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CNC Milling of Complex Aluminum Parts

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CNC Milling of Complex Aluminum Parts

by

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Certificate of approval

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Date

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I would also like to thank the engineers who were involved in the manufacturing work for this project, Eli C. Towne and William J. Maroun. Without their passionate participation and input, the machining work could not have been successful.

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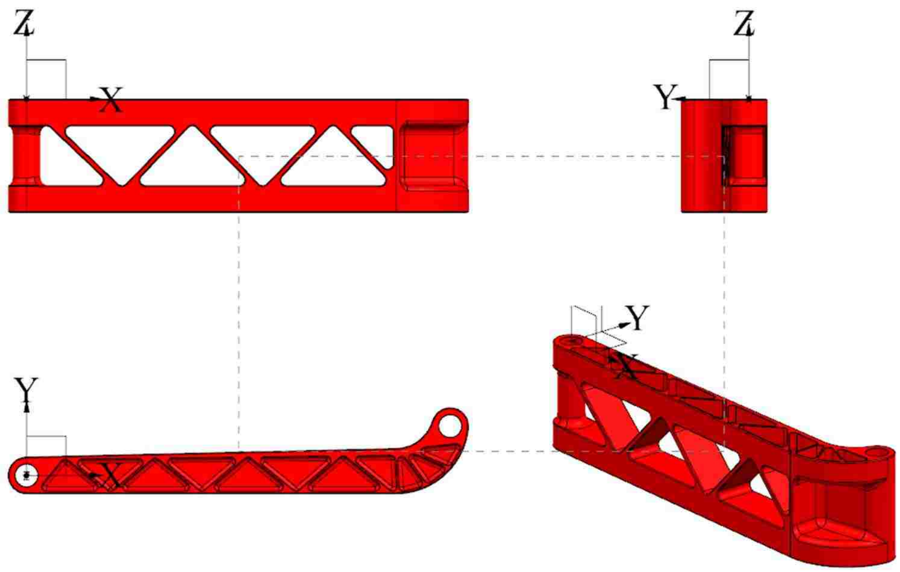
Abstract

Nowadays CAD/CAM/CNC is widely used in all fields of manufacturing and production. With the help of them, ideas and designs can be quickly and accurately brought to reality. This thesis deals with manufacturing of rather complex high-strength aluminum parts. The parts will be used for a new kind of alpine ski which incorporates suspension with springs and dampeners. The requirements of the parts are quite typical for high-performance equipment - they need to be lightweight, strong, stiff, and are subjected to various packaging constraints. The parts that were designed are extensively pocketed to reduce weight yet retain high strength and stiffness. The packaging constraints were all fulfilled but this resulted in quite complex geometry of the parts. The parts would be considered rather difficult to machine. Various jigs etc. were required to be able to machine all sides of the parts. The challenges of machining the parts, and the methods used to solve the challenges, are outlined in the main body of this thesis.

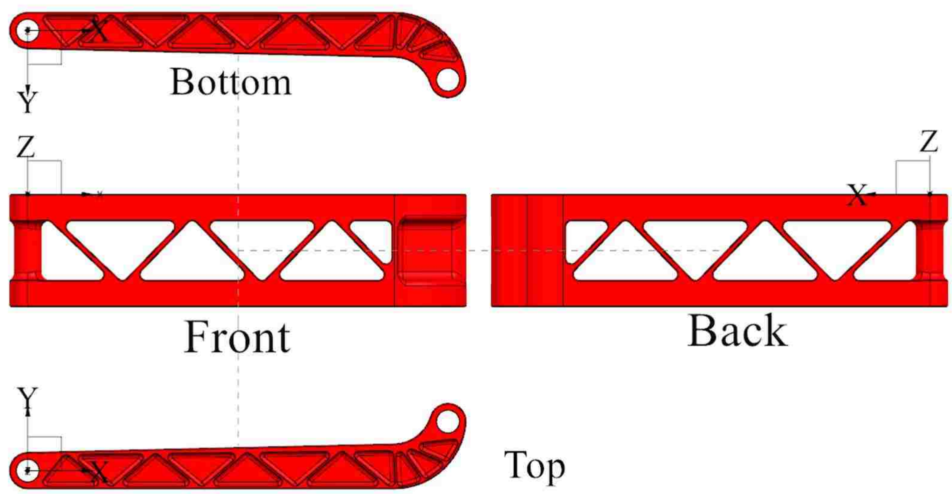
Part 1:

1.1 Description of Part 1



Drawing 1.1 Three-view drawing of CAD model of Part 1

Part 1 is shown in the Drawing 1.1 above. The machine used for making this part, a HAAS DT-1, is a vertical machining center with three-degrees-of-freedom. This part would be machined from four different directions. According to the shape of this part, it can be divided into four positions, which are named as “top”, “bottom”, “front” and “back” .



Drawing 1.2 Four positions for multiple steps of processing

Most triangular holes and slots on this part have planar bottoms and vertical walls, so to use end mills would be the priority selection for cavity milling. As to the fillets, cylindrical and sloped surfaces, ball mills were chosen.

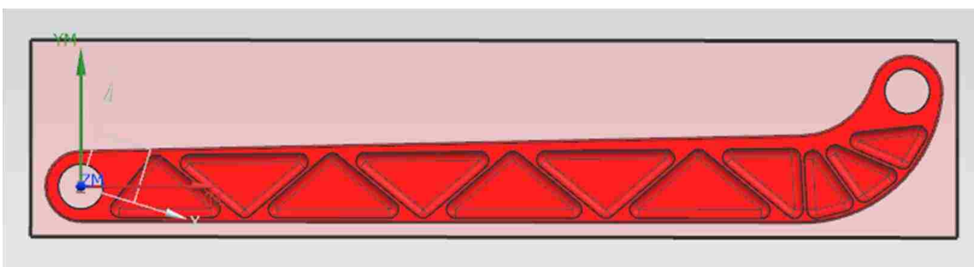
1.2 Determine the blank

The material for making this part is 7075 aluminum. For some initial tests, 6061 aluminum was used due to its lower cost. A block with the size of 165mm (6.5 inch) ×38mm (1.5 inch) ×40mm (1.6 inch)[1] is appropriate. The length and width are a few millimeters longer than the exact size of the part, which will leave enough allowance for milling the profile, and the height is just the exact size since the top and bottom surfaces are flat, and no more processing was needed after milling the pockets.

As mentioned earlier, the part is machined in such order: top surface, bottom surface,

[1] All the tools and machines used for processing were using English units, but throughout this thesis those have been converted to metric units. For special sizes, such as 1/2-inch mill, the English size follows metric sizes with parentheses.

front surface and back surface and the very first operation is to mill the profile of the part. From Drawing 1.2, it is clear to see that when the top and bottom surfaces are machined, a vise cannot be used to grab the blank. The reason is that after the contour is machined, the profile of the blank becomes irregular and is hard to be grabbed in a vise to process the top and bottom surfaces, which is shown in Drawing 1.3: the pink block is the unprocessed blank which could be fixed with a vise easily. However, after the contour is machined, it is difficult to use a vise to grab the profile in red.



Drawing 1.3 Top views of the blank when drilling the holes (pink block is the blank)

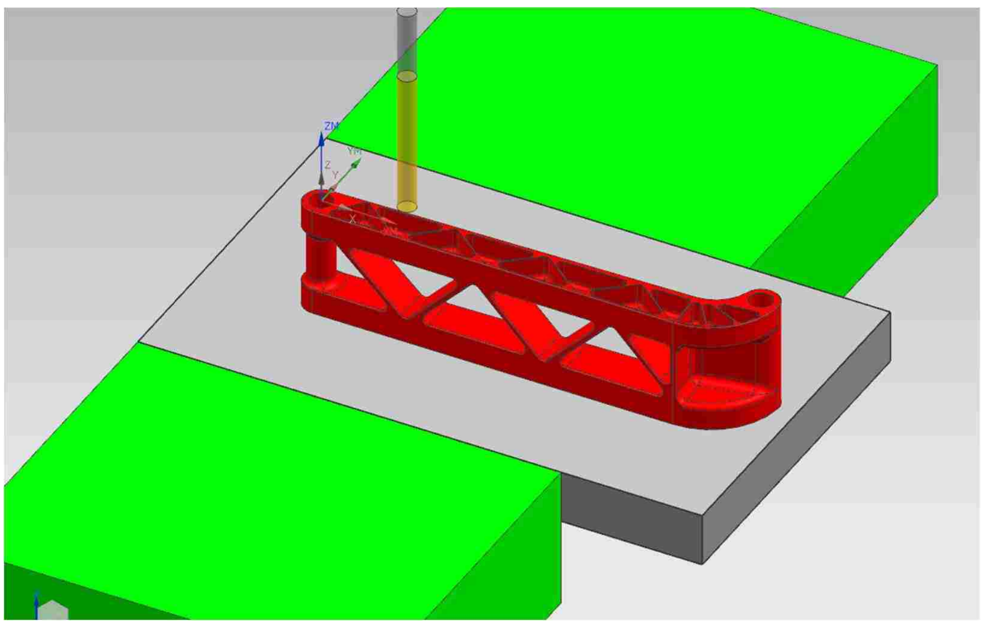
Instead, the two holes in the part were used for location and fixing. Therefore, before milling the four surfaces, the very first process was to drill holes in the location of two Φ8mm holes when the blank was clamped in a vice as shown in Drawing 1.3. Relative positions of centers of the Φ8mm holes were taken from the CAD model. The holes were drilled slightly undersize. They were drilled to size in a final operation. The hole was machined by first spot drilling and then drilling through with a 5.41 mm (#3) drill and tapped with 1/4-20” tap.

1.3 Determine preliminary processing route

Since it takes four steps to machine all the part, multiple references and clamping methods were required:

1.3.1 Machining the top surface

In this operation, the centers of two Φ8mm holes in the part are chosen for location as mentioned above. And the left center is chosen as the origin, which is shown in Drawing 1.4. The blank is fixed in a plate with two screws. The plate is clamped in the vise and positioned with parallel bars placed under the plate.



Drawing 1.4 Clamping of the blank when the top surface is machined

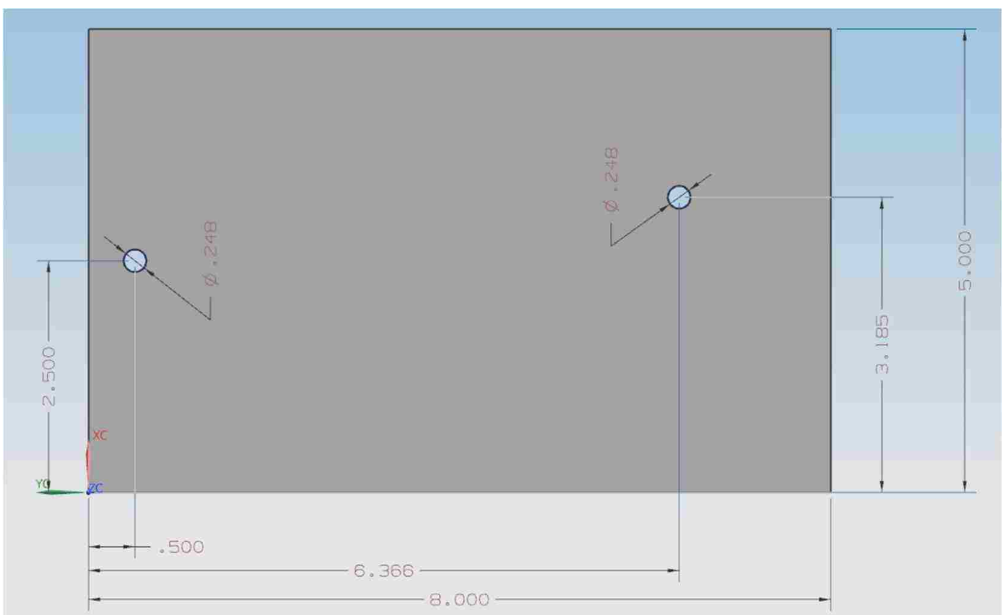
To be specific, the plate is processed in the following order:

a. Select an appropriate sacrificial plate, mill all six surfaces to 203.2 mm (8.0 inch) × 127.0 mm (5.0 inch) ×19.1 mm (0.75 inch);

b. Find coordinates of two centers, locate on the plate, drill holes with “c” drill (6.15 mm) and reamed to 6.30 mm;

Note: drill through-hole for utilizing both sides of the plate

c. When machining Part 1, screw 1/4-20” bolts through the plate from the bottom and into two holes in the blank and tighten them to fix the blank.

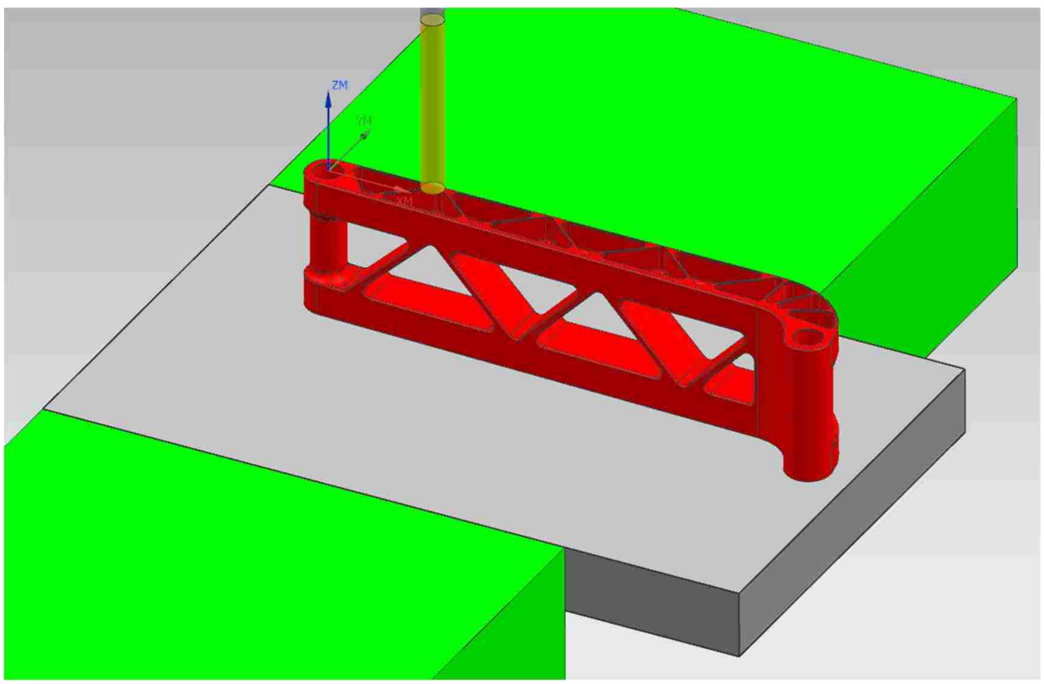


Drawing 1.5 Locations and diameters of two location holes

In this operation, firstly, a 19.05 mm (3/4 inch) end mill is chosen to mill the profile of the part; then the triangular holes on the top surface are milled roughly with a 6.35 mm (1/4 inch) end mill and finished using a 3.175 mm (1/8 inch) ball mill.

1.3.2 Machining the bottom surface

In this operation, the blank is still fixed to the plate as done in the first operation and the left center is the origin. The difference between these two operations is that after finishing the first operation, the blank is unbolted and removed. The plate is turned upside down and the blank is fixed again with the same bolts. Note that this time the processed top surface of the blank needs to face the sacrificial plate to leave the unprocessed bottom surface exposed. How the blank is clamped is shown below:

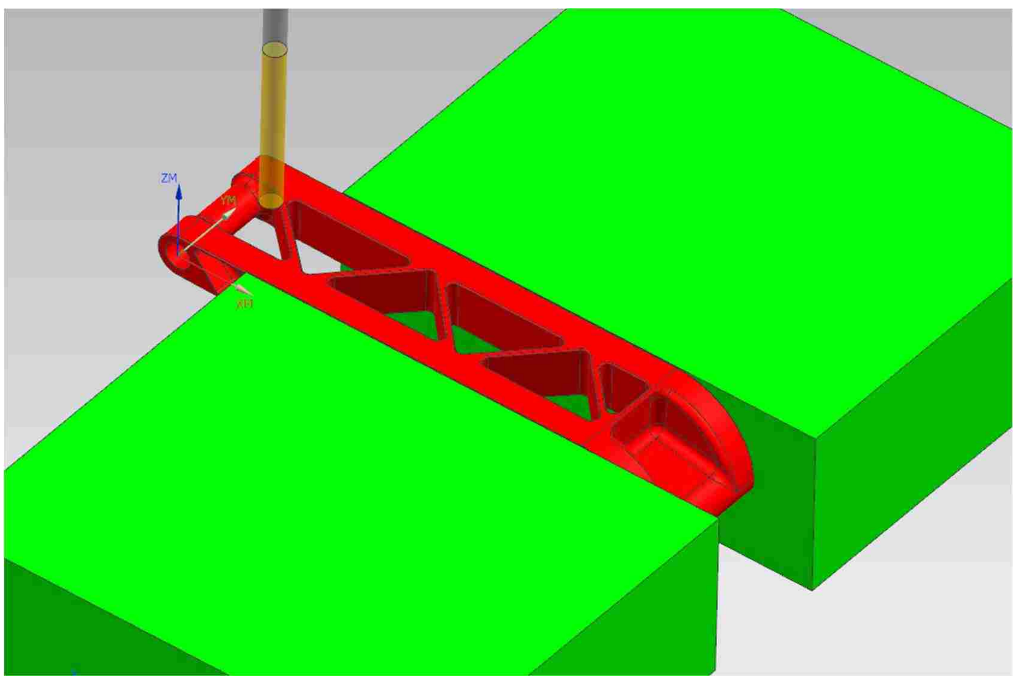


Drawing 1.6 Clamping of the blank when the bottom surface is machined

The process required to finish the bottom was the same as for the top, except that the profile did not have to be milled.

1.3.3 Machining the front surface

The center of the left Φ8mm hole is still the origin. And in this operation, the blank could be directly clamped in the vise. To ensure that the front surface of the blank was parallel to XY plane, a parallel bar was laid on the top of the vise, and the blank was held up until the front surface of the blank touched the bottom of the bar. Then the vise was tightened to fix the blank as shown below:

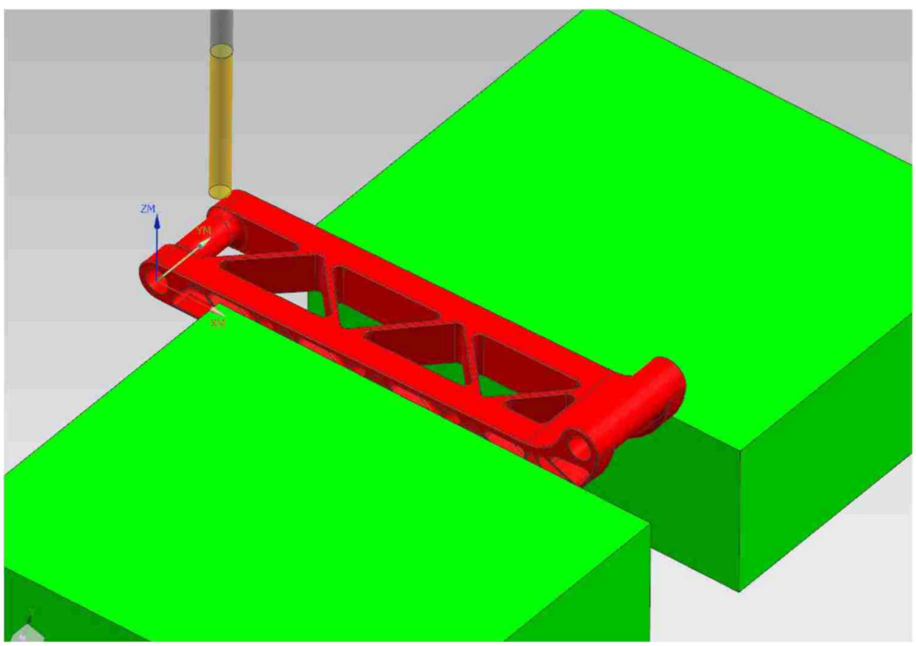


Drawing 1.7 Clamping of the blank when the front surface is machined

Note that the front and back surfaces are not parallel and the triangular through-holes are perpendicular to the front surface. They need to be finished in this operation. Firstly, the triangular through-holes are roughly milled with a 6.35 mm (1/4 inch) end mill and finished with a 3.175 mm (1/8 inch) ball mill. Then the top half cylindrical undercut surface on the left side and sloped pocket on the right side are milled with a 6.35 mm (1/4 inch) end mill and a 3.175 mm (1/8 inch) ball mill.

1.3.4 Machining the back surface

The center of the left Φ8mm hole is the origin. The blank could also be clamped in the vise. Since in this operation, the reference surface ("front") faces down, the blank is pressed down on the parallel bars to locate the blank square. The Drawing 1.5 below shows how the blank was clamped:



Drawing 1.8 Clamping of the blank when the back surface is machined

In this operation, the bottom half cylindrical undercut surface is milled with a 6.35 mm (1/4 inch) end mill and a 3.175 mm (1/8 inch) ball mill.

1.4 Test and modification

While testing the preliminary processing plan using the CNC machine, a variety of problems were encountered. The following are the problems and corresponding modifications:

a. The profile of the part was not flat and smooth when it was cut and finished by the CNC for the first time. Many levels of parallel lines, or striations, could be seen along the part. The 19.05 mm (3/4 inch) end mill cut the whole profile level by level, and as a result striations were visible, which can be seen from photos below:

Illustration 1.1 Tool marks caused by multiple-level cutting

The conflict is, when cutting the block, it is inappropriate for milling cutter to move for only one loop to get a smooth surface, so it is necessary to let it cut material off by multiple levels to avoid being broken or breaking the block. Then there would be no allowance for finishing. The following approach was used to solve this problem: When setting parameters in the CAM program (UG NX) which generates the tool paths for the

CNC mill, the diameter of end mill was changed from 19.05 mm to 19.56 mm (0.77 inch) before the G-code was generated. However, a 19.05 mm (3/4 inch) end mill was still used to mill the profile, so there would be approximately 0.25 mm left after the end mill cut off most material. Then the same cutter run again with the flute covering the whole profile (from top to bottom) to cut the remaining material in a single pass. The resulting profile was flat and smooth.

Illustration 1.2 Contrast of processed surface (top: initial trial; bottom: final part)

b. There were triangular tool marks on the bottom of the triangular pockets, which resulted from using a 3.175 mm (1/8 inch) ball mill in finishing the bottom. A better part was made by using a 3.175 mm (1/8 inch) end mill cutting the flat part of the bottom of the pocket and a 3.175 mm (1/8 inch) ball mill cutting the fillets. The end mills used were in general stronger than the ball mills, so for all subsequent machining, end mills would be used more often for cutting off most material and ball mills only for final steps such as filleting or contour area milling. This modification resulted in faster material removal as well as reduced risk of breaking tools.

Illustration 1.3 Contrast of processed bottom (top: milled with ball mill; bottom: milled with end mill)

c. There were small steps on the sloped surface of this part shown in Illustration 1.5. Step-overs were reduced to solve this problem at the expense of longer machining time. For example, to reduce step-overs from “25% of the diameter of the tool” to “5% of the diameter of the tool” in UG NX settings could make the space between adjacent loops shorter but the time is quadrupled. Considering the shape the sloped surface, another machining option, “contour area mill” may have been more useful. Unlike cavity mill which cut off material level by level, contour area mill drives the tool to move along the periphery of the part and finish all the area in one loop. However, adopting this operation has a certain requirement: Most of the material needs to be cut off before contour area mill is used. Otherwise, when the tool is following the periphery, the material standing in its way may be too much for the tool to cut off at one time. As a result, the tool is easy to be broken. For this reason, this operation was not used to machine this feature. Further discussion, use and analysis will be stated later in this thesis.

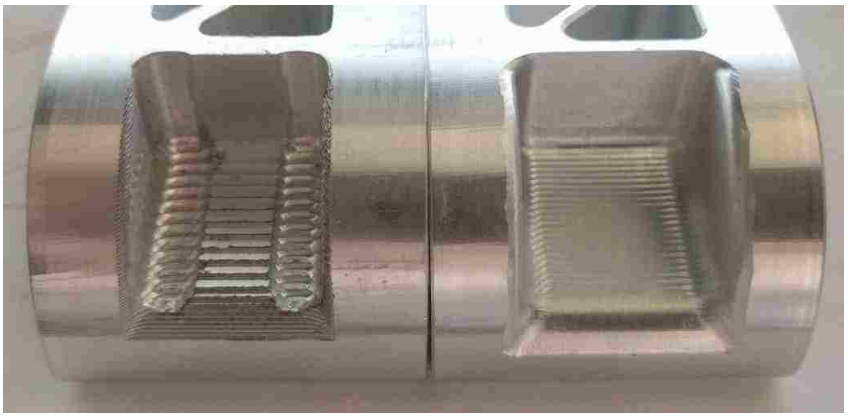


Illustration 1.4 Contrast of sloped surface processed with different step-overs

1.5 Complete processing route

The complete machining procedure is included in *Appendix A: Full processing route of Part 1*.

1.6 Future work

After reviewing the machining processes used for manufacturing two pieces of Part 1, it is clear that there are areas that could be improved. For example:

a. If properly placed, two parts could be cut from one block, which can save both material and time;

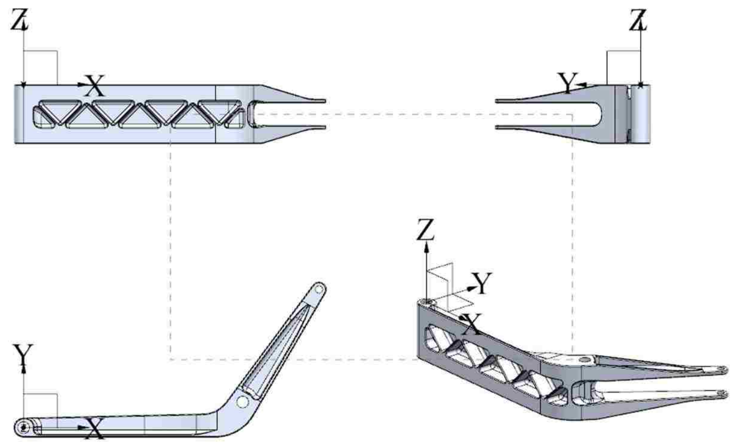
b. Contour area milling was not used when making the first part. The curved surfaces on the part processed by cavity milling could be processed better in less time by contour area milling

c. Reaming the two through-holes would have been preferred over drilling them.

Fortunately, in the subsequent work, the lessons learned could be put into practice to improve the process route.

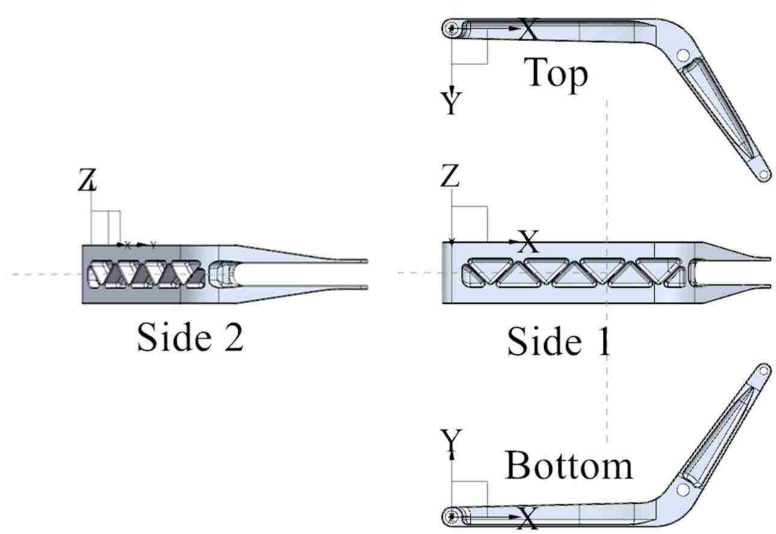
Part 2

2.1 Description of Part 2



Drawing 2.1 Three-view drawing of CAD model of Part 2

This part has some similarities with the first part, so it appeared reasonable to machine the part from four positions, which are named “top”, “bottom”, “side 1” and “side 2”.

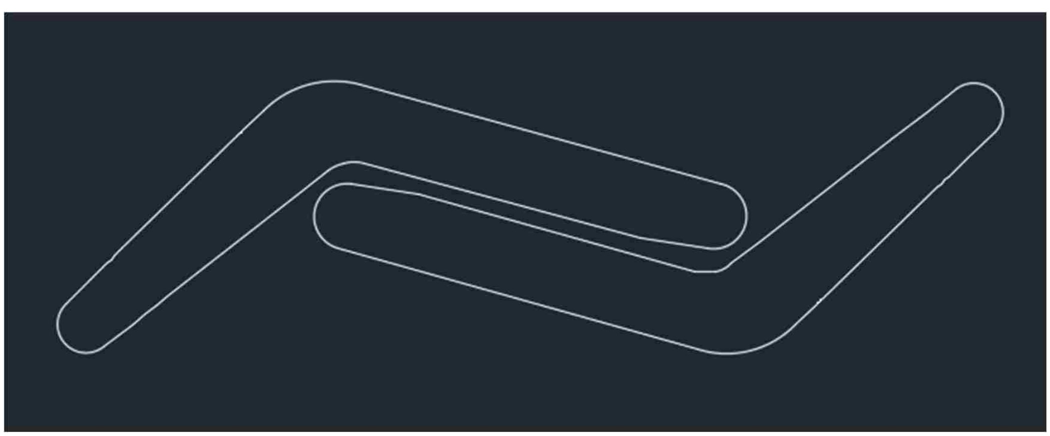


Drawing 2.2 Four positions for multiple steps of processing

Note that this part looks like a distorted “L”. In the bottom view in the drawing 2.2, the overall height of the part in the Y- direction is 105.45 mm (4.15 inch), which is measured in CAD model. This distance is longer than most tools used for processing this part. When a tool is milling the horizontal arm of the “L” from the top, the collet is likely to hit the other upturned arm. Considering that, a plate was required to fix the blank. There are many curved surfaces and smooth transitions on this part. Compared to the machining of the first part, more ball millings and contour area milling were used to finish the curved surfaces and transitions.

2.2 Determine the blank

Considering the profile of this part, “L” shape would waste a lot of material if each part were machined from one rectangular block. Therefore, two blanks were positioned as shown in Drawing 2.3. These two blanks have the same profile as the part but with an offset of 2~3 mm.

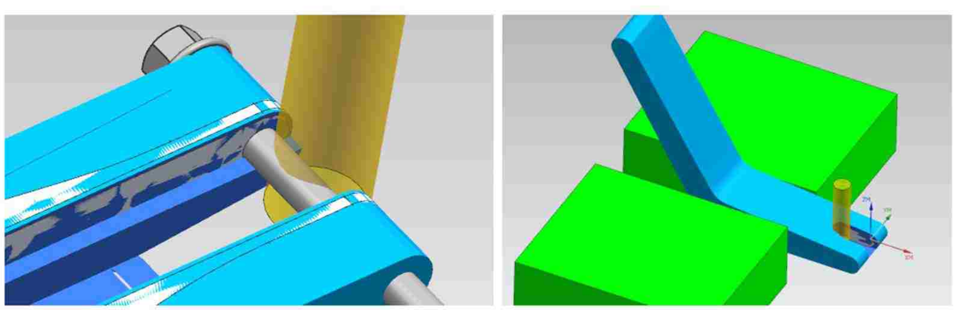


Drawing 2.3 Place two blanks in one block

The order of cutting is very important. If the two blanks were cut from a block without locating three holes, it would be difficult to locate the three centers of the holes on the blank because the profile of blank is not square and is hard to measure size from its sides. It is essential to locate and drill the three holes (six holes for two blanks) first. After this, the blanks were cut using an abrasive waterjet cutter.

When machining, a bolt was used to fix the “U” fork through the Φ5mm hole (the gray bolt shown in Drawing 2.4) to avoid the arms of the fork breaking off since the arms are long and slender. This bolt may interfere with the tool that is milling the slot in the “U” fork. This area is required to be machined beforehand to reserve space for the bolt, which is shown in Drawing 2.4 below. In this operation, the blank was clamped in the vise, and the tool only milled the top end of the fork.

Note: The tool could not move to the left too much otherwise the collet would touch the upturned arm damaging the part. To avoid this, travel to the left of the origin was limited to 28 mm for all tool path generation for this step.

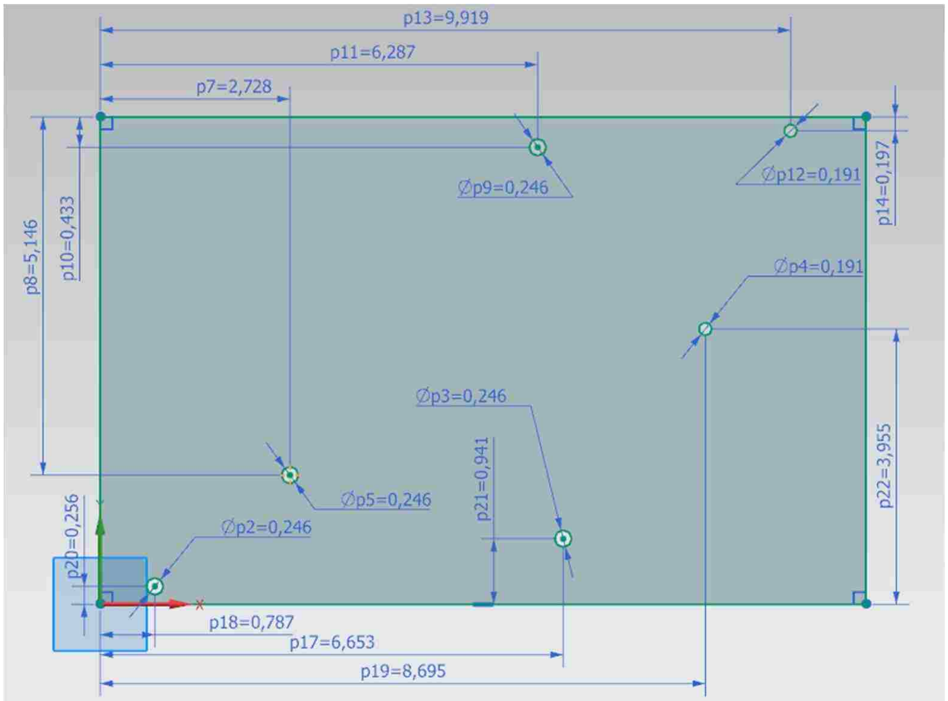


Drawing 2.4 Simulations of the end mill interfering with the bolt and the preparation work required to avoid this

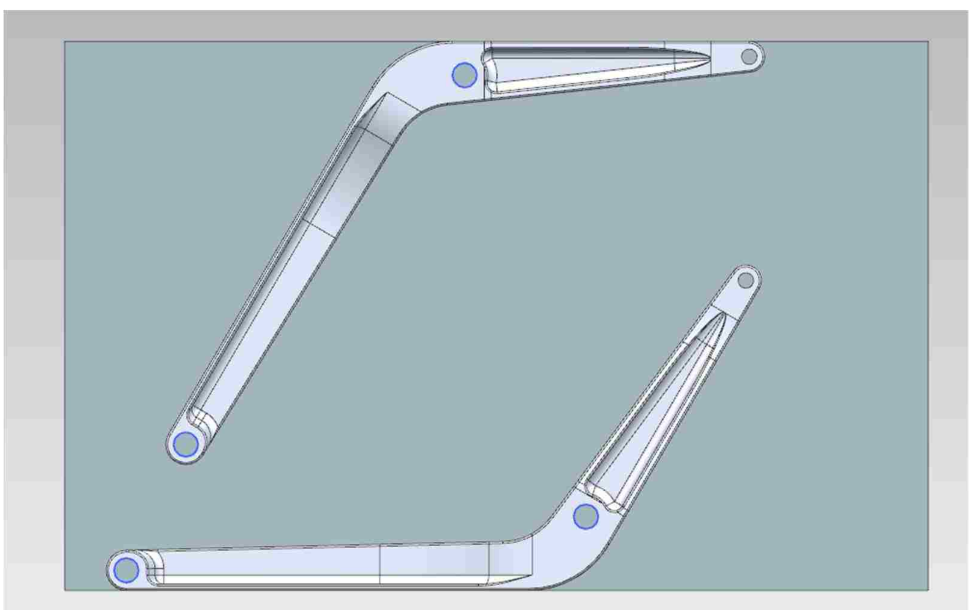
2.3 Determine preliminary processing route

Since the height of this part is more than that of the vise, for all the four positions, the vise cannot be used to grab the blank. When either arm of “L” is clamped in the vise horizontally and the other arm points up, the latter would become an obstacle to tool paths. As mentioned earlier, since the overall height of part is more than that of the vise, one arm cannot be clamped in the vise horizontally with the other arm pointing down. The latter may interfere with the foundation of CNC machine. Instead, a plate was used for the clamping as depicted in Drawing 2.4. The blank could be fixed on the plate with screws. Drilling three through-holes in the plate is enough for fixing the blank and machining the “top”, “bottom” and “side 1 (or side 2)”, but the last two operations cannot be processed in the same position. The reason is that the angle between two arms of “L” is not 90 degrees. Since the plate is square, when the part is placed on the plate with one of its arms parallel with one side of the plate, the other arm is not parallel with the adjacent side.

In this plate, two groups of through-holes were drilled. Each group has three through-holes corresponding to three holes in the part. One group is used for the “top” and “side 1” (the part below in Drawing 2.7), the other one is for the “bottom” and “side 2” (the part above in Drawing 2.7).



Drawing 2.5 Locations and diameters of two groups of location holes



Drawing 2.6 Sketch of how the part is located on the plate (the larger circles in blue are the Φ8mm holes used for location)

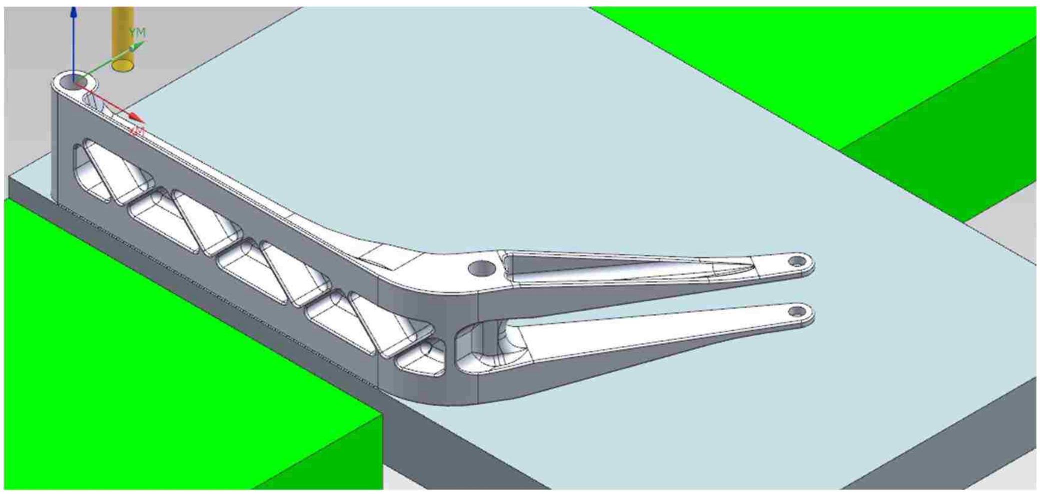
When the part is placed on the plate as shown in Drawing 2.6, the end of the arm of the "U" fork does not touch the plate and has to be supported to avoid breaking off. Three supports were turned using a manual lathe, which are shown in Illustration 2.1. The shorter one is applied between the plate and the part. The other longer two are for holding the slot. One of them has been tapped inside. These small cylinders, combined with a bolt and a nut, could meet the requirement of fixing for all the four positions. The left picture shows how to support the impending fork when processing the top and bottom surface. The shorter one supports the lower arm and the longer one supports the higher arm. Here the longer one is the one with thread that could tighten the bolt. Note that the bolt does not stick out of the upper surface otherwise it may interfere with tools. The right picture shows how to support the impending fork when processing "side 1" and "side 2". Especially, when tools are processing the "side 2", they engage in the direction perpendicular to the bolt. Both arms need to be supported. The bolt has to go through the long support in the middle (now it is the one without threads), stick out and be tightened by the tapped long support.

Illustration 2.1 Different combination of supports for different processing position

Since it takes four steps to machine all the part, multiple references and clamping methods were required:

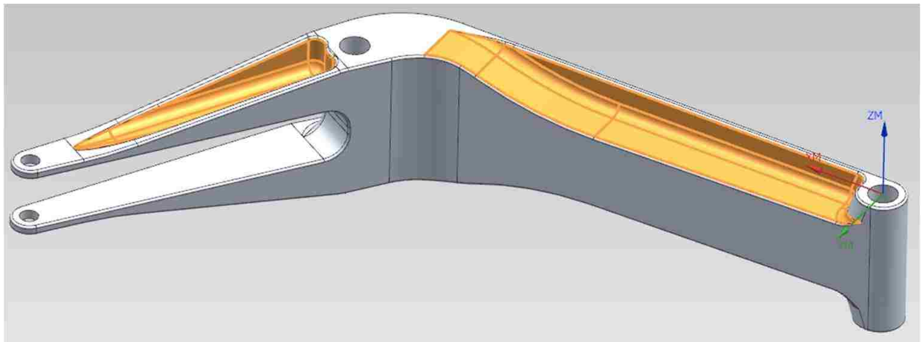
2.3.1 Machining the top surface

In this operation, the centers of two Φ8mm holes in the part are chosen for location as mentioned above. And the left center is chosen as the origin as shown below:



Drawing 2.7 Clamping of the blank when the top surface is machined

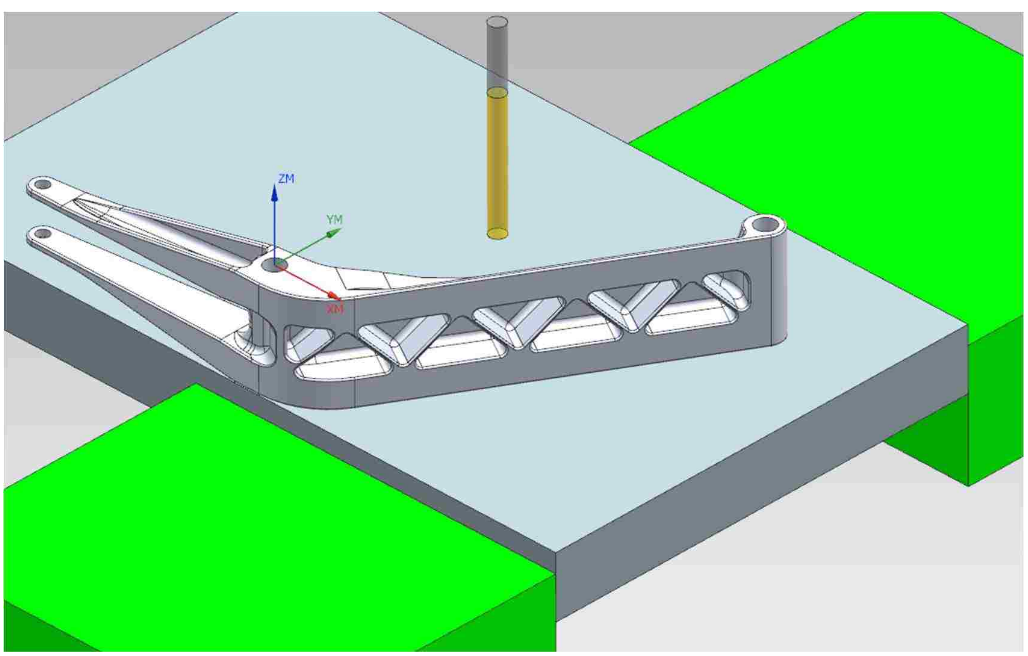
In this operation, the contour of the part is milled with a 19.05 mm (3/4 inch) end mill first. Then the “long slots” (see Drawing 2.8) on the top surface is roughly milled with a 9.525 mm (3/8 inch) end mill. Finally, the top surface is finished using contour area milling with a 4.7625 mm (3/16 inch) ball mill.



Drawing 2.8 Long slots on top surface (the same on bottom surface) marked in orange

2.3.2 Machining the bottom surface

In this operation, centers of holes are still used for location. The center of the right Φ8mm hole is chosen as the origin. After the top surface is processed, the blank is unbolted and removed. Then the other group of holes in the plate is used to locate and fix the blank, which is shown in Drawing 2.8:

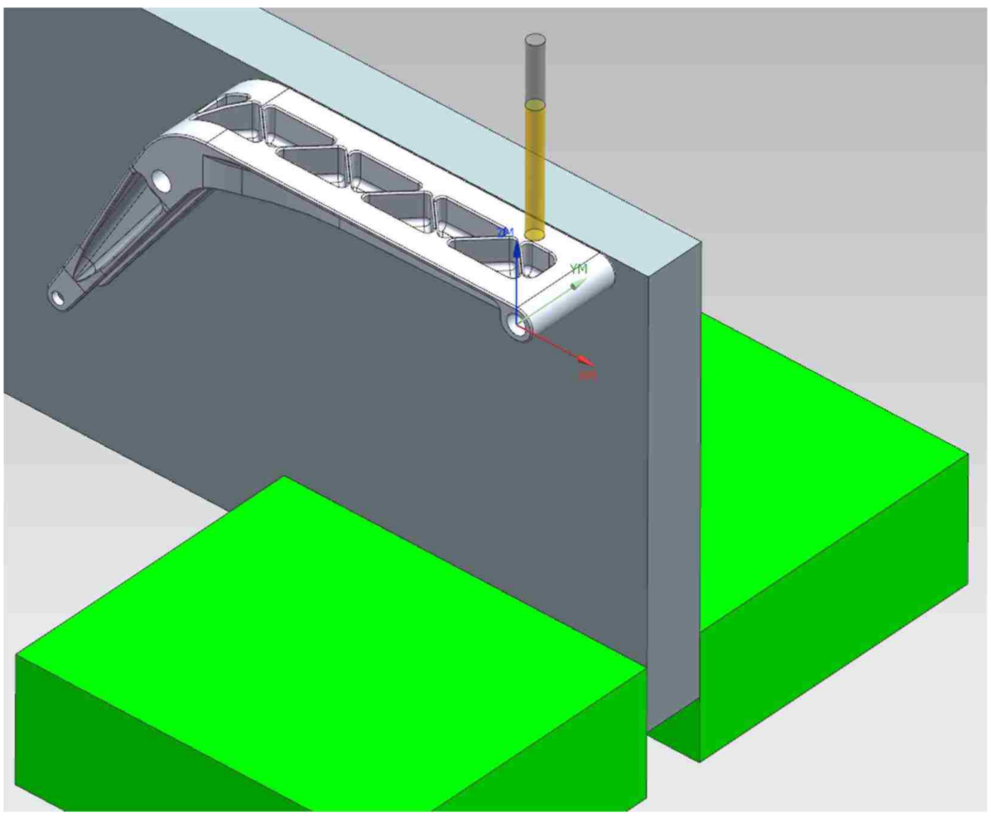


Drawing 2.9 Clamping of the blank when the bottom surface is machined

The process required to finish the bottom was the same as for the top, except that the profile did not have to be milled.

2.3.3 Machining the “side 1” surface

The blank is located and fixed in the same way as the top surface. However, in this operation, the plate is set up and clamped in the vise as shown below:

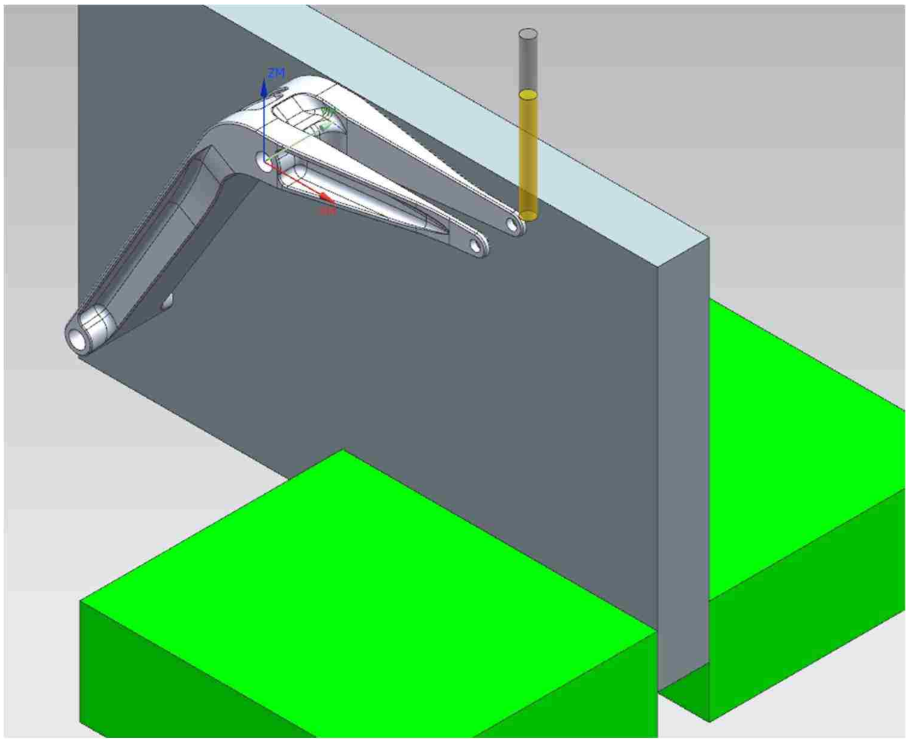


Drawing 2.10 Clamping of the blank when the “side 1” surface is machined

In this operation, the triangular holes are milled roughly with a 6.35 mm (1/4 inch) end mill and a 3.175 mm (1/8 inch) end mill. Then they are finished and chamfered with a 3.175 mm (1/8 inch) ball mill.

2.3.4 Machining the “side 2” surface

The blank is located and fixed in the same way as the bottom surface. However, in this operation, the plate is set up and clamped in the vise as shown below:



Drawing 2.11 Clamping of the blank when the “side 2” surface is machined

The remaining area of “U” fork (part of the fork has been processed before) and the slot near the fork are milled with a 12.7 mm (1/2 inch) end mill. Then the irregular slot is finished using contour area milling with a 3.175 mm (1/8 inch) ball mill.

2.4 Test and modification

When testing the tool path in CNC, there were no obvious problems. Two steps need to be paid attention to:

a. In the first operation, the technique applied on the first part could be used again to get a smoother profile. That is, set the diameter of end mill to 19.56 mm in UG NX and generate tool paths, but still use 19.05 mm (3/4 inch) end mill in actual processing;

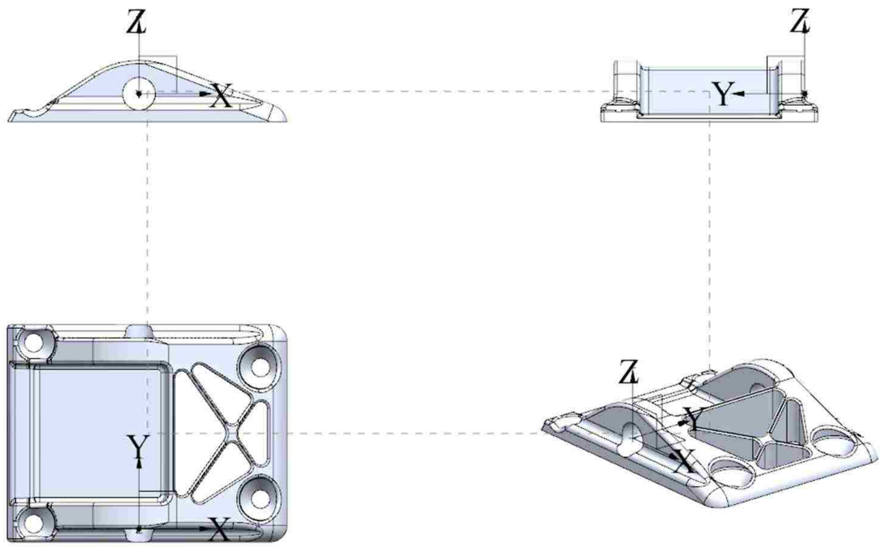
b. If 3.175 mm (1/8 inch) ball mill follows the 12.7 mm (1/2 inch) end mill in the last operation, the risk of breaking the tool still probably existed and the processing time was too long. Therefore, one operation "finish irregular slot with 1/4-inch ball mill" was added between these two operations. The risk was reduced while the time was shortened from 11 minutes to 5 minutes.

2.5 Processing procedure (complete route)

The complete machining procedure is included in *Appendix B: Full processing route of Part 2*.

Part 3

3.1 Description of Part 3

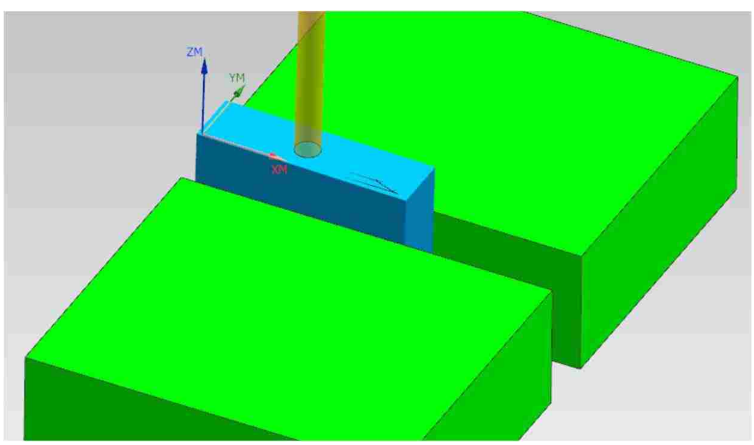


Drawing 3.1 Three-view drawing of CAD model of Part 3

This part is different from the first two parts. On the one hand, almost all the areas that need to be machined are on top of the part, which means there is no need to move or turn the blank when machining most areas. But on the other hand, there is no vertical wall around the part. It is difficult to grab the blank directly using the vise when the tool is processing four sides. Instead, the four slots and holes distributed on the part could be used for fixing the part. The whole machining process is a collection of cavity milling, contour area milling and planar milling. End mills cut off material in the center and ball mills were used when machining sloped surfaces and the four slots.

3.2 Determine the blank

The blank was cut by the same waterjet cutter used before and finished to 84.98 mm (3.346 inch) ×65.98 mm (2.598 inch) ×25.4 mm (1.000 inch) at the very start. The length and the width are the exact sizes of the model. However, the height turned out to be not appropriate in the following machining work. The flute lengths of required tools in the workshop were no more than 19.05 mm (3/4 inch). When cutting deeper, they (or collets) often hit the blank and break off. Even though longer tools which have 25.4 mm (1 inch) lengths of cut were ordered later, all the blanks were milled further until their heights are no more than 19.05 mm (3/4 inch) to ensure there is enough clearance to keep tools and the machine safe. Then the biggest hole that traverses the part in the Y direction was drilled with a “w” drill with the diameter of 9.80 mm (0.386 inch) and reamed by 10-mm reamer. This operation is shown below:



Drawing 3.2 Simulation of drilling and reaming the 10mm hole

This operation has to be finished separately and beforehand because only this operation required the tool engaged from the front surface while in all the other operations the tools engaged from the top of this part.

At last, four holes distributed on the part could be drilled using a 4.85 mm drill (#11 drill bit, 0.191 inch) which is smaller than the exact size because this preprocessing is for location and the holes would be machined to the exact size in a subsequent operation.

Illustration 3.1 Blank with location holes

3.3 Determine preliminary processing route

The whole process can be divided into two parts: “four corners” and “central part”. The order of these two operations is determined based on these two principles:

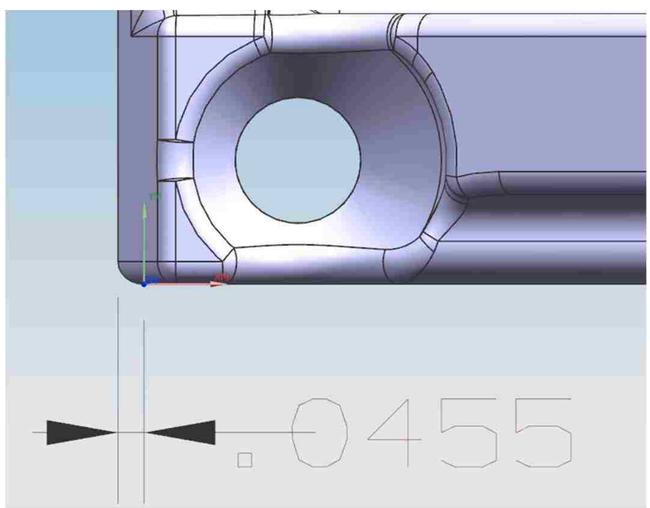
i. The less the blank is relocated, the better the tolerances will be;

ii. Being grabbed by a vise is more accurate than being fixed by screws.

Therefore, the “four corners” need to be processed first since the vise could be used when milling and finishing the “four corners” area. It will contribute to not only better machining effects of four corners but also more accurate location for the following process.

3.3.1 Machining the “four corners” surface

In this operation, one certain point is chosen as the origin. This point is an endpoint which is selected at the bottom of the front surface on the CAD model, the projected distance from the left side is 1.156 mm (0.0455 inch).



Drawing 3.3 Top view of the position of the origin [The blue point, on the front side, 1.156 mm (0.0455 inch) from the left side]

The blank was grabbed by the vise. It is worth noting that the left of blank is exposed without covering by the jaw of the vise to let tools reach and process the two slots and holes on the left, which is shown below:

Illustration 3.2 Grab part of the blank to make room for processing slots

Firstly, four slots are milled with a 6.35 mm (1/4 inch) end mill and semi-finished with a 3.175 mm (1/8 inch) end mill. Then they are finished with a 6.35 mm (1/4 inch) ball mill and a 3.175 mm (1/8 inch) ball mill using contour area milling.

3.3.2 Machining the “central part” surface

The blank is located in the same way as the first operation. A plate is required to fix the blank in this operation. The length and width of the plate are no longer than those of the part to avoid the pointed end of tools when they engage deeply and cut the sides of the blank.

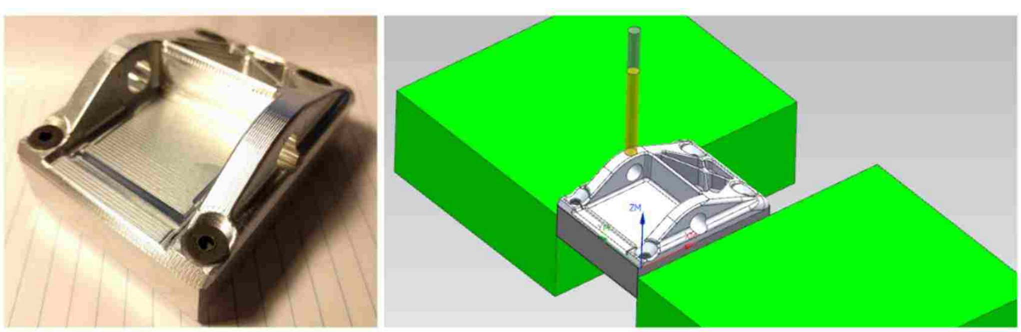


Illustration 3.3 Use 82-degree countersunk screws to fix blank on the plate

Similarly, the "central part" is milled with a 6.35 mm (1/4 inch) end mill and semi-finished with a 3.175 mm (1/8 inch) end mill first. Then it is finished with a 6.35 mm (1/4 inch) ball mill and a 3.175 mm (1/8 inch) ball mill using contour area milling.

3.4 Test and modification

After following the route above to process the blank in CNC, some problems appeared:

a. The "cutting pattern[2]" of end mills were set to "follow periphery" in UG NX. When milling the sloped surface, they left such tool marks like steps parallel to the short side of the blank. In the following operation "contour area milling", tool paths of ball mills were set to "follow periphery" in the initial test. The ball mills move along the similar tracks with smaller step-overs. As a result, tool paths of end mills and ball mills would have overlaps and some steps left by end mills could not be finished by the ball mills, which can be seen on the left of picture below; To mitigate this condition, the "cutting pattern" of ball mills were set to "zig-zag", which would let tools move along such paths perpendicular to previous tool paths of end mills and clear away more remaining material.

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[2] When inserting operations in CAM software (UG NX), there is an important setting called "cutting pattern". It defines what kind of path the tool moves along when cutting off material from the blank. For example, by choosing "follow periphery", the tool cut the blank along the periphery of the part. Choosing "zig-zag" makes the tool reciprocate.

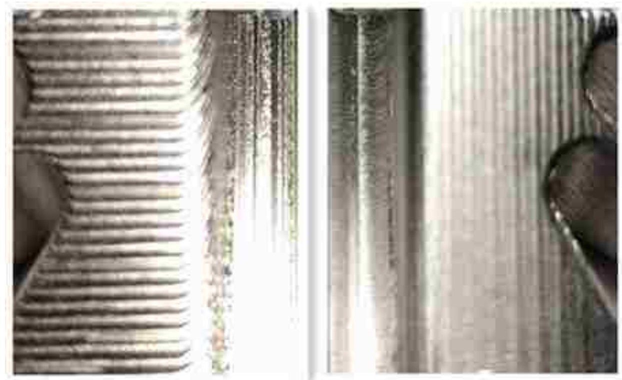
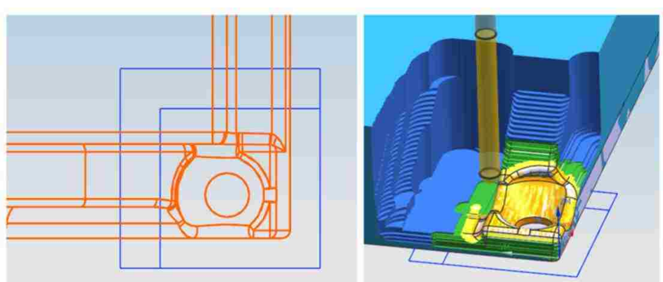


Illustration 3.3 Contrast of processing effect on the sloped surface (left: “follow periphery”; right: “zig-zag”)

b. To address the possiblity that smaller tools may hit walls and break off when finishing the four slots, two different kinds of “trim boundaries[3]” were set, which are shown as blue squares in Drawing 3.4 below: The bigger square confined the area showed in deep blue where 6.35 mm (1/4 inch) end mill cut and the smaller square confined the area showed in green and yellow where 3.175 mm (1/8 inch) end mill, 6.35 mm (1/4 inch) ball mill and 3.175 mm (1/8 inch) end mill cut. When smaller tools are milling the slot, there is safe clearance between the tools and walls around them



Drawing 3.4 Two trim boundaries for different tools

[3] “Trim boundaries” is another useful setting in UG NX. The tool is confined in a defined area. Only material inside the area could be cut off.

After finishing the four slots, 82-degree countersunk screws were used to fix the blank, and the central part was milled and finished without relocation. Here it is important to set “trim boundaries” to keep tools away from the screws. The difference between these two kinds of processing sequences can be seen from the comparison below:

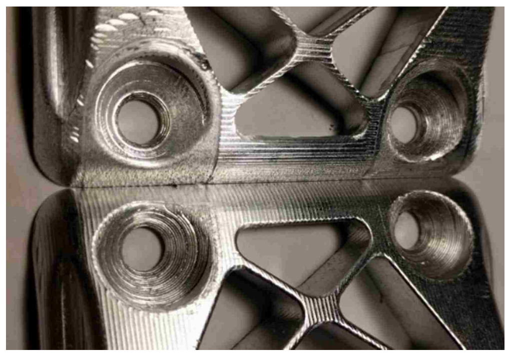


Illustration 3.4 Contrast of transition between two cutting areas with different processing order (top: older route; bottom: modified route)

3.5 Processing procedure (complete route)

The complete machining procedure is included in *Appendix C: Full processing route of Part 3.*

3.6 Future work

Here is another plan to process Part 3:

a. Select a thick block as the blank, with a height of more than 35 mm, that is, the height of one part plus 15 mm;

b. Grab the lower part of this block with a vise and process all areas on the top;

c. Cut the processed half from the blank.

Although this plan may cause some waste of material, a better part would be expected.

This plan is worth putting into effect if there is suitable material and enough time.

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1) Haas Automation, Inc. USA. (2015). Pocket Guide and Reference Charts for CNC Machinists. Oxford, CA: Haas Automation, Inc. USA.

2) Peter Smid. (2003). CNC Programming Handbook, 2nd Edition. New York: Industrial Press Inc.

3) Franklin D Jones, Henry H Ryffel, Erik Oberg, Christopher J McCauley, Ricardo M Heald. (2004). Machinery's Handbook, 27th Edition (Toolbox Edition). New York: Industrial Press Inc.

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Appendix A: Full processing route of Part 1

Po.	Step no.	Step	Tool no.	Tool	RPM	Feed rate (ipm)	Stepover	Depth of Cut	Comment
1	1	spot drill in the location of two Φ8mm holes	T2	Spot drill	1400	4.2			
	2	drill holes for location and fixing	T3	#3 drill	2700	10.2			
2	1	cavity mill profile by levels	T4	3/4-in end mill	5000	40	25%flat	10%tool	set diameter of tool as 0.77
	2	mill profile in one loop				40	10%flat	10%tool	
	3	roughly mill triangel holes	T7	1/4-in end mill	12000	48	25%flat	10%tool	
	4	semi-finish corners	T5	1/8-in end mill	12000	48	10%flat	10%tool	
	5	finsh corners		3/16-in ball mill	12000	36	10%flat	10%tool	contour area mill prefered
	6	chamfer	T19	3/8-inch drill	12000	16.8	50%flat	0.25 in	
3	1	roughly mill triangel holes	T7	1/4-in end mill	12000	48	25%flat	10%tool	
	2	semi-finish corners	T5	1/8-in end mill	12000	48	10%flat	10%tool	
	3	finsh corners		3/16-in ball mill	12000	36	10%flat	10%tool	contour area mill prefered
	4	chamfer	T19	3/8-in drill	12000	16.8	50%flat	0.25 in	
4	1	roughly mill top half cylinder and slope	T13	1/4-in ball mill	12000	48	25%flat	10%tool	
	2	roughly mill triangel through-holes	T7	1/4-in end mill	12000	48	25%flat	10%tool	
	3	finish triangel through-holes	T5	1/8-in end mill	12000	48	25%flat	10%tool	
	4	finsh top half cylinder and slope	T11	1/8-in ball mill	12000	48	5%flat	5%tool	contour area mill prefered
	5	chamfer triangle through-holes	T19	3/8-in drill	12000	16.8	50%flat	0.25 in	
5	1	roughly mill bottom half cylinder	T13	1/4-in ball mill	12000	48	25%flat	10%tool	
	2	finish bottom half cylinder	T11	1/8-in ball mill	12000				contour area mill prefered
	3	chamfer triangle through-holes	T19	3/8-in drill	12000	12		0.04 in	manual operation (front & back are not parallel)
6	1	manual drill Φ8mm holes to exact diameter		8mm drill	1400				reaming preferred if possible

Appendix B: Full processing route of Part 2

Pos.	Step no.	Step	Tool no.	Tool	RPM	Feed rate (ipm)	Stepover	Depth of Cut	Comment
1	1	spot drill in the location of two Φ8mm holes	T2	Spot drill	1400	4.2			
	2	drill holes for location and fixing	T3	#3 drill	2700	10.2			
	3	spot drill in the location of Φ5mm holes	T2	Spot drill	1400	4.2			
	4	roughly drill Φ5mm holes	T12	#12 drill	3000	9			
	5	drill the hole to the exact diameter	T13	5mm drill	1400	8.4			reaming preferred if possible
	6	cut the blank along outline		water jet					0.1-0.2 in offset
2	1	mill the top of "U" fork	T9	1/2-in end mill	4600	27.6			G-code is written by hand
3	1	cavity mill profile by levels	T4	3/4-in end mill	5000	40	25%flat	10%tool	set diameter of tool as 0.77
	2	mill profile in one loop				40	25%flat	10%tool	
	3	roughly mill long slots on top	T8	3/8-in end mill	12000	36	25%flat	0.1 in	
	4	finish top	T12	3/16-in end mill	12000	48	25%flat		
4	1	roughly mill long slots on bottom	T8	3/8-in end mill	12000	36	25%flat	0.1 in	
	2	finish bottom	T12	3/16-in end mill	12000	48	25%flat		
5	1	roughly mill triangel holes	T7	1/4-in end mill	12000	48	0.05 in	0.05 in	
	2	semi-finish corners	T5	1/8-in end mill	12000	48	0.05 in	0.05 in	
	3	finsh and chamfer	T11	1/8-in ball mill	12000	48	0.01 in		
5	1	roughly mill "U" fork	T9	1/2-in end mill	10000	40	50%flat	0.05 in	specify trim boundaries to avoid the bolt
	2	semi-finish slot	T13	1/4-in ball mill	12000	48	0.01 in		
	3	finsh slot	T12	1/2-in ball drill	12000	48	0.01 in		
6	1	manual drill Φ8mm holes to exact diameter		8mm drill	1400				reaming preferred if possible

Appendix C: Full processing route of Part 3

Pos.	Step no.	Step	Tool no.	Tool	RPM	Feed rate (ipm)	Stepover	Depth of Cut	Comment
1	1	spot drill in the location of Φ10mm hole	T2	Spot drill	1800	3.6			
	2	drill holes	T3	"w" drill	1400	8.4			
	3	ream to the exact size	T4	10 mm reamer	730	7.3			
2	1	spot drill in the location of four Φ5.6mm holes	T2	Spot drill	1800	3.6			
	2	drill holes for location and fixing	T6	#11 drill	3000	10.5			
	3	roughly mill four slots	T7	1/4-in end mill	7500	30	0.01scallop	0.01scallop	pay attention to clamping and trim boundaries
	4	semi-finish corners	T5	1/8-in end mill	7500	15	0.003scallop	0.003scallop	
	5	finish most areas in slots	T13	1/4-in ball mill	7500	30	0.0005scallop		
	6	finish corners	T11	3 mm ball mill	7500	15	0.0005scallop		
3	1	roughly mill central part	T7	1/4-in end mill	7500	30	0.025scallop	0.025scallop	pay attention to avoid screw caps
	2	semi-finish central part	T5	1/8-in end mill	7500	15	0.0125scallop	0.0125scallop	
	3	finish most areas in central part	T13	1/4-in ball mill	7500	30	0.0005scallop		
	4	finish corners and fillets	T11	3 mm ball mill	7500	15	0.0005scallop		

Vita

Longfu Hu was born in Wuhu, Anhui Province, China. Between 2010 and 2015 he studied Mechanical Engineering and Japanese at Dalian University of Technology in Dalian, China. Then he entered into P.C. Rossin College of Engineering and Applied Science of Lehigh University to pursue his Master of Science degree. His research area is CAD/CAM and process design.