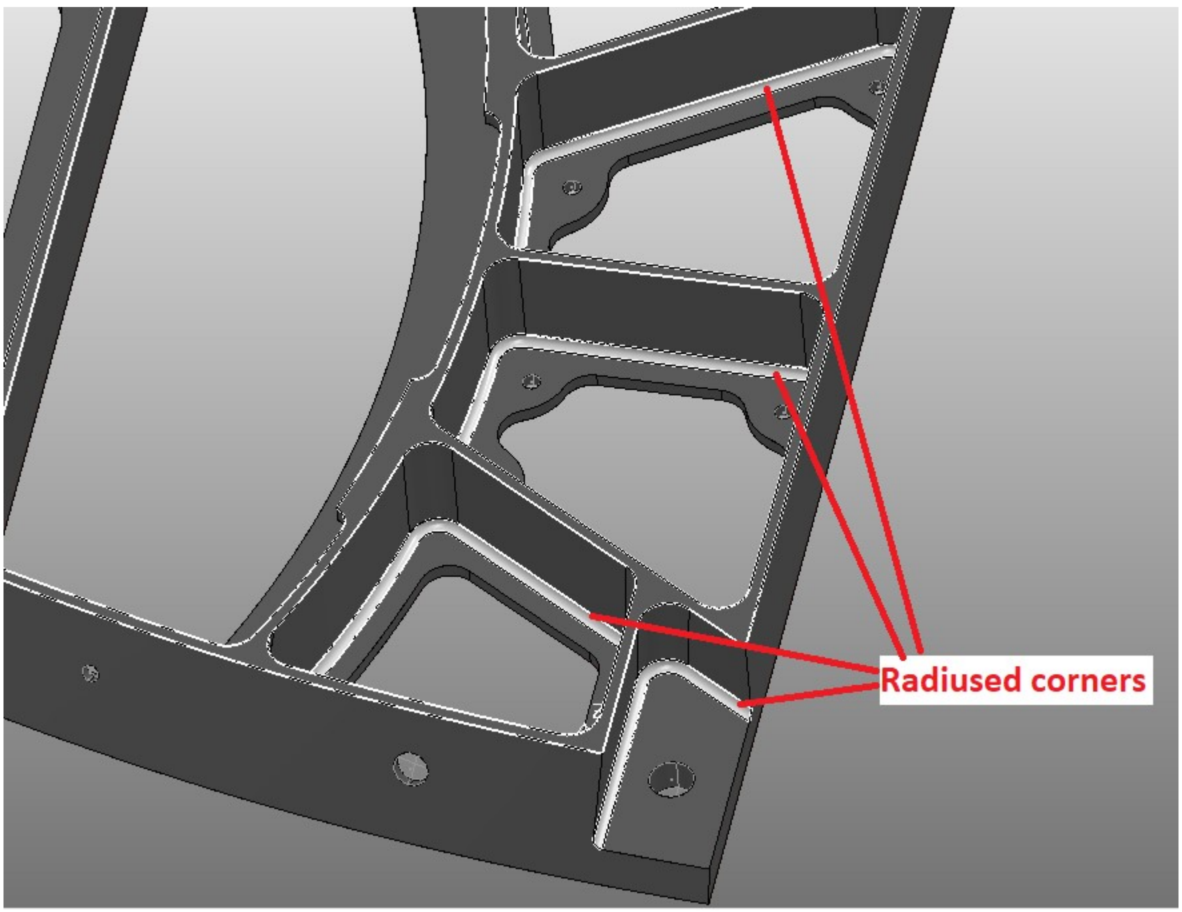


Figure 21. Radiused corners

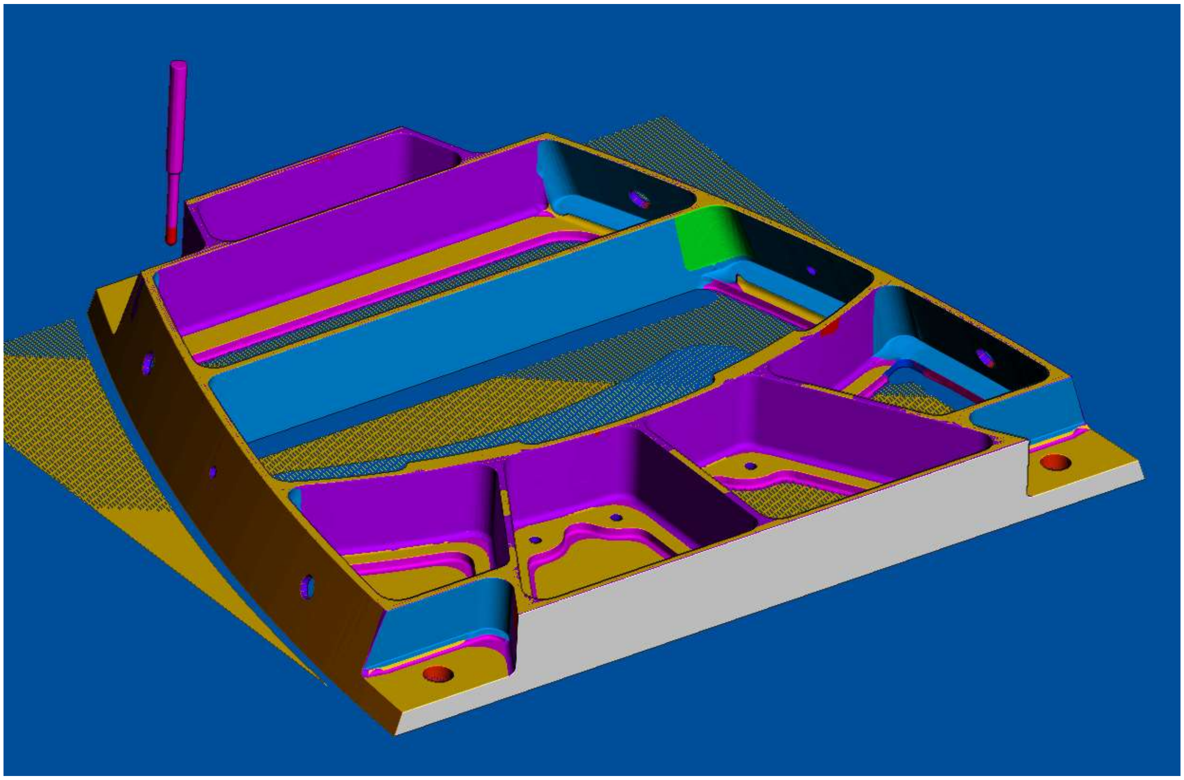


Figure 22. Nonhidden area finishing

Table 12. Nonhidden area finishing details. They are same for all finishing toolpaths

Toolpath Type	Steep and Shallow finishing
Tool (diameter and style)	4.0mm Ball nose
Tolerance	0.01mm
Thickness	0.0mm
Stepover	0.25mm
Stepdown	1.0mm
Spindle speed	11,000 rpm
Cutting feed rate	1,056 mm/min

4.4.3. Hidden Area Finishing

Hidden area are those areas of the component which cannot be milled with the vertical axis from the top. Therefore, new workplanes for every pocket are made. And then the steep and shallow finishing is applied on it with the same tool as Nonhidden Area Clearance finishing. All the hidden areas are displayed in the Figure 23 and Figure 24.

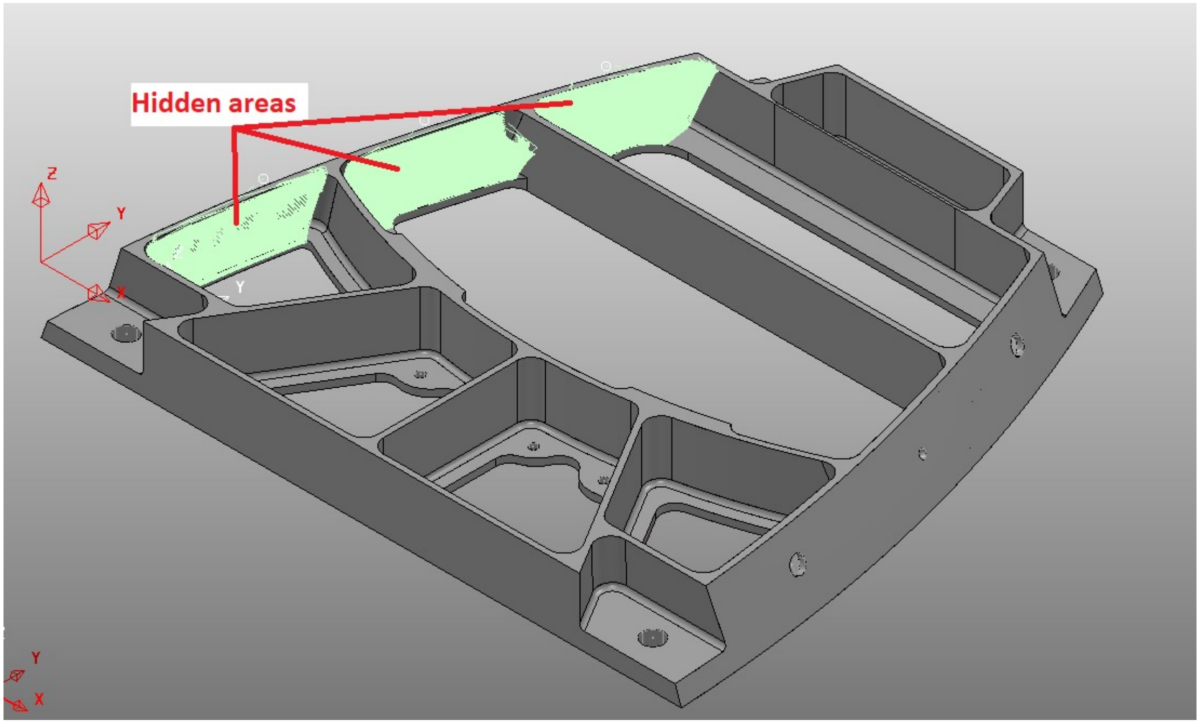


Figure 23. Hidden Areas on left side

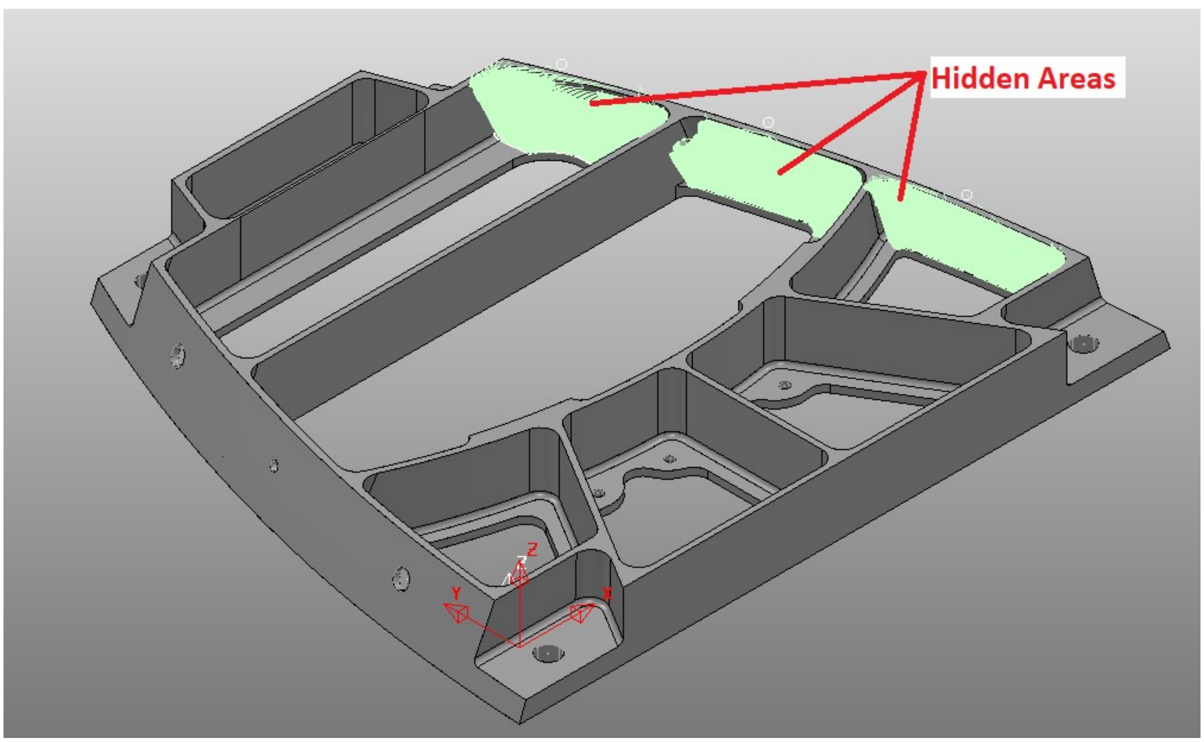


Figure 24. Hidden areas on right side

4.4.4. Leftover Area Finishing

The leftover areas include radiuses and corners, which are left by the finishing strategies because of curvature in the component model. The areas which are left over are shown in the Figure 25. The toolpath strategy and the tool used are all the same which are used in the previous finishing toolpaths.

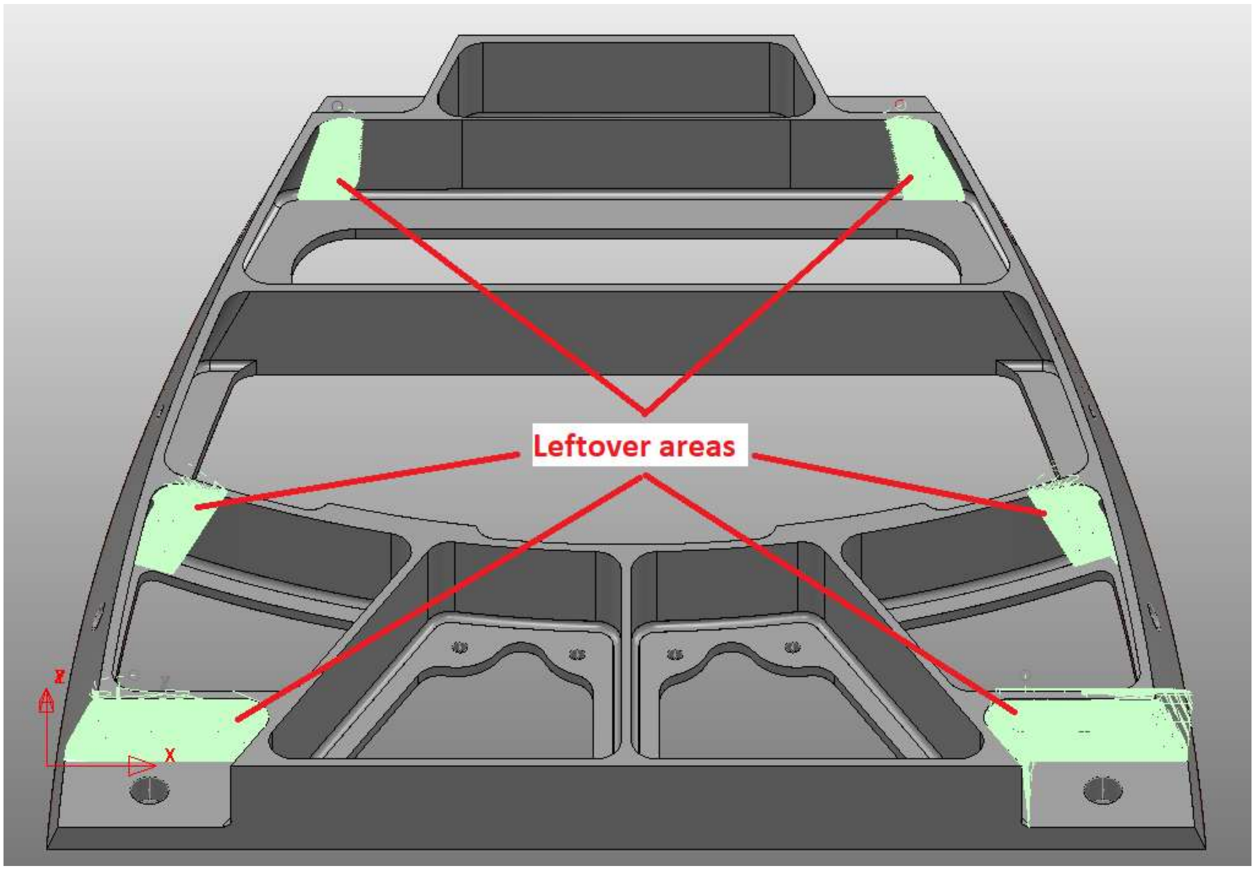


Figure 25. Leftover areas for finishing

4.4.5. Bottom Finishing

This is the last finishing toolpath and the last toolpath of the milling process. The workpiece is rotated upside down and the toolpath is applied on it to make the bottom of the workpiece finish, shown in Figure 26. The facts of this toolpath are shown in Table 13.

The tool used is same as rest roughing that is JHP490 10mm diameter.

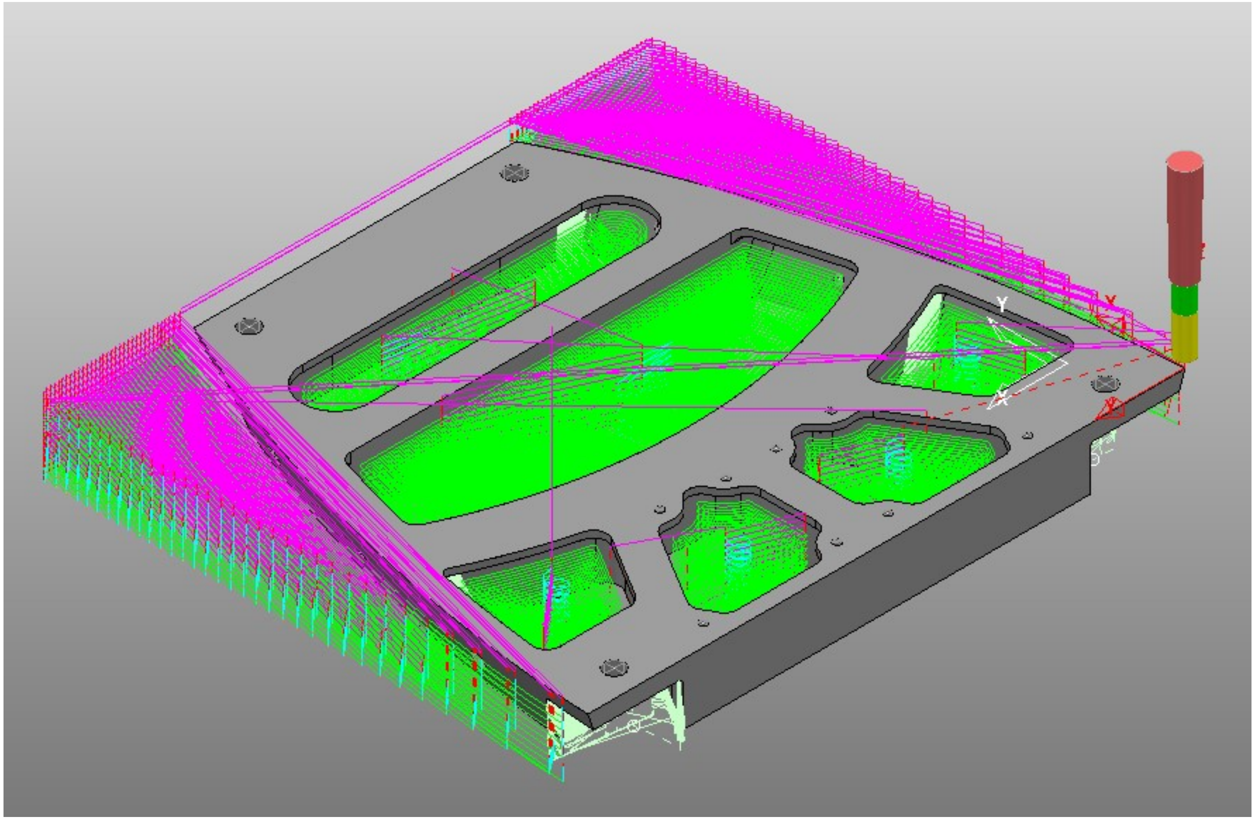


Figure 26. Bottom clearance toolpath

Table 13. Bottom clearance details

Toolpath Type	3D model Area Clearance (offset model style)
Tool (diameter and style)	10.0mm Ball nose
Tolerance	0.01mm
Thickness	0.0mm
Stepover	2.0mm
Stepdown	3.0mm
Spindle speed	11,000 rpm
Cutting feed rate	4,400 mm/min

5. Final product

The final product can be seen in the Figure 27, 28, 29 and 30.

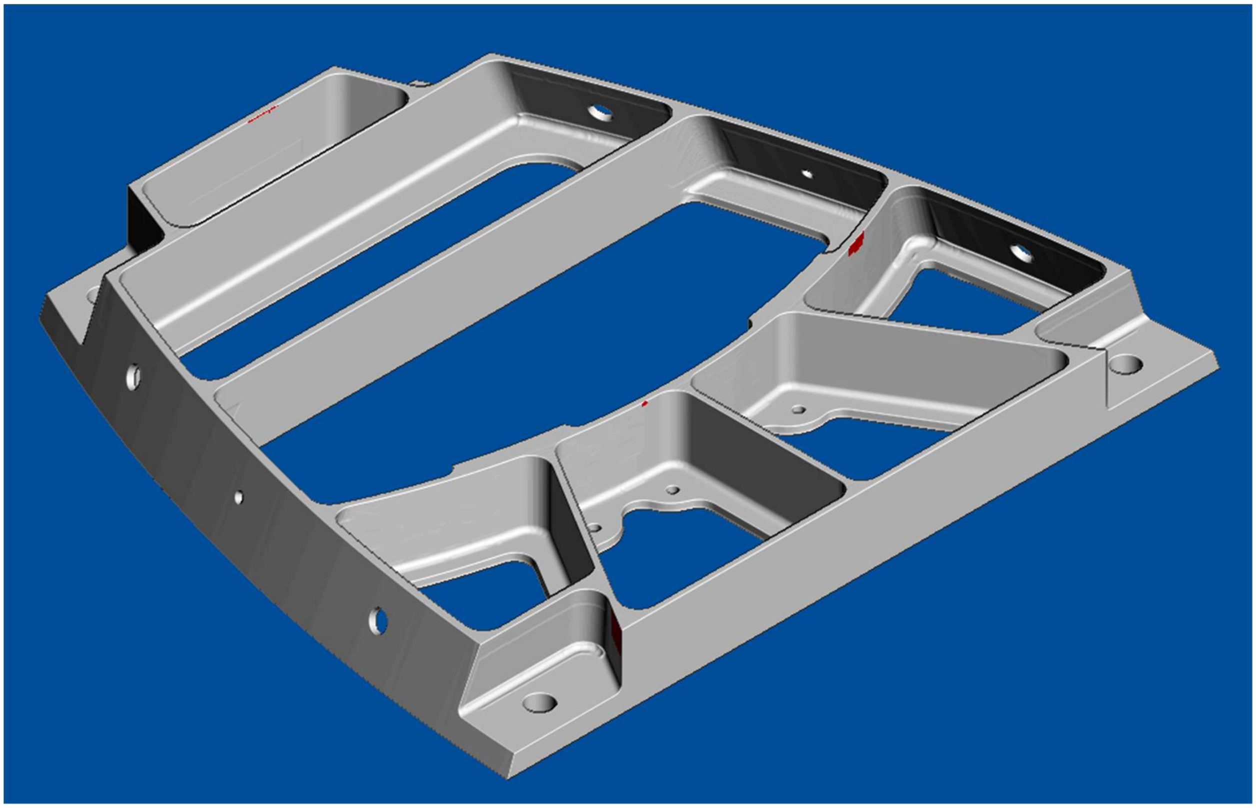


Figure 27. Final product ISO view 1

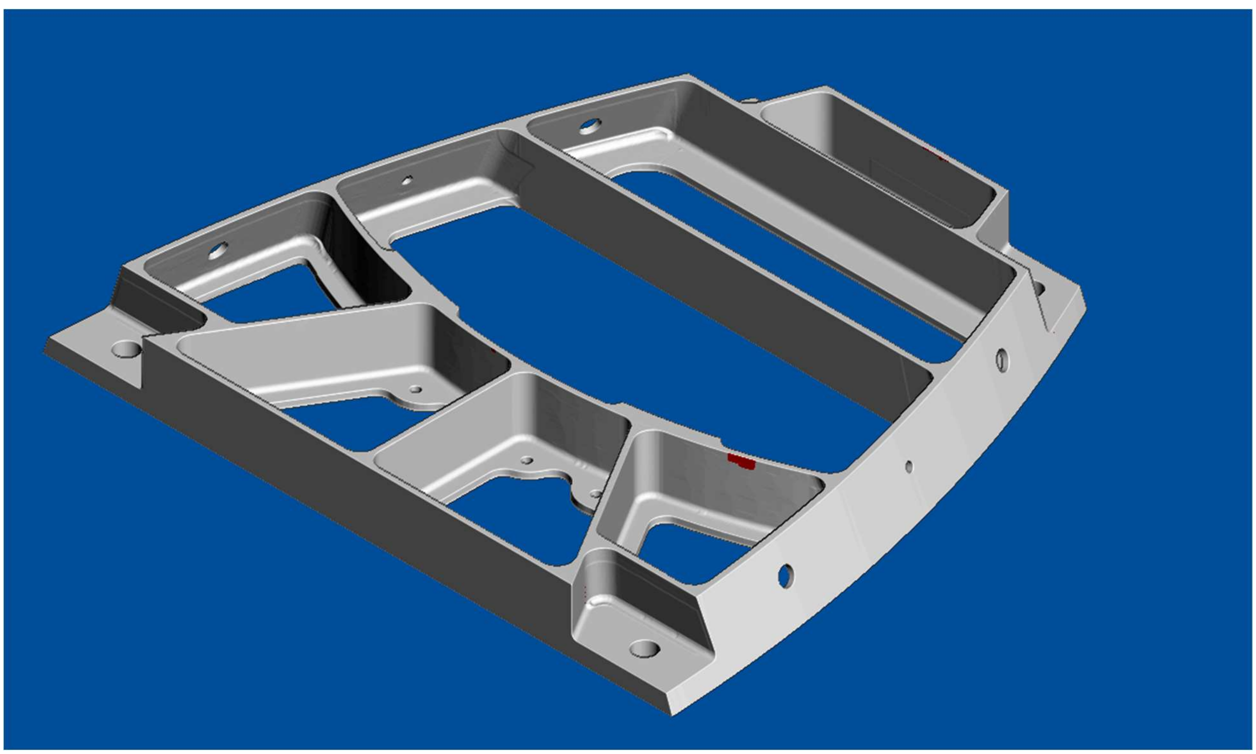


Figure 28. Final product ISO view 2

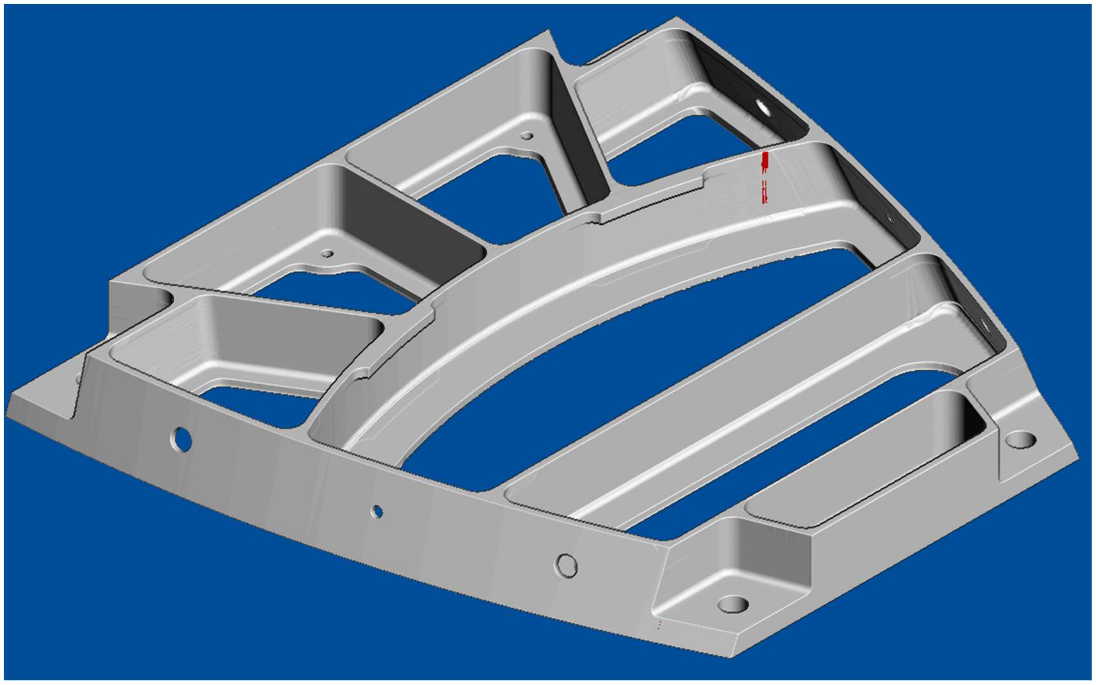


Figure 29. Final product ISO view 3

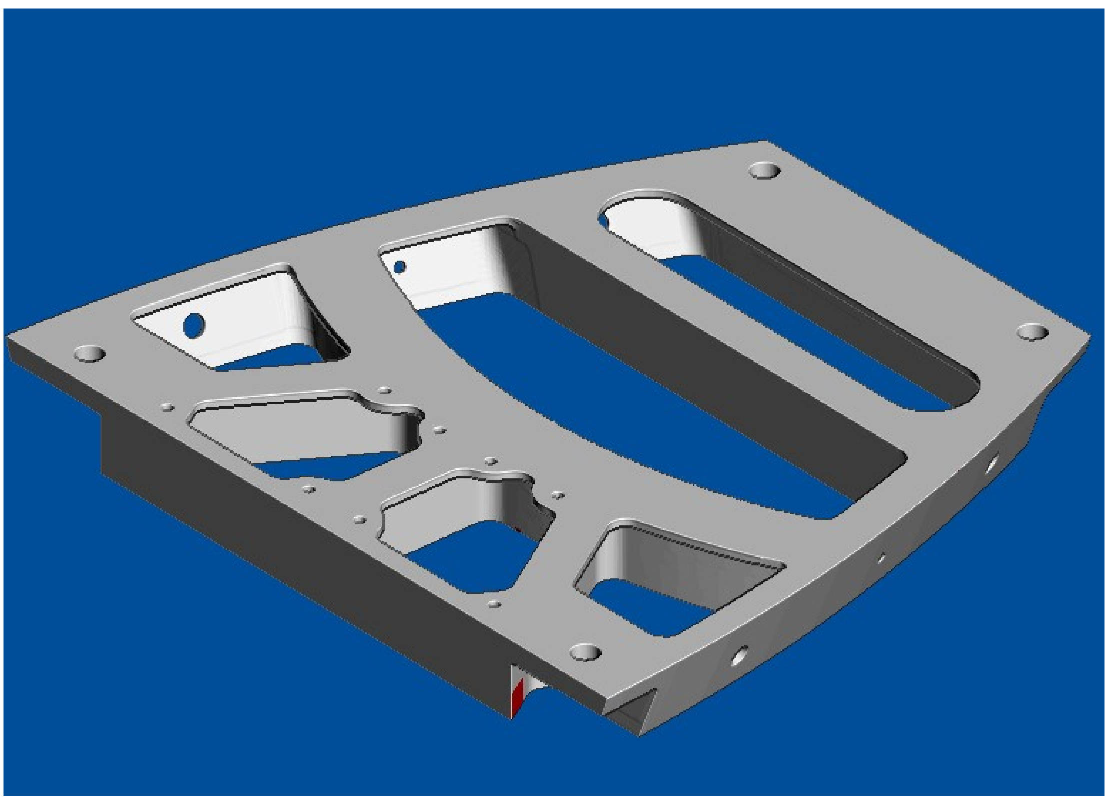


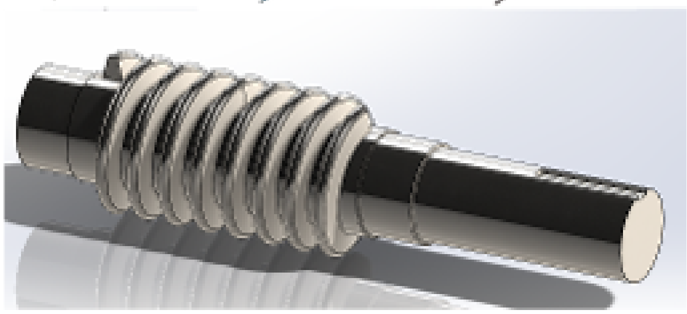
Figure 30. Final product ISO view 4

E-JOBS

We do it better

E-Jobs always stands to the height of its motto. In E-Jobs, we can machine a better gear for you. The gear either its bevel, Rack and pinion or Worm gear, we will make it perfect for you, because we aim to make our client 'Wow!'.

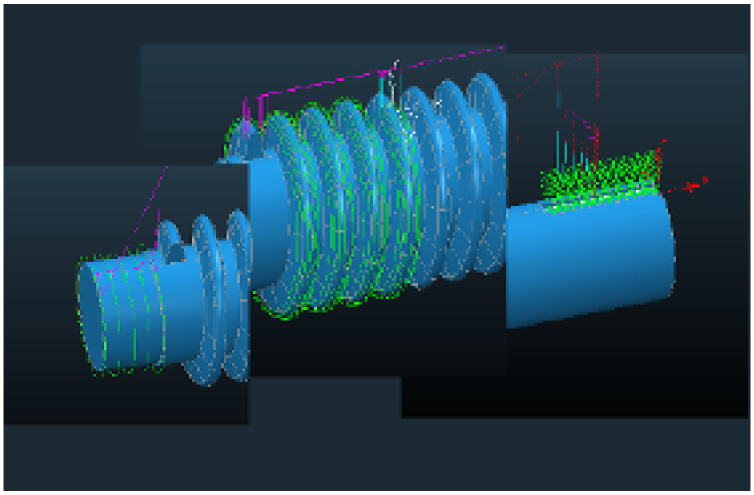
E-Jobs make itself open to the use any brands tools.



TOOLS USED FOR THE BELOW PROCESS

1. APT 4mm Diameter 4 Flute 75mm Long (SC4LS-04040075-550)
2. APT Long Neck Ball Nose 1mm Diameter 16mm Neck Length 50mm Long (EHLN2B-04R0.5-N16-50)
3. APT 1mm Diameter 2 Flute General Use End Mill (2SEM-04010050-450)

PROCESS OVERVIEW



Our quality of finishing can be predicted from our approach.

By dividing the small worm gear in a eleven number of surfaces and then each surface is having its own toolpath to machined.

Roughing – all the eleven surfaces are rough machined with the tools mentioned above. Used Tool 1 surface of the gear, whereas, Tool 2 is used for the worms of the gear and Tool 3 for the keyway.

Finishing – when the stepdown is as small as 0.1mm then of course it is finishing. All the toolpaths of finishing are covered with the Tool 2, except the keyway which was done with Tool 3.

Section 3: Machining process of a watch body

1. Introduction

In this section, the complete machining process of a watch body is going to be narrated. The finalised product is shown in Figure 31. It is designed by Dr Hood and machined by Group 1. The designer of the watch has already chosen some parameters for machining of the watch, shown in Table 14. Moreover, the machining is done on Matsuura LX1 CNC machine. Two toolpaths were used to produce the machined product, which are roughing and finishing. Additionally, the machining process took several steps to manufacture the watch. These steps are divided into three phases, namely as pre-machining, machining and post machining. These steps will be elaborated below.

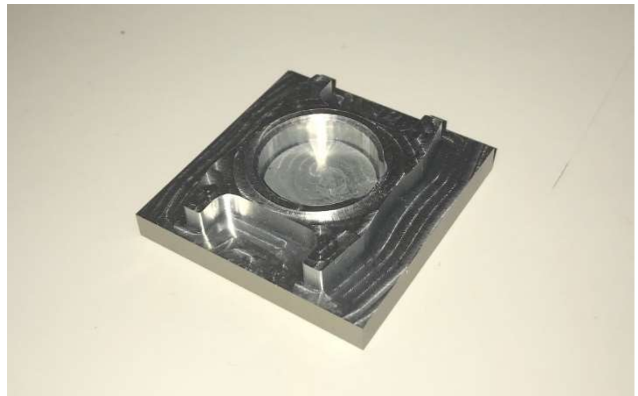


Figure 31. Final product after finishing process

Table 14. Parameters given

Cutting tool	6.0mm diameter End mill with 4 flutes
Spindle speed	10,000rpm
Feed rate	0.05mm/tooth
Depth of cut	0.5mm
Stepover/width of cut	2.0mm

2. Material and Equipment

The tool used for this process was already selected by the designer, Dr Hood, which was a four flute, 6mm diameter end-mill tool, shown in Figure 32. The workpiece prototype material available was 50×50×20mm in dimension.

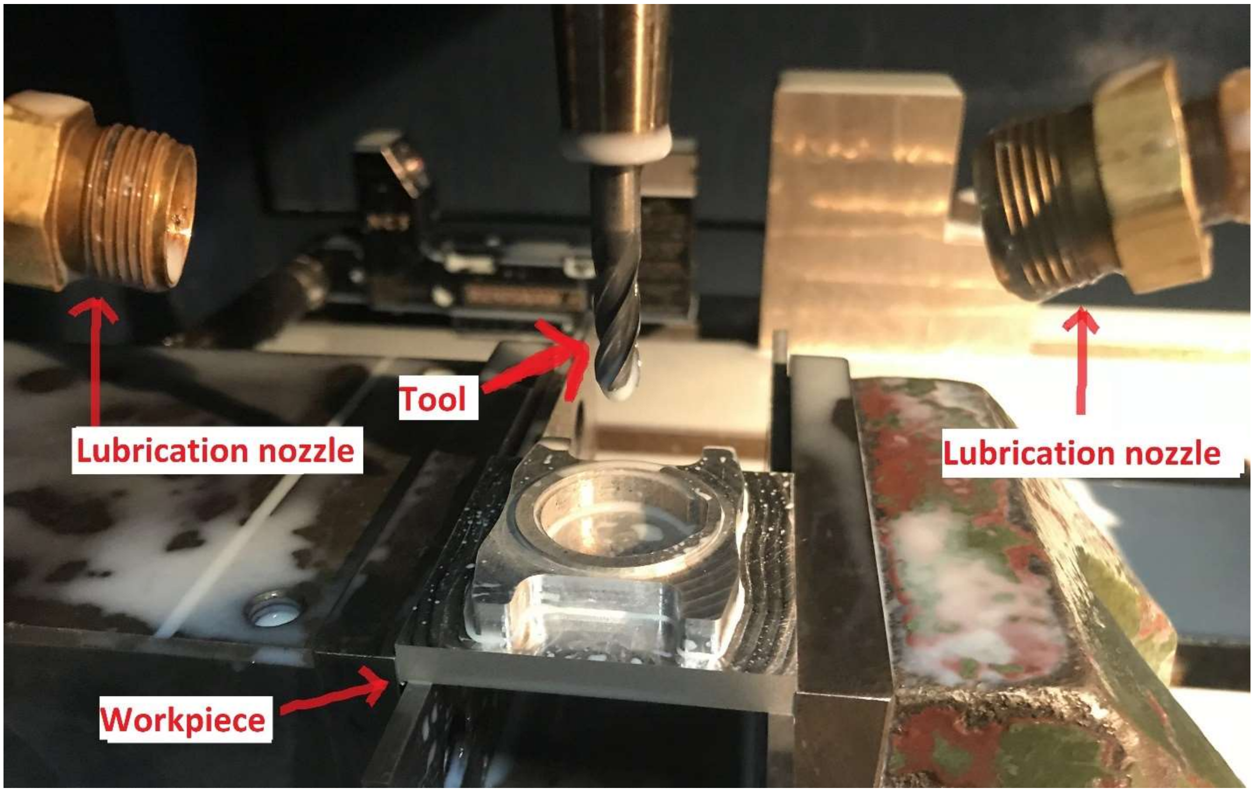


Figure 32. Workpiece in the machine after roughing

3. Pre-Machining phase

In this phase, a machining strategy was designed in the CAM software PowerMill to generate the toolpath strategies and the NC program for the machining process.

The parameters given by the designer are shown in Table 14.

3.1. Block

The block in PowerMill was created according to the 50×50×20mm in dimension (given).

3.2. Toolpaths

There were only two toolpaths used, namely roughing and finishing.

3.2.1. Roughing

For roughing, a Model Area Clearance toolpath strategy was used to slice rapidly the excess material from the workpiece and leaving 0.5mm thickness behind. In addition, the stepover and stepdown used in this toolpath are given. To obtain a good result from the high-speed machining process, the toolpath style was set to offset model [1].

3.2.2. Finishing

Steep and Shallow toolpath was used for the finishing stage of the machining process and the remaining thickness after machining was set to zero. The steep and shallow strategy uses slicing of a model at a constant height of Z-axis in the steep regions of the model and uses offset style toolpath in the shallow regions of the model [6].

3.3. NC Program

After creating a complete model and validating it through simulation with the help of PowerMill. The last step was creating a NC program from the model. And this NC program was then exported to the computer connected to the CNC machine.

4. Machining phase

Matsuura LX 1 CNC machine was used to machine the watch. First, three steps should be taken for a setup of the CNC machine. These three steps are:

1) Calibration of the measuring probe of the machine. In Figure 33 shows the block with which the probe was calibrated.
2) Setting the datum point of the workpiece, which was the centre of the workpiece in this case.
3) And the last one is measuring the tool geometry and condition with built-in laser apparatus inside the CNC machine, shown in Figure 33.

Figure 33

After the setup is complete the NC program file, which is exported from the PowerMill software, is fetched by the CNC machine and executed. The roughing toolpath takes 20mins to get completed. The CNC machine uses a lube, which consists of 7% oil and 93% water, the nozzles of the lubricant that can be seen in Figure 32. And the finishing process took 5mins to get completed and the result can be seen in Figure 31.

5. Post Machining phase

After the workpiece is fully machined, the dimensions need to be checked. And for that, the Mitutoyo Euro-C-A544 coordinate measuring machine was used. To measure the dimensions of the workpiece, the probe of the machine was calibrated with a ceramic ball of diameter of 19.9913mm, shown in Figure 34.

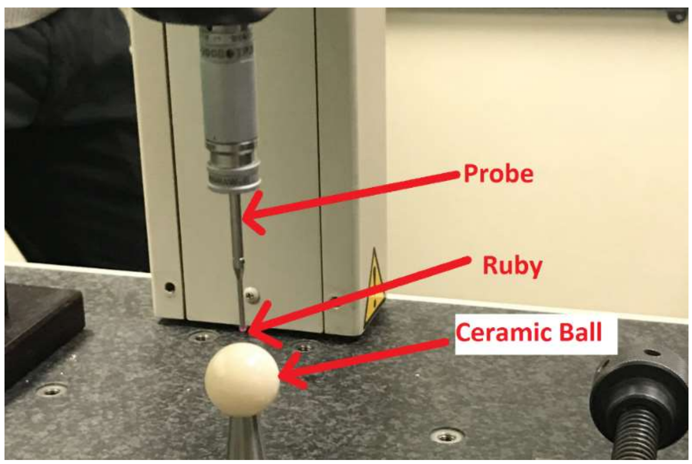


Figure 34

6. Results and discussion

The measurements taken are presented in a Table in Appendix A for detail see the excel file attached. For 18 different parameters the measurements are taken and every measurement is taken three times. The table presents the description; type (diameter or length); how the measurement was taken; nominal value; upper and lower tolerances and deviation of measurement from the nominal value.

All the measurements are between the tolerance range except the right circle diameter, left circle diameter and centre height length. The lower tolerance of right circle diameter should not be more than -0.100mm. However, the measurement shows that it has a deviation of -5.713mm (average of all three readings), which is slightly more than the lower tolerance. Furthermore, the left circle diameter should have lower tolerance of -0.100mm, whereas, it is having a deviation of -6.150mm, which is also more than the required tolerance. In addition, the centre height does not have to be any bigger than the nominal size. However, the measured workpiece shows a difference of 9 micrometres. Despite this difference, the overall finished product is acceptable and the micrometre differences can be ignored.

7. Conclusion

It is concluded that only two toolpaths with the use of state-of-the-art CNC machine and coordinate measuring machine, are enough to get a required watch model, which results in a very small tolerance differences.

Section 4: Statistical Process Control

1. Introduction

In this section, a quality control check is made on ten number of watches, which are machined. The data of central diameter of the watch body, centre height (Z-height), the x position measurements (X-distance) and y position (Y-distance) measurements are given in the provided table in Appendix B. The control charts for every dimension should be produced and CP and CPk values are to be calculated. In addition, a critical analysis needs to be made on the result produced.

2. Methodology

To find the process capability some steps must be followed. The very first step is to find the control charts, which tell whether the process is in statistical control or not. If the process is not statistically stable there is no need to go further because the process is not predictable and consistent. Hence it is not possible to find the process capability. [7]

Once the process control charts are found, the new step to be taken is to construct the histogram and compare the results to specification, which are set externally set by a customer. The histogram will show whether the process is meeting its specification or not. [7]

After the histogram, the next step is to find out the natural variation of the process. It is also called "Natural Process Limits". But in this case, the customer (Dr Hood) provided the limit values. These values can be used to find Mean and Standard deviation (StDev). [7]

The next step is to find CP and CPk values. It can be found by using the formulae below.

$$CP = \frac{Upper\ limit - Lower\ limit}{6 \times StDev}$$

$$CPk = min\left[\frac{Upper\ limit - Mean}{3 \times StDev}, \frac{Mean - Lower\ limit}{3 \times StDev}\right]$$

If the control charts are not consistent and predictable, it's CP an CPk does not mean anything. [7]

3. Result and discussion

The Figure 35, Figure 36, Figure 37 and Figure 38 show the control charts of the Diameter, Z-height, Y-distance and X-distance. Table 15 shows the CP and CPk values of all the dimensions.

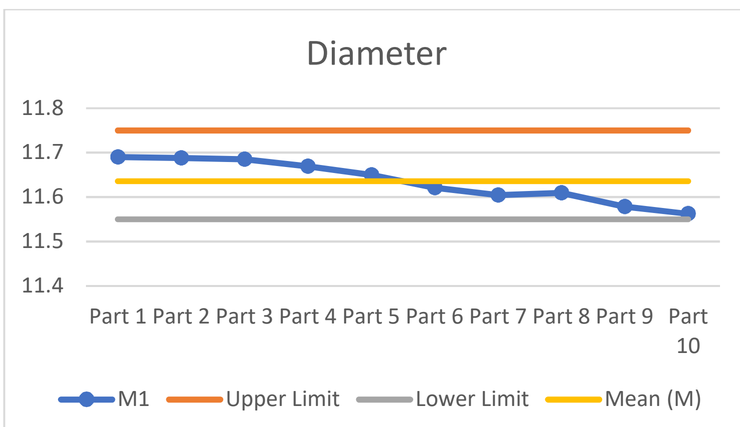


Figure 35. Control chart for Diameter

The control chart of Diameter shows a continuing decreasing trend and is not a normal variation. Therefore, it tends for investigation for that special cause of variation because this type of trend gradually increases or decreases the average of the process. In machining process, the special cause associated with this type of trends are usually tool varying, temperature change etc [8]. Therefore, the control chart shows that the process for diameter is not in control and not predictable. The CP and CPk values for diameter are of no meaning.

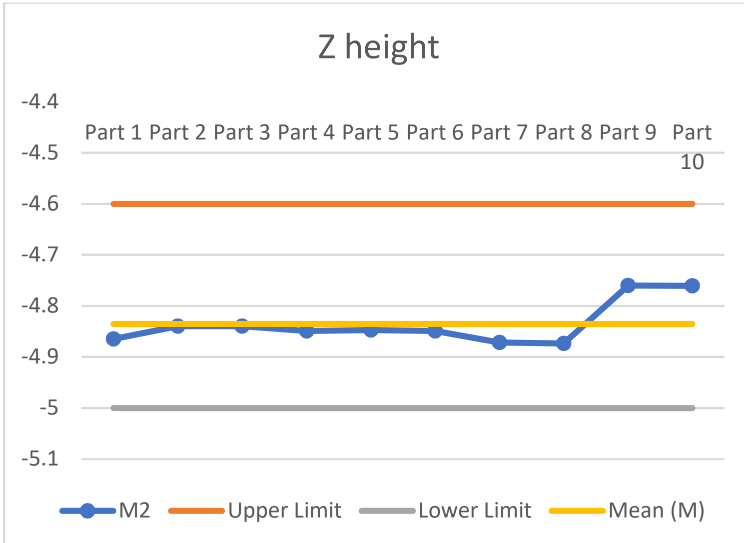


Figure 36. Control chart for Z-height

Similarly, the Z-height control chart has a run of 5 points under the mean line. Therefore, the process is not in control and hence it needs investigation for the cause of assignable variation. This is small shifts from the average and the most probable reasons for these types of patterns are change in setup procedure, human - change in the operator, change in work instruction etc. [8]. Therefore, the process being not consistent and predictable, hence, its CP and CPk values are of no use.

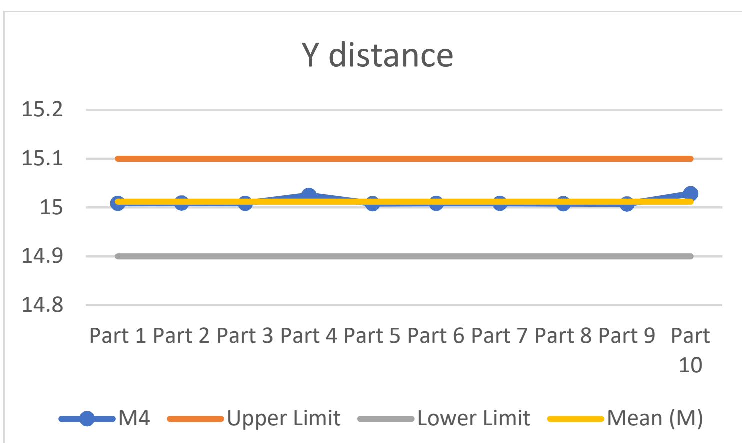


Figure 37. Control chart for Y-distance

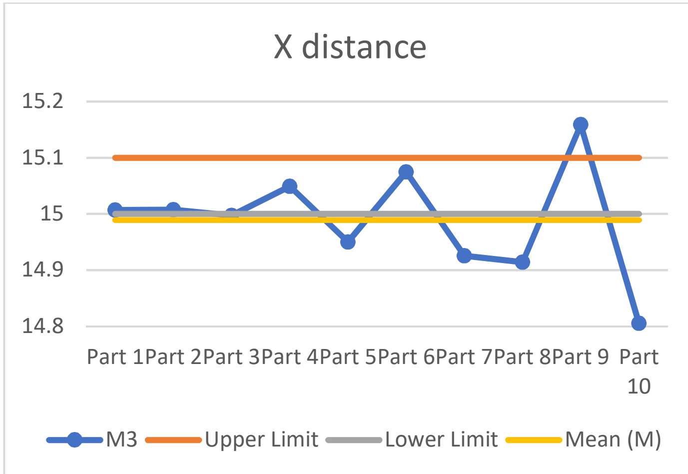


Figure 38. Control chart for X-distance

Table 15. Cp and Cpk values

Processes	Upper limit	Lower Limit	Mean	StDev	Cp	Cpk
Diameter	11.75	11.55	11.64	0.04	0.74	0.63
Z-height	-4.6	-5	-4.83	0.04	1.68	1.38
Y-distance	15.1	14.9	15.01	0.02	1.32	1.17
X-distance	15.1	15	14.98	0.09	0.18	-0.04

The control chart of Y-distance is pretty much converged to it mean line and in showing a perfect pattern of being control and consistent. This pattern is often called tempering. And the most common cause of this pattern is tempering done by an operator [8]. However, the process is in the control limits hence, it is in consistent and predictable. Therefore, its histogram in Figure 39 shows that the process is in limits, which are set by the customer (Dr Hood). Therefore, if the process' control chart is in control and the histogram is within the limits, it is proved that the process is working. The CP and CPk values for the Y-distance are shown in Table 15. The CP value for Y-distance is greater than 1, So the process can meet the required specification [8]. Furthermore, it can be seen from the histogram that the process is not centred as required by the nominal value of customer and it is closer to the upper limit. Therefore, we have less room on that side of the range.

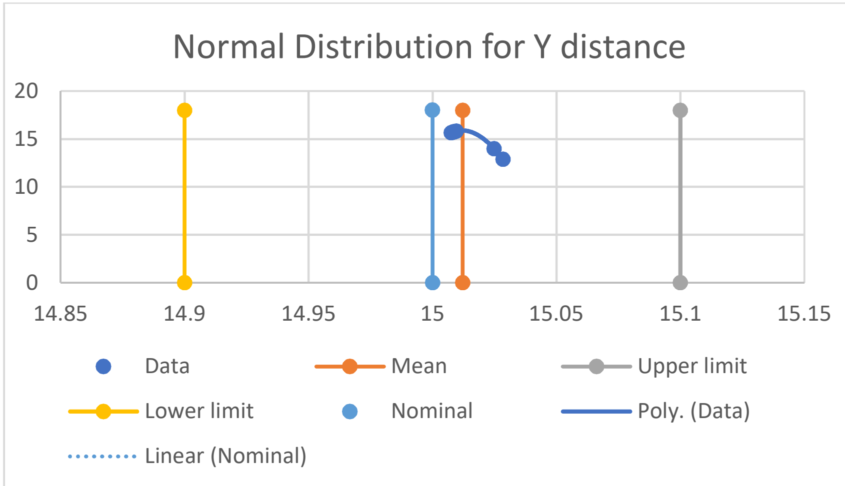


Figure 39. Histogram for Y-distance

On the other hand, the control chart of X-distance is also out of control and it's not statistically stable. Therefore, its CP and CPk value are of no use.

4. Conclusion

It is concluded that only the Y-distance is in statistical control and predictable process. On the other side, all the other processes are not controlled and predictable, therefore, their CP and CPk values have no meaning.

References

1. Ltd., Y.M.U. *Mazak VARIAXIS i-600 Siemens*. 2014; Available from: https://www.mazakeu.co.uk/machines/variaxis-i-600-siemens_/.
2. Solutions, S.M. *Seco Tools Ltd*. 2017; Available from: https://www.secotools.com/.
3. Inc., M. *Introduction to Selecting Milling Tools* 2018; Available from: https://www.machiningcloud.com/wp-content/uploads/2016/05/MachiningCloud_SelectingMillingTools.pdf.
4. Prasad, N.E. and R. Wanhill, *Aerospace Materials and Material Technologies*. 2017: Springer.
5. Coromant, S. *Sandvik Coromant online catalogue 2017 released*. 2017; Available from: https://www.sandvik.coromant.com/en-gb/news/pages/main-catalogue-2017-released.aspx.
6. Inc., A. *PowerMill User Guide*. 2018.
7. BPI Consulting, L. *Cpk Alone is Not Sufficient*. 2014, April; Available from: https://www.spcforexcel.com/knowledge/process-capability/cpk-alone-not-sufficient.
8. BPI Consulting, L. *Control Chart Rules and Interpretation*. 2016, March; Available from: https://www.spcforexcel.com/knowledge/control-chart-basics/control-chart-rules-interpretation.

Appendix A

Measurement code	Description	Type	Notes	Nominal value	Upper tolerance	Lower tolerance	Deviation from Nominal			% Deviation from Nominal			Average of deviation
							Repeat 1	Repeat 2	Repeat 3	Repeat 1	Repeat 2	Repeat 3	
				mm	*mm*	*mm*	*mm*	*mm*	*mm*	*%*	*%*	*%*	*mm*
A	Centre circle	Circle diameter	20 points, z height -2mm	22.950	0.100	-0.100	-0.038	-0.037	-0.038	0.001656	0.001612	0.001656	-0.038
B	Centre circle	Circle diameter	20 points, z height -4mm	22.950	0.100	-0.100	-0.054	-0.054	-0.054	0.002353	0.002353	0.002353	-0.054
C	Right circle	Circle diameter	5 points	100.000	0.100	-0.100	-6.444	-5.570	-5.126	0.06444	0.0557	0.05126	-5.713
D	Left circle	Circle diameter	5 points	100.000	0.100	-0.100	-7.200	-5.259	-5.991	0.072	0.05259	0.05991	-6.150
E	Front left length	Length	2mm below datum	22.000	0.100	-0.100	0.011	0.012	0.013	0.0005	0.000545	0.000591	0.012
F	Front right length	Length	2mm below datum	22.000	0.100	-0.100	0.006	0.007	0.006	0.000273	0.000318	0.000273	0.006
G	Back left length	Length	2mm below datum	22.000	0.100	-0.100	0.010	0.009	0.009	0.000455	0.000409	0.000409	0.009
H	Back right length	Length	2mm below datum	22.000	0.100	-0.100	0.015	0.015	0.015	0.000682	0.000682	0.000682	0.015
I	Left length	Length	2mm below datum	44.000	0.100	-0.100	0.021	0.021	0.022	0.000477	0.000477	0.0005	0.021
J	Right length	Length	2mm below datum	44.000	0.100	-0.100	0.015	0.016	0.015	0.000341	0.000364	0.000341	0.015
K	Front strap	Length	2mm below datum	15.000	0.100	-0.100	0.005	0.004	0.004	0.000333	0.000267	0.000267	0.004
L	Back strap	Length	2mm below datum	15.000	0.100	-0.100	0.007	0.007	0.006	0.000467	0.000467	0.0004	0.007
M	Timing location	Length	2mm below datum	13.000	0.100	-0.100	-0.003	-0.003	-0.001	0.000231	0.000231	7.69E-05	-0.002
N	Centre height	Length		5.000	0.000	-0.005	0.008	0.009	0.009	0.0016	0.0018	0.0018	0.009
O	Front left height	Length		5.000	0.015	-0.010	-0.001	-0.002	-0.002	0.0002	0.0004	0.0004	-0.002
P	Front right height	Length		5.000	0.015	-0.010	-0.002	0.000	0.000	0.0004	0	0	-0.001
Q	Back left height	Length		5.000	0.015	-0.010	-0.002	-0.002	-0.001	0.0004	0.0004	0.0002	-0.002
R	Back right height	Length		5.000	0.015	-0.010	-0.002	-0.002	-0.002	0.0004	0.0004	0.0004	-0.002

Appendix B

Diameter	Measurement	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10
		mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
Operator A	1	11.69	11.691	11.685	11.67	11.652	11.62	11.6	11.61	11.581	11.56
Operator A	2	11.691	11.69	11.7	11.67	11.651	11.624	11.62	11.61	11.58	11.56
Operator A	3	11.67	11.69	11.684	11.671	11.641	11.62	11.599	11.608	11.581	11.56
Operator B	1	11.69	11.68	11.685	11.67	11.652	11.62	11.602	11.611	11.58	11.559
Operator B	2	11.691	11.688	11.687	11.662	11.651	11.624	11.6	11.61	11.57	11.56
Operator B	3	11.697	11.688	11.684	11.671	11.647	11.617	11.62	11.61	11.579	11.561
Operator C	1	11.69	11.688	11.685	11.67	11.652	11.62	11.6	11.61	11.581	11.561
Operator C	2	11.691	11.69	11.671	11.67	11.65	11.624	11.607	11.61	11.58	11.56
Operator C	3	11.7	11.688	11.684	11.67	11.65	11.62	11.591	11.608	11.577	11.58

Z height	Measurement	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10
		mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
Operator A	1	-4.863	-4.84	-4.84	-4.844	-4.84	-4.848	-4.872	-4.875	-4.76	-4.76
Operator A	2	-4.861	-4.841	-4.84	-4.847	-4.85	-4.847	-4.872	-4.872	-4.76	-4.76
Operator A	3	-4.858	-4.84	-4.84	-4.844	-4.851	-4.848	-4.872	-4.873	-4.76	-4.76
Operator B	1	-4.87	-4.839	-4.838	-4.862	-4.84	-4.861	-4.87	-4.875	-4.76	-4.76
Operator B	2	-4.871	-4.839	-4.839	-4.861	-4.85	-4.846	-4.87	-4.872	-4.761	-4.76
Operator B	3	-4.875	-4.839	-4.838	-4.851	-4.851	-4.846	-4.87	-4.873	-4.76	-4.76
Operator C	1	-4.863	-4.839	-4.84	-4.844	-4.84	-4.848	-4.872	-4.875	-4.76	-4.76
Operator C	2	-4.861	-4.841	-4.84	-4.847	-4.85	-4.847	-4.872	-4.872	-4.76	-4.765
Operator C	3	-4.858	-4.84	-4.84	-4.844	-4.851	-4.848	-4.872	-4.873	-4.76	-4.76

X distance	Measurement	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10
		mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
Operator A	1	15.008	15.009	14.994	15.045	14.95	15.075	14.925	14.91	15.15	14.801
Operator A	2	15.007	15.009	14.994	15.048	14.95	15.074	14.925	14.91	15.15	14.805
Operator A	3	15.01	15.008	14.995	15.05	14.95	15.076	14.924	14.915	15.16	14.8
Operator B	1	15.006	15.005	14.998	15.05	14.949	15.078	14.926	14.915	15.167	14.805
Operator B	2	15.007	15.006	14.999	15.052	14.948	15.079	14.924	14.914	15.16	14.805
Operator B	3	15.006	15.005	14.998	15.049	14.951	15.072	14.927	14.913	15.16	14.804
Operator C	1	15.004	15.009	14.999	15.05	14.953	15.07	14.925	14.92	15.159	14.81
Operator C	2	15.007	15.009	15	15.05	14.95	15.075	14.925	14.915	15.162	14.811
Operator C	3	15.007	15.01	14.999	15.05	14.95	15.076	14.928	14.915	15.163	14.81

Y distance	Measurement	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10
		mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
Operator A	1	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.005
Operator A	2	15.007	15.006	15.007	15.008	15.007	15.007	15.007	15.007	15.004	15.005
Operator A	3	15.01	15.018	15.011	15.015	15.01	15.01	15.011	15.01	15.01	15.006
Operator B	1	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.008
Operator B	2	15.01	15.006	15.006	15.004	15.007	15.01	15.007	15.007	15.006	15.2
Operator B	3	15.01	15.008	15.011	15.015	15.01	15.01	15.011	15.01	15.01	15.01
Operator C	1	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.008	15.008
Operator C	2	15.007	15.006	15.007	15.008	15.007	15.007	15.007	15.007	15.004	15.004
Operator C	3	15.01	15.018	15.011	15.15	15.01	15.01	15.011	15.01	15.01	15.01

Appendix C

$$RPM = n = \frac{v_c \times 1000}{\pi \times D_c}$$

$$v_f = n \,.\, z_n \,.\, f_z$$

Where,

n = RPM (rev/min)

v_c = cutting speed (m/min)

D_c = cutter diameter

v_f = feed speed (mm/min)

z_n = No. flutes

f_z = feed per tooth (mm/tooth)