CAM Routine for Generative Design Component

Stock

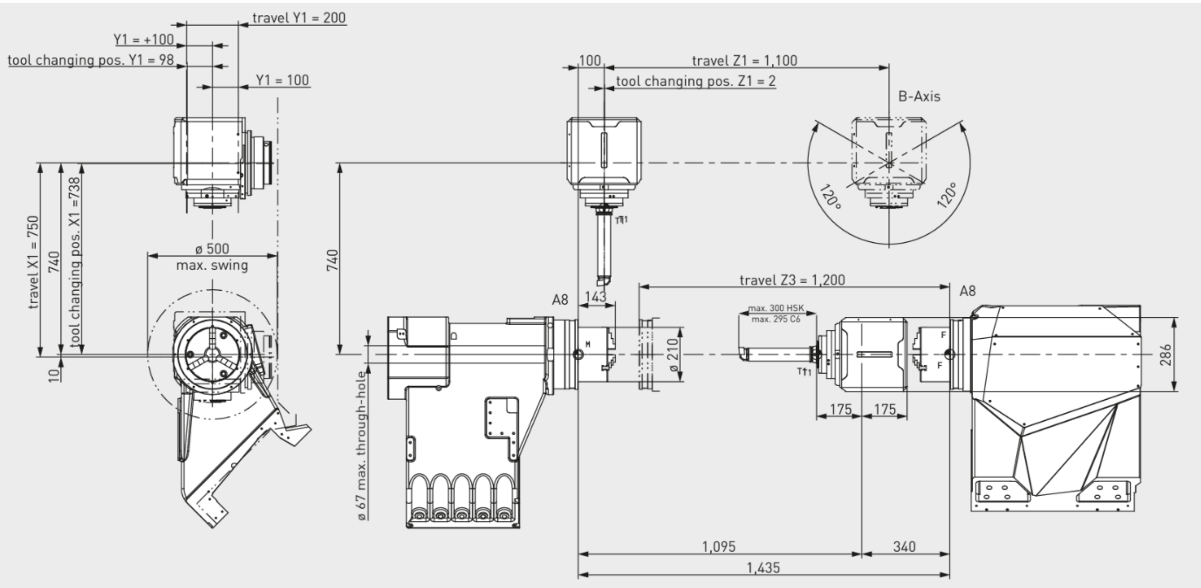
Shape and Dimensions: Stock chosen for this part is 110 mm diameter cylinder stock with a length of 330 mm.

Material: The material specification is confidential, but it shares properties with medium/high alloy and duplex stainless steels. Therefore, cutting speed and feeds are referenced based on high-alloy austenitic and duplex stainless-steel standards. ISO workpiece material code is **M4** and colour code is yellow.

Surface Finish and Tolerance: Surface finish and tolerance are currently not important as datums will be defined at a later stage.

Machine Tool

The optimal machine tool for this part is a turn mill with a chuck on the sub-spindle, as it reduce the number of setups and automates the process. The DMG MORI CLX 450 TC, equipped with an optional sub-spindle, is selected for this purpose. The working length of this machine tool is 1,435 mm, with both the main spindle chuck and sub-spindle chuck measuring 143 mm in length. Consequently, the effective turning length is 1,100 mm after accounting for chuck lengths. The turning head has a length of 350 mm, and the gauge length of the longest tool, a 300 mm drill bit, is 380 mm. This calculation results in a maximum stock length for axial machining of 370 mm, calculated as 1,100 mm - 350 mm - 380 mm.



Source: https://en.dmgmori.com/products/machines/turning/turn-mill/clx-tc/clx-450-tc

Figure 1: Description of machine tool work area

Machine Tool Setup: Since the DMG MORI CLX 450 TC machine tool isn't available in Fusion's tool library, a new machine tool is added. Under the capabilities tab, both turning and milling capabilities are selected, and the automatic tool changer is checked. The number of tools is set to 30, and the maximum feed rate is set to 40,000 mm/min. Moving to the kinematics tab, C-axis rotation is set to table, and the motion of Z, X, Y, and A is configured to the head in the specified order. In the post-processing tab, the DMG MORI NLX MILL-TURN post processor is selected, and the setup is saved to the local library.

Tools and Holders

The tools used for all three setups and their recommended feeds and speeds are provided in Appendix A. Since the selected machine tools only accept Capto C6 size tool holders, C6 holders for each tool are also listed in Appendix A.

Tools are manually added to the tool library, with their geometry information sourced from the manufacturer's website. Cutting speed and feed rates for each operation are also available for various materials. The detailed 3D models of the tool holders are available on the manufacturer's website. These models are then installed in the tool library using the "holderCreatorNEW" script provided by NYCCNC.

Fixturing

Since our stock is cylindrical so machine self-centring 3 jaw chuck is used as fixture.

Datum

For Setup 2, the machined OD and face of the stock were used as the datum. In Setup 3, the finished bottom face and the OD of the **model** served as the datum.

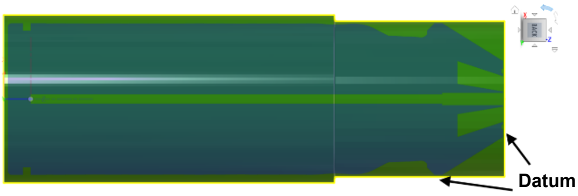


Figure 2: Datum for Setup 2

Figure 3: Datum for Setup 3

Design

The CAD file (Part design) and a three-jaw chuck are imported into the same file as internal components. The origin is then relocated to the centre of the bottom face of the model. Following this, the three-jaw chuck is assembled with the model at the bottom side using a rigid joint. Right, top, and front faces are described according to Figure4.

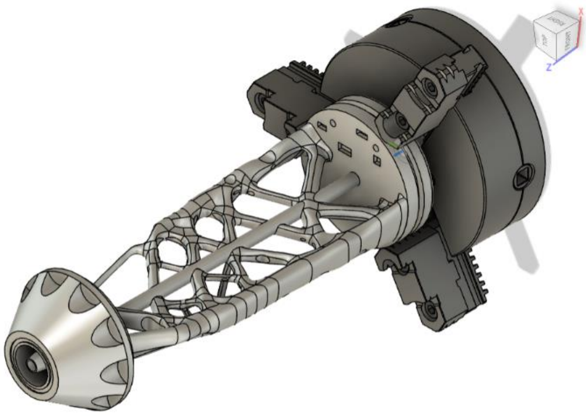


Figure 4: Depiction of Top, Front and Right Faces

Manufacture

The units were set to millimetres (mm) throughout the process. An image of each operation is provided with an orientation reference.

Setup 1: Front

A new setup was created and named "front." The machine was selected from the local library, i.e. DMG MORI CLX 450 TC. The operation type was designated as "Turning or Mill/Turn," with the primary spindle chosen. Orientation and origin were left as model orientation and model origin, respectively. The model and fixture were specified accordingly. Under the stock tab, a fixed-sized cylinder was selected, with the stock diameter set to 110 mm and the length to 330 mm.

OP 1: Turning Face

The "turning face" operation was selected from the Turning tab. Under the tool tab, tool T1 (Insert: DNMU110404-FF2 CP500, Holder: C6-DDNNN-00065-11-M) and preset M4 were chosen. Coolant mode was set to "Flood and through tool." Since the hand of the tool is neutral, a tool orientation of 51 degrees was applied. In the geometry tab, "model front" was selected. In the passes tab, 0.5 mm of axial stock was left for the finishing pass. In the linking tab, the retraction policy was set to minimum.

OP 2: Turning Profile Roughing

The "turning profile roughing" operation was selected from the Turning tab. Tool T1 (Insert: DNMU110404-FF2 CP500, Holder: C6-DDNNN-00065-11-M) and preset M4 were chosen under the tool tab. Coolant mode was set to "Flood and through tool." Since the hand of the tool is neutral, a tool orientation of 39 degrees and a tool front clearance of 6 degrees were applied. Under the geometry tab, the back mode was offset 215 mm from the model back, and the inner height was set to 51 mm. In the passes tab, 0.5 mm of axial stock was left for the finishing pass. The cycle and direction were set to horizontal passes and front to back, respectively. This front face and OD are used as the datum for the next operations i.e. Setup 2.

OP 3: Subspindle Grab

To machine the back side of the model, the stock must be transferred to the secondary spindle. Therefore, the "sub spindle grab" operation was selected from the Turning tab. The stock front was chosen as the grab plane mode with an offset of -46 mm. Additionally, a dwelling period of 3 seconds was set.

OP 4: Subspindle Return

The "Sub spindle return" operation was selected from the Turning tab. The stock front was designated as the return plane mode with an offset of 0 mm. Additionally, a dwelling period of 3 seconds was set. Furthermore, the "Unclamp primary spindle" option was selected from the "Open spindle chucks" menu.

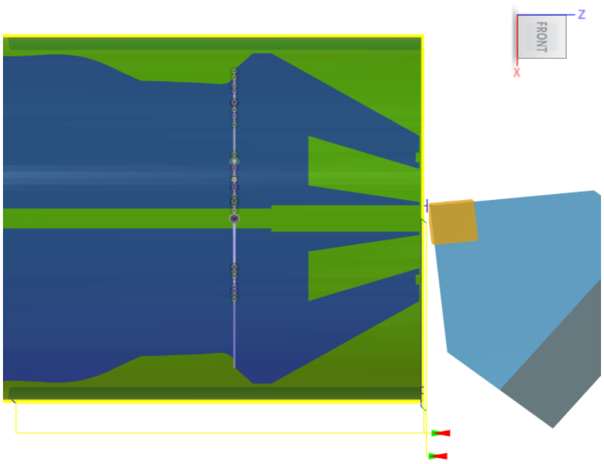


Figure 6: Facing and turning operation (i.e. 1&2)

Figure 5: Operation 3 position of chuck

Setup 2: Back

A new setup was created and renamed to “Back”. The machine from the local library (i.e., DMG MORI CLX 450 TC) was selected. The operation type was set as “Turning or Mill/Turn”. The spindle was switched to the secondary spindle. The origin was left at the model origin, and the flip Z axis checkbox was checked. "Model to surface" was selected for orientation selection. The chuck was offset 46 mm from the stock back to maximize rigidity, as the clamping distance of the chuck is 46 mm. Under the stock tab, "From preceding step" was selected, and "Continue rest machining" was turned on.

OP 5: Turning Face

Turning face operation was selected from the Turning tab. Tool T1 (i.e., Insert: DNMU110404-FF2 CP500, Holder: C6-DDNNN-00065-11-M) and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood and through tool”. Since the hand of the tool is neutral, a tool orientation of 51 degrees was applied. In the geometry tab, model back was selected with an offset of 0 mm. In the passes tab, 0.5 mm axial stock was left for the finishing pass. In the linking tab, the retraction policy was set to minimum.

OP 6: Turning Profile Roughing

Turning profile roughing operation from the Turning tab was selected. Tool T1 (i.e., Insert: DNMU110404-FF2 CP500, Holder: C6-DDNNN-00065-11-M) and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood and through tool”. Since the hand of the tool is neutral, a tool orientation of 39 degrees and a tool front and back clearance of 6 degrees were applied to avoid gouging. In the geometry tab, the back mode was offset 270 mm from the model back. Rest machining was set to “From previous operation(s)”. The inner height was set to 47.5 mm from the stock ID. In the passes tab, 0.5 mm axial and radial stock were left for the finishing pass. The cycle and direction were set to horizontal passes and front to back, respectively, and grooving was turned off.

OP 7: Turning Profile Finishing

Turning profile finishing operation from the Turning tab was selected to finish the face. Tool T2 (i.e., Insert: SNMG120408-MR7 TP40, Holder: C6-DSDNN-00065-12-M) and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood and through tool”. Since the hand of the tool is neutral, a tool orientation of 32.5 degrees was applied. In the geometry tab, the back mode was offset 325 mm from the model back (i.e., bottom surface of the model), and the front mode was offset 0.5 mm from the model front. Rest machining was set to “From previous operation(s)”. The outer radius was exactly equal to the model OD. The stepover distance was set to 0.125 mm, and the number of stepovers was 2. The direction was set from front to back, and grooving was turned off.

OP 8: Turning Profile Finishing

Turning profile finishing operation from the Turning tab was selected to work on the sides and corner radius. Tool T2 (i.e., Insert: SNMG120408-MR7 TP40, Holder: C6-DSDNN-00065-12-M) and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood and through tool”. Since the hand of the tool is neutral, a tool orientation of 57.5 degrees was applied. In the geometry tab, the back mode was offset 270 mm from “model back”, and the front mode was set to 0 mm from “model front”. Rest machining was set to “From previous operation(s)”. The inner radius was set to 47.5 mm (i.e., exactly equal to the bottom face of the model). The stepover distance was set to 0.25 mm, and the number of stepovers was 2. The direction was set from front to back, and grooving was turned off. This bottom face and OD were used as the datum for the next operations i.e. Setup 3.

OP 9: Turning Groove

Turning groove operation from the Turning tab was selected to turn the groove. Tool T3 (i.e., Insert: 20ER5.0FG CP500, Holder: C6-CER-45065-20HD) and preset M4 were chosen under the tool tab. Coolant mode was set to "Flood and through tool". Turning mode was set to outside grooving. In the geometry tab, the front and back were set 1 mm on either side of the groove. Rest machining was set to "From previous operation(s)". The stepover distance was set to 1 mm, and "Even stepovers" was checked. The pecking option was turned on, and the pecking depth was set to 1 mm.

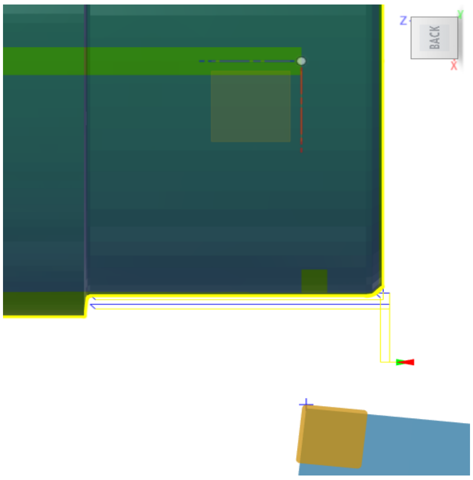


Figure 7: Finishing Operation (i.e. 7 and 8)

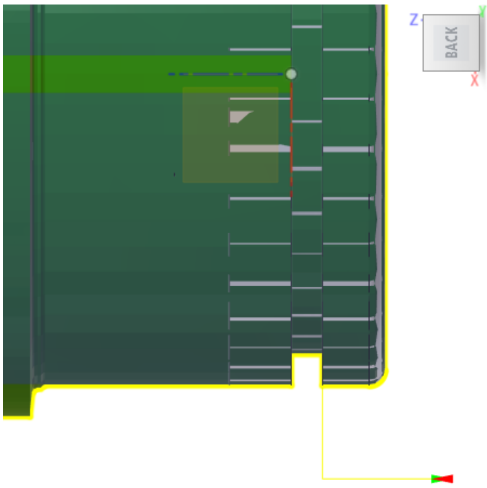


Figure 8: Operation 9 Grooving

OP 10: Drilling

Drill operation from the Milling tab was selected. A recommended pre-machined hole diameter for the M6 machine tap is 5.1 mm; therefore, a Ø 5.1 mm drill bit was chosen for this operation. Tool T5 (i.e., Tool: SD1105A-0500-035-06R1, Holder: C6-HC06-065) and preset M4 were selected under the tool tab. Coolant mode was set to "Flood". In the geometry tab, one of six holes was selected, and "Select same diameter" was checked. The bottom height was set to "Hole bottom". "Drill tip through bottom" was turned on, and the breakthrough depth was set as 5 mm. The cycle type was set as "Chip breaking – partial retract", and the pecking depth was set to 1.275 mm (i.e., 25% of the tool diameter).

OP 11: Tapping

Drill operation from the Milling tab was selected for tapping threads using a right-hand M6 machine tap. Since the shank of this tool is not cylindrical, a collet in combination with a collet chuck is used to adapt it to a Capto C6 holder. Tool T8 (i.e., Tool: MTP-M6X1.00ISO6H-TB-M003-A, Collet: 393.14-11D060X049, Collet Chuck: 54501612R, Holder: C6-HC16-085) and preset M4 were selected under the tool tab. Coolant mode was set to "Flood". In the geometry tab, one of six holes was selected, and "Select same diameter" was checked. Bottom height was set to "Hole bottom". "Drill tip through bottom" was turned on, and break-through depth was set as 2 mm. Cycle type was set as "Tapping with chip breaking", and pecking depth was set to 1.5 mm.

OP 12: Subspindle Grab

The stock was moved back to the primary spindle to machine the front. Sub-spindle grab operation was selected from the Turning tab to transfer the stock to the main spindle. "Stock back" was selected as the grab plane mode with an offset of -46 mm. The dwelling period was set at 3 seconds. As shown in Figure 10.

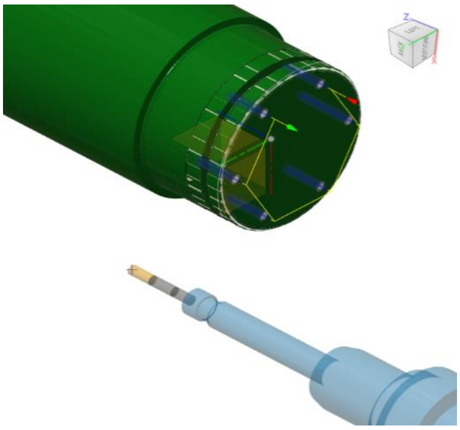


Figure 9: Depiction of model after operation 12

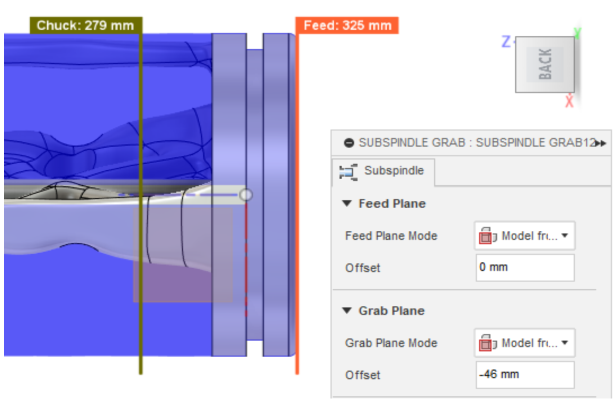


Figure 10: Position of Chuck for setup 3

OP 13: Subspindle Return

Sub-spindle return operation was selected from the Turning tab. The dwelling period was set at 3 seconds. "Unclamp secondary spindle" was selected from the "Open spindle chucks" option.

Setup 3: Front 2

A new setup was created and named "front 2". The machine tool (i.e., DMG MORI CLX 450 TC) was selected from the local library. The operation type was set to “Turning or Mill/Turn”, and the primary spindle was selected. The orientation and origin were left as model orientation and model origin respectively. The chuck was referenced from the back of the stock with an offset of 46 mm. The model and fixture were specified. Under the stock tab, “From preceding step” was selected, and “Continue rest machining” was turned on.

OP 14: Turning Profile Roughing

Turning profile roughing operation from the Turning tab was selected. Tool T1 (i.e., Insert: DNMU110404-FF2 CP500, Holder: C6-DDNNN-00065-11-M) and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood and through tool”. Since the hand of the tool is neutral, a tool orientation of 39 degrees was applied. Under the geometry tab, the front mode was set to “Model front”, and the back distance was just after the conical section of the part (i.e., 215 mm offset from the model back). In the passes tab, 0.5 mm stock was left both in the X and Z directions for the finishing pass. The cycle and direction were set to “Horizontal passes” and “Front to back” respectively.

OP 15: Turning Profile Roughing

Turning profile roughing operation from the Turning tab was selected. Tool T1 and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood and through tool”. Since the hand of the tool is neutral, a tool orientation of -6 degrees was applied, and a tool back clearance of 5 degrees was set to avoid gouging. Under the geometry tab, the front mode was set to -45 mm from the model front, and the back mode was set to 230 mm from the model back to machine right after the conical section. In the passes tab, 0.5 mm stock was left both in the X and Z directions for the finishing pass. The cycle was set to “Back cutting”, and radial grooving was turned on.

OP 16: Turning Face

Turning face operation from the Turning tab was selected for the finishing pass. Under the tool tab, tool T2 (i.e., Insert: SNMG120408-MR7 TP40, Holder: C6-DSDNN-00065-12-M) and preset M4 were chosen. Coolant mode was set to “Flood and through tool”. Since the hand of the tool is neutral, a tool orientation of 32.5 degrees was applied. Under the geometry tab, "model front" was selected without any offset. In the passes tab, the direction was set to “Outside to inside”.

OP 17: Turning Profile Finishing

Turning profile finishing operation from the Turning tab was selected to finish the face. Tool T2 (i.e., Insert: SNMG120408-MR7 TP40, Holder: C6-DSDNN-00065-12-M) and preset M4 were selected under the tool tab. Coolant mode was set to “Flood and through tool”. Since the hand of the tool is neutral, a tool orientation of 57.5 degrees was applied to finish the flat surface. The front and back distance were set to 1 mm on either side of the surface. Rest machining was set to "From previous operation(s)". The stepover distance was set to 0.25 mm, and the number of stepovers was set to 2. The direction was set from front to back, and grooving was turned off. For two subsequent finishing operations for tapered surfaces, the same settings were used, but the tool orientation and geometry settings were changed.

OP 18: Turning Profile Finishing

Turning profile finishing operation from the Turning tab was selected to finish the negative tapered cylindrical face (i.e., behind the flat surface). All the settings were exactly similar to OP 17. The tool orientation was set to 12.5 degrees. The front and back distances were set to the same as the starting and ending of the face.

OP 19: Turning Profile Finishing

Turning profile finishing operation from the Turning tab was selected to finish the tapered cylindrical face. All the settings were exactly similar to OP 17. The tool orientation was set to -25.5 degrees. The front and back distances were set to the same as the starting and ending of the tapered face.

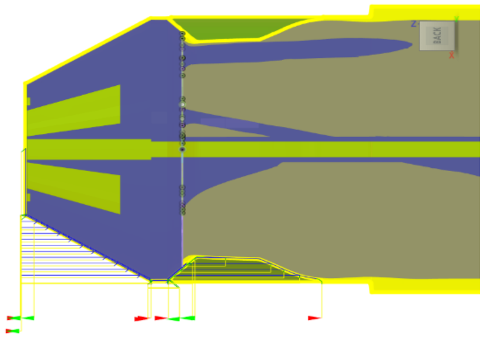


Figure 11: Depiction of roughing operation 14, 15

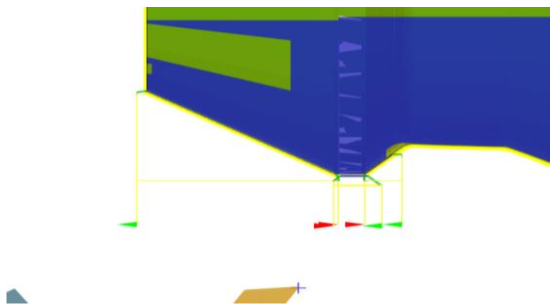


Figure 12: Finishing Operation 16-19

OP 20: 2D Pocket

2D Pocket operation from the Milling tab was selected to machine a 3 mm slot on the top face. Tool T12 - 2 mm flat endmill (i.e., Tool: 553L020Z3.0-SIRON-A, Holder: C6-391.5603-06080) and preset M4 were selected under the tool tab. Coolant mode was set to “Flood”. Machining type was set to 3-axis. In the pocket selections, the bottom face of the pocket was chosen. Bottom height was set to the selected contour. Finishing passes were turned on with a stepover distance of 0.2 mm. Ramp type was set to profile with an angle of 2 degrees since there was not enough space for a helical ramp.

OP 21: Drilling

Drill operation from the Turning tab was selected. Since the recommended pre-machined hole diameter for a Ø 8 mm reamer is 7.76 mm, a Ø 7.8 mm drill bit was chosen for this operation. Tool T7 (i.e., Tool: SD1105A-0780-043-08R1, Holder: C6-HC08-065) and preset M4 were selected under the tool tab. Coolant mode was set to “Flood”. In the geometry tab, the face of the centre hole was selected. Bottom height was set to “Hole bottom”. Cycle type was set as “Chip breaking – partial retract”, and pecking depth was set to 1.95 mm (i.e., 25% of tool diameter).

OP 22: Drilling

Drill operation from the Turning tab was selected. Tool T6 (i.e., Tool: SD2050A-0600-300-06R1, Holder: C6-HC06-065) and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood”. In the geometry tab, the face of the centre hole was selected. Bottom height was set to “Hole bottom”. Cycle type was set as “Deep Drilling – full retract” and pecking depth was set to 1.5 mm (i.e., 25% of tool diameter).

OP 23: Reaming

Drill operation from the Turning tab was selected. Tool T9 (i.e., Tool: N5TS-8H7-EB45 RX2000, Reamer holder: NFQF10-05200-12N1, Holder: C6-HC12-080) and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood”. In the geometry tab, the face of the centre hole was selected. Bottom height was set to “Hole bottom”. Cycle type was set as “Reaming – Feed out”.

OP 24: Flat

Flat operation from the Milling tab was selected. Tool T10 - 8 mm roughing endmill (i.e., Tool: JS754080E3C.0Z4C-HXT, Holder: C6-391.5603-08080) and preset M4 were chosen under the tool tab. Coolant mode was set to “Flood”. Machining type was set to 3-axis. In the geometry tab, machining boundary was set to “None” as it automatically detects flat faces. Top and bottom heights were set just above and below the features. Type was set to “Pocket” with “Optimize open pockets” turned on. "Multiple depths" were allowed with a maximum stepdown of 4 mm. "Stock to leave" was set to 0.5 mm in both radial and axial directions. Retraction policy was set to minimum, and Ramp was not allowed.

OP 25: Flat

For the finishing pass, all settings remained exactly the same except for three changes. Firstly, the tool was changed to T11 - 6 mm finishing endmill (i.e., Tool: JSE514060D4C.0Z4 SIRA, Holder: C6-391.5603-06080). Secondly, "Multiple depths" was turned off. Lastly, "Stock to leave" was turned off as well.

OP 26: Swarf

To machine the slanted pocket, tool must be tilted (in 5-axis) because the bottom face of the pocket is not aligned with the opening. Swarf operation under the multi-axis dropdown was selected. To clear the bulk of material, a 6 mm flat endmill was used. Since the inner and outer surfaces of the conic feature are not parallel, two subsequent swarf operations were required—one referenced to the inner surface of the pocket and the other to the outer.

Tool T11 (i.e., Tool: JSE514060D4C.0Z4 SIRA, Holder: C6-391.5603-06080) and preset M4 were selected under the tool tab. The coolant mode was set to “Flood”. Under the geometry tab, the drive mode and selection mode were set to surfaces and faces, respectively. The inner conical surface was chosen as the reference surface. The bottom height was left as selection with an offset of 0 mm. Cutting mode was set to spiral with two stepovers, and the stepover distance was set to 1.5 mm. The maximum stepdown distance was set to 1 mm. A stock of 0.5 mm in both axial and radial directions was left for the finishing operation. It's important to remember to turn off “Lead-out (exit)” to prevent tool from going straight up and gouging the stock. Also, ensure that the red arrow is on the correct side of the selection.

OP 27: Swarf

The settings that were used were exactly similar to OP 26, with just the reference surface being changed. The outer surface was selected to machine along the outer surface of the feature. Due to insufficient material remaining for two passes, the number of stepovers was reduced to one.

OP 28: Swarf

Two swarf operations were required to finish the feature. To reach the corners, a 6 mm ball nose endmill was used. Tool T13 (i.e., Tool: JS534060D2B.0Z4-NXT, Holder: C6-391.5603-06080) and preset M4 under the tool tab were selected. All settings were exactly similar to OP 26. The stepover distance was changed to 0.25 mm, and "Stock to leave" was turned off.

OP 29: Swarf

The settings that were used were exactly similar to OP 28, with just the reference surface being changed. The outer surface was selected to machine along the outer surface of the feature.

OP 30: Geodesic

The geodesic operation was used to clear the stock that remained on the floor between the two swarf tool paths. The floor's undercut nature led to the selection of a geodesic operation.

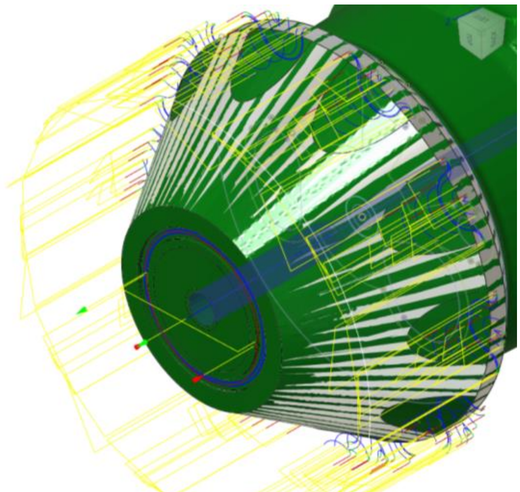


Figure 13: Depiction of stock after operation 25 with toolpaths included

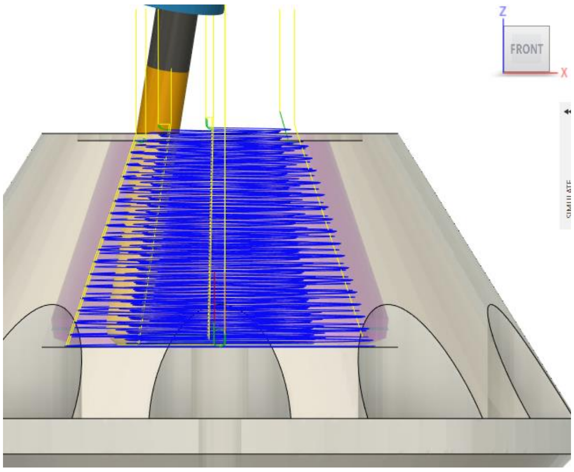


Figure 14: Toolpaths of operation 26-29

OP 31: Subspindle Grab

The "Sub spindle grab" operation was selected from the Turning tab to utilize the secondary spindle. The secondary spindle enhances rigidity and minimizes chatter. "Model front" was chosen for the "Grab plane mode," with an offset of -44 mm. Additionally, a dwelling period of 3 seconds was set.

OP 32-37: Adaptive Clearing

The bulk of the material was removed by a roughing endmill using the Adaptive clearing strategy. The area to be cleared was divided into four equal parts, as shown in Figure 15. Reference planes were designed to orient the tool and approach the part from four different sides i.e. Figure 16. To allow the tool to cut deeper, a smaller rectangle offset by the holder neck radius was sketched, enabling the tool to reach even deeper and clear as much material as possible using adaptive clearing. The reason for doing that was to reduce chatter and achieve a better surface finish. Therefore, the maximum amount of stock was kept for as long as possible.

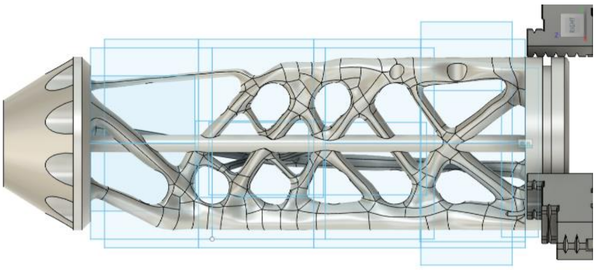


Figure 15:Depiction of sketches

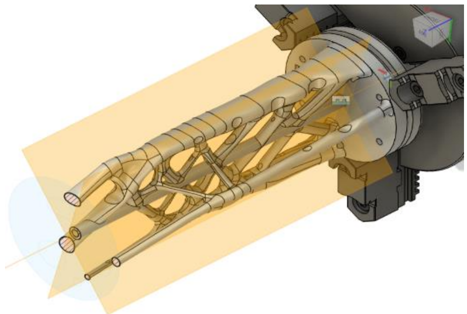


Figure 16: Depiction of sketch planes

The Adaptive Clearing operation was selected from the 3D tab. Tool T10 - 8 mm roughing endmill (i.e. Tool: JS754080E3C.0Z4C-HXT, Holder: C6-391.5603-08080) and preset M4 under the tool tab were selected. The coolant mode was set to “Flood”, and the machining type was set to 3-axis. "Shaft & Holder" detection was turned on with a shaft and holder clearance of 1 mm and 5 mm respectively. The machining boundary was set to selection, and the sketch was selected. Tool containment was set to “Tool inside boundary”. Rest machining was turned on with the source set to “From previous operation(s)”. Tool orientation was set perpendicular to the selection. The top height was set to “Stock Top”, and the bottom height was -35 mm from the top height.

Under the passes tab, the direction was set to climb milling with a maximum roughing stepdown of 20 mm and a fine stepdown of 2 mm. "Stock to leave" was set to 1 mm in both radial and axial directions. The retraction policy was set to minimum, and the Ramp type was set to helix.

OP 38-44: Adaptive Clearing

The material removal in the second section, as previously described, was accomplished using adaptive clearing. All settings were exactly identical to those of OP 32. In fact, it actually is a duplicate of operation 32. The selections were overlapped to prevent any stock material from being left between them.

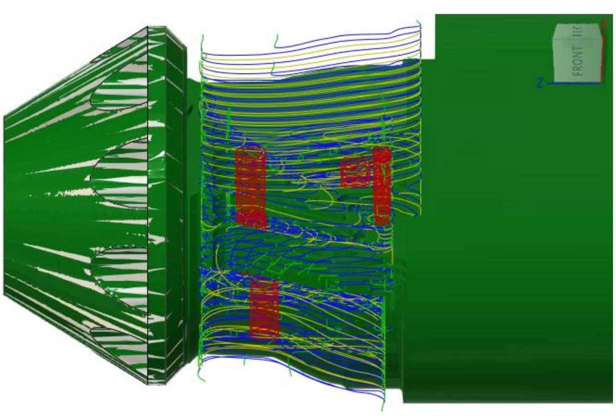


Figure 17: Cutting passes of operation 22-27

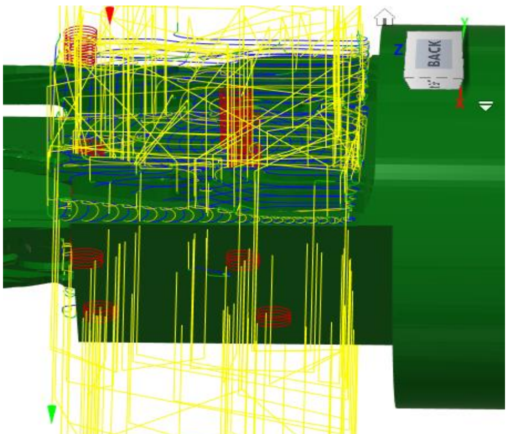


Figure 18: Toolpaths of operation 38-44

OP 45-50: Adaptive Clearing

To clear the maximum amount of material on the underside of the conic section before applying Geodesic, the tool was tilted at an angle of 30 degrees. All settings were similar to OP 32.

OP 51: Geodesic

The geodesic operation was used to clear the material remaining on the bottom side of the conical section, utilizing the periphery of the tool. The floor's undercut nature led to the selection of a geodesic operation. A 6 mm ball nose endmill, Tool T13 (i.e. Tool: JS534060D2B.0Z4-NXT, Holder: C6-391.5603-06080), and preset M4 under the tool tab were chosen. In the geometry tab, the machine boundary was set to “Surface boundary” and the type of passes to “Blend”. The bottom face was selected as the drive surface. Heights were set to automatic, and the maximum stepover was set to 3 mm. The machining type was 5-axis, with the primary mode set to vertical. Additionally, "collision avoidance" was activated.

OP 52: Geodesic

The tool was tilted by 30 degrees to reach the points that were inaccessible during peripheral cutting. All settings remained identical to OP 51, with the exception of the overridden tilt angle set at 30 degrees.

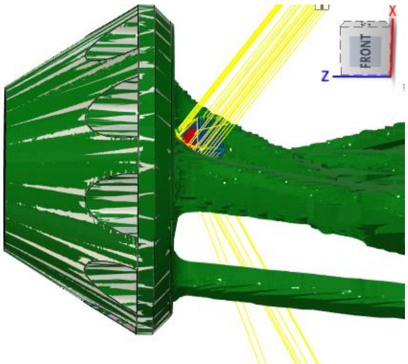


Figure 19: Toolpaths of operation 45-50

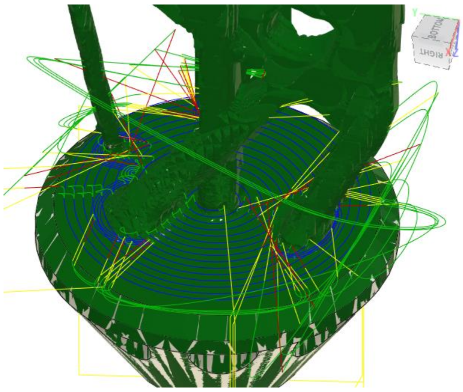


Figure 20: Depiction of Geodesic toolpath

OP 54-57: Adaptive Clearing

A smaller tool, 2 mm flat endmill, was necessary to access the corners left by the 8 mm roughing endmill. In the sketch section, a new sketch was created by intersecting the body with the YZ plane to obtain a selection of these corners.

Tool T12 (i.e. Tool: 553L020Z3.0-SIRON-A, Holder: C6-391.5603-06080) and preset M4 under the tool tab is selected. Coolant mode is set to “Flood”. Machining type is set to 3-axis. "Shaft & Holder" detection was turned on with a shaft and holder clearance of 1 mm and 5 mm respectively. The machining boundary was set to selection, and the sketch was selected. Tool containment was set to “Tool inside boundary”. Rest machining was turned on with the source set to “From previous operation(s)”. Tool orientation was set perpendicular to the selection. Heights are set in such a way that is clears maximum material without any collisions. Under the passes tab, the direction was set to climb milling with a maximum roughing stepdown of 5 mm and a fine stepdown of 0.5 mm. "Stock to leave" was set to 0.5 mm in both radial and axial directions for subsequent finishing operations. The retraction policy was set to minimum, and the Ramp type was set to helix.

OP 58-77: Flow

To finish the linking arms of the model, particularly those with organic shapes, the preferred tool strategy is flow due to its effectiveness with free-form shapes. For this operation, a 4 mm ball nose endmill with a flute length of 6 mm and a reach of 52 mm was utilized. Any flow tool path with this tool has used the following settings.

Tool T14 (i.e. Tool: JHB970040G3B.0Z2 SIRA, Holder: C6-391.5603-06080) and preset M4 under the tool tab is selected. Cutting feeds and speed are obtained from manufacturer's website by selecting the cutting method to profile milling and material to M4. Coolant mode is set to "Flood". "Shaft & Holder" detection was turned on with a shaft and holder clearance of 1 mm and 5 mm respectively. Under the geometry tab faces to finish are selected as "Drive surfaces". Under the passes tab, the direction was set to "Both ways" with (advertised) stepover distance of 0.24 mm and a tolerance of 0.01 mm. "Stock to leave" was turned off.

Under the multi-axis tab, the machining type was set to 5-axis, with the primary mode being vertical. Collision avoidance was configured to automatic. The minimum and maximum tilt angles were set to 30 and 90 degrees respectively, to avoid using the tip of tool where cutting speed remains zero. Additionally, the retraction policy was set to the shortest path.

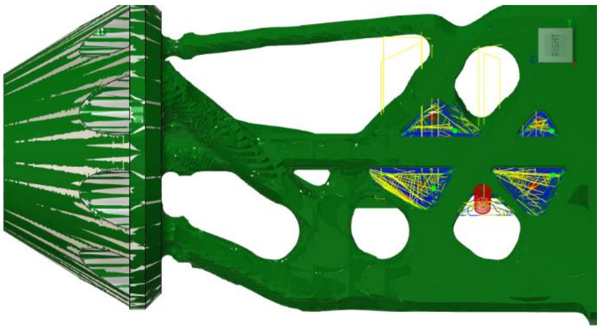


Figure 21: Toolpaths of operation 54-57

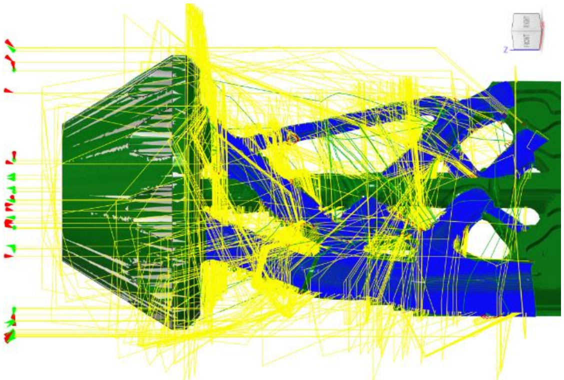


Figure 22: Depiction of flow toolpath 58-77

OP 78-84: Adaptive Clearing

The material removal in the third section, as previously described, was accomplished using adaptive clearing. All settings were exactly identical to those of OP 32. In fact, it actually is a duplicate of operation 32. The selections were overlapped to prevent any stock material from being left between them.

OP 85-86: Adaptive Clearing

To access the corners left by OP 78-84, a smaller tool bit, as described in OP 54, was used.

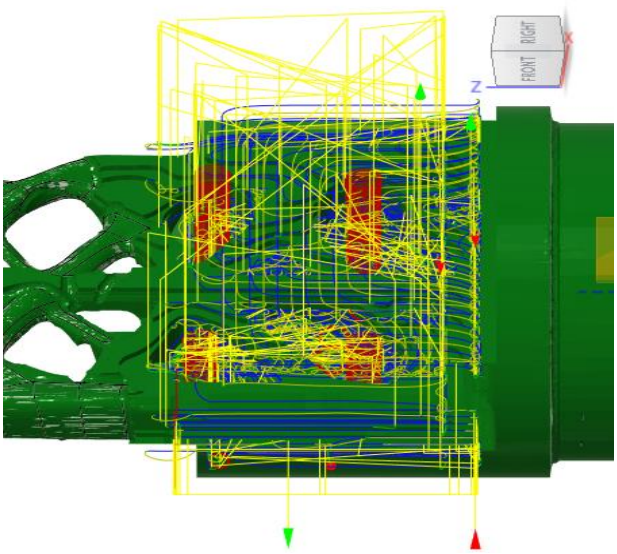


Figure 23: Adaptive clearing 78-84

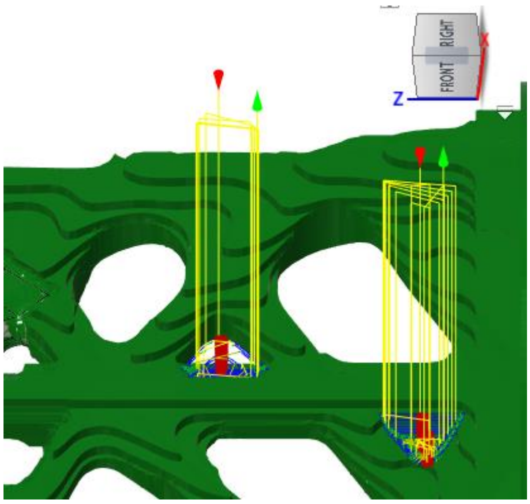


Figure 24: Adaptive clearing using 2 mm Endmill

OP 87-94: Flow

For the finishing operations in the third section, the same 4 mm tool and flow operation were used, as described in OP 58.

OP 95: Subspindle Return

As the primary spindle obstructs the machining of section 4, it was necessary to move it back. The "Sub spindle return" operation was selected from the Turning tab. The "Unclamp primary spindle" option was chosen from the "Open spindle chucks" menu.

OP 96: Subspindle Grab

Sub [illegible] om Turning tab to move main spindle back. Stock back is se [illegible] ffset of 10 mm. Dwelling period is set at 3 second.

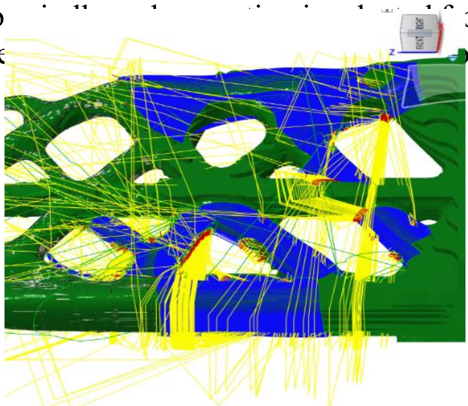


Figure 25: Depiction of flow toolpath 87-94

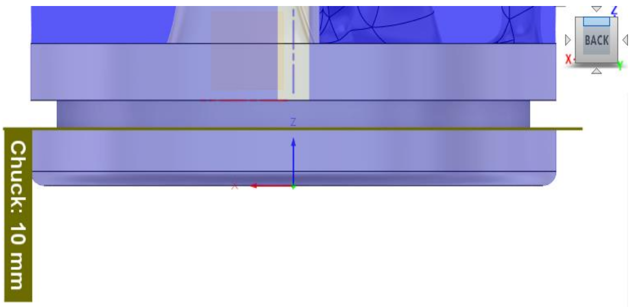


Figure 26: Position of chuck for next operations

OP 97-101: Adaptive Clearing

The material removal in the fourth section, as previously described, was accomplished using adaptive clearing. All settings were exactly identical to those of OP 32. The selections were overlapped to prevent any stock material from being left between them.

OP 102-105: Adaptive Clearing

To clear the max amount of material on the upperside of the bottom section before applying Geodesic, the tool was tilted at an angle of 30 degrees. All settings were similar to OP 32.

OP 106-107: Adaptive Clearing

To access the corners left by OP 97-105, a smaller tool bit, as described in OP 54, was used with a tilt angle of 30 degrees.

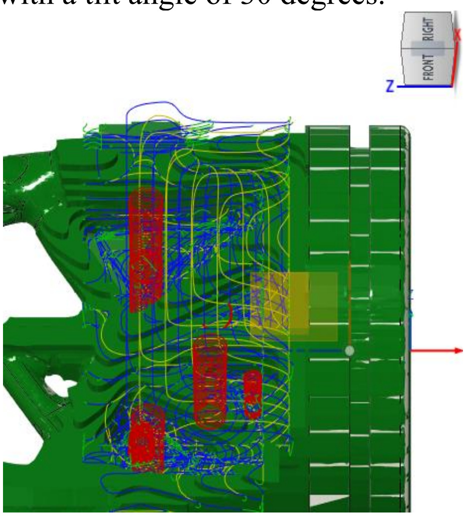


Figure 27: Adaptive clearing 97-101

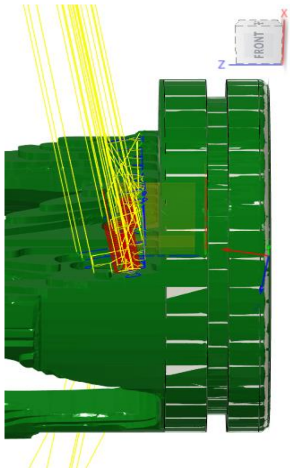


Figure 28: Adaptive clearing 102-105

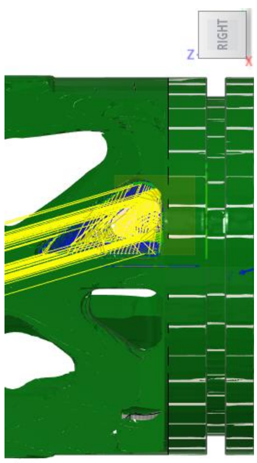


Figure 29: Adaptive clearing 106-107

OP 108-115: Flow

For the finishing operations in the third section, the same 4 mm tool and flow operation were used, as described in OP 58.

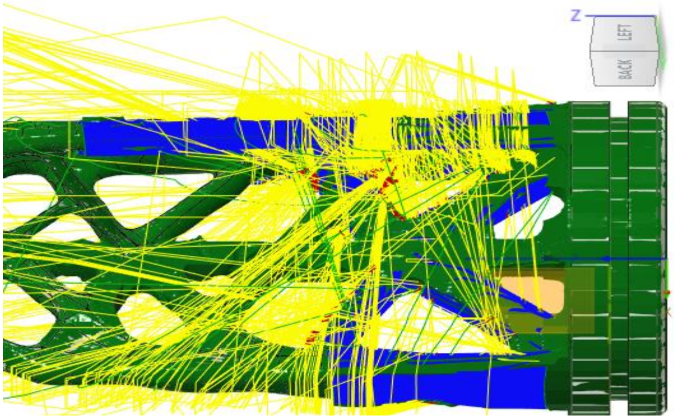


Figure 30: Depiction of flow toolpath operation108-115

OP 116-118: Circular

To clear the radial face available on the body, the Circular operation from the Milling tab was selected. Tool T11 - 6 mm finishing endmill (i.e., Tool: JSE514060D4C.0Z4 SIRA, Holder: C6-391.5603-06080) and preset M4 under the tool tab were selected. Coolant mode was set to "Flood". One of the faces was selected for the selection, and "Select same diameter" was turned on. Bottom height was set as "Hole bottom". Under the passes tab, the direction was set to climb milling with a stepover distance of 0.5 mm, and the number of stepovers was set to 2.

OP 119-120: Geodesic

The geodesic operation was used to clear the material remaining on the upper side of the bottom section, utilizing the periphery of the tool. The floor's undercut nature led to the selection of a geodesic operation. All settings, except for the selection, were similar to OP 51-52.

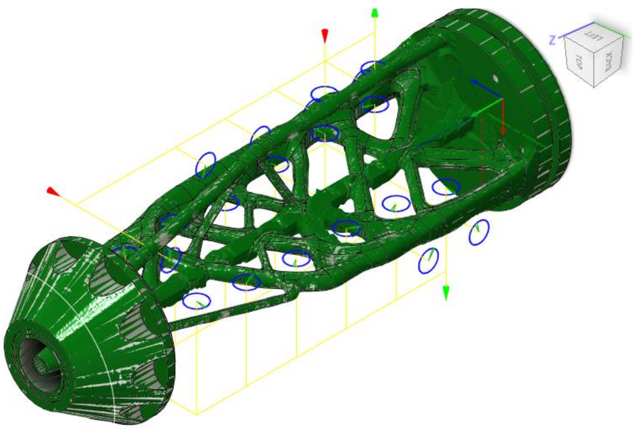


Figure 31: Depiction of crcular toolpath

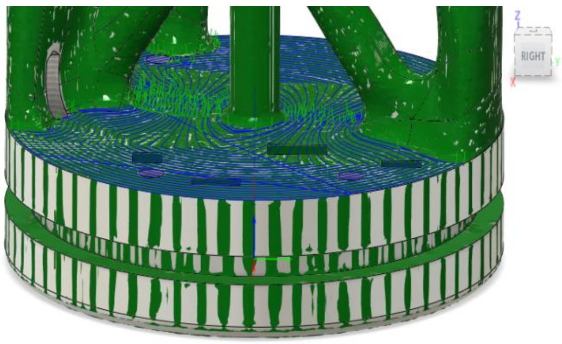


Figure 32: Geodesic toolpath

OP 120-124: Flow

For the finishing operations of last bits above the bottom face, the same 4 mm tool and flow operation were used, as described in OP 58.

OP 125 Pocket Clearing

3D Pocket operation from the Milling tab was selected to machine the pockets on bottom floor. And tool is tilted at an angle of 20 degrees to avoid collision with model. Tool T12 - 2 mm flat endmill (i.e., Tool: 553L020Z3.0-SIRON-A, Holder: C6-391.5603-06080) and preset M4 were selected under the tool tab. Coolant mode was set to “Flood”. In the pocket selections, the bottom faces of the pockets were chosen. Bottom height was set to the selected contour. Finishing passes were turned on with a stepover distance of 0.2 mm. Ramp type was set to profile with an angle of 2 degrees since there was not enough space for a helical ramp. Some of the material remains in the corners and sides of the pocket.

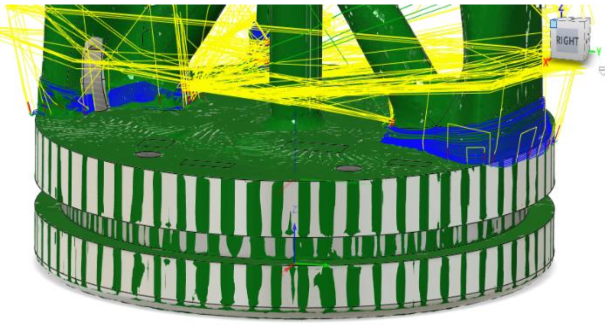


Figure 33: Flow toolpath 120-124

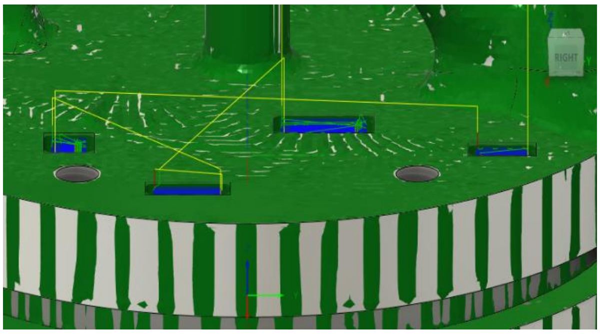


Figure 34: 3D pocket clearing

Inspection

For inspection, the Renishaw OMP 400 optical machine probe was used, capable of accepting M4 styluses of up to 100mm in length. A Renishaw M4 Ø4 mm ruby ball with a ceramic stem, L 50 mm, and EWL 33.5 mm stylus was used. The probe was integrated into the Fusion tool library with specified dimensions. The chosen features of the model for inspection included the upper OD, lower OD, and central hole. The probe geometry operation was selected from the inspection tab. Under the tool tab, the probe was designated as the tool. In the geometry tab, the features to be inspected were selected, with a feature tolerance set to ± 0.5 mm. To inspect the top surface of the model, the "inspect surface" function was chosen from the inspection tab, and 8 points on the surface were selected for inspection.

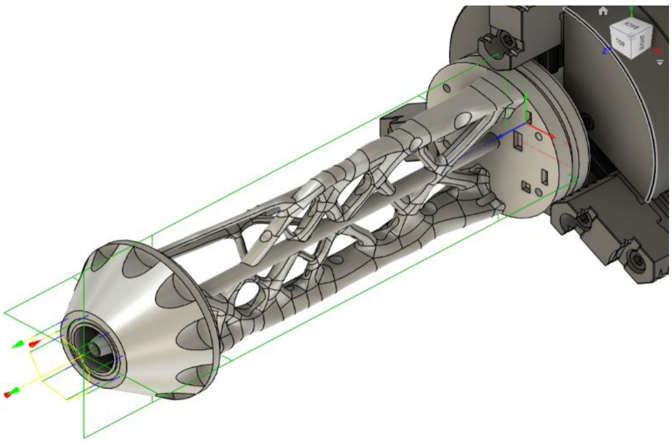


Figure 35: Depiction of Probing path

Optimisation

The total number of tools used to machine this part was 14, along with a probe for inspection. For optimization purposes, a few tools can be reduced with a trade-off between cost and surface finish. Specifically:

1. T9 reamer can be removed.
2. T10, the Ø8 mm roughing endmill, can be eliminated. Instead, a Ø6 mm flat end mill can be used in its place, with an increase in machining time.
3. T15, the Ø3 mm ball nose end mill, can be removed, although this would result in more material being left in the corners.

Current machining time is 36 hours, and 28 mins. To reduce machining time a step oved distance must be increased to at least greater than 1.5 mm. Tolerance could be reduced to 0.5mm.

Final Model

Final images of model after all operations are given with origin block for reference.

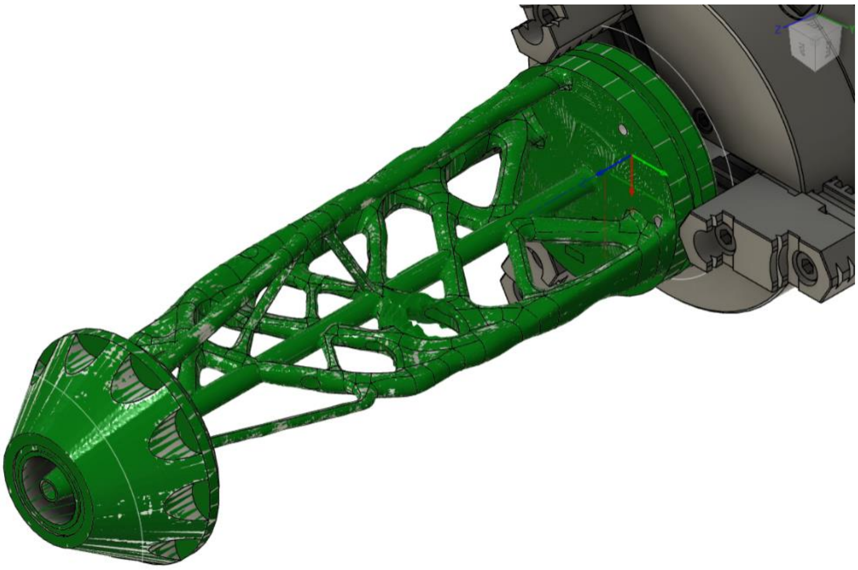


Figure 36: Orthographic view from Front

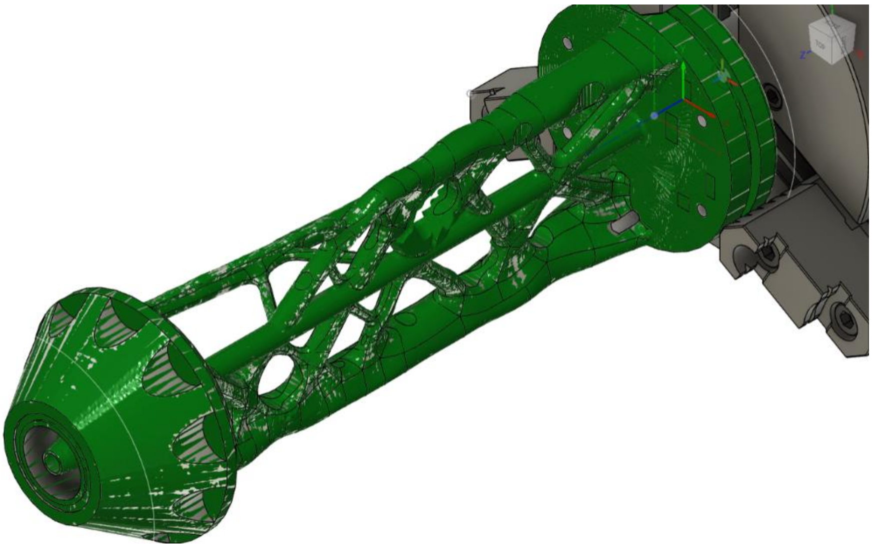


Figure 37: Orthographic view from back

Design Improvements

Conic section

Avoid sharp corners at the bottom of the conic cut out. Instead, put a radius of 3 mm if possible.

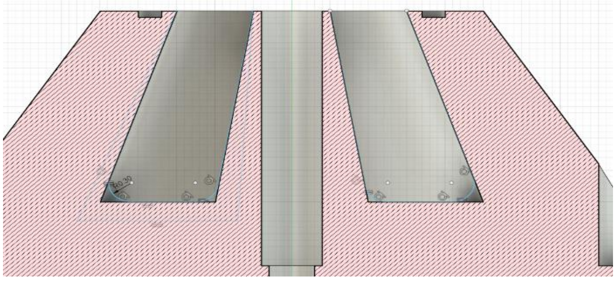


Figure 38:Depiction of design alterations of conic section

Bottom of hole

Avoid flat bottom for the deeper holes, put an angle at the bottom preferably one that matches the point angle of available drill bits.

Under cut features

Undercut features are difficult to machine and should be avoided if possible. Consider adding a tool relief at each corner of the square feature, so that tilted tool have a relief, and that can still accommodate the square insert, easing the machining process. Another option is to make these feature through bottom so that they can be broached from other side, as this machine tool has broaching capability.

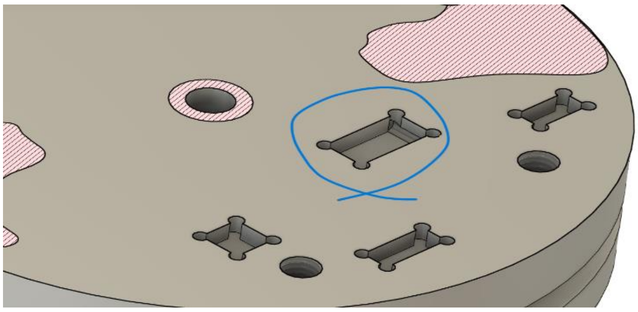


Figure 39: Depiction of improved design of undercut features

Sharp corners

In generative design, avoid sharp corners as they can be challenging to machine. Instead, consider rounding them to facilitate the machining process.

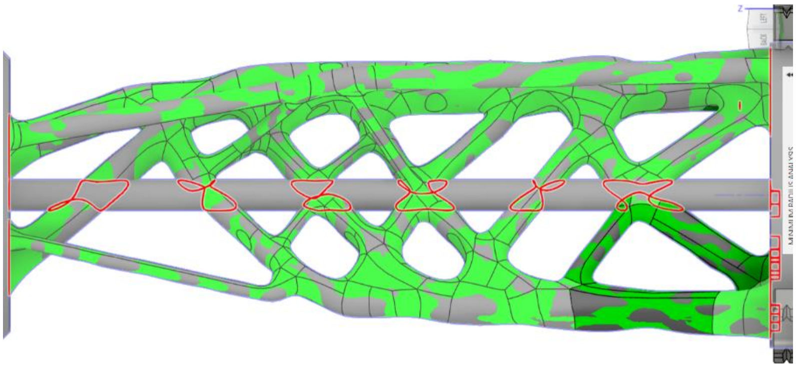


Figure 40: Depiction of sharp edges to avoid (red)

Appendix A

Tool	Disc	Product ID	Holder/Insert	Cutting Speed (m/min)	Feed (mm/rev)
T1	Turning Roughing	C6-DSDNN-00065-12-M	SNMG120408-MR7 TP40	75	0.36
T2	Turning Finishing	C6-DDNNN-00065-11-M	DNMU110404-FF2 CP500	200	0.09
T3	Turning Grooving	C6-CER-45065-20HD	20ER5.0FG CP500	85	0.12
T4	Probe	OMP 400	A-5003-0233		
T5	Ø5.1 mm Drill	SD1105A-0500-035-06R1	C6-HC06-065	120	509
T6	Ø7.8 mm Drill	SD2050A-0600-300-06R1	C6-HC06-065	17	85.7
T7	Ø6 mm Drill	SD1105A-0780-043-08R1	C6-HC08-065	33	135
T8	M6 Machine Tap	MTP-M6X1.00ISO6H-TB-M003-A	393.14-11D060X049	5.7	
T9	Ø8 mm Reamer	N5TS-8H7-EB45 RX2000	NFQF10-05200-12N1	6	38.2
T10	Ø8 mm Roughing Endmill	JS754080E3C.0Z4C-HXT	C6-391.5603-08080	105	1170
T11	Ø6 mm Flat Endmill	JSE514060D4C.0Z4 SIRA	C6-391.5603-06080	95	726
T12	Ø2 mm Flat Endmill	553L020Z3.0-SIRON-A	C6-391.5603-06080	41	73.8
T13	Ø6 mm Ballnose Endmill	JS534060D2B.0Z4-NXT	C6-391.5603-06080	120	509
T14	Ø4 mm Ballnose Endmill	JHB970040G3B.0Z2 SIRA	C6-391.5603-06080	55	175
T15	Ø3 mm Ballnose Endmill	JMB562030G7B.0Z2 -SIRA	C6-391.5603-06080	89	760